Developing a measuring & monitoring strategy for dikes reinforced with innovative anti-piping filter solutions

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Developing a measuring & monitoring strategy for dikes reinforced with innovative anti-piping filter solutions

by

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Cover Image: BZIM stock photo of a dike with sheep (BZIM, 2023)

Preface

Before you lies my Master Thesis, ‘Developing a measuring & monitoring strategy for dikes reinforced with innovative anti-piping filter solutions’. This MSc thesis was carried out to graduate for the degree of Master of Science in Civil Engineering & Management with the integrated profile Civil Engineering Structures. I carried out this research between February and August 2023 at BZ Ingenieurs & Managers at the request of water board Hoogheemraadschap De Stichtse Rijnlanden.

I found the research topic to be challenging, but I am definitely proud of the result presented here, and I have learned a lot about this relatively new research topic. I received much support from people around me, and therefore, I would like to thank my girlfriend, friends and family. I would also like to take the opportunity to thank Peter van Dijk for his excellent guidance as my daily external supervisor and for our weekly meetings, which always proved very helpful. At the University of Twente, I was supervised by Johan Damveld, whom I would like to thank for his superb feedback and outstanding supervision. I also would like to thank Jord Warmink, Head of the graduation committee, for his feedback that helped me improve my thesis scientifically. Furthermore, I would like to thank Wouter Zomer for providing the opportunity to do this research at BZIM and for sharing his expertise on the subject of dike monitoring. Finally, I would like to thank Paul Neijenhuis from HDSR for providing the opportunity, resources and contacts to perform my master’s thesis successfully on such a relevant research topic.

During the research, I conducted multiple interviews, which were very interesting conversations that were very important for my research and from which I learned a lot. Therefore, I would like to thank Eric van der Tas and Ruud Weijs from HDSR, Andre Koelewijn from Deltares and Martin van der Meer from Fugro for taking the time and participating in the interviews conducted.

I hope you enjoy reading my work and hope that it may provide some valuable insights!

Kevin Vermeulen
Enschede, August 2023

Summary

Problem – Backward Internal Erosion Piping, called piping in the Dutch context, is a dike failure mechanism caused by a process by which seepage forces gradually erode cohesionless material from the foundation of dikes, thereby forming shallow pipes at the interface of the granular material and a cohesive cover layer. One new innovative type of reinforcement measure to increase the resistance of a dike to the piping failure mechanism are filter solutions. These solutions work by blocking the soil particles in the seepage paths with an erosion-resistant permeable filter, preventing the formation of a full-grown pipe erosion channel. The purpose of an erosion-resistant filter is to prevent erosion while also enabling the discharge of seepage, unlike anti-piping heave screens, which do not enable seepage of discharge. HDSR, a water authority with dikes, is implementing a new innovative filter screen solution as part of a pilot project. While HDSR as a water manager with dikes, is experienced with piping as a failure mechanism, with implementing these innovative filter screens, there is no experience. Given the innovative nature of these filter screens, long-term monitoring might be an option for HDSR to implement and increase confidence in the chosen filter screen solution. Relevant knowledge on how a monitoring plan can be created to monitor the long-term functionality of a filter solution is lacking, and additionally, it is unclear how the three different filter solutions available, vertically inserted geotextile, course sand barrier and Prolock, differ from each other in monitoring possibilities. As water manager with dikes, HDSR, therefore, desires an improved understanding of the long-term risks of failure of the various anti-piping filter solutions and the role of monitoring in risk mitigation in order to ultimately develop and manage measuring & monitoring systems to monitor the continued functionality of a filter throughout the management life cycle phase of a dike.

Goal – In this research, a measuring & monitoring strategy for innovative anti-piping filter solutions is developed. A measurement and monitoring strategy should be able to provide insight into the continued functionality with regard to piping of the filter screen during the management life cycle. The research is requested by HDSR and is, therefore, the primary stakeholder of this research. The target group, in general, are water managers of dikes (to be) reinforced with an anti-piping filter screen. HDSR is a part of this target group as; currently, the Sterke Lekdijk is to be reinforced with a new filter screen solution Prolock. This study is requested by HDSR as a second opinion for the designed monitoring plan, while they also wish to gain insight into the different filter solutions available and differences in monitoring these filters: Vertically Inserted Geotextile, Course Sand Barrier, Prolock. The following research goal has been formulated: To design a measurement & monitoring strategy to monitor the continued functionality of a filter as an anti-piping measure during the management life cycle phase of a dike.

Methododology – This research consists of a design problem, and therefore, an appropriate iterative design cycle methodology is chosen. While the methodology is theoretically iterative, only one complete iteration has been performed. The methodology consists of three (iterative) phases, problem investigation, where a theoretical framework is established. Additionally, the target group is interviewed to set up the requirements of measurement & monitoring strategy within its intended problem context: creating location and filter-specific measurement & monitoring plans for innovative anti-piping solutions by the target group (water managers with dikes). The second phase is the design phase, where using the results of the problem investigation and an analysis of the different filters, failure modes and monitoring options, a monitoring strategy is designed. In the final iterative phase, the validity of the final design product is assessed through verification of design requirements, target group satisfaction and expert opinion interviews.

Results and discussion – The final result can be captured in one large diagram as part of a monitoring strategy. The essence of this diagram is that when assessing possible monitoring options, these are measures part of many different measures taken or assumptions made to decrease the failure of the filter. With consideration of all these measures/assumptions that may or may not have been taken and the project and site-specific circumstance, a well-considered decision can be made for implementing a monitoring option. The diagram shows which causes of failure monitoring can contribute to their risk reduction, as well as insight into the differences and similarities between the three different filters. The failure scenarios are also a way of making many different causes of failure comprehensible, requiring reading through all documentation or having extensive knowledge of all three filters. One of the main discussion points of this research is that according to expert opinion the final monitoring options listed may currently not always be practically feasible due to unfavourable cost-benefits ratios or measurement uncertainties. However, as also stated during expert opinon sessions, this a current temporary problem as monitoring technologies are expected to improve on all aspects, such as costs and accuracy, in the future. Additionally, due to the filter generic approach, without location and project-specific circumstances, no definitive recommendations on monitoring can be made. However, a the resulting design result, an extensive diagram makes the different failure modes of filter solutions, the differences in these for the three filters, the different risk mitigation measures available per life phase and the monitoring possibilities during the management phase all have been made insightful and comprehendible for water managers with dikes, which is the main added value of this diagram and study.

Conclusion – It can be concluded that the monitoring strategy and associated diagram are of added value when drawing up a monitoring plan for the various filters. It contains information relevant to a dike manager, and the diagram is logically structured. An important conclusion from the iterative process is that a systematic understanding of how a filter functions, the failure scenarios and the corresponding risk mitigation measures are essential to arrive at a well-founded measuring & monitoring strategy. These aspects are therefore highlighted in the monitoring strategy and diagram.

Keywords: Dikes, Backward Internal Erosion Piping, Filter Screen Solutions, Anti-piping Filters, Vertically Inserted Geotextile, Course Sand Barrier, Prolock, Measuring & Monitoring Strategy, Failure risk mitigation

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1

Introduction

In this first chapter, the research topic of the MSc thesis is introduced by providing background on the related sub-topics, following this the problem context, research goal, objectives, questions and scope are formulated.

1.1. Background

1.1.1. Flood Protection & Dikes

Dikes are an essential component of flood protection systems, and their proper functioning is critical for the safety of communities near rivers and coastlines. In the Netherlands, a significant portion of 59% of the land is at risk of flooding. Floods are among the most destructive disasters that can occur in the country and have major consequences. While the probability of flooding has significantly declined, the risk persists, and the potential consequences would be severe, especially given that a large portion of 70 % of the total Dutch population lives in areas prone to flooding. Additionally, the population in these at-risk areas is growing rapidly (PBL, 2023). Dikes are flood protection systems that mostly serve one of these two main functions: prevent fluvial floods (river floods) and coastal floods (storm surges). With regard to fluvial floods, 29% of the Netherlands is susceptible to river flooding (Solomon et al., 2007).

In the Netherlands, there has recently been a fluvial flood in the provinces of North Brabant and Limburg during the summer of 2021. According to international sources, the total material damage attributed to the flood is estimated between €350 and €600 million (TaskForce Fact Finding hoogwater 2021, 2021). An economic impact assessment of future floodings in the Netherlands projects that moderate flooding (50 cm) and severe flooding (>200 cm) would have a GDP impact of -1.5 to -3% in the year of the flood. And while the probabilities of flooding remain small to extremely small, they are rising (Abcouwer et al., 2020).

The Dutch government is tasked with protecting the Netherlands, now and in the future, from flooding. In addition, the government is working on a climate-proof and water-robust design for the country. The national Delta Program sets out how the government is cooperating to accomplish this with provinces, municipalities and water boards (Rijksoverheid, 2023). The water boards manage and maintain almost all of the primary flood defences, of which a large portion are river dikes (Unie van Waterschappen, 2023). Primary defences directly protect the hinterland from flooding. To ensure the safety and functioning of primary flood defences, standards are established by law in Appendix II of the Water Act. This act establishes that primary flood defences must be assessed every 12 years for safety. Additionally, it is established by the act that dike managers have a duty of care, meaning they are obliged to maintain and inspect the dike for their safety. (Waterwet, 2021).

1.1.2. Piping

In ensuring the safety of dikes, one needs to consider that dikes can be subject to various types of damage, including erosion, settlement or overtopping, which can reduce their effectiveness and eventually cause the failure of a dike. Several types of mechanisms are defined that can lead to dike failure. One such mechanism is piping, mostly occurring when levees are exposed to prolonged high water with only slightly varying water levels. Therefore river dikes are most at risk of the piping failure mechanism compared to sea dikes (’t Hart, 2018). Failure due to piping is the result of a process by which seepage forces gradually erode cohesionless material from the foundation of dikes, thereby forming shallow pipes at the interface of the granular material and a cohesive cover layer (Robbins & van Beek, 2015). In the national Dutch flood risk analysis in 2016, it was found that piping plays a much greater role in the probability of flooding and flood risk than overflow and overtopping (Vergouwe et al., 2016).

The Dutch Water Act requires water managers (Rijkswaterstaat and the water boards) to properly manage and maintain the flood defenses, which is called the duty of care (Waterwet, 2021).This includes regular dike inspections mandatory dike safety assessments. As a result of a dike assessment as part of the duty of care, dikes can be determined to be at risk of piping. The methods and norms for such an assessment are included in the law and described in the Statutory Assessment Instruments 2017 (de Waal, 2016). Assessment methods are included in determining the risk of piping and are also useful in assessing dike reinforcement designs. A probability of flooding on account of piping that is not negligible as the outcome of an assessment will lead to a rejected design or, in the case of an existing dike, require intervention (de Waal, 2016). A revised calculation rule to determine the piping risk included in the new standard WBI 2017 has great consequences. The research found that of 940 km of dikes reviewed, approximately 540 km do not satisfy this new calculation rule at the time. As a result, during assessment rounds of river dikes, many dikes will be rejected and need to be reinforced in the coming years. (Arcadis, 2012).

1.1.3. Anti-piping Filters

To reinforce a dike and reduce the risk of piping, the development of a continuous pipe beneath the dike should be impeded. This risk of piping can be decreased by dike reinforcement or intervention measures such as drainage solutions or impermeable sheet pile screens (van Beek, 2017). In recent years, dutch market parties have come up with new innovative piping solutions. Innovative piping solutions are still in various stages of development or implementation. Overall, these solutions are not yet widely implemented and tested (Wiggers et al., 2019). One type of innovative solution is a filter screen; these work by blocking the soil particles in the seepage paths with an erosion-resistant permeable filter, preventing the formation of a full-grown pipe. The purpose of an erosion-resistant filter is to prevent erosion while enabling the discharge of seepage. This is one benefit of implementing a filter solution as opposed to an impermeable sheet pile wall. Another benefit of a filter is that, unlike a dike reinforcement, a filter does not require space above ground level. For a filter to work properly, it should be sand-tight and be more permeable than the subsoil. Three types of filters currently exist: Vertically Inserted Geotextile (VIG), the Course Sand Barrier (CSB) and the Prolock Filter screen. The VIG works through perforations in geotextile to provide erosion resistance and permeability. The Course Sand Barrier is a granular filter that provides erosion resistance and permeability through coarser filter sand than the surrounding soil. The Prolock filter is essentially a combination of a geotextile filter and a granular filter, as the filter consists of plastic perforated filter tubes with filter sand.

To guarantee the calculated safety of a dike with an anti-piping filter, failure of the filter itself should be avoided or be timely detected to repair before high water occurs. Extensive efforts are therefore made to avoid or timely detect the impending failure of a filter via various measures during the different life cycle phases of a dike system with a filter: design, implementation and management (van Beek, 2017). The duty of care of water managers for the embankments is also affected by installing a filter solution. If a sand boil, the starting point of a pipe, is observed downstream of the filter during a visual inspection as part of a water manager's duty of care; it would theoretically not pose a threat as the filter blocks the development of continuous pipe. However, without insight into the subsurface, the assumption of proper filter functioning relies mostly on appropriate design and implementation. Monitoring can be an addition to the duty of care of water managers by providing more continuous insight into the functional performance of a filter. Meaning chances of timely appropriate intervention, as part of the duty of care of the water manager, can be increased by monitoring (van der Kolk et al., 2011).

1.1.4. Measuring & Monitoring of Piping

Measuring & monitoring of embankments is defined as the entirety of time-dependent, where necessary, repeated measurings of a water barrier and the processing thereof to be able to make well-founded decisions about changes with regard to the water barrier, its management or the monitoring itself (van den

Berg & Koelewijn, 2014). The use of monitoring techniques can be useful in different phases of a dike's life cycle. Monitoring data in all phases, including management and maintenance, can reduce uncertainties and make better use of these in dike management (van Beek, 2017). In the Netherlands, 'Stichting IJkdijk FloodControl' has conducted various validation experiments between 2008 and 2014, aiming to test the applicability of measuring and monitoring techniques in susceptible levees to different failure mechanisms (de Vries et al., 2013). It was concluded that with the use of monitoring techniques, piping could be monitored and even be followed in real-time and predicted (Koelewijn et al., 2010). A proof of concept of detecting piping by monitoring has been done by successfully applying proven monitoring systems in practice in the 'LiveDijk' projects (Nieuwenhuis et al., 2016). In 2015, research was conducted for the first time on monitoring the functionality of a filter screen. At that time, it was concluded that monitoring the functionality of a vertical sand-tight geotextile screen as a preventive measure under normative conditions was largely achieved (Koelewijn, 2017)

Over the past decade, dike monitoring has evolved from an idea to a concept with established methodologies. In several (pilot) projects, including FloodControl IJkdijk, the value of the application of dike monitoring has been demonstrated. While there are many types of monitoring purposes, the general purpose of monitoring is to identify and explain key developments at an early stage in order to take timely corrective action.(de Vries et al., 2013). This likewise applies to monitoring the functionality of anti-piping filter screens.

1.2. Problem Context

Currently, relevant knowledge on how to create and implement monitoring strategies among water managers with dikes is often lacking (Zomer et al., 2019). While water managers with dikes are evidently experienced with piping as a failure mechanism, implementing a monitoring strategy as failure risk reduction of a filter requires extensive knowledge of these filters and their failure modes, which given the innovative nature of these filters, is not very prevalent among water managers with dikes. Consequently, how can long-term monitoring assist water managers with dikes in mitigating the risk of anti-piping filter failure? Additionally, three different filter solutions have been created in recent years. This poses the question of how these filters differ from each other in their functionality and failure modes. And what is relevant to monitor for these filters in the long term? And how can this be monitored?

These raised questions are also relevant for Hoogheemraadschap De Stichtse Rijnlanden as they are currently planning to implement the new Prolock filter solution in a pilot project Salmsteke. As the involved water board and water manager with dikes, they underline the necessity of a measuring & monitoring strategy to validate if the innovative anti-piping measure actually functions as intended and to decrease the dike failure risk due to filter failure. This study is requested by HDSR to investigate a measuring & monitoring strategy, independentely from of the Prolock pilot, while they also wish to gain insight into the different filter solutions available and differences in monitoring these filters.

The following problem statement is defined: *As water manager with dikes, HDSR desires an improved understanding of the long-term risks of failure of the various anti-piping filter solutions and the role of monitoring in risk mitigation in order to ultimately develop and manage measuring and monitoring systems to monitor the continued functionality of a filter throughout the management life cycle phase of a dike.*

1.3. Research Goal

Based on the problem context described in the previous section and the formulated problem statement, the research goal is:

To develop a measuring & monitoring strategy to assist dike managers with creating measuring & monitoring plans to monitor the continued functionality of a filter as an anti-piping measure

Here a measuring & monitoring strategy (M&M) is defined as a tool to aid in creating a monitoring plan and system that, unlike the strategy itself, is specific to a filter and location.

1.4. Knowledge Questions & Design Objectives

Given the design objective stated in the previous section, an appropriate design methodology is chosen, elaborated in the next chapter. Given this design methodology, two knowledge questions and three design objectives can be formulated (Wieringa, 2014):

Knowledge questions:

1. How do the various filters work in their function to prevent dike failure by piping and what could cause these filters to fail in this?
2. How can monitoring provide insight into the functionality of a filter, thereby reducing the risk of dike failure due to failure of a filter, and how does this differ for each filter?

Design objectives:

a. To investigate the requirements of measuring & monitoring strategy within its intended problem context: *creating location and filter specific measuring & monitoring plans for innovative anti-piping solutions by the target group (water managers).*
b. To integrate current knowledge about the different filters and monitoring in a general measuring & monitoring strategy that can be used in its intended problem context.
c. To include a monitoring diagram with failure scenarios and risk mitigation measures, including monitoring options, of three different filters aimed at the target group, and supporting the measuring & monitoring strategy.
d. To verify and validate the measuring & monitoring strategy for its intended problem context.

By meeting the main research goal, a design problem is solved, which can be achieved by completing the design objectives, which can only be accomplished by answering the formulated knowledge questions. The target group is the design problem owner.

1.5. Scope

This section contains a list of statements that determine the scope and key concepts of this study

- Filter solutions refer to any anti-piping measure placed in the aquifer that prevents the movement of grains but allows seepage to pass through
- The difference between monitoring and measurings is that monitoring is collecting measurings continuously on intervals while measurements are done in instances.
- Piping refers to the Dutch context, where only backward erosion piping can occur. Other types of erosion are sometimes referred to by the term piping in international literature. Piping in this report refers to backward erosion piping.
- The target group of the measurement & monitoring strategy is primarily HSDR but secondarily, all water managers with dikes that want to implement innovative anti-piping filter solutions. However, general conclusions about the target group outside of HSDR should be drawn with caution and be reflected on thoroughly.
- The research focus is on investigating the theoretical monitoring options as filter failure risk mitigating measures, therefore cost-benefit ratios or project location-specific conditions are outside of the scope of this research.
- Implementation of actual measuring & monitoring strategies is outside of the scope of this research.

2
Methodology

In this chapter, the methodology of the research will be discussed. The research strategy is based on a design-science methodology (Wieringa, 2014) and is presented below in figure 2.1. The complete design cycle normally consists of 5 iterative phases. Two phases, implementation and evaluation, are beyond the scope of this research as discussed in section 1.5 and are removed from the design cycle. The methodology uses knowledge questions to achieve design objectives to solve the main design problem. These design objectives as listed in section 1.4 are each related to the three iterative steps of the design cycle: problem investigation, design and validation. This chapter is divided into these three respective steps.

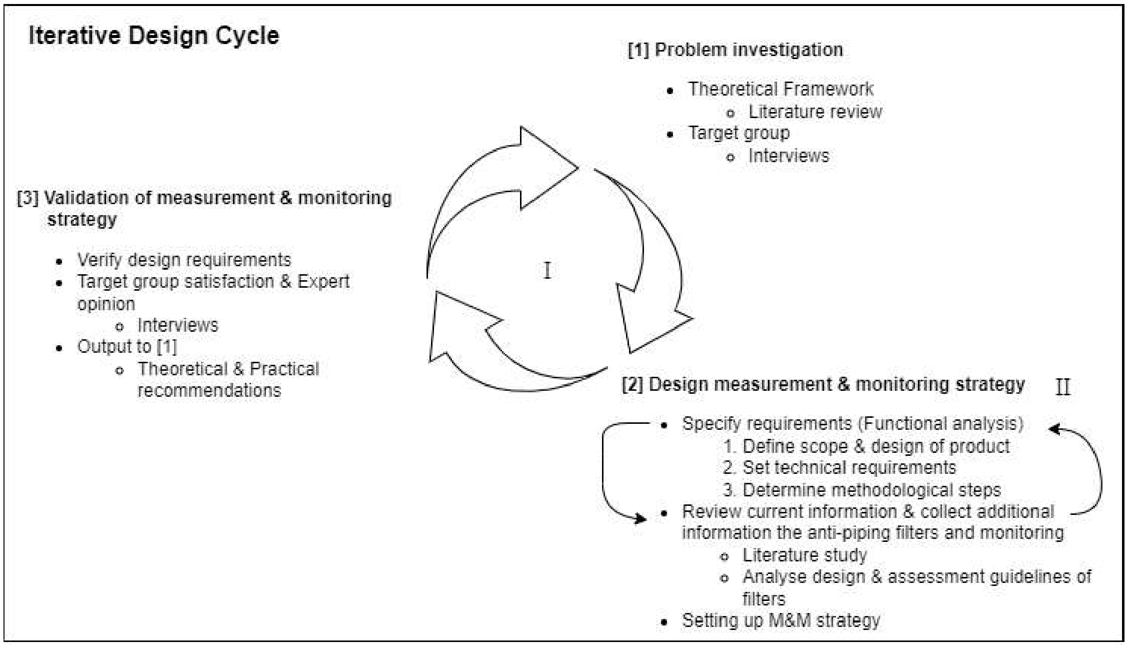


Figure 2.1: Research methodology, including design cycle (I) adapted from Design Science (Wieringa, 2014), and requirements loop (II) adapted from Systems Engineering (Alsem et al., 2013).

2.1. Iterative Process

It should be noted that while the design cycle is in theory iterative, in practice only one complete iteration has been performed. With the results of this complete iteration some changes have been iteratively made, however, this can not considered as a complete iteration. The design cycle thus captures an ideal theoretical situation to describe the process conceptually. In practice, iterations are not followed strictly step by step; target group satisfaction and expert opinion, for instance, are skipped for many iterations. The experts and target group can not be interviewed at any iteration as this provides a lot of redundant work, and the feasibility of arranging this is not realistic either. The experts and target group are therefore consulted when nearing the end of this research. Verification is the only validation step done every iteration, in practice meaning simultaneously with the design.

2.2. Problem Investigation

The first phase, problem investigation, is defined as the investigation of real-world problems as a preparation for the design of a treatment for the problem. The problem investigation objectives are to (1) understand the problem to be treated and to (2) learn about stakeholder (target group) goals and to understand the problem to be treated (Wieringa, 2014).

The problem investigation commences with the review of relevant theoretical knowledge about the three different anti-piping filter screens as input for the design phase and to meet problem investigation objective 1. Fundamental key concepts to understand how backward erosion piping works, how anti-piping filters affect the backward internal erosion piping process, the different sub-failure mechanisms of the filters and how these filters differ from each other are investigated by a literature study and the results are presented in a theoretical framework in section 3.1

The target group is also investigated to meet problem investigation objective 2. This entails the investigation of the stakeholder's (HDSR or other water managers) need for a measuring and monitoring strategy for innovative anti-piping filter solutions, the current knowledge gap and constraints to establishing such a strategy, and the problem that such a strategy will solve. In other words, it is important to understand when and how the strategy can be useful for the stakeholder in its intended problem context. Where the problem context is: creating M&M plans to monitor the continued functionality of a filter as an anti-piping measure during the management life cycle phase of a dike.

Two interviews with individuals employed at the target group HDSR are conducted as part of the target group investigation. The first interview is conducted with a geotechnical expert at HDSR tasked with setting up a generic monitoring strategy for a larger section of dikes, including the Prolock pilot project at Salmsteke. The second interviewee is a member of the asset team flood defences, responsible for managing all dikes within the area of HDSR. While conducting just two interviews is limited, the interviewees are estimated to be very representative of the set target group based on their function within HDSR. Approximately sixty minutes were used for these interviews. The interview manual is following a semi-structured approach and was set up using van Thiel (2007). No consensus-seeking method was used; the interviewees did not contradict each other, so presenting each other's answers after both interviews proved unnecessary. The interviews are summarized, and the most important findings of these interviews are presented in section 3.2. The interview manuals, transcriptions which are approved by the interviewees, and summaries can be found in C.

The results of the problem investigation phase are the input for the design phase and setting up the design requirements and thereby an intent towards achieving the first design objective of this research:

a. To investigate the requirements of M&M strategy within its intended problem context.

The theoretical framework, set up using a literature review, is a sufficient fundamental theoretical basis to start the design phase on the first iteration and a preliminary answer to the first knowledge question of this research:

1. How do the various filters work in their function to prevent dike failure by piping, and what could cause these filters to fail in this?

2.3. Design

In the design phase, the measuring & monitoring strategy is created by setting design requirements based off the results of the problem investigation and considering the theoretical framework as a result of the previous phase. During this phase, new requirements can surface as additional information about the different filter screens and monitoring is gathered and analyzed through literature study as part of the design process. This is an iterative requirements loop within the design phase and is adapted from the Systems Engineering methodology (Alsem et al., 2013). The design requirements are also formulated following this methodologies' terminology using functions and objects. A function describes the function of a requirement in relation to the corresponding object. Objects are distinguishable components of the final design result. Besides new requirements also, new objects can be a result of the iterative requirements loop. New requirements and objects can require additional literature review. Three different purposes for setting design requirements can be related to the requirements: to (1) define the scope & design of the final product, (2) set technical requirements, and (3) determine methodological steps to design the final product. Besides the requirements loop, new requirements can be set after subsequent iterations based on the results of (updated) previous phases (Validation Problem Investigation) in the iterative process. The output of the validation phase is formulated in theoretical & practical recommendations. Theoretical recommendations are more significant and fundamental to the design result, while practical recommendations is more general and minor feedback.

After the final iteration of the design phase, the following design objectives are achieved:

a. To investigate the requirements of M&M strategy within its intended problem context.

b. To integrate current knowledge about the different filters and monitoring in a general M&M that can be used in its intended problem context

As discussed in the previous paragraphs, new requirements and objects surface due to the iterative nature of the chosen methodology using a requirements and objects loop. The initial objects are the M&M strategy and plans. Where strategy refers to the generic strategy as the result of this research to create location-, filter- and project-specific measuring monitoring plans. Two new objects that surfaced are analysis and diagram. An analysis of the filters is found to be necessary as a basis for a diagram, including the different failure scenarios, risk mitigation measures and monitoring options per filter. This is further elaborated in the results section in section 4.1, as these objects and requirements are partial results of the iterative process. However, it is mentioned in this section as this also iteratively introduced a new research objective which is formulated below:

c. To include a monitoring diagram with failure scenarios and risk mitigation measures, including monitoring options, of three different filters aimed at the target group, and supporting the M&M strategy.

2.4. Validation

Through validation, it is investigated whether the designed final product of the design phase is useful in its intended problem context. Generally, the aim of validation is to justify that the delivered product would contribute to the target group goals in its intended problem context when implemented. Additionally, validation should predict how the result will interact in its context without actually implementing the result, meaning observing an implemented M&M strategy in a real-world context. Multiple validation objectives can be identified to determine how the final result is useful to the problem context. Each validation objective can be related to one of the different validation steps. Below, the validation objectives with their corresponding validation steps are listed, which result in theoretical & practical recommendations for the iterative process:

Validation Objective 1: Verify if the final product meets the design requirements. [Verification]

Validation Objective 2: Justify that the final product would contribute to meeting the research goal stated and, therefore, can be used in its intended problem context.
[Target Group Satisfaction & Expert Opinion]

Validation Objective 3: Predict how a monitoring plan created with the help of this study's result will perform in its intended context. [Target Group Satisfaction & Expert Opinion]

The first validation method, verification, entails assessing if all design requirements are met. When not all requirements are met a new iteration is necessary, or when due to constraints, they cannot be met, this is recognized. The second method are target group satisfaction interviews to investigate if, according to the opinion of individuals representing the target group HDSR, the design product meets the set research goal and is of added value in the problem context. One interview is conducted with a member of the asset team flood defences at HDSR. And a written reply to the same validation questions is included from the technical manager of the Salmsteke project, where the Prolock filter is applied as a pilot.

The third validation method consists of two expert opinion interviews, for which the same validation objectives apply as for the target group satisfaction. With this method, experts evaluate the design to the set research objectives and added value in the problem context based on their expertise. Two experts have been selected based on their relevant expertise in monitoring and in consultation with the external supervisors of this thesis. They are highly experienced in monitoring of dikes and failure mechanisms. As the interviewed experts are of external organizations, the time available was limited. Thirty-minute online sessions have been held.

Both the target group individuals and experts reacted to a summary of this research including a draft version of the final diagram design result. Only a handful of questions were asked related to either validation objective 3 or 4. These were also included in the summary and interview manual. The questions were adressed semi-structured. For validation objective 4 different questions were asked during the target group satisfaction compared to the expert opinion interviews, as for the target group for this objective, the aim is to investigate how the result can be applicable to the target group, and with experts the quality of the content and resulting monitoring options is investigated. The interview manuals, transcriptions which are approved by the interviewees, and summaries can be found in appendix D. The main findings of these interviews can be found in subsection 5.2

After the final iteration of the validation phase, both knowledge questions can be answered and the following design objective is met:

d. To verify and validate the M&M strategy for its intended problem context

3

Problem Investigation

In this chapter, the results from the problem investigation phase are presented. Here, the fundamental key theoretical concepts are reviewed by a literature study presented in 3.1. Then with this theoretical framework in mind, the perception of the research problem by the target group (HDSR) is further investigated. The results of this investigation by conducting interviews are presented in section 3.2

3.1. Theoretical Framework

This section presents the primary findings of the literature review. This is vital information for comprehending how an embankment can be affected by the failure mechanism piping. In addition, the section investigates how the addition of a filter to a dike system impacts the piping failure mechanism.

3.1.1. Piping

This section is derived from the WBI report, unless other citation is included. This report describes the major failure mechanisms of dikes and embankements extensively ('t Hart, 2018).

Piping only occurs in situations where an erosion-prone sandy aquifer at the location of the dike is covered by a clay dike core or a relatively thin package of compressible layers of clay or peat, called the covering layer or overburden (Rijkswaterstaat, 2021). Both situations are shown below in Figure 3.1. Without incompressible and impermeable clay above the sandy aquifer, a pipe cannot be formed at the boundary layer of these layers. This sandy aquifer layer in contact with river water is relatively fine-grained and uniform (Robbins & van Beek, 2015).

Figure 3.1: 1. Situation with weak cover layer on the inner dike ground level. 2. Situation with sand directly below the inner dike ground level. Both: No water level difference between outer and inner water present and thus no groundwater flow ('t Hart, 2018)

A difference in water level as a result of rising water levels causes water to flow through the erosion-prone sand layer as this aquifer is in contact with the river water. This results in a hydraulic gradient along the embankment, and as this gradient increases, the pore pressures in the sand layer increase. The flow rate flowing under the dike depends on the thickness and permeability of the aquifer sand layers and the hydraulic head of water across the dike. Piping mainly occurs at river dikes, where prolonged high water generally occurs with only slightly varying water levels. The water level slowly rises to the peak value and then slowly lowers again; the flood wave thus can last up to two weeks. In the lower river area, the tide affects the water level. In addition, a storm may cause a brief water level rise. However, a long-lasting hydraulic gradient along the embankment is required for piping to be a significant threat to the stability of a dike ('t Hart, 2018).

The driving load of the failure mechanism is formed by the water level difference and the duration of time over which it is present. When the pore pressure on the inside of the dike becomes greater than the weight of the covering layer, it will first begin to float. This creates cracks or holes, allowing water to flow to the surface and cause erosion over the covering layer behind the dike. Piping however, does not occur immediately after bursting. The water must first be able to provide a sufficient upward force to push the grains of sand from the sand package vertically upwards over the thickness of the poorly permeable sand package. This process is called Heave. This exit point is formed after Heave has occurred. Bursting and Heave are not required for forming an exit point if an overburden is not present. The exit point can be found directly at the dike toe but also in a ditch or the hinterland in case of an overburden. The water flow will follow the path of least resistance and flow towards the formed seepage channel causing high flow velocities at the exit point ('t Hart, 2018).

Figure 3.2: 1. Rising external water level causes a gradient along the dike, which increases the head in the sandy layer and hence the water pressure under the weak layer package, slowly pushing up the overburden 2. The inner dike ground level floats due to the high water pressure in the aquifer. The location with the lowest overburden weight (here, the ditch bottom) cracks and bursts first, after which Heave can then occur and pipe formation is initiated due to receding erosion, sand carrying wells then become visible ('t Hart, 2018)

Increasing resistance due to the sand-water mixture as a result of Heave can stop the erosion process again if the heave criterion is not met, meaning there is not sufficient upward pressure. Heave is defined as the vertical groundwater flow towards the exit point as a result of the vertical gradient (i.e., the water pressure difference across the layer thickness). When the vertical gradient reduces the effective stresses in the soil to zero, the sand grains are transported upward from the aquifer toward the exit point. The heave criterion is therefore defined by the gradient along the vertical seepage path and drives the Heave process Förster et al. (2012).

When Heave occurs, a sand-carrying well is formed as the fluidized sand particles are transported to the edges of the exit point (sand boil), and an erosion channel is now able to form under the dike. The formation of sand carrying well is illustrated in Figure 3.2. The erosion channel occurs right below the bottom edge of the clay layer above the aquifer. A piping channel is a very shallow cavity (several grain diameters deep). The width of the channel varies greatly and increases with length and may be several centimetres in the case of large dykes. Moreover, with larger dykes, the pipe also migrates laterally. The embankment or cohesive overburden forms the roof of the channel, which remains stable as a result of cohesion and arching (Förster et al., 2012).

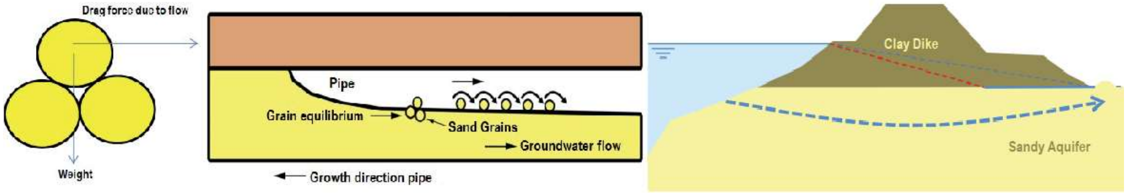


Figure 3.3: 1. Grain equilibrium (de Bruijn, 2013). 2. Pipe growth: pressure drop to the pipe (red dashed line). Pressure drop in the pipe is low(er) ('t Hart, 2018)

With a sustained sufficiently high gradient, erosion channels will continue to form and grow. A channel can grow if the grains at the front of the pipe become detached (primary erosion). This occurs when the gradient in front of the pipe is sufficiently high that fluidization occurs. However, the channel itself also affects the flow near the front. In principle, the channel acts as a drain. As the pipe gets longer, the mean gradient over the remaining sand package gradually increases, as seen in Figure 3.3.2. Once the pipe passes the critical gradient has been reached, the ever-increasing gradient near the front makes it unable to stop growing('t Hart, 2018).

The critical gradient is defined as the gradient above which the pipe formation does not stop under a constant load. The corresponding critical pipe length usually lies around ½ to ⅓ of the total seepage path length. Increasing the seepage path length is, therefore, an effective measure against piping. This can be done by creating/extending a clay berm to move the exit point location further away from the embankment or installing an impermeable heave screen, adding additional seepage length around this screen. Using Sellmeijer's rule, the minimum seepage length for normative high water levels can be determined ('t Hart, 2018).
In addition to primary erosion, secondary erosion causes the cross-sectional area of the pipe to increase and, thus, the drainage capacity of the pipe. The stronger the pipe drains the sand, the lower the pressure drop in the pipe and the higher the flow velocity at the head of the pipe. In calculation models, only secondary erosion is considered under the assumption that the pipe cannot grow in length when deck grains at the bottom of the pipe are in equilibrium('t Hart, 2018; Förster et al., 2012). This grain equilibrium is illustrated in figure 3.3.1.

In a piping channel, blockages can also occur and cause channels to disappear or meander. Piping canals can also grow toward each other. A once-occurring well often recurs during the next flood. For a given piping channel, if the erosion process, with a constant high outside water level, continues (progressive erosion), the piping channel will eventually reach the entry point. In time, this will create a continuous connection under the dike and with the outside water. Then the channel gradually widens and deepens from the upstream side to the downstream side. Once the pipe is completely widened, the seepage flow and sand transport increase sharply, after which failure of the dike can occur in a short period of time (Förster et al., 2012; 't Hart, 2018).

Figure 3.4: 1. After the entry point has been reached, the widening process starts from the upstream side. 2. After the widening process reaches the exit point, the soil beneath the embankment quickly fails, resulting in a dike breach (de Bruijn, 2013; 't Hart, 2018)

3.1.2. Filter as anti-piping measure

This section investigates how a filter can prevent the failure of a dike due to the failure mechanism piping, which was discussed in the previous section. As opposed to installing a heave screen or a berm above the overburden to extend the seepage length, a filter screen completely halts the backwards erosion process. With seepage length extensions, the pipe is theoretically still able to grow to the entry point. However, outside water levels significantly higher than normative design conditions are then required as a result of the seepage length extension, which cannot be realistically expected. The benefit of a filter solution is that it minimally affects the groundwater regime, unlike a heave screen. Additionally, it does not require a lot of space above the surface, unlike creating or extending a berm (Wiggers et al., 2019).

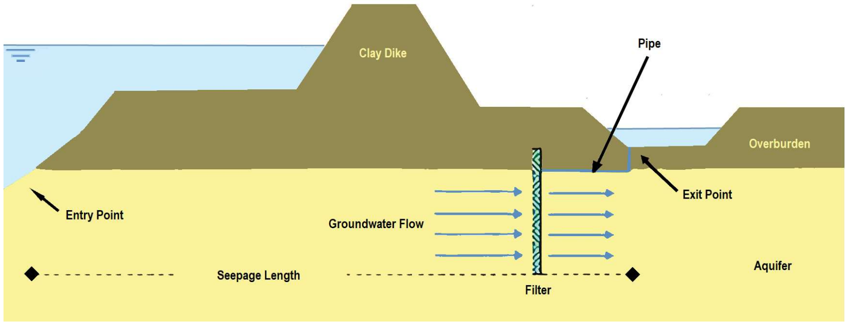


Figure 3.5: Working principle of anti-piping filter: blocking pipe development in erosion prone aquifer (Förster et al., 2015)

A piping filter is installed in the subsurface as shown in figure 3.5 above. The filter should be placed upstream of the normative exit point. Then when an exit point is formed downstream of the filter, the pipe formation process can take place as usual until it reaches the filter. The pipe then deadends at the filter. This is caused by the natural sand upstream that cannot be transported by the seepage flow through the filter and into the pipe channel that has formed. Relative to the upstream surrounding sand, a geotextile, screen or barrier serves as a filter (Förster et al., 2015; Wiggers et al., 2019). The application of the filter eliminates the need for a minimum seepage path length according to Selmeijer's rule to ensure the stability of a dike system for piping (Koelewijn, 2021). When a filter is clogged, the heave criterion becomes the primary safety indicator as the filter then functions as an impermeable heave screen. The heave criterin is met when, for a vertical seepage flow in sandy soil behind a heave screen, the maximum occurring head is less than the critical head at which heave (fluidization) occurs (Förster et al., 2012). Below in Figure 3.6, the events leading to the failure of a dike due to piping is schematized, including the intervention of a filter in this chain of events.

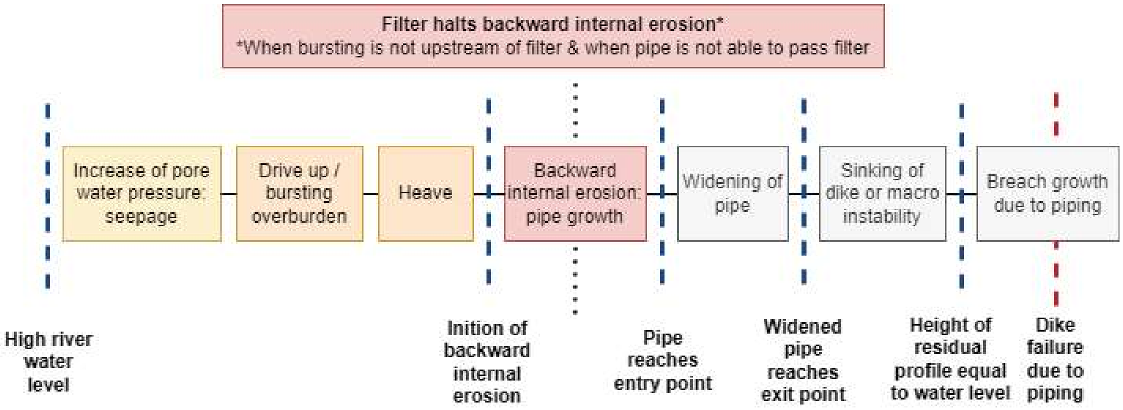


Figure 3.6: Events leading to failure of an embankment due to piping & Filter intervention ('t Hart, 2018)

Filter Constructions & Types

Filter structures can consist of granular material, a geotextile, or a combination of these. The purpose of an erosion-resistant filter is to prevent erosion (filter function) and enable the discharge of seepage (drainage function). For a filter to work properly, it should be sand-tight and be more permeable than the subsoil. It is crucial to observe that erosion control and drainage are not goals in themselves, but rather a means of preventing the failure of a flood defense without significantly affecting the groundwater regime. (200, 2009; Förster et al., 2012)

The behaviour of a filter structure is determined by the size of the perforations or pores, the composition of the subsoil, and the hydraulic load exerted on the structure. There are two varieties of filters: geometrically closed filters and geometrically open filters. In a geometrically closed filter, no sediment is transported through the filter regardless of the applied hydraulic loads. Sand particles can pass through a geometrically open filter, but when the critical hydraulic load is not attained, no transport will occur 200 (2009). When designing a filter, requirements must be established for the filter's openings/pores. These should not be excessively large for the purpose of blocking backward internal eroison, or sand transport may occur. In contradiction, they should be large enough for adequate water discharge (Taal et al., 2017; Koelewijn, 2021; Maatkamp et al., 2023). The literature contains filter criteria (Rosenbrand et al., 2017; Terzaghi et al., 1948; Giroud, 2010), that can be used to design filters that satisfy both requirements. Mapping the surrounding sand and precisely matching the filter to it is crucial in this situation. Filter criteria are available for both granular filters and geotextiles (Giroud, 2010).

3.1.3. Failure Mechanisms Filter Screens

The piping failure mechanism can be divided into five sub-mechanisms when a filter screen as an anti-piping measure is installed. These five sub-mechanisms are defined below in table 3.1.

Table 3.1: Overview of sub-failure mechanisms for anti-piping filter screens (Taal et al., 2017)

#	Sub-failure Mechanism	Description
1	Pipe behind	The pipe develops in the longitudinal direction of the flood defence to the end of the geotextile, which means that the pipe may develop *behind* the filter
2	Pipe trough	The pipe develops *through* the filter
3	Pipe before	The pipe with exit point occurs on the wrong (upstream) side, i.e. *before* the filter causing the filter to have no effect.
4	Pipe above	The pipe develops *above* the filter in the anchoring zone
5	Pipe below	The pipe develops *below* the filter

Several events can lead to one of the failure mechanisms listed in table 3.1 and illustrated in Figure 3.7 below.

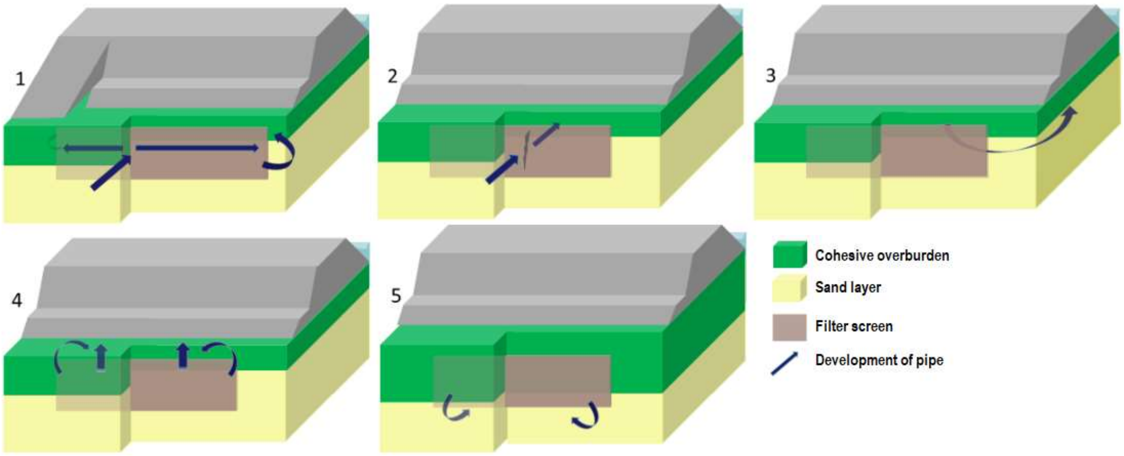


Figure 3.7: Sub-failure mechanisms of piping when a filter screen measure is installed, labeled 1-5 as in table 3.1 (Taal et al., 2017)

When a sub-failure mechanism has occured, the installed filter screen no longer has any effect, meaning a continuous pipe can grow underneath the embankment. The events from the occurrence of the sub-failure mechanisms to the collapse of the dike are shown in figure 3.7 below.

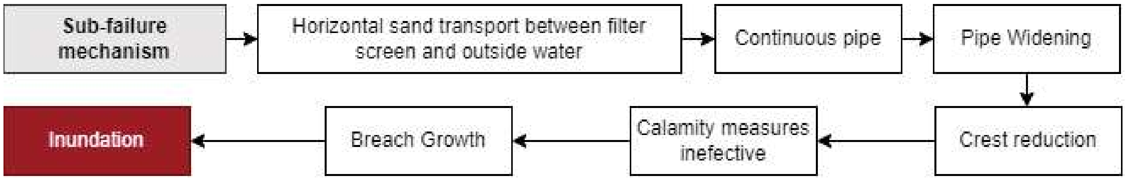


Figure 3.8: Events from sub-failure mechanisms leading to dike failure (Koelewijn, 2021)

3.1.4. Filter Criteria

Filter criteria can be divided two types of criteria for granulair filters (Giroud, 2010): the retention and the permeability criteria. Geotextile filters require two additional criteria: porosity & thickness criteria. This is because granulair filters have been proven always to meet these criteria. Retention is presumably the most important aspect of the filtration function of a filter. Retention is the ability of the filter to prevent upstream soil to flow through the filter. Filters can be classified based on their mode of retention: total retention, optimum retention, and partial retention. The function of a total retention filter is to retain all soil particles. They become progressively clogged, this is however, not detrimental as the primary function is to retain water. The filter openings are sufficiently small to retain all particles likely to migrate and the filter therefore has a low permeability. Filters providing optimum retention are most common in geotechnical structures, and anti-piping filters fall into this category. Partial retention filters on the other and allow flushing of some soil particles when they are washed by turbulent, intermittent, and multi-directional flow. In such filters, progressive erosion of the soil occurs but is slowed by the filter. The second criterion determines the impact of the filter on groundwater flow through the permeability of the filter itself (Giroud, 2010).

As mentioned in the previous paragraph, in case of geotextile filters it is necessary to have a porosity criterion to ensure that the number of filter openings is sufficient. This criterion specific to the number of openings per unit area that is needed. Due too the permeability of many geotextiles itself, a geotextile with a very limited number of openings may still meet the permability criterion. The porosity criterion for granular filters was never formulated as all granular filters have approximately a porosity between 20-30%. Geotextile filters on the other hand have a wide range in porosity from 1% for some woven geotextiles to 92% for some non-woven geotetxtiles (Giroud, 2010).

The thickness criterion is relevant for non-woven geotextiles as the mesh size of these geotextiles is dependent on its thickness. This is because a soil particle travelling through a nonwoven geotextile travels from one constriction to another, thereby following a filtration path. These are identical to tortuous flow channels found in granular filters. The constrictions in case of a geotextile are fibers. If a nonwoven geotextile filter is thick enough to contain more than 25 constrictions in its filtration paths, its opening size is not substantially affected by variations in thickness. In other words, nonwoven geotextile filters must be sufficiently thick to be reliable. In the case of woven geotextile filters, there is only one constriction in each filter path. Changing the thickness does therefore not affect its reliability. A thickness criterion for granular filters does not exist as due too construction constraints these filters are always significantly thick enough to pass any thickness criterion. For an anti-piping geotextile nonwoven geotextiles are not recommended because of the limited strenght and stretch properties and limited experience relative to woven geotextile (Giroud, 2010).

3.1.5. Filter Conditions

In the previous section, the different filter criteria discussed. These are included in filter conditions for an ani-piping filter. Filters should generally meet five conditions to perform their function with respect to piping (International Committee on Large Dams 2015):

1. Retention: Prevent grains of upstream soil from being washed out through it.

This condition garantuees the filter effect relative to the surrounding sand. The retention criterion is used to design the required size of perforations (geotexile mesh size) or the pores (filtersand composition) (Giroud, 2010). Because the pore size of surrounding sand or filter sand is difficult to measure, and depends largely on grain size, criteria are often formulated in terms of grain size (distribution). Thus, most filter criteria in the literature are based on a grain size ratio between sand and filter pores or mesh width . For a geometric open filter, hydraulic loads are also always of great importance. But even with a geometrically closed filter, flow velocity, packing density, grain shape and the concentration of soil particles flowing into the filter can be important. These factors are also (variably) included in the filter criteria found in the literature (Rosenbrand et al., 2017), in addition to the ratio of grain size of surrounding sand to the filter pores or mesh width. To meet this retention condition it is of vital importance that by conducting soil surveys the composition of the in-situ sand is correctly determined.

2 Permeability: Sufficient drainage capability

Strict permeability requirements similar to drainage systems are not necessary for anti-piping filters in flood defences that have no primary drainage function (USACE, 2000). However, the permeability must be such that water flow can pass through the filter and not flow under the screen, similar to an impermeable sheet pile wall. The permeability of the filter should therefore be greater than the permeability of the surrounding soil. This is achieved by using the filter permeability criterion in the design. These criteria always include a pore water pressure requirement and a flow rate requirement, as they influence the disturbance of groundwater flow by a filter. The pore water pressure requirement is determined based on the hydraulic gradient in the soil next to the filter. The flow rate requirements account for the reduction in flow rate caused by a filter. If the requirements are generally met, the flow rate reduction because the filter should be less than 10% (Giroud, 2010).

3 Material Properties: Incapable of forming a crack

For a granular filter, this requirement means that the filter sand must be non-cohesive. In non-cohesive sand, a crack will not be able to form. Cohesive sand is, however, not able to meet the permeability criterion and, therefore, is not able to function as a filter (Rosenbrand et al., 2017). For geotextiles, the formation of a crack is a more pressing concern during design. These can occur during the implementation phase as well as during the use phase. Examples include installation damage due to excessive tensile loads or penetration of the fabric by soil stirring activities. The strain properties should receive sufficient consideration during design (Taal et al., 2017). Granular filters can additionally be combined with plastic tubes. In that case, strength properties of these plastics are also relevant to meet this condition (Maatkamp et al., 2023).

4 Grain Distribution: Internally Stable [Granular Filters]

Internal instability of sand means that the finest fraction of a sand mixture can flow out through its pores, causing a less fine fraction to leach out subsequently (Skempton & Brogan, 1994). In natural sands in the Netherlands outside of Limburg, this is not a risk; in artificial sand used in a granular filter, this is a risk (Koelewijn, 2021). During the design of a granular filter, it is of utmost importance that the filter sand is internally stable. Internally unstable sand is characterised by a fine and coarse fraction of sand present with little to no intermediate grain sizes. This implies that internally stable sand is either well-graded or very uniform. Graded soils are to be avoided; besides being more susceptible to internal instability compared to uniform soils, these soils have a risk of segregation during construction. Therefore simple intern stability criteria for uniform sands are most suitable for granular filters (Rosenbrand et al., 2017).

5 Material properties: Being sufficiently strong.

In a general sense, this condition primarily means that the filter sand under the in situ pressure is not crushed (thus reducing grain size) (Rosenbrand et al., 2017). For geotextile, no strict requirements are needed; after installation, the geotextile is strained by loads (Taal et al., 2017). Plastic filter sand tubes have a significantly higher load, and therefore due to settlements and their own weight, a strength assessment is required during design (Maatkamp et al., 2023).

3.1.6. Vertically Inserted Geotextile

A vertically inserted geotextile is an anti-piping filter that consists of a vertical geotextile that is impermeable to sand grains yet permeable to water. A VZG is inserted vertically on the inside of the dike, at the top of the piping-prone sand layer beneath the impermeable cover layer. The geotextile inhibits the sand grains' seepage path and prevents a pipe from forming beneath the flood barrier. This means that sand-maintained seepage may occur but poses no threat to the integrity of the flood defence in terms of fully grown pipes (Wiggers et al., 2019).

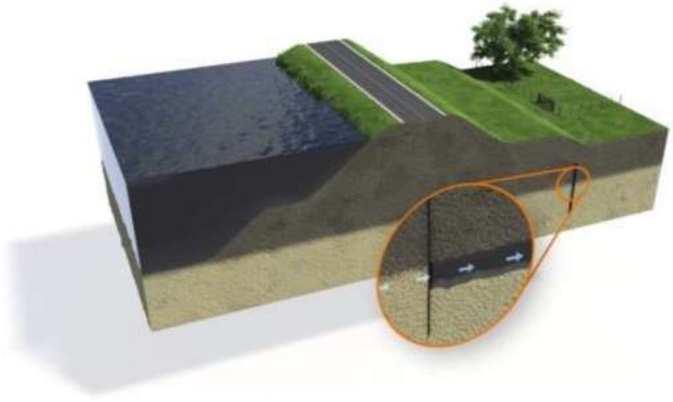


Figure 3.9: Illustration of the principle of the Vertical Sand Dense Geotextile (VZG) (Taal et al., 2017)

In Förster et al. (2015), the effectiveness of a vertically inserted geotextile against piping has been studied. Several small- and medium-scale experiments, as well as a field-scale test, were conducted and compared with test series conducted without any piping measure. All experiments revealed that the geotextile shield was successful in preventing backwards erosion. According to numerical analysis, it was more effective than an impermeable sheet pile of equal length.

The research also found the primary failure mode of vertically inserted geotextile. With the geotextile inserted, backward internal erosion is incapable of expanding behind the geotextile. Therefore the pipe can continue to grow wider, which results in the head in the whole pipe reaching the same constant value as on the adjacent downstream side of the geotextile resulting in an upward gradient. When this gradient becomes excessively high, the affected aquifer zone and the embedded geotextile barrier collapse. The permeability of the geotextile influences the potential of aquifer liquefaction as the result of vertical flow (heave) around the geotextile (Förster et al., 2015).

3.1.7. Course Sand Barrier

The coarse sand barrier is a granular filter, and like the vertical sand-tight geotextile, it is placed on the landward side of a dike. In this process, a ”wall” of coarse sand is placed underground that extends above and below the interface between the aquifer and the thick cover layer (overburden) along which piping can occur. The operating principle of the coarse sand barrier is illustrated below in Figure 3.10. The composition of the coarse sand barrier is matched to the composition of the piping-prone sand layer so that the sand is sufficiently retained while maximizing the permeability of the coarse sand barrier.

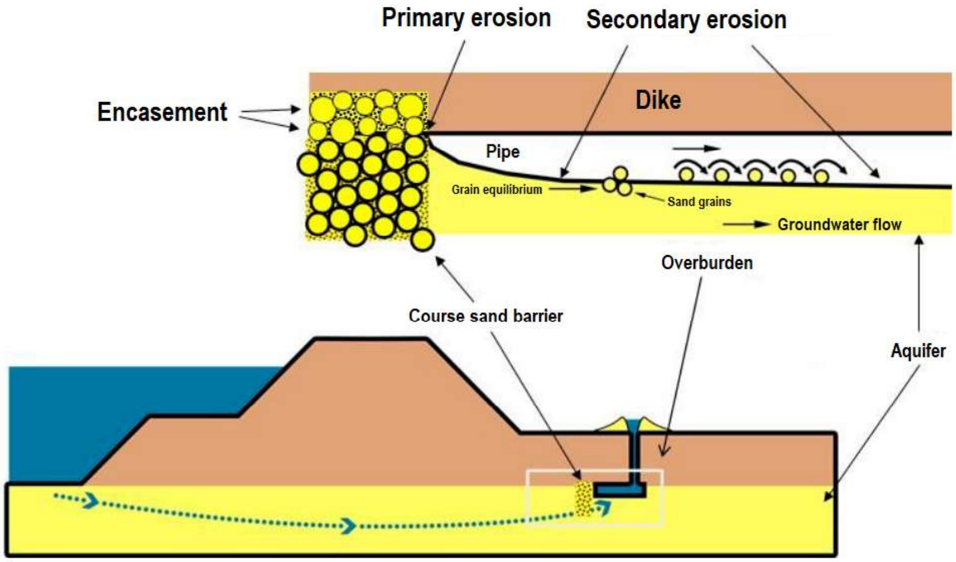


Figure 3.10: Failure mechanism piping interfered with a coarse sand barrier (barrier with encasement) (Rosenbrand & van Beek, 2017).

The piping erosion process is impeded by allowing a greater water level difference (hydraulic gradient) to be resisted before failure by piping occurs compared to a situation without CSB in two ways. Firstly, the barrier material of the CSB has greater resistance to erosion because the grains are larger. Secondly, the flow load on the grains in the barrier is relatively small due to the relatively high permeability of the barrier material compared to the surrounding sand. The greater the contrast in permeability, the more effective the barrier is. This is because an even smaller portion of the total gradient then has to be absorbed by the highly permeable barrier, while its resistance to erosion by the coarser grains is relatively high (Rosenbrand & van Beek, 2017; Koelewijn, 2021).

The CSB has the advantage that more resistance to piping can be created with natural material. However, unlike, for example, the situation with a VIG, a pipe can partially erode the barrier if the water flow is too strong, initially maintaining its erosion-resisting function. However, if the water flow increases further, the barrier may breach, losing its function. It is, therefore, extremely important to correctly determine the strength of the barrier. For the strength of a barrier, one should distinguish between a CSB with or without encasement. A CSB without encasement protrudes its top layer into the cohesive overburden, whereas a barrier with encasement extends much higher into the overburden, as shown in Figure 3.11. An encasement provides more strength since more coarse sand grains must be eroded before a through pipe can form. For a barrier that contains no obstructions and whose encasement is high enough to allow a natural slope to form over the full thickness of the barrier, primary y erosion does not play a significant role. However, if there are obstacles or the embankment is relatively low, primary erosion plays a significant role. For piping without a barrier, secondary erosion is the most relevant mechanism (Rosenbrand & van Beek, 2017; Koelewijn, 2021).

When a pipe arrives at the barrier and has become deep enough, the high-lying coarse grains of the barrier will roll into the already-formed part of the pipe. This process takes time and requires a gradually slightly higher gradient as the coarse grains have a higher flow resistance (Rosenbrand & van Beek, 2017; Koelewijn, 2021). Figure 3.11 shows a schematic representation of a course sand barrier.

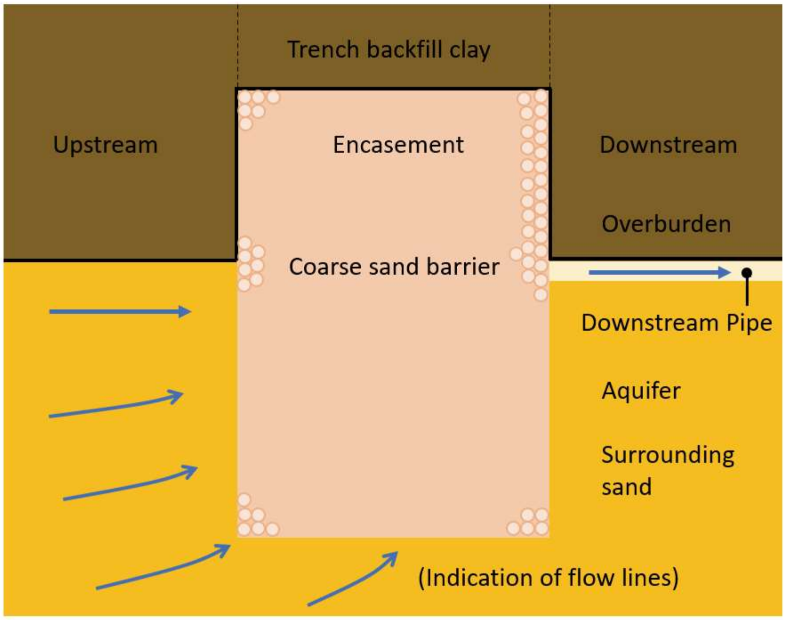


Figure 3.11: Side view of a coarse sand barrier to which a pipe has grown all the way from the downstream exit point. Figure adapted from Koelewijn (2021)

Lateral pipe growth will also occur along the downstream side of the coarse sand barrier, in the surrounding sand (Rosenbrand & van Beek, 2017; Koelewijn, 2021). The initial step is illustrated using a schematic top view of the course sand barrier below in figure 3.12.

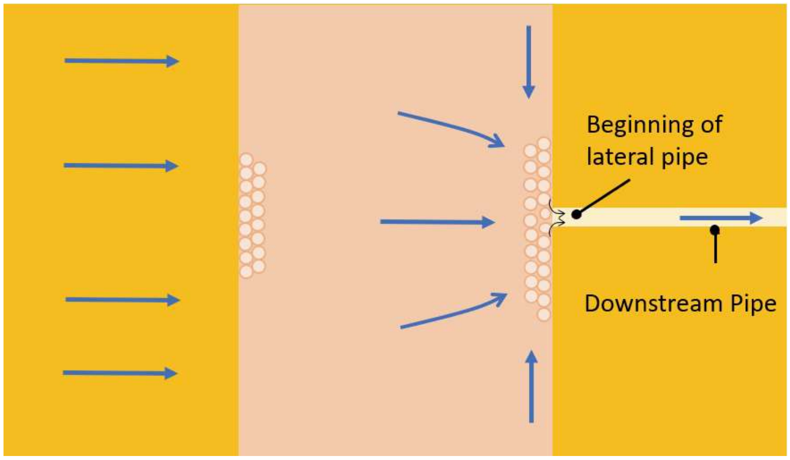


Figure 3.12: Top view of course sand barrier showing the first onset of lateral pipe growth. Figure adapted from Koelewijn (2021).

In the encasement of the barrier itself, a slope will form approximately under its natural slope, with the bottom of the pipe as its base. When the slope is fully formed, it will touch the overburden upstream at a relatively high incidence (Rosenbrand & van Beek, 2017; Koelewijn, 2021). This is shown below in Figure 3.13.

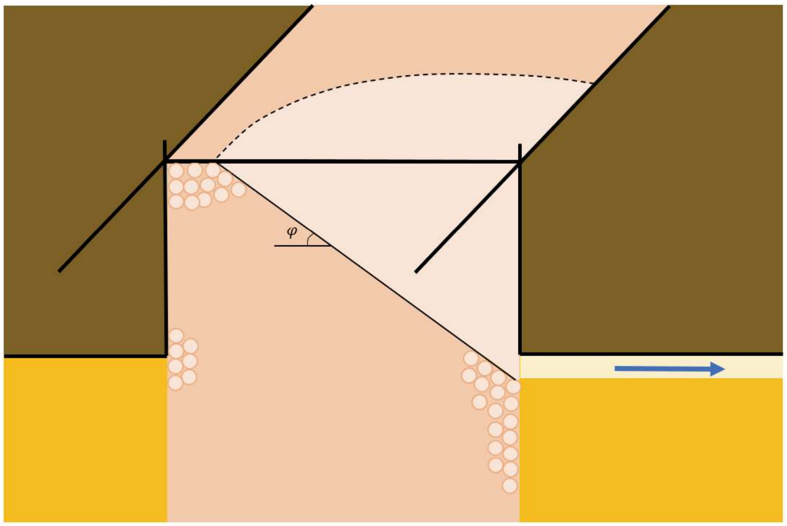


Figure 3.13: Erosion of a portion of the encasement of the coarse sand barrier adjacent to the downstream pipe to a gradient approximately equal to the angle of internal friction ϕ (natural slope) of the barrier sand. The situation outlined involves a relatively wide barrier with a relatively low indentation (side view with some 3D suggestion in the longitudinal direction). Figure adapted from Koelewijn (2021)

.

Thereafter, with a further growing gradient, the slope will become flatter, where eventually only a so-called heave height h_h remains on the upstream side at a critical angle β. At this stage, a sharp increase in the gradient is possible without the failure of the coarse sand barrier (Rosenbrand & van Beek, 2017; Koelewijn, 2021).

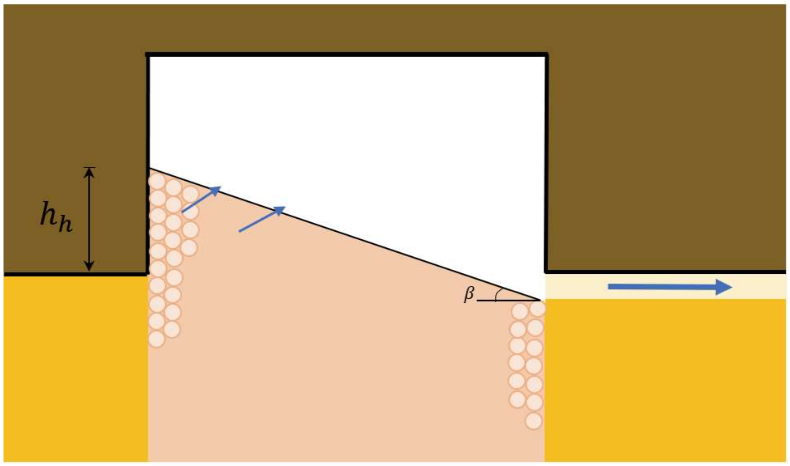


Figure 3.14: Critical slope after further flattening, with the minimum heave height h_h and angle β. Figure adapted from Koelewijn (2021)

Then, with a further increase of the hydraulic gradient, the remaining portion of the coarse sand barrier will become unstable under the further increased flow pressure and collapse through heave will occur. In more detail, the collapse process is as follows: Another small shear will occur on the lower portion of the slope, and then suddenly, a larger portion of the upper slope will shear. Then at the upstream edge, there is insufficient resistance to heave, and failure by heave occurs there (Förster & Van Beek, 2021). After this, the pipe can continue to grow through the background sand towards the outside water (Rosenbrand & van Beek, 2017; Koelewijn, 2021).

3.1.8. Prolock Filter Screen

The Prolock filter screen is an innovative anti-piping measure based on the filtering principle of a granular geometric closed filter. The Prolock screen consists of 500 mm wide plastic sheet piles equipped with two hollow tubes in the shape of a honeycomb. The planks are manufactured by extrusion, where the nominal wall thickness of the body is 5.0 mm and of the tube walls is 4.5 mm. The walls of the tubes are provided with vertical slits over a limited length, hereafter called perforations, through which the screen becomes permeable to water. The hollow tubes are also filled with filter sand, whose composition is adjusted to the natural sand present. The filter sand gives the screen a filter effect, allowing the groundwater to pass through the screen (almost) unhindered and preventing sand transport. Because the filter sand provides the filter effect, the perforations can be made wider than the grain diameter of the natural sand package. With this filter effect, the Prolock filter screen directly intervenes in the submechanism of backward internal erosion and is thus an effective measure against piping (Veenbergen & van der Mieden, 2021; Maatkamp et al., 2023). A principle sketch of the Prolock filter screen is shown in Figure 3.15

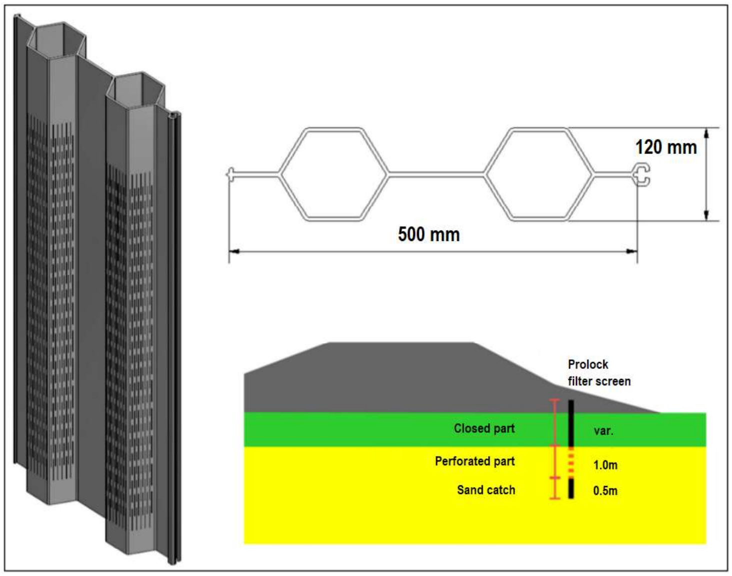


Figure 3.15: Principle sketch of the Prolock filter screen (Maatkamp et al., 2023).

The Prolock screen is installed in the dike profile from ground level to at least 1.5 m in the piping-sensitive sand layer. the piping-sensitive sand layer and then finished below ground level. The box walls are provided with perforations in the upper meter of the sand package. Above this, the filter screen is closed, i.e. that is, without perforated box walls. Below the perforations, at least 0.5 m of the dense screen is still present. This 0.5 m is referred to as a 'blind tube' and acts as a sand catch. The sand catch is intended to catch sand grains that flow into the tube during installation through the perforations and also serves as a space for the cleaning tool (Veenbergen & van der Mieden, 2021; Maatkamp et al., 2023).

3.1.9. Application Methods

Two types of insertion techniques are available for the VIG: a horizontal and vertical insertion technique (Taal et al., 2017). The vertical technique consists of panels that are vibrated vertically into the ground. Because of the loose panels, the VZG can be installed around obstacles such as trees, houses, driveways, cables, and pipes. Curves can be made easily; there are fewer restrictions on the maximum insertion depth, and variation in depth of the piping sensitive layer is easily solved, while the daily production is limited. The horizontal technique consists of a tiller that removes the soil while driving and, at the same time, inserts the geotextile. This technique has limitations for bends, insertion depth and obstacles. The ground level must be horizontal. The installation speed is higher than with the vertical technique (Broere & van Cuyck, 2019).

There are also several possible application methods for the CSB. The simplest method, which was also used in the pilot of the CSB in Gameren, is the open trench method. This simply involves mechanically digging an open trench, dumping the coarse sand and sealing it with a clay fill. Another possible option is the chain trench method, in which a self-propelled machine or chain cutter is used to dig a trench. Finally, it is also possible to construct the CSB using soil displacement techniques. The idea here is that soil-displacing sand piles with coarse sand are installed. The idea here is that these piles do not have to be placed overlapping because the surrounding background sand, including the background sand between the sand piles, becomes so compacted that the flow will be concentrated through the sand piles. However, further experimental research is needed before this method can be safely applied (Koelewijn, 2021).

Two different installation methods are possible for the Prolock filter screen; soil removal and soil displacement. A technically suitable installation method was determined for the Salmsteke pilot site through feasibility tests. From this, it follows that the perforated plastic profiles can be installed vibrating. This installation method softens the soil by vibration, allowing the plastic profiles to be inserted with a low compression force. To vibrate the plastic profiles, vibrating needles are inserted into the tubes, which connect to closed steel points at the bottom. The steel points have a flat base plate, are hexagonal, and remain in the ground after installation. After installation, the filter perforations are cleaned. This is because, during installation through the overburden, there is a risk that the perforations will become clogged with clay, which will no longer guarantee filter performance. After cleaning, the tubes are filled with filter sand, which is closed at the top with a lid (Maatkamp et al., 2023).

3.2. Target Group

In this section, the results of the target group investigation are discussed. For this problem investigation method, two interviews are conducted. One interview is conducted with a technical specialist in geohydrology & geotechnology, with expertise in groundwater monitoring. This interviewee is tasked with creating a general monitoring plan for the Sterke Ledijk. The second interviewee is a member of the asset team flood defences, which is tasked with managing all flood defences of the HDSR water board. Monitoring is, therefore, the responsibility of this team. The reports of these interviews can be found in Appendix. Besides these interviews, a monitoring session organized by HDSR was attended, of which a concise summary and interpretation are included in Appendix C. The following paragraphs present the most relevant results, which examine the perception of the target group HDSR on the problem context.

3.2.1. Asset Team Flood Defences & Salmsteke Prolock Pilot

Within HDSR, the asset team flood defence is the primary beneficiary of a monitoring strategy to be developed. As an asset team, they own and manage a dike. In the case of the current Sterke Lekdijk project, contractor combinations are working on dike reinforcements on dike sections, where different innovations are implemented for each section. For one dike section named Salmsteke, the new innovative Prolock filter screen is applied as a pilot. According to the judgement of the interviewed geotechnical specialist, the asset team flood defences of HDSR is better served by monitoring the continued functionality of the filter screen in the long term.

Monitoring at HDSR Innovative Monitoring Techniques Current monitoring at the Strong Lekdijk project aims to understand the dike system better and consists mainly of monitoring well measurements. After the construction of the innovations, monitoring can be used to determine the change in the system. HDSR does not yet have experience with specific monitoring of new innovations. A monitoring strategy is of added value within HDSR if it explains, based on scientific knowledge, the promising technologies that can be applied in a monitoring system or are promising to be investigated further. Based on his expertise as a geohydrological specialist, the interviewee assessed that new innovative techniques, such as fibre optics and Aquavector to measure temperature increase and flow velocities as a result of erosion pipes, respectively, are sufficiently developed for application in an HDSR monitoring plan.

3.2.2. Monitoring Philosophies

The starting point for the management and maintenance plan of the Sterke Lekdijk with regard to monitoring is: being able to unambiguously demonstrate the permanent functioning of the product innovation at low costs during its life cycle. This was discussed during the monitoring session reported in Appendix C. Here, limited effort means not having to carry out a separate long-term project to implement monitoring. Unambiguous refers to having a uniform method to set up a monitoring system for the various innovations, preferably using mainly comparable techniques. A monitoring strategy should consider the whole lifetime of the embankment.

A geotechnical engineer of the contractor that is currently developing the Prolock filter screen explained the starting point of the development team is to monitor as little as possible, only the necessary monitoring to ensure the functionality of the filter screen. Their approach was to determine dominant failure paths at the pilot location, where the failure probability contribution should be reduced by monitoring. A geo-environmental professor suggested making a new life cycle distinction with a delivery phase, a phase after implementation, in which monitoring can be used to demonstrate the operation of the innovation. In all likelihood, this requires more intensive monitoring than in the management/maintenance phase in the longer term, where the lasting effect of the innovation needs to be monitored. This is a different approach compared to the contractor, which illustrates how there can be different monitoring philosophies. Based on the first problem investigation interview and after confirmation in the second interview, this research should remain focused on long-term monitoring instead of delivery. The interviewed member of the asset team flood defences indicated that, ideally prefer a monitoring approach to filter screens which can be uniformly applied. The monitoring strategy should therefore provide insights into the differences between these filters.

4

Design Results

In this chapter, the design results of this study are presented. The main result is a monitoring diagram targeted at water managers with dikes, such as HDSR. This diagram includes monitoring options and all other failure risk mitigation measures for all defined failure scenarios for the three anti-piping filters. This is the result of a design process for which design requirements were gradually set during the design process. These requirements are first presented along with the design considerations in section 4.1, and then the final design result is presented in appendix A.

4.1. Design Requirements

In this section, the design requirements are presented. There are four categories used to present the requirements: scope, structure, analysis and diagram. The scope requirements are mainly set based on the problem context, the design problem to be treated, elaborated in Chapter 1, and the results of the problem investigation phase found in Chapter 3, which includes the investigation of the target group HDSR as water managers. The first category scope can be considered to be most of the initial requirements, while the second category, Structure & Steps, includes the iteratively set requirements on detailing the structure and, thereby, the content and steps of the to-be-designed monitoring strategy. The analysis and diagram categories emerged from the iterative process as objects and included many new requirements, which therefore required new categories. These objects are explained in the following paragraphs. The iterative design requirements and considerations are elaborated and listed in the following sections.

Objects are used to describe to which aspect of the final design result the requirements relate. Requirements are defined based on the problem investigation presented in chapter 3. This was done iteratively, meaning when new information was gathered, this could create new requirements. In some cases, this created a need for a new object. This occurred for the analysis and diagram objects, as the need for analysis to support the step in the monitoring strategy structure to choose to be monitored parameters and suitable technologies occurred from the problem investigation phase. A diagram to display the results more concisely was also included. These new objects also led to a new design objective, as mentioned in chapter 2. Ultimately, the iterative process concluded with this final diagram due to limited time and already sufficiently aiding in the problem context, contributing to the design problem.

4.1.1. Scope

The first category of requirements mainly contains the initial scope and goal-defining requirements based on the problem context, research goal and problem investigation phase. Given the research goal to assess all three different anti-piping filters, the necessity of distinguishing between filter-generic and filter-specific aspects became apparent from the iterative design process. From the problem investigation interviews, which can be found in appendix C, it became apparent that the preferably deficient functioning of the filter is detected by monitoring before high waters occur and that the monitoring strategy should be aimed at the management & maintenance life cycle phase of a dike. All final design requirements of this category, which have iteratively changed throughout the research process, are shown below in table 4.1.

Table 4.1: Overview of scope defining design requirements of M&M strategy

#	Name	Requirement	Function	Object
1.1	Applicability	The monitoring strategy must apply to piping-prone dikes reinforced with a filter application in the aquifer.	Applicable to anti-piping filters	Monitoring strategy
1.2	Monitoring goal	Monitoring plans developed with the aid of the strategy must have the following monitoring goal: monitoring the continued functionality of an aquifer filter application as a preventive measure against piping in the long term.	Monitoring continued filter functionality	Monitoring plan
1.3	Filter types	The monitoring strategy must (at least) include the following filter applications: the Prolock filter, Vertically Inserted Geotextile and the Course Sand Barrier.	Include Prolock, VIG,CSB	Monitoring strategy
1.4	Primary target group	The primary target group of the monitoring strategy is the asset team flood defences at HDSR as dike manager of piping filter reinforced dikes.	Target HDSR asset team flood defences	Monitoring strategy
1.5	Secondary target group	The monitoring strategy must besides the primary target group also be applicable to other dike managers of anti-piping filter-reinforced dikes.	Target dike managers	Monitoring strategy
1.6	Monitoring differences filters	Given the set monitoring goal, the monitoring strategy should give insight into the differences in monitoring the different filter applications.	Give insight into filter differences	Monitoring strategy
1.7	Life cycle phase	The monitoring strategy must be to set up monitoring plans for the filter-reinforced dike's management & maintenance life cycle phase.	Aimed at management & maintenance	Monitoring plan
1.8	Generic filter specific	The monitoring strategy must distinguish between filter-generic aspects and filter-generic aspects.	Distinguish generic filter specific	Monitoring strategy
1.9	Early detection	Deficient functioning of the filter applied is preferably detected during daily circumstances and before high waters occur.	Detect deficiency early	Monitoring plan

4.1.2. Structure & Steps

This section elaborates on the design considerations and requirements surrounding the structure and steps of the final M&M strategy. At the beginning of the design phase, it quickly became apparent that only one monitoring strategy could be found in the literature. In van den Berg & Koelewijn (2014), a generic scheme is given for setting up a monitoring plan. The strategy is applicable for all failure mechanisms and parts of the life cycle of a dike; therefore, in van Beek (2017), the strategy is made more specific for piping and the different life cycles of a dike. Therefore this strategy is taken as the basis for the to-be-designed strategy and is thus further specified for this specific monitoring goal, life cycle phase and types of filters as set in the requirements. For simplicity, the many steps of this strategy were first grouped together, and the first grouped step could be left unaltered as it was related to the exploratory phase, meaning the mapping of a project location and determining normative failure mechanisms. Then the second step was taken as the starting point of the specification of the monitoring strategy for the problem context of this study. This step includes choosing the monitored parameters and technologies to use. A suitable approach was determined after multiple iterations. The analysis supporting this approach is elaborated along with the requirements for this analysis in the next section. Below in table 4.2, all final design requirements of the category steps & structure are listed.

Table 4.2: Overview of structure and step defining design requirements of M&M strategy

#	Name	Requirement	Function	Object
2.1	Generic Scheme Basis	The final monitoring strategy must build on the the current established generic monitoring scheme by Van Beek (2017) and be further specified to the problem context of this research.	Build on generic monitoring scheme	Monitoring strategy
2.2	Generic Scheme Steps	The steps of this generic scheme must be grouped together into the following steps for clarity: (1) Dike Investigation (2) Setting up a Monitoring Plan (3) Monitoring Instruments, (4) Monitoring Data (5) Execution of Monitoring Plan	Distinguish steps based on generic scheme	Monitoring strategy
2.3	Dike Investigation	The first step of the generic scheme (1) dike investigation is project-specific and exploratory and does not require specification for this specific monitoring goal	Skip dike investigation step for design of strategy	Monitoring strategy
2.4	Starting Point	The second step of the generic scheme starts with choosing the to-be-monitored parameters and technologies to be used, which must be the starting point of the specification of the generic scheme and basis of the to-be-designed monitoring strategy	Start with set up monitoring strategy step: choose parameters technologies	Monitoring strategy
2.5	Analysis of monitoring parameters technologies	An extensive analysis must be performed to gain new insights on choosing the to be monitored parameters and technologies to be used for this specific monitoring goal	Perform analysis on parameters technologies	Monitoring strategy
2.6	Secondary Steps	The following secondary steps must only be specified for this monitoring goal based on the the previous step and thus must be started when this step is completed	Hold specification of subsequent steps	Monitoring strategy

4.1.3. Analysis

This section elaborates on the design considerations and requirements surrounding the analysis supporting the step: choosing to be monitored parameters as a step of the M&M strategy. Initially, numerous pipe monitoring literature studies were reviewed for analysis. However, these studies frequently researched pipe detection through monitoring (Bersan et al., 2018; Koelewijn, 2017). However, pipe detection is not the only possible monitoring•objective with a filter installed, particularly if you want to detect reduced filter functionality before the pipe has passed the filter. However, there was a study of vertical sand-tight geotextiles in which the feasibility of the same monitoring objective as of this to-be-developed strategy was investigated using different technologies (Koelewijn, 2017). This generated only four measurement sub-objectives, none directly applicable to the Prolock filter screen and the coarse sand barrier. Therefore, another approach is required to determine the appropriate monitoring parameters.

Then, failure trees, which describe all failure causes and subsequent chains of events that can lead to failure in a flowchart diagram, were used to study the failure behaviour of the filter applications. Initially, this was taken as the basis to determine possible monitoring options for each failure cause. This was perhaps an unnecessarily intensive method with many possible failure causes and three different filters. But mostly, this 'bottom-up' approach was ill-suited to understand a filter's functioning and failure modes fundamentally. Therefore a new approach was used, which was initiated by a more thorough analysis of a dike system without a filter installed, and how the failure mechanism piping affects this system. Then this analysis was extended by reviewing the principle of an erosion-resistant filter and how these anti-piping filters affect the dike system and failure mechanism in the literature. This resulted in a more fundamental and improved theoretical framework, essential input for the subsequent step. A' top-down' approach was formulated by analysing the design guidelines, and filter failure scenarios for each sub-failure mechanism. Then all failure causes were linked to these scenarios, which resulted in a few more failure scenarios and added an extra level of detail to the failure scenarios.

With the failure scenarios defined, it had become apparent that monitoring should be viewed as a component of many different failure risk mitigation measures. Besides filter and project-specific circumstances, the decision to implement monitoring as a failure risk mitigation measure depends on the failure risk mitigation measures and their effectiveness. Therefore the failure risk measures for filter scenarios generally, as well as for specific failure causes, were included in the analysis, including the possible monitoring options. The specific risk mitigation measures are taken from the design guidelines of these filters. A monitoring option is included for a failure scenario based on an assessment of the risk estimations provided in the design guidelines of the filters. Based on the theoretical framework and analysis of the failure scenarios, an indirect parameter is provided for the monitoring option, and using an overview table of available monitoring technologies for each indirect parameter related to piping. The discussed design considerations are listed as requirements below in table 4.3.

Table 4.3: Overview of analysis defining design requirements of M&M strategy

#	Name	Requirement	Function	Object
3.1	Analysis Steps	The analysis must consist of three steps (I) understand the different filter workings and how these can fail (II) determine what the risk and the mitigation measures assumptions are (III) determine the monitoring possibilities for risk mitigation	Define steps	Analysis
3.2	Failure Scenarios	Analysis step (I) must result in failure scenarios that group failure causes based by a similar failure course	Group failure causes	Analysis
3.3	Risk Mitigation Measures	Analysis step (II) must result in an overview of most important risk mitigation measures.	Determine risk mitigation measures	Analysis
3.4	Monitoring Options	Analysis step (III) must result in monitoring options specific to a complete failure scenario or a failure cause.	Setup monitoring options	Analysis
3.5	Monitoring Options Structure	Monitoring options consist of a direct parameter, a suitable technology to monitor this parameter, and the indirect parameter that is actually measured.	Define components	Monitoring options
3.6	Generic Filter-Specific	The results of the analysis must distinguish in filter-generic or filter-specific failure scenarios, failure risk mitigation measures and monitoring options.	Distinguish generic filter specific	Failure scenarios, failure risk mitigation measures, monitoring options
3.7	Diagram	The results of the analysis must be captured in one diagram to make the content easily-understood.	Create diagram	Diagram

4.1.4. Diagram

In this section, the design considerations and requirements surrounding the monitoring diagram as part of a M&M strategy are discussed. Since the final analysis found in Appendix B has become very extensive, this is assumed to be not very easily comprehendible and accessible. While the analysis is significantly more convenient than the three extensive filter design guidelines from which you could retrieve this information, the resulting analysis remains too extensive. Therefore, with HDSR and water managers with dikes as the target group in mind, the requirement for a diagram summarizing this analysis was set. The aim of a diagram is that without reading many pages, the target group should easily get an overview of the failure scenarios, risk mitigation measures and monitoring options and use the diagram to look up the desired information in the analysis itself.

The diagram is designed to be read from the middle, which starts with the most basic failure scenario distinction, a pipe either passes the filters or forms upstream, to the sub-failure mechanisms, failure scenario's with different underlying failure causes. Then these failure scenarios logically flow to failure mitigation measures and detailed monitoring options. Throughout the iterative process, it became apparent that when monitoring options are implemented, the diagram could be read in reverse to assist with determining possible failure causes using the monitoring data. Therefore a new requirement was set to include a reading guide above the diagram. Additionally, clear colour indications to indicate the related filter application(s) for the failure scenarios, risk mitigation measures and monitoring options. Also, an extensive legend was added. From the validation, one important recommendation is included as a requirement, for instance, to include more technical drawings to make the diagram more comprehensible and give better insight into the risk profiles of the filter. The discussed design considerations are listed as requirements below in table 4.4.

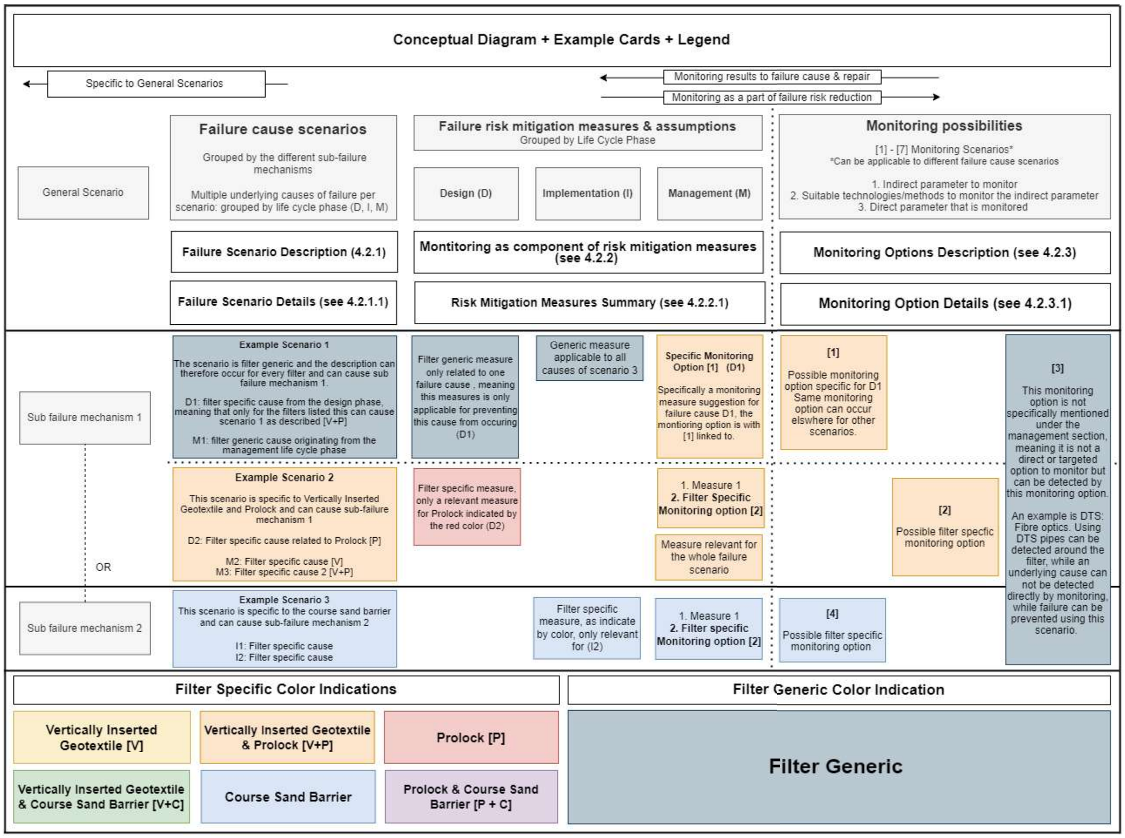
Table 4.4: Overview of diagram defining design requirements of M&M strategy

#	Name	Requirement	Function	Object
4.1	Failure modes	The diagram must start with the most basic failure distinction: exit point formation upstream of filter and passage of the filter.	Distinguish basic failure possibilities	Diagram
4.2	Reading direction	The diagram must be readable from basic failure scenario to sub-failure mechanism to the failure cause scenarios with the underlying failure causes.	Logical reading direction	Diagram
4.3	Life cycle phase risk mitigation	The failure risk mitigation measures must be grouped by relevant life cycle phases.	Group by lifecycle phase	Failure risk mitigation measures
4.4	Two way reading direction	The diagram must indicate a two-way reading direction between monitoring options and failure risk mitigation measures: failure risk mitigation by monitoring or monitoring results to failure cause repair.	Indicate reading directions	Diagram
4.5	Filter-generic and filter-specific colours	Distinctive colours must be used to indicate filter-generic or (combinations of) filter-specific failure scenarios, risk mitigation measures and monitoring options	Use distinctive colours	Failure scenarios, Failure risk mitigation measures, Monitoring options
4.6	Technical drawings	Technical drawings must be included to clarify the failure scenarios and sub-failure mechanisms.	Include technical failure drawings	Diagram
4.7	Legend	An extensive legend with example cards must be included for additional clarification.	Include legend	Diagram
4.8	Conceptual explanation	A conceptual explanation diagram of the complete diagram must be designed and accompanied by the main report of the research.	Include conceptual diagram explanation	Report

4.2. Final Design Result

The final result is found in a large diagram which captures the entire analysis of the different filters, their failure scenarios and risk mitigation measures. This complete analysis can be found in Appendix B. The diagram can be found in appendix A. In this section, a conceptual explanation of the diagram is provided.

The essence of the diagram is that when exploring possible monitoring options, monitoring should be viewed as a risk mitigation measure part of many different risk mitigation measures taken or even substantiated assumptions that result in an acceptable failure risk of the filter. With consideration of all these measures/assumptions that may or may not have been taken and the project and site-specific circumstances, a well-considered decision can be made for implementing a monitoring option. The diagram shows each failure scenario, how monitoring can contribute to risk mitigation, and insight into the differences and similarities between the three filters. Below in figure 4.1 the main concept of the diagram is illustrated. Each box corresponds to the following subsections of this section.



The scenario is filter generic and the description can therefore occur for every filter and can cause sub failure mechanism 1.

D1: filter specific cause from the design phase, meaning that only for the filters listed this can cause scenario 1 as described [V+P]

M1: filter generic cause originating from the management life cycle phase

Filter generic measure only related to one failure cause , meaning this measures is only applicable for preventing this cause from occuring (D1)

Specifically a monitoring measure suggestion for failure cause D1, the montioring option is with [1] linked to.

Possible monitoring option specific for D1 Same monitoring option can occur elswhere for other scenarios.

This monitoring option is not specifically mentioned under the management section, meaning it is not a direct or targeted option to monitor but can be detected by this monitoring option.

An example is DTS: Fibre optics. Using DTS pipes can be detected around the filter, while an underlying cause can not be detected directly by monitoring, while failure can be prevented using this scenario.

This scenario is specific to Vertically Inserted Geotextile and Prolock and can cause sub-failure mechanism 1

D2: Filter specific cause related to Prolock [P]

M2: Filter specific cause [V]
M3: Filter specific cause 2 [V+P]

Filter specific measure, only a relevant measure for Prolock indicated by the red color (D2)

This scenario is specific to the course sand barrier and can cause sub-failure mechanism 2

I1: Filter specific cause
I2: Filter specific cause

Filter specific measure, as indicate by color, only relevant for (I2)

Figure 4.1: Conceptual Explanation of Monitoring Diagram. Conceptual cards refer to the following sections in this chapter. Example cards and a legend denoting the colour indications are added for clarification.

In the diagram and analysis, there is a distinction made between the most basic failure scenario distinction: a pipe either passes the filter or a pipe and exit point forms upstream of the filter. Furthermore, the sub-failure mechanisms are included in the diagram. The diagram can primarily be read from the failure scenario to the most important risk reduction measures per life cycle phase and then the resulting monitoring options. However, it could be read in the opposite direction when a monitoring option is implemented to assist in determining the underlying cause of the failure of the filter based on monitoring results, as understanding the complete life cycle and functioning of the filter is very important for deciding on appropriate monitoring options.

4.2.1. Failure Cause Scenarios

Scenarios group multiple failure causes that lead to a more or less similar fail scenario consistent with the description given. Scenarios can be filter-generic or filter-specific, indicated by the colour in the diagram. The purpose of failure scenarios is to group different failure causes that result in one largely similar failure scenario. By reducing significantly fewer failure scenarios compared to failure causes found in failure trees, the failure modes of the different filters can be more easily understood and compared. With these scenarios reading through all three filter design manuals to make comparisons about filter failure scenarios is not necessary. The failure causes are included in the scenarios and can either be filter-generic or filter-specific. Below all defined failure causes can be found in table 4.5

Table 4.5: Defined failure cause scenarios for all the different sub-failure mechanisms

Sub-failure mechanism	Failure Scenario	Description	Generic or Specific
Pipe before	BF1	Weakness in the overburden leads to bursting	Generic
	BF2	Pressure build up due to decrease in filter permeability leads to bursting of overburden	Prolock
Pipe through	T1	Filter cannot prevent upstream soil grains from being washed out (does not meet filter criteria)	Generic
	T1.1	Surrounding sand too fine relative to (1) the filter sand or (2) the mesh size of the perforations in the filter	
	T1.2	Filter sand does not reach the top of perforations	
	T2	A crack/hole has developed in the filter allowing upstream soil to flow through the crack	
	T2.1	Calculated material properties (strain properties/strength capacity) are insufficient	Prolock
	T2.2	Incorrect execution of installation creates a crack/hole in the filter	VIG
	T2.3	Root growth, animal grazing, soil stirring activities or degradation	Generic
	T3	The granular filter partially erodes or washes away allowing a pipe to form through	CSB
	T3.1	Incorrect composition makes filter sand internally unstable	
	T3.2	Critical heave height has been reached, causing remaining filter sand under slope to succumb to heave	
	T3.2.1	The effective (remaining) heave height has decreased due too cause other than erosion	
	T3.2.2	Erosion process accelerated in barrier due to increase of flow velocity or decrease of erosion resistance	
	T3.2.3	Too low permeability contrast with surrounding sand due to the barrier sand being too fine	
Pipe behind	BH1	Insufficient finish, connection to piping safe grounds, other piping measures or discontinious produced filter parts	Generic
Pipe below	BL1	Low permeability contrast: Filter/surrounding sand insufficiently permable or too permeable surrounding sand	
	BL2	Filter does not reach the correct depth (anymore)	
	BL3	Space around filter due to local variation in aquifer	VIG
Pipe above (2 variants)	A1.2 (v1)	Backfill clay fails and exit point forms directly above the filter allowing pipe through [C] or along [V] the filter	CSB VIG
	A1.2 (v1)	Filter cap fails and drainage path exit point forms directly above the filter allowing pipe through the filter	Prolock
	A2.1 (v2)	Pipe can grow above the filter via backfill clay due to weakened backfill clay	Prolock VIG
	A2.2 (v2)	Top of filter (locally) does not reach overburden	VIG

Failure Scenario Details

Failure scenario group failure causes based on their similar effect on the filter and the dike system. However, due to the differences in the filters, one filter-generic failure scenario can still result in different monitoring options per filter. Monitoring possibilities also do not have to be applicable to the whole scenario. When a failure cause occurs, it does not mean the failure of the filter immediately. Multiple different events have to occur also before failure; this can be checked in the failure trees of the filters. These events include at least bursting and heave and, in most cases, pipe growth until the filter if the exit point is not upstream of the filter.

4.2.2. Monitoring as a Component of Risk Mitigation Measures

Monitoring is one of many different measures to mitigate dike failure risk due to the failure of the anti-piping filter solution. It is important to understand which measures or assumptions have been made to determine the necessity of monitoring, the remaining failure risk and whether this is acceptable. When a filter is not designed for heave in terms of depth, for instance, the failure risk contribution of pipe below is much more significant. Monitoring, therefore, has a larger contribution to the failure risk reduction in that case. Therefore a sufficient understanding of monitoring within all these risk mitigation measures is important.

Risk Mitigation Measurs

Risk mitigation measures in the design phase of a dike reconstruction mainly concern the correct mapping of the subsurface that will ensure the calculated and estimated safety of a dike with an anti-piping filter installed. Design choices such as designing for heave or a conservative length, as in the case of an impermeable screen, are also relevant to the risk mitigation monitoring necessity assessment. Weaknesses may also emerge from the design phase for targeted monitoring, for instance, from soil surveys. Risk mitigation measures during the implementation phase mainly concern quality control during construction, of which implementation monitoring can be a component. Field trial results can also be used to assume low failure risk contribution safely. Implementation monitoring can sometimes identify weak spots for location-targeted long-term monitoring. Risk mitigation measures taken during the management phase are mainly related to the duty of care of the water manager, with dikes in the Dutch context. Many measures involve inspection to detect threats to the safety of the embankment, where monitoring is often included as an option but not necessarily always required. This depends on project-specific circumstances and the complete package of risk mitigation measures.

4.2.3. Monitoring Options

A monitoring option consists of an indirect parameter to be monitored, a suitable technology to measure this indirect parameter and the direct parameter measured by this technology. Implementing a monitoring option can contribute to the detection of multiple different failure scenarios or mechanisms. The diagram marks the scenarios using [1] - [7]. All seven monitoring options are listed and elaborated in section 4.4.

Monitorin Option Details

Multiple monitoring scenarios can be suggested as possible risk reduction measures for one monitoring scenario. These can be filter-generic or filter-specific. They can be relevant to the whole scenario or only a select number of failure causes which can be monitored. All monitoring options are also included in the risk mitigation measures section of the diagram. In between the risk mitigation measures, they are marked in bold in the diagram. Only monitoring option 7, non-targeted pipe detection, is not listed as it is applicable to all failure scenarios of all sub-failure mechanisms except those of pipe before. With this monitoring option (Fibre optics), any pipe that occurs in the vicinity of the filter can be detected, therefore, applicable to all these sub-failure mechanisms.

4.3. Resulting Montioring Options

The monitoring options from the complete monitoring diagram are listed below in the table 4.6 as an overview.

Table 4.6: Monitoring Options taken from the monitoring diagram

#	Monitoring Option	Indirect Parameter	Technology	Direct Parameter	Related Sub Failure Mechanism	Filter Generic / Specific	Continous / Early Warning
1.	Surface Monitoring	Exit Points Surf ace Cracks	Infrared	Temperature	pipe before	Generic	Continous (Surface Cracks, Vegetation, engravings) Early warning (Exit points)
		Vegetation, Engravings / Animal Grazing			pipe through	Generic	
		Exit Points Surface Cracks			pipe above	Generic	
2.	Filter permeability	Clogging	Pump test	Hydraulic Head Difference (+ or -)	pipe below (+), pipe before (+)	Prolock, VIG (not in NL)	Continous
					pipe through (-)	VIG	
3.	Anaerobic conditions	Clogging (bacterial/chemical)	Scent	Sulphur Scent	pipe below	Prolock	Continous
					pipe before		
4.	Non-targeted crack/hole detection	Crack/hole - Increase in flow velocity	DTS: Fibre Optics	Temperature	pipe through	Generic	Continous
5.	Non-targeted pipe detection	Pipe - Increase in flow velocity		Temperature	All but pipe before		Early Warning
6.	Targeted pipe detection	Pipe - Increase in flow velocity	1. Pore pressure gauge 2.Aquavector	1. Pore water pressure 2.Flow velocity, Flow direction	1. Pipe behind 2. All but pipe before	1. Generic 2. VIC + Prolock	Early Warning
7	Gravel sample exit point	Pipe reaching barrier and erosion of the barrier	Soil sample	Presence of gravel	All, except no horizontal pipe growth behind	CSB	Post highwater (degredation)
8	Settlement Monitoring	Settlement overburden	Settlement measuring hose	Vertical deformation	pipe through	CSB	Early Warning (degredation)
					pipe above	VIC	Continious

In the following paragraphs, the presented monitoring options and considerations are discussed. The overview of failure scenarios explaining what is monitored with these monitoring options can be found in B. First, the difference between early warning, continuous and post-highwater monitoring options is explained.

4.3.1. Continious, Early Warning & Post-highwater

During the target group interviews, as part of the problem investigation phase, found in appendix C, it appeared that the target group prefers monitoring options that provide insight into whether the filter does not function before a high water situation. Therefore this is indicated in table 4.6. A monitoring option meets the continuous requirement if the defect can be monitored continuously, which means that a failure scenario can be detected at any time and not only during high water conditions. A defect can then be monitored before a pipe can pass the filter. Continuous does not mean real-time and mainly involves periodic monitoring that can provide continuous insight for a dike manager. Early warning means that during a high water event, the filter can be monitored to see if a pipe is growing past the filter so that timely corrective measures can be taken. The third category concerns post-high water and applies to monitoring that can detect damage or degradation after high water. This category is specific to the coarse sand barrier since significant high water is expected to erode a portion of the barrier. This requires sufficient confidence in the realized design. One immediate conclusion that can be drawn is that only when clogging forms a significant safety risk, or with the addition of a significant risk on the collapse existing pipe leading to pipe above in case of a VIG, a monitoring system can provide continuous insight. For many monitoring systems, failure detection relies on an early warning. An important note is that a monitoring option which can provide continuous insight does not necessarily show filter failure with certainty. When clogging is monitored, it cannot always be said with certainty whether it will lead to failure.

4.3.2. Surface Monitoring

Surface monitoring complements inspection as part of the manager's duty of care. It can be applied to detect exit points, surface cracks, digging and vegetation through infrared technology. Drought cracks can lead to the formation of an exit point. When an exit point forms upstream of the filter, pipe before can occur since the pipe has passed the filter immediately. Also, an exit point may not form directly above the filter, which causes pipe above, where the pipe grows through or past the filter. With the Prolock filter, the filter cap should also fail for this to occur. In addition to the inspection, of which surface monitoring can therefore be a component, it should be indicated where the filter is located in the subsurface so that there is a marked no burst zone directly above and upstream of the filter. Furthermore, depending on the type of filter, root growth (vegetation) and (animal) grazing can affect the filter and cause pipe through. For this sub-failure mechanism, the no-burst zone must be extended downstream beyond the filter because engravings can damage the filter from both sides of the filter screen. As mentioned earlier, surface monitoring complements inspection and cannot completely replace inspection. Thereby, surface monitoring must be clearly weighed on what the added value is based on the project-specific risks, previous experiences and consultation with the dike managers.

Infrared measurements use electromagnetic radiation not visible to the human eye to accurately measure temperature differences in planar coverage at a surface. The measurements are made using a camera, which may also be applied as remote-sensing. This camera provides a thermogram, a visual representation of the prevailing temperatures on the surface where different colours indicate different temperatures. Weak spots on the surface may not yet be visible to the human eye but can be easily identified on infrared thermography images and is an improved method of observing critical locations compared to visual inspection. This improved inspection method increases the objectivity of assessing critical locations (Netwerk Dijkmonitoring, 2023b; van Beek, 2017). Therefore, this is mostly applicable to surface cracks, as exit points, and vegetation to a lesser extent, are difficult to miss by visual inspection .

4.3.3. Filter permeability

The filter permeability can be monitored periodically using a pump test. This involves using a pump to lower the water level in an extraction well. As a result of the extraction, the groundwater level is also lowered in the surroundings of the extraction well, and groundwater flows through the filter to the extraction well (Bodemrichtlijn, 2023). During the test, monitoring wells upstream and downstream of the filter is used to measure whether the hydraulic head difference across the filter has increased from the reference measurement, which is an indication that the filter is clogging, or in the case of a decrease in hydraulic head difference, that the filter is becoming more permeable.

The Prolock filter screen is the only filter application susceptible to clogging. For the coarse sand barrier, the surrounding sand, being finer, is more susceptible to clogging than the barrier sand. This implies that when the barrier becomes clogged, the surrounding is already clogged, which solves the piping problem as clogged sand is not susceptible to erosion (Koelewijn, 2021). Research has been conducted for the vertically inserted geotextile, concluding that there is no risk of clogging in the Dutch River area (Burger & Waterloo, 2020). However, this might be a possibility outside the Dutch context. Clogging is, therefore, only a risk for the Prolock filter screen, given its lower permeability, due to the alternation between closed sections and tubes with perforations, the porosity criterion, determined by the number of openings per unit area, is relatively low. This will most likely require permeability monitoring. Clogging will lead to a preferential flow path under the filter through which pipe below can lead to failure. Also, clogging of the Prolock filter screen can lead to pipe before, where pressure build-up due to the clogged filter can create an exit point upstream due to bursting. With the other filter solutions, this is also theoretically impossible outside the Dutch context due to the higher permeability.

While clogging is not a significant risk with the vertically inserted geotextile, ageing of the geotextile could potentially increase the mesh width of the perforations, whereby the permeability of the screen also increases. As the mesh width increases, erosion may eventually occur through the filter, causing pipe through. Based on the type of geotextile used, strength requirements and future experience with ageing, a choice can be made to monitor permeability with a pump test. In this case, the head difference across the filter will decrease.

4.3.4. Anaerobic conditions

There is a small risk of biological clogging for the Prolock filter screen. This cannot occur if anaerobic conditions are maintained within the tube because oxygen does not diffuse to the depth of the perforated section. Since this risk is small with a sound design and execution, periodic sampling is sufficient. This sampling includes digging up a cap at critical locations and opening it up to smell if a sulfur odour is present. Although this is not monitoring, it is included for completeness, and if the risk of biological clogging is greater during service life, monitoring options could be explored.

4.3.5. Non-targeted crack/hole & pipe detection

A challenge in detecting pipes with monitoring is that using conventional point measurements makes it difficult to detect pipes since it cannot be determined in advance with certainty where a pipe will arise due to the usually high spatial variation in the aquifer and uncertainties involved. To address this problem, line measurements offer a solution compared to point measurements, as they allow monitoring the entire length of the filter across the dike. Fibre optics is a relatively new and innovative technology for this purpose and consists of a glass or plastic waveguide with a diameter of about 0.1 mm that allows light to be sent along kilometres of length, allowing temperature monitoring (Netwerk Dijkmonitoring, 2023a). This technique is also called distributed temperature sensing (DTS). The working principle is based on the fact that leakage through a filter or subsoil changes its temperature field due to a concentrated increase in the flow velocity (Bersan & Koelewijn, 2015; van Beek, 2017). Optical cables can be buried into the aquifer and run for kilometres long along the length filter. The optimal location is near the toe of the dike, just below the thick cover layer where the piping process takes place; although advection also influences the spatial temperature field, the sensor is less effective at detecting pipes at greater distances from the pipe. This effectiveness depends on the local composition of the aquifer (Bersan et al., 2018).

There are two approaches to detecting seepage using DTS. The first approach, the gradient method, is a passive method based on absolute temperature changes caused by seepage water within the subsurface. This method is limited to cases with a temperature gradient between the seepage water and the soil. When the groundwater and the soil have almost equal temperatures due to a lack of temperature variation, the passive method does not work. An active approach can surpass this limitation, also named the heat-pulse method that warms the soil. The average spatial resolution is 1m, and the measurement accuracy is 0.1 °C. In both cases, a readout box must be placed at the end of the fibre optic cable to read the fibre optic cable data (Bersan et al., 2015). Because this technique allows pipes to be detected along the entire length of the filter, in theory, almost all other monitoring options can be dropped except for detecting pipe before since it has already passed the line measurement in advance and observation of a change in the temperature field due to advection can therefore not be guaranteed. When implementing DTS as the primary monitoring system in place, the monitoring system does function fully as an early warning system. In case of clogging, for example, a pump test can detect a risk of pipe below due to clogging, even before a high water situation occurs, unlike with DTS. Of course, this is more beneficial than when no monitoring system is installed. The major advantage of DTS is that it can provide full coverage along the length of the filter, which cannot be done using solely continuous monitoring options. Because of this full coverage, this monitoring option theoretically allows the detection of holes or cracks in the filter because of increased flow velocity. As far as known, in the literature, no demonstration of this has been performed of this possibility.

4.3.6. Targeted Pipe Detection & Gravel sample method

As described in the previous section, targeted monitoring for piping is difficult due to the uncertainty regarding the likely locations where a pipe will develop due to local variation in the subsurface. When conventional geotechnical sensors are used to detect pipes, e.g., pore pressure sensors, to do point measurements, the sensor can detect a pipe approximately in a radius of 1 meter around the sensor (Koelewijn, 2017). So this option is only possible when one wants to monitor a known critical point along the length of the filter, for example, a location where the overburden is thinnest or the filter is placed closest to the normative exit point. Only pipe behind can be specifically monitored by placing a sensor at the sides of a filter. Although, in many cases, there are enough risk-mitigating measures to rule this sub-failure mechanism out. It could be a promising method in some cases, for example, to place sensors at a connection between different types of filters, which due to the limited number of implementations of these filters itself, is a new situation without an existing implementation yet.

As mentioned in the previous section, a pore pressure gauge can be applied for this monitoring option. Water pressure gauges are also often referred to as piezometers. The term piezometer is used to refer to a sensor that is sealed and placed in the subsurface. This gauge responds only to the surrounding groundwater, not groundwater levels at other depths. A commonly used water pressure gauge is the vibrating wire type. Through two filters in the cone, the pore water is brought into contact with the membrane of the pressure element. On the inside of the pressure element, a string is tensioned between the membrane and the fixed side of the pressure element. The membrane displacement due to pore pressure differences creates a measurable tension difference in the string. (Source network dike monitoring) However, a new innovative technique has also entered the market called aquavector. This technique can determine the flow velocity and direction through a point measurement at the placed location of the sensor. Due to the innovative nature of this technique, there is as yet no known experience with this technique and piping detection. However, because a piping erosion channel functions as a kind of extraction well for the surrounding groundwater, which increases seepage and flow velocity around the pipe enormously, it can be stated that pipes can be detected with this technology. In addition, the direction of the water flow can also be determined, meaning one could relatively determine the location of the point measurement. Due to the solution's innovative nature, it is impossible to say with certainty anything about the distance of the sensor to a pipe needed for proper detection, especially as no related research has been conducted.

Aquavector uses a heat-pulse flow measurement principle. The device works on the basis of measuring differences in the diffusion of heat generated by a heating element. The device consists of a probe with a diameter of 50 mm. In this probe, there are eight temperature sensors and a heating element. The probe is inserted into a monitoring well with extendable sticks. After the stabilization period, a heat pulse is generated with the heating element and the distribution of heat is measured. Reaction time and temperature differences are recorded by sensors and are a measure of groundwater flow (Gerritsen et al., 2022).

As part of the validation phase, an expert opinion session was held and can be found in appendix D; based on this interview, it became apparent that targeted pipe detection for a coarse sand barrier is not very useful. This is due to expected erosion of the barrier itself during high water situations, where an applied gravel layer in the barrier, at a tactically chosen position, flows through the pipe channel to the exit point. This gravel can be recovered by taking a sample of the exit point. If this gravel is found, the barrier has partly eroded, the location of the damage can easily be determined, and the barrier can be repaired by excavation. It should be noted that this can only be done after high water. In the current situation in the Netherlands, this is not a problem since, at normative high water, which rarely occurs, and in site-specific conditions, a maximum of 1/3 of the barrier is expected to erode (Validation Interview 1). However, in a different context, or when a barrier in the far future, due to an unexpected, very extreme increase in normative high water levels due to climate change, for instance, it may not be possible to assume with certainty that the barrier will not erode completely, allowing a pipe to develop through the barrier. In such a case, monitoring pipes upstream may be relevant because detection after high water in such a situation is likely unsafe. This reasoning also applies to non-targeted pipe detection with DTS, meaning that in the case of a high risk of pipes passing through the barrier, DTS can have a higher contribution to reducing failure risks.

4.3.7. Settlement Monitoring

The gravel method, discussed in the previous section, for the coarse sand barrier can be undesirable if it cannot be safely assumed that a pipe will not grow through the barrier, and therefore detection of barrier erosion itself after high water is unsafe. In that case, a settlement measuring hose might be an alternative. A settlement measuring hose can only be used as an early warning system when the settlement measuring hose is installed above the coarse sand. It would also be possible in the overburden or on the surface. However, due to the delayed subsidence of the overburden as a result of erosion, this can only be detected after high water and taking a sample of the exit points is, in that case, a better alternative to find out whether the erosion of the coarse sand barrier has occurred. The settlement measurement tube, however, should be placed at the upstream end of the barrier to indicate failure due to heave if the vertical deformation is equal to the calculated heave height of the barrier. However, due to the incline and erosion dome formed in the barrier, it is not sure if the measuring hose will stay in place or settle sufficiently enough to determine a pipe running through. This should be researched further before implementation. When placed at the downstream end of the barrier, the settlement measuring hose functions as an early warning system for degradation. Then the only benefit compared to the gravel method is monitoring degradation remotely and during high water and a slightly more precise location of the degradation. Then in case of a significant risk of complete erosion, DTS is more suitable in case placing a settlement measuring hose is not possible at the upstream end to reliably detect complete erosion and failure due to heave. .

The vertically inserted geotextile can also be monitored with a settlement measuring hose. Because the geotextile is very thin, it must be well anchored in the overburden. When a pipe grown up to the filter collapses, the resulting pressure build-up can cause the overburden layer to collapse partially, causing it to settle further and the anchoring of the geotextile to become loose. This can result in pipe above. Although visual inspections can also detect this subsidence of the overburden at the signalized pipe in the hinterland, a settlement measurement tube can provide more reliability to complement the inspections. Because the situation occurs after high water, this monitoring option is, at first glance, a post-highwater detection method. However, only when the anchoring is loose does it constitute a hazard, so from the moment this hazard forms, it can be detected using a settlement measuring hose, which can be regarded as continuous insight.

A settlement measuring tube is a hollow flexible tube that can be inserted into the subsurface to monitor vertical deformation and can be used to efficiently determine the deformation along a line. The height profile of the tube can be determined by using a pressure sensor to measure the hydrostatic pressure in the tube (Netwerk Dijkmonitoring, 2023c).

4.3.8. Notes on monitoring options

Based on the validation interviews in Appendix D, some important caveats were provided and discussed here. When implementing the possible monitoring options, feasibility may be compromised because the measurement accuracy is not feasible. Although the explicitly given example of this was not included in the monitoring options in advance, possible examples of this can be given based on the final monitoring options. When applying DTS to detect holes in the filter in addition to pipes, it is questionable whether a small hole will cause a sufficient increase in flow velocity to be detected. As far as known in the literature, no research has been done on detecting holes in a filter. Therefore, measurement uncertainty can make the detection of smaller cracks or holes not feasible.

Another note is that a number of monitoring options have a risk of being unfavourable due to their cost-benefit ratio at the current time. However, this is something that may change quickly in the near future. In addition, it was mentioned that monitoring options could provide insight into the robustness of the filter, but the results of table 4.6 or the final diagram shown in 4.1 are unsuitable for this purpose. This cannot be said without linking the monitoring options to at least the qualitative failure probability contributions. For example, looking at the diagram, one cannot precisely assess the significance of the failure scenarios and the associated monitoring options without these contributions. The significance of the failure scenarios is generally estimated in the supporting analysis of the diagram. However, the qualitative failure probability contributions depend on project-specific conditions and risk mitigation measures. Ideally, as a case study, one could compare the failure probabilities of the filters without and with different monitoring options under equal project-specific conditions. Nevertheless, this study concerns a general analysis of monitoring options, and project-specific conditions are beyond the scope of this study. Quantitative failure probability contributions could provide even better insight into the significance of failure scenarios and monitoring options, but little data is available for this due to a lack of implementations of the filters.

4.4. Final M&M Strategy

The monitoring diagram result, as presented in section 4.2, is a diagram that results in possible monitoring options for all failure scenarios, where monitoring options are regarded as integral components of numerous risk mitigation measures. Using the diagram, an informed decision can be made regarding expanding and implementing these monitoring options based on the package of risk mitigation measures implemented within the project and considering site-specific conditions. The diagram is the starting point for determining whether the risk of a failure scenario is acceptable and, if necessary, whether it can be made acceptable through monitoring.

However, the diagram is not a monitoring strategy in and of itself. As detailed in section 4.1.2, on the iterative process, the diagram evolved from the design decision to further specify a generic monitoring strategy already specified for piping by van Beek (2017) into a strategy specified for the monitoring objective stated in this study. Although selecting the to-be-monitored parameters and technologies can be considered the core component of a monitoring strategy, it is essential to contextualize the final result within this strategy. This also emerged as a theoretical recommendation from the validation method for target group satisfaction. This phase of validation is discussed in the following chapter. The diagram in sect illustrates where the design result can be accessed in the monitoring strategy's road map.

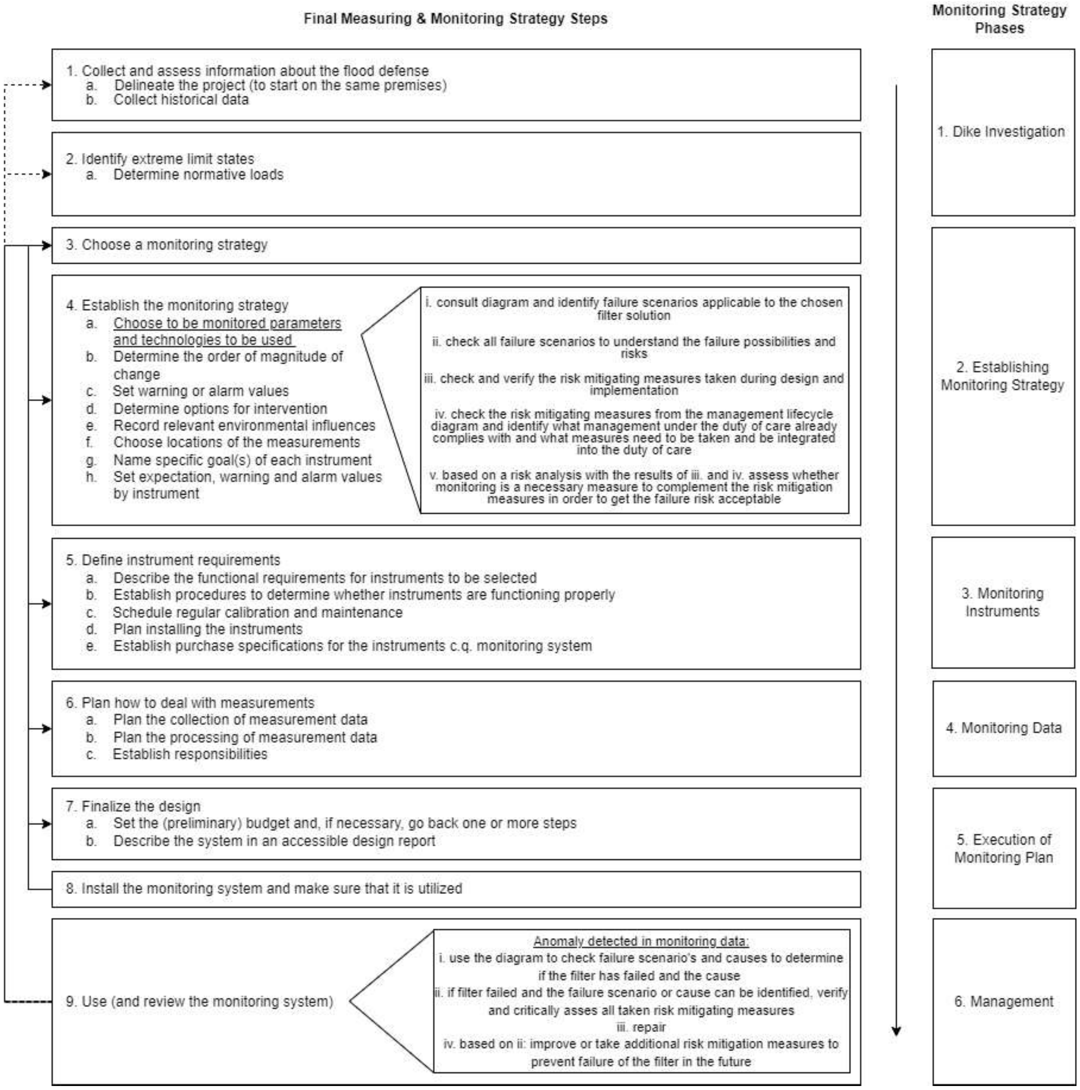


Figure 4.2: Monitoring Strategy steps & phases, based off van den Berg & Koelewijn (2014) & van Beek (2017).

This paragraph elaborates on the additional specified steps integrating the monitoring diagram into the monitoring strategy of van Beek (2017) as seen above in figure 4.2. There are two steps in the diagram where the diagram is integrated: primarily 4a and secondarily 9. Sub-steps are defined for these steps, as seen in the figure.

Step 4a step involves determining the to-be-monitored parameters and technologies. This inherently includes assessing the necessity of monitoring by determining the failure risks and the decrease of these risks by monitoring. To do this, start by consulting the diagram associated with the chosen filter solution and identifying the applicable failure scenarios. The diagram includes filter scenarios for three different filter solutions. Next, check all the failure scenarios and understand the possibilities and risks associated. It is crucial to understand the working principles of the filter and failure scenarios in order to choose monitoring options to monitor these filters. Then the implemented risk mitigation measures should be verified during the design and implementation of the filter solution. Given the target group of water managers with dikes, the time of consulting this diagram is at least before the start of the management lifecycle phase. It is assumed that the implementation phase plan is at least prepared. If installation has not been executed yet, or results from implementation monitoring, for instance, can possibly impact the risk assessment and necessity of monitoring. Therefore, the monitoring plan should be evaluated after implementation has finished. Without a finished design and implementation plan, no proper risk assessment can be made, and consequently, the necessity of monitoring cannot be assessed, and it is not recommended to start drawing up a monitoring strategy. The next step is to check the risk mitigation measures. These need to be integrated with the duty of care and inspection routine of the dike manager. Some measures are perhaps already met with the current routine. The remaining measures need to be explored on how they could be integrated within the duty of care. Finally, based on a risk analysis using the results obtained, assess whether monitoring is required to complement the existing risk mitigations and maintain an acceptable level of failure risk. Methods to determine failure risks are provided in the design guidelines of filters. It should be noted that the failure risks are qualitative currently; there does not appear to be sufficient experience and data available from applied filters to quantify in detail concrete failure probability contributions for failure causes (Taal et al., 2017; Koelewijn, 2021; Maatkamp et al., 2023). As information from previous life cycle phases is very important, cooperation between the design team, contractor and the water manager with dikes is crucial to achieving a monitoring plan of good quality according to the life cycle monitoring concept (Koelewijn & van der Meer, 2019).

The second moment during the execution of the strategy, when the diagram can be consulted, is during the management phase at step 9 when one of the monitoring options is implemented and in the processed data anomalies are detected, indicating a possible failure of the filter. In that case, the diagram can be used to check the failure scenarios associated with the monitoring option. If the failure scenario corresponds with the interpreted monitoring data, the failure cause can be identified. If it is determined that the filter has indeed failed and the failure scenario or cause can be identified, then using the diagram, the risk mitigation measures can be verified and critically assessed to determine if the (incorrect) implementation of these has caused the failure of the filter. Then besides repairing the filter to resolve the failure, based on the assessment of the risk mitigation measures conducted, take measures or implement additional risk mitigation measures to decrease the failure risk if necessary.

5

Validation

This validation section comprises five key subsections: verification, application to the Salmsteke case, target group satisfaction, expert opinion, and theoretical & practical recommendations. In the verification section, the design requirements are verified. In the next section, the applicability of the final result of the design phase is related to the specific case of the Salmsteke project, emphasizing the result within that context. Then the satisfaction of the target group with the final result is, gauging their response to the final result. Additionally, the perspectives of domain experts through their opinions and recommendations. Lastly, the theoretical and practical recommendations based on the validation outcomes are presented.

5.1. Verification

This section discusses the results of the verification after the final iteration. Intermediate iterations are not discussed; a description of the iterative process and design considerations can be found in section 4.1. By verification, validation goal 1, as formulated below, is met:

> *Validation Goal 1:* Verify if the final product meets the design requirements.

Validation is done by assessing whether the presented design requirements in section 4.1 are met. The three design requirements that are not (fully) met are listed below and discussed in the following paragraph:

- The monitoring strategy must also apply to other dike managers of anti-piping filter-reinforced dikes besides the primary target group.

  While there are no apparent indications that the final strategy and diagram could not be applicable to other water managers with dikes, which aim to reinforce a dike with anti-piping filters. However, no validation method is applied to check the relevance of the final result to other water managers with dikes. Therefore, no conclusive statements can be made regarding this.

- Deficient functioning of the filter applied is preferably detected during daily circumstances and before high waters occur

  Based on table 4.6, which includes all identified monitoring options, it can be concluded that continuous insight into the state of the filter cannot be provided with all monitoring options. In fact, most options can only be applied as an early warning system during highwater situations, as these options rely on the detection of a pipe, meaning a filter can only be detected when a pipe is detected upstream of the filter. A pipe occurring downstream is naturally expected behaviour with a filter.

- The following secondary steps must only be specified for this monitoring goal based on the previous step and thus must be started when this step is completed

  This requirement is not met as the subsequent steps are not further specified. Besides obvious time constraints, the design cycle could already be completed based on the target group satisfaction and expert opinion discussed in the following sections; the final design product already provides a substantial contribution to treating the design problem. The implications of not completing the design cycle will be addressed in the discussion of this research in chapter 6.

5.2. Target Group Satisfaction & Expert Opinion

This section discusses the results of the target group satisfaction & expert opinion interviews conducted to check both validation goals 2 and 3 as formulated below:

> *Validation Goal 2:* Justify that the final product would contribute to meeting the research goal stated and, therefore, can be used in its intended problem context.
>
> *Validation Goal 3:* Predict how a monitoring plan created with the help of this study's result will perform in its intended context.

Both the target group and the experts were asked whether the final product of this study does justice to the research aim, thereby checking validation goal 2. However, both methods check goal 3 more explicitly from a different context. For the target group, the question is whether the final result is useful when making monitoring plans for an anti-piping filter. With the expert opinion method, the question is whether the monitoring options provided are suitable in practice to provide a solution to the raised monitoring questions. This, therefore, is indirectly related to the usefulness of the final product for the target group. The full expert opinion report can be found in Appendix D.

Target Group Satisfaction Summary

The target group satisfaction showed that the interviewees were generally positive about the final result of the study. They indicated that it does justice to the stated design goal. The parameters that are interesting for a dike manager to gain insight into the functioning of a construction have been visualised insightfully. The fact that this was done using failure mechanisms makes it very recognisable for a dike manager. Then, in the same scheme, the techniques with which those parameters can be monitored were worked out, resulting in a clear set of eight types of monitoring. Moreover, attention has been paid to different innovations, and the diagram allows the same elaboration for other innovations. Also, according to interviewees, the diagram is logically structured and understandable despite its size. However, there is a risk that the user may lose the overview or find it too complicated in advance. One suggestion is to place the diagram in a digital environment where the information can be filtered by content to make it more manageable, although the colours in the diagram already partly provide for this. A note of criticism is that the filter has not yet been applied in practice when drawing up a monitoring plan. An elaboration for the Salmsteke Prolock pilot project would strengthen the final result. There is also the practical wish to have the scheme translated into Dutch. Another wish would be to go one step further than the monitoring method but also indicate the location and spatial density of measurements (distance between sensors) and the measurement frequency. Finally, it was mentioned that based only on the diagram, the interpretation of the diagram within a roadmap, flowchart or strategy is missing.

Expert Opinion Summary

The first expert agrees with the relevance of the research and its chosen research goal. The resulting diagram as the final product was found to be comprehendible and valuable for giving insight into the different monitoring possibilities related to the failure causes for each filter. According to this first expert, who is very familiar with the research topic, validation goal 3 is met. However, the interviewee misses the practical considerations, given that currently, many monitoring options due will be discarded when applied in practice due to high measuring uncertainty or unfavourable cost-benefit ratios. However, technological breakthroughs could improve costs, benefits, ease of use, and measuring accuracy, therefore considering validation goal 4 still partially met. In the future, practical usefulness in the intended problem context can increase significantly based on the interviewee's statements on the likelihood of costs and accuracy improvements of current monitoring technologies in the future.

The first expert is confident about the study's relevance, as comparing different filter solutions in monitoring their risk profiles can also indicate something about their robustness. The validation goal remains inconclusive, but improvements include making risk profiles more concrete and clarifying failure sensitivity using figures for sub-failure mechanisms and failure scenarios. This improvement is implied to have met validation goal 3, but a concrete monitoring plan with figures is ultimately needed for validation goal 4 to the opinion of the second expert, which makes this specific expert opinion on this goal inconclusive due to making a project-specific monitoring plan being outside the study's scope and time frame. It should be noted that this can mostly be attributed to the limited time available with the experts as their contribution was voluntary. Overall, validation is largely satisfactory as validation goal 3 is met, and while validation goal 4 is difficult to assess with certainty, based on the first expert's opinion, this is partially met considering some practical notes due to limitations of current monitoring options regarding costs and measurement accuracy. Recommendations based on the expert opinion are further discussed in the following discussion chapter.

6

Discussion

This chapter presents a discussion of the results of this research. The discussion consists of the interpretation of results, validity of the research, research limitations and the implications of this research, which can be distinguished between scientific implications and implications for the target group.

6.1. Interpretation of results

Because this study is a design study, the results cannot be interpreted as well as, for example, an empirical study, which can be compared with initial hypotheses. Of course, during the problem investigation phase, with the knowledge of the piping process and exploring the monitoring techniques, an estimate could be made of potentially suitable monitoring techniques. Particularly given that the location where a pipe originates is uncertain due to local variation, it is quickly apparent after an initial exploration of the various monitoring techniques that fibre optics is a very promising monitoring technique as it is a line measurement compared to many point measurement techniques available. But why apply fibre optics, and can you achieve a similar monitoring view using point measurements, and especially how can a filter solution fail? Although these questions, along with many other possible knowledge questions, are not the primary research questions of this study, the aim is that the final design contributes to being able to provide answers to these mentioned monitoring-related questions. Although the generic approach of this study to monitoring without site-specific aspects included does not result in specific advice, the following paragraphs attempt to provide an interpretation of the results by providing generic monitoring advice. Here, each suggestion remains strongly dependent on costs-benefits, and the estimated risk reduction contribution, which is location and time specific. For example, normative high water levels are a large influencing factor; location-specific and also time-specific conditions can change over time; think of climate change, for example.

First and foremost, a full coverage monitoring system, meaning that every possible failure scenario can ultimately be detected by monitoring, can only be achieved by applying fibre optics (DTS), which can detect pipes growing upstream of the filter along the entire length of the laid cable. For the sub-failure mechanism pipe before, inspection as part of the duty of care of an administrator is still needed to be certainly detected in such a system, but here surface monitoring can provide more certainty. A trade-off in such a proposed system is that it cannot provide continuous insight, and filter failure is detected as an early warning during high water. A full coverage monitoring system that could be continuously monitored at all times is not possible based on the results of this study.

In the case of a coarse sand barrier, if the calculated safety level is very high, similar to the pilot situation as indicated in expert interview 1, it can thus be assumed with reasonable certainty that failure of the coarse sand barrier during normative high water is not a realistic risk, then taking a sample of the exit points to detect damage to the barrier is sufficient, and no DTS should be recommended. Using a settlement measuring hose is additionally an option which offers a number of advantages in ease of use for the manager. An early detection monitoring method for failure can be advised when the expected safety level decreases for an existing barrier, for example, in the future due to climate change. If further research shows that an upstream settlement measuring hose is suitable for this, this is an obvious option. Otherwise, though, a DTS system is recommended.

If DTS is not implemented, the permeability can be monitored for the vertically inserted geotextile. Here, it must be considered that on account of the research conducted, clogging of the VIG has been ruled out in the Dutch River area. In this case, the permeability might still be checked with a one-time pump test since the risk of clogging after installation using the vertical technique remains despite correct execution monitoring. In addition, a settlement measurement hose can be used to check the post-settlement of formed pipes in addition to visual inspection, which can increase reliability and convenience for the administrator. For Prolock, due to its lower permeability, it is, in any case, recommended to check it by monitoring with a pump test. A scent test for biological clogging as an addition is also recommended, given the simplicity of the method.

Surface monitoring is, for any type of filter, a relevant option because during visual inspections as part of the duty of care, with the application of a clear no burst zone, pipe before, and the variant of pipe above where the discharge point arises directly above the filter can always be detected with more objectivity. Surface monitoring can increase the reliability of detecting vegetation and engravings. Then finally, when there are very critical locations, it can be recommended to monitor pipes at these critical locations with a pore pressure meter or aquavector technology. A good example is when a filter connects to a different type of filter, of which there is little experience in the field, targeted pipe detection can be used to increase the trust of an administrator in a new situation.

6.2. Validity of research

The validity of this study is an important discussion point. Three different validation methods were applied: verification, target group satisfaction and expert opinion. Verification and target group satisfaction indicate something about the face validity, i.e. does this design result do justice to the stated design goal and, thereby, usability for the target group? The expert opinion method indicates something about content validity. For all validation methods, it is difficult to determine when they can be considered successful. Clear validation goals have been formulated for each method, but assessing the success of these goals remains sensitive to subjectivity. Similar, to a lesser extent, the design goals due to the limited validation possibilities.

For the target group satisfaction, it is important to mention that only two individuals from the target group were consulted. Of course, general conclusions about the entire target group should be made with caution. However, the two interviewees are technical managers of the Salmsteke project, of which the Prolock pilot is a part and an individual from the asset team flood defences. Given these positions, the results of the target group satisfaction are estimated to be mostly representative, which was also addressed in the methodology. Besides the fact that a larger number of interviewees would obviously improve representativeness, an individual within the target group within a position involved in the technical implementation of monitoring would have been a valuable addition.

Ideally, one would like to assess the research's content validity by validating the monitoring simply by working out monitoring plans and implementing them in a real dike with a filter. And in the case of monitoring, some form of modelling or scaling down does not offer possibilities either. Therefore, two very experienced and relevant experts were asked for their expert opinion. One of these experts has been intensively involved in developing two of the three filter solutions and has extensive experience monitoring failure mechanisms. This is positive for content validity. However, both experts only read a summary and spoke relatively briefly. This is not avoidable because experts cooperate voluntarily, and the time that can be made available for this is limited. Ideally, you would also send more information to experts and have them respond to your research in detail. Also, an additional iterative cycle, including sending the draft research report, would greatly enhance content validity. Furthermore, the content validity of the result and this research would be stronger if the strategy, including the diagram, was used in a case study implementation to demonstrate both the applicability and identify possible improvements based on the case study results.

6.3. Limitations

One of the limitations of this study is due to the stated goal of investigating a filter-generic monitoring strategy: without site-specific conditions, no very definitive statements can be made regarding results and advice. This also emerged in the previous section, where the results were interpreted. Ultimately, a well-considered decision on implementing a monitoring option must be made by the manager based on aspects highlighted in this study, such as a clear understanding of the failure scenarios, the design, implementation, and the risk mitigation measures taken, but also based on aspects not highlighted in this study, such as ease of use, costs and benefits, level of effort required for the monitoring options and more.

Another discussion topic is that monitoring of dike failure mechanisms is a relatively new field of research. As a result, there is little international scientific literature available. In addition, a lot of technical reports were used, and less reviewed scientific literature. Much information can be found in the literature about monitoring technologies, but often in a different context because the monitoring goal of this study is very specific. This is, of course, due to the innovative nature of the filters. There is also a lot of literature demonstrating working principles, where the usefulness of monitoring in water safety and potential safety or cost reductions are demonstrated. The monitoring of a dike for the purpose of piping detection has been the subject of several studies, but only one study with the specific monitoring purpose of monitoring the functionality of a filter solution has been conducted. An example of how a limited number of applications in the literature threaten the validity of the results is the monitoring option targeted pipe detection. Here an innovative new technique aqua vector is included in the monitoring option, which due to the innovative status, only had a few applications in the field and outside of this context. Based on the knowledge about piping presented in the theoretical framework, it has been reasoned that this technique can detect piping. The uncertainty in this reasoning is that it cannot be stated how suitable this solution is for this purpose in practice with certainty because it has never been applied in this context.

It is also important to be aware that due to the low number of implementations of the filters themselves, and in the case of Prolock, no executed implementation yet, the information used regarding the causes of failure might be adjusted after more field applications, including many more different locations, including outside of the Netherlands. Although in the design guidelines, it is indicated that there is high confidence that all causes of failure have been identified by sufficient research and field trials, a few new causes may still emerge. More likely, perhaps, is that certain causes of failure turn out to be more significant, but the significance can also lower, which in turn lowers the relevance of a monitoring option. An example is that the design guideline of VIG states that clogging is a long-term risk, and later research has shown that in the Dutch context, clogging cannot occur.

During an expert opinion interview, it was mentioned that monitoring options could provide insight into the robustness of the filter, but the final monitoring options or diagram are unsuitable for this purpose. This cannot be stated without linking the monitoring options to at least the qualitative failure probability contributions. For example, looking at the diagram, one cannot precisely assess the significance of the failure scenarios and the associated monitoring options without these contributions. The significance of the failure scenarios is generally estimated in the supporting analysis of the diagram. However, the qualitative failure probability contributions depend on project-specific conditions and risk mitigation measures. This is also discussed in the recommendations for further research in chapter 7.

Another issue raised is that feasibility may be compromised when implementing the possible monitoring options because the measurement accuracy is not feasible. Although the explicitly given example of this was not included in the monitoring options in advance, possible examples of this can be given of the final monitoring options. When applying DTS to detect holes in the filter in addition to pipes, for instance, it is questionable whether a small hole will cause a sufficient increase in flow velocity to be detected by the monitoring option. As far as known in the literature, no research has been done on detecting holes in a filter using DTS. Therefore, measurement uncertainty can make the detection of smaller cracks or holes not feasible. Another possible limitation is that a number of monitoring options have a risk of being unfavourable due to their cost-benefit ratio at the current time. However, this is something that may change quickly in the near future. While it thus affects the current practicality at

the moment, it does not significantly affect this research's relevance.
Another limitation of this study concerns the relevance to other water boards or water authorities with dikes. In this research, it is argued that one could imply the findings of this research must be relevant to other water managers with dikes aiming to implement innovative anti-piping filters. This argument would have been much stronger if this was actually validated within this research by investigating whether the problem context of this research exists and is similar for other water boards and assessing if the results of this research also contribute to solving the stated problem context similar to HDSR. This would ideally have been done by

6.4. Implications of results

This subsection discusses the implications of the study. Because this is not empirical or quantitative research, but a design study aimed at a target group, the implications of the results are discussed by highlighting the added value scientifically and the implications for the target group as well.

6.4.1. Scientific implications

The scientific added value lies in the comparison between the filters in failure scenarios, risk mitigation measures and monitoring options. To the best of the authorś knowledge, this is the first study to consider these three filters together, thus making the established failure scenarios a good basis for other comparative studies between these filters. Some suggestions are given in chapter 7. There is, in fact, only one generic monitoring strategy specified for piping as well, which provides general guidelines for choosing parameters to be monitored. These guidelines are very general, and therefore further specification is scientifically relevant. Additionally, the description of the iterative process, which describes the scientific approach to this design problem, is of scientific value. An example of this is when a 4th filter solution is brought to the market, this process can be consulted to extend the diagram to provide new insights relevant to an administrator for this new filter solution.

6.4.2. Target group implications

For the target group, the design result makes it easier to absorb a lot of knowledge about the filter solutions and monitoring because complex failure causes are made more comprehensible by linking them to clearly formulated failure scenarios. It also gives an administrator insight into the risk mitigation measures taken during design and implementation, which are essential to understand how these measures can be complemented by monitoring and why these measures may need to be taken.

Another implication of the design result is that when a dike manager intends to apply another filter solution within one of their dikes, they can use the diagram to easily understand how this filter solution compares to the filter solution with which experience has already been gained. Both in terms of failure scenarios, risk mitigation measures during management, as part of the duty of care, and monitoring. This also allows the manager to see whether an implemented monitoring system for a different filter would suffice for another to be implemented filter solution. It makes establishing a unified monitoring solution and determining the consequences of such a unified approach better possible. With Prolock, for example, permeability monitoring in the Dutch context is more relevant than for the other filter solutions, and if this were to be implemented unambiguously, for example, it could give an unfavourable cost-benefit ratio as permeability monitoring is less relevant for these filters. Another implication of the results is that, as mentioned earlier, the target group's wish for a monitoring system that can provide continuous insight based on these results is not feasible when there are significant threats besides clogging. Other monitoring options cannot provide continuous insight and only provide early warnings during high water.

7

Recommendations

The recommendations given in this chapter can be distinguished between scientific suggestions for further research and practical suggestions to improve the design result further. For the scientific suggestions, a distinction can be made between expanding and continuing the research and possibilities for related research that is brought up.

7.1. Scientific suggestions

- Continuation of the design cycle

As mentioned earlier in this discussion, although the final result does justice to the stated design goal, a complete measurement & monitoring strategy has not been designed. The current strategy, combined with the diagram, can be used to make a choice in determining monitoring options, which includes the parameters to be measured and the technology that can be used. Continuing the design cycle will explore how to specify and walk through the follow-up steps in a generic way for the specific measurement goal of long-term monitoring of the functionality of an anti-piping filter. This will provide many additional insights.

- Elaboration of monitoring options

The resulting monitoring options can be elaborated through a literature review looking at the current knowledge about these technologies and previous implementations within and outside the context of this research in order to derive relevant recommendations on how to use and implement these techniques for the set monitoring goal. Further consideration could be given to what are the most appropriate sensors on the current market for the stated monitoring options. The next step is to develop a generic approach for data interpretation of the resulting monitoring options. Generic estimates of costs and benefits could also be made to strengthen and benefit the strategy.

- Implementation under site- and project-specific conditions

The second possibility to extend the current research is to apply the strategy with a diagram when creating a site-specific monitoring plan. Improvements on the monitoring strategy and diagram based on the process and final plan of such a case study could be a result. In any case, it is a good suggestion to strengthen the validation of this research. One suggestion for such a case study is to implement the strategy for the pilot project of Prolock in Salmsteke, which initiated this research. This does require a lot of information from this project; think of design drawings, design specifications, embankment cross sections, soil survey results, implementation plans etc. In addition, ideally, you would do some kind of application for the coarse sand barrier and the vertical sand-tight geotextile to be able to say more about the validity of the results concerning these two filter solutions as well.

- Revise monitoring strategy & diagram after implementation

Besides implementation as part of further research discussed in the previous paragraph, one would ideally always revise the monitoring strategy, including the diagram and monitoring options, after implementation of the resulting monitoring strategy and diagram of this research. In that way, the research remains applicable in the future by having been revised based on future developments such as new or improved monitoring options or new findings from field research and implementations of anti-piping filter solutions. Therefore it is recommended that when water managers with dikes use the resulting monitoring strategy and diagram of this study, the strategy and diagram are revised, if necessary.

Then there are relevant suggestions for further research that fall outside the design cycle because it does not fully match the stated design goal.

- Determine quantitative failure risk probabilities

As mentioned earlier, risk profiles, which say something about the robustness of a filter and the role of monitoring in risk reduction, are very relevant and would be a significant addition to this research. As stated earlier, quantitative failure probability contributions and, thus, quantitative failure risk reductions of monitoring options are lacking. This is obviously a suggestion for further research, but there is not enough data to determine this quantitatively due to the still limited implementations of filters, where the lack of failure data always remains a challenge. A good start would be first to compare the qualitative failure probability contributions for the filters and the reductions that monitoring can provide. A research proposal for this could be: to compare the failure probabilities of the filters without and with different monitoring options under equal project-specific conditions using case studies. Based on such a study, it would also be much easier to say something generic about the costs and benefits of the various resulting monitoring options and to conduct research into this.

7.2. Practical suggestions

Practical suggestions concern the further development of the design product rather than further research that contributes to scientific research, and these are therefore largely based on target group satisfaction method.

- Translation of monitoring diagram to dutch language

Translation to Dutch is most relevant because among the target group English is not the official language. In addition, adding a filter function on the colors related to the filters, by adding the diagram in a digital environment is a suggestion for better overview.

- Inlcude monitoring diagram in a more comprehensive roadmap or decision tree

Another practical suggestion is that, although steps for using the diagram have been allocated, a more comprehensive roadmap or decision tree can be developed to eventually make an informed choice to implement a monitoring option using the diagram as a source of information. It should be noted that a such a roadmap to make choices on implementation in a deterministic way, is not fully possible. That is because implementation of a monitoring option can still be a valid choice, despite a qualitatively insignificant failure probability contribution reduction on paper to increase confidence in a new innovative solution, to validate design assumptions, or to gain experience with monitoring, or due to a risk averse management philosophy on dike management.

8

Conclusion

This chapter discusses the main conclusions of this study. Using an iterative design cycle, a measurements monitoring strategy was developed. This strategy was developed with the aim of assisting water managers with dikes, specifically the HDSR water board, to draw up site-specific monitoring plans, with the monitoring goal of monitoring an anti-piping filters during the management dike life cycle phase for continued operation as an anti-piping filter. This involved comparing and understanding the three different filter solutions, vertically inserted geotextile, coarse sand barrier and Prolock.

The design result from the iterative process consists of a monitoring diagram, supported by an analysis, that provides insight into the various failure causes of the filters by relating the failure causes to newly defined failure scenarios and the sub-failure mechanisms defined in the literature. For each failure scenario, insight is provided to the water manager with dikes, which risk mitigating measures can be taken during the three different life cycle phases: design, execution and management. Without knowledge of these measures, no good risk assessment can be made, nor estimating what contribution monitoring makes to reducing the risk of the failure of a filter. Per failure scenario, possible monitoring options have been mapped and defined with the indirect parameter to be monitored, the appropriate technology(s) and the direct parameter to be monitored. The diagram distinguishes with clear color indications between filter-specific and filter-generic failure scenarios, risk mitigation measures and monitoring options. The diagram is placed in a general monitoring strategy to set up a site-specific monitoring plans, and thus specifies this existing strategy by providing relevant insights to arrive at an informed choice to determine the parameters and technologies to be monitored when monitoring on of three different filter screens. This is the core of the result as follow-up steps are not elaborated.

It can be concluded, based mainly on target group satisfaction and expert opinion interviews, that the diagram is of added value when preparing a monitoring plan for the different filters. It therefore meets the stated research goal: to develop a measuring & monitoring strategy to assist dike managers with creating measuring & monitoring plans to monitor the continued functionality of a filter as an anti-piping measure. This can be further supported by the target group satisfaction and expert opinion interviews, as they found that the monitoring diagram the information relevant to a dike manager contains, such as the risk mitigation measures during the management & maintenance life cycle phase, failure scenario's that can occur for each filter along with the corresponding monitoring options. Thereby also providing the dike managers sufficient insight into how the various filters work, what could cause these filters to fail in their function, and how monitoring can reduce the failure risk for each filter, which satisfies the stated knowledge questions, which are thus provided in the final monitoring diagram. Additionally the diagram is logically structured. It is generally estimated to be a theoretically correct diagram, however, due to the lack of practical aspects such as cost-benefit and measurement accuracies of technologies, these aspects can potentially jeopardize the practical feasibility of the monitoring options. For this, technological developments may greatly improve this situation in the near future. An important conclusion from the iterative process , is that a system understanding of how a filter functions, the failure scenarios and the risk mitigation measures taken for it are essential to arrive at a well-founded measuring & monitoring strategy. In the next chapter the discussion is presented, this includes an interpretation of the insights that the design and this research can provide.

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A

Appendix A: Final Monitoring Diagram

The final diagram is shown on the next page.

← Monitoring as a part of failure risk reduction

Monitoring results to failure cause & repair →

Specific to General Scenarios →

← Specific to General Scenarios

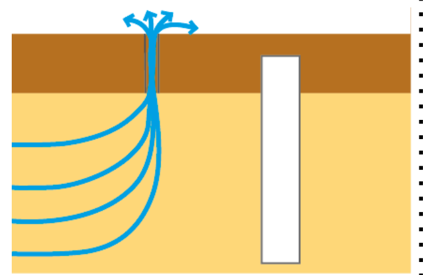
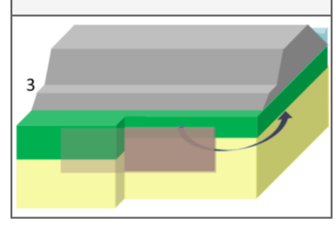
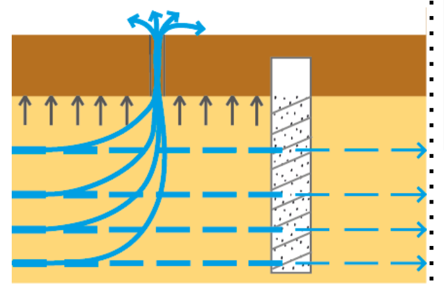
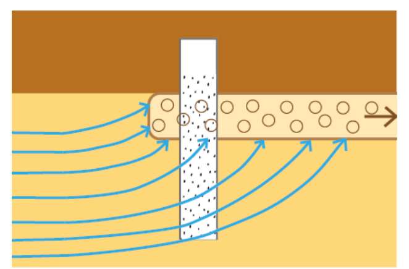
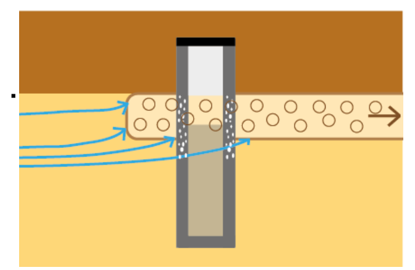
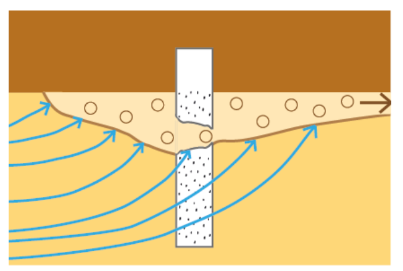
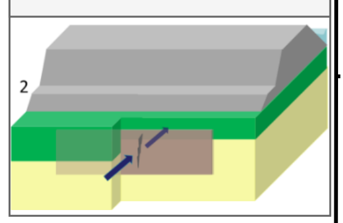
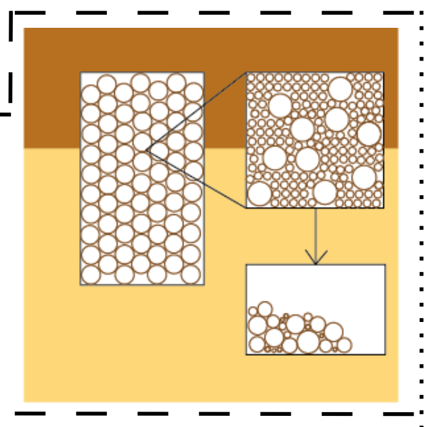
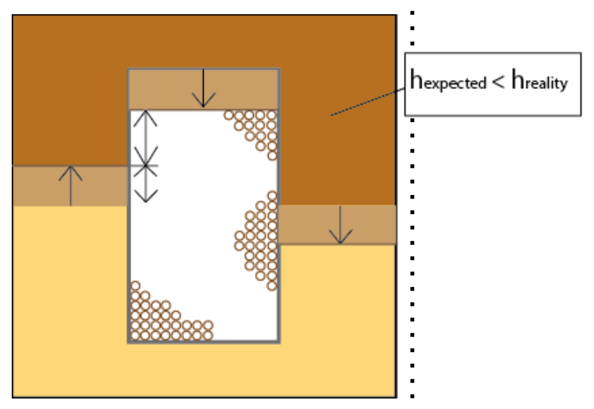
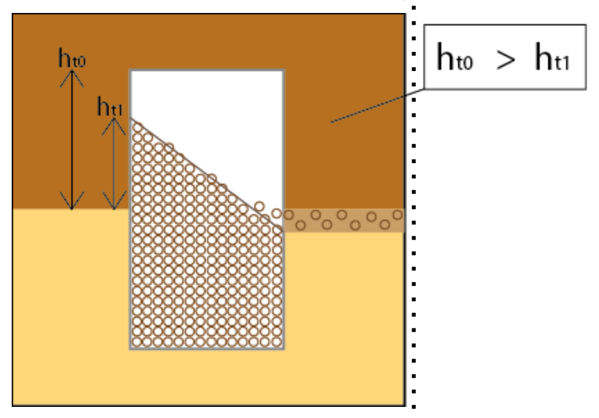
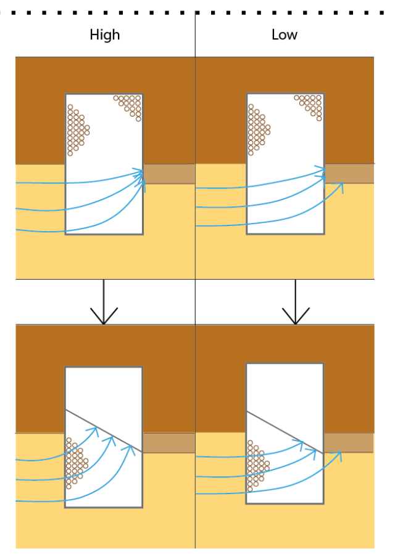
← Monitoring results to failure cause & repair

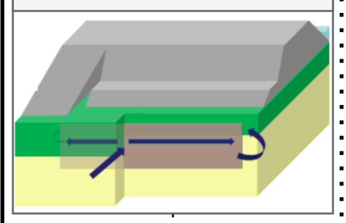
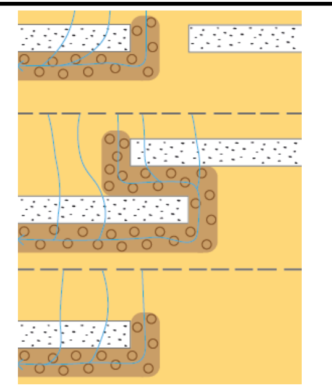
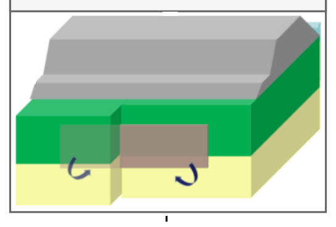
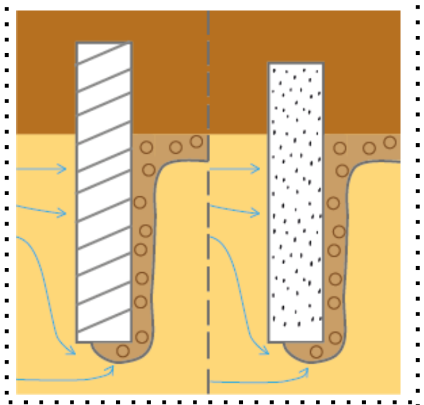
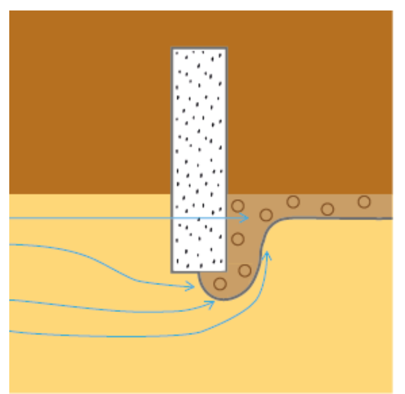
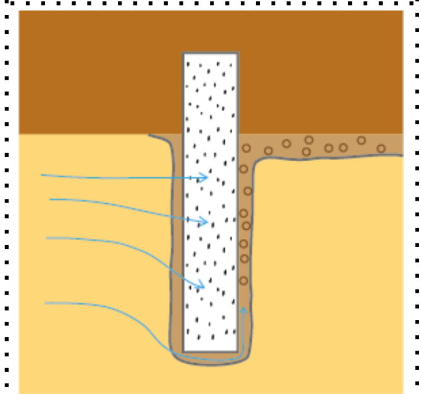
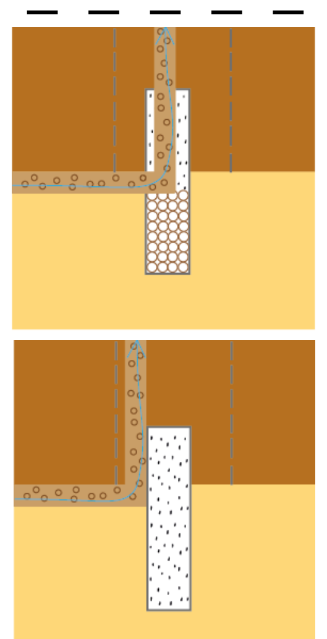
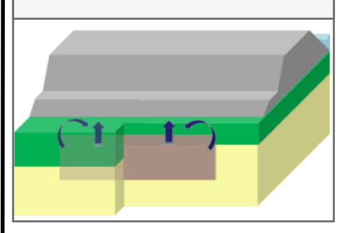
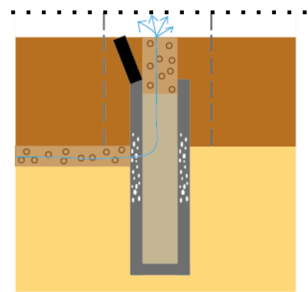
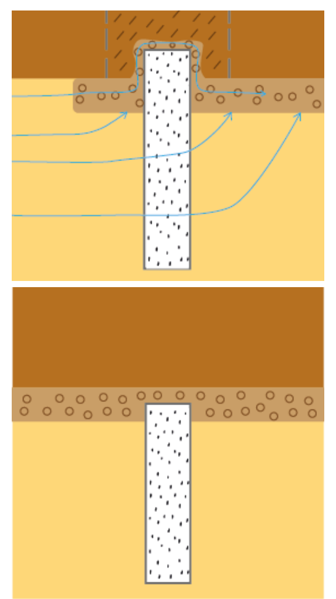
Monitoring as a part of failure risk reduction →

Most General Failure Scenarios

Pipe formation upstream of the filter

Pipe is able to pass the filter from upstream to downstream

Monitoring Options [1] - [7] Monitoring Scenarios* *Can be applicable to different failure cause scenarios 1. Indirect parameter to monitor 2. Suitable technologies/methods to monitor the indirect parameter 3. Direct parameter that is monitored	Failure risk mitigation measures & assumptions (Grouped by Life Cycle Phase) Management (M)	Implementation (I)	Design (D)	Failure cause scenarios Grouped by the different sub-failure mechanisms Multiple underlying causes of failure per scenario: grouped by life cycle phase (D, I, M)		Most General Failure Scenarios
[1] **To monitor/indirect parameter:** Surface cracks (V1) Exit points (V1 & V2) **Technology:** Infrared **Direct parameter:** Temperature	Crack formation (high water & drought) estimated low severity (M25) Detection to repair: 1.Clear no burst zone 2. Inspection **3. Surface monitoring [1]**	Installation vibrations: low overburden influence: verify by field trials (I21)	Bursting calculations Representative soil survey (Overburden thickness & weight) (D25)	**Scenario BF1: Weakness in the overburden -> Bursting** D25: Normative exit point upstream due to local variation I21: Overburden leakage by vibrating installation [P] M15: Crack formation		Pipe before  3
[3] **To monitor/indirect parameter:** Anaerobic conditions **Method:** Scent test **Direct paramter:** Scent of Sulphur **[2]** **To monitor/indirect parameter:** Filter permeability/clogging **Technology:** Pump test **Direct parameter:** Hydraulic head difference	Timely detection to repair: 1.Clear no burst zone 2. Inspection 3. Surface monitoring **4. Permeability monitoring [2] (M16)** **5. Monitoring anaerobic conditions [3] (M16)**	Cleaning perforations & strict execution protocol + monitoring (I23)	Include decreased permeability in bursting calculation Include filter sand to the top of closed tubes (M16)	**Scenario BF2: Pressure build up due to decrease in filter permeability -> Bursting** I22: Soil compaction by soil displacing installation [P] I23: Smearing of perforations [P] M16: Clogging of the screen [P]		
				Scenario T1: Filter cannot prevent upstream soil grains from being washed out (Does not meet filter rules)		
[5] **Non-targeted pipe detection:** **To monitor/indirect parameter:** Pipe -> Increased flow velocity **Technology:** Fibre Optics **Direct Parameter:** Temperature **[3]** **To monitor/indirect parameter:** Increased filter permeability **Technology:** Pump test **Direct parameter:** Hydraulic head difference	**Filter permability monitoring** (M1)	Strict implementation protocols (I1) Field trial to show no seggregation can occur (I1a)	Representative soil survey (Grain size samples) (D1) Trench filling with grain size gradient as uncertainty buffer (D1) Field trial to show no failure when grains flow through (D1)	**Scenario T1.1: Surrounding sand too fine relative to (1) the filter sand or (2) the mesh size of the perforations in the filter** D1: Grain size of surrounding sand too coarsely estimated I1a: Demixing of filter sand [C + P] I1b: Application wrong material as filter sand [C+P] M1: Mesh size of geotextile increased due to aging [V]		
		Strict implementation protocols & quality control		**Scenario T1.2: Filter sand does not reach the top of perforations** I2: Too little filter sand applied [P] M2: Settling of filter sand [P]		
				Scenario T2: A crack/hole has developed in the filter allowing upstream soil to flow through the crack		
[4] **Non-targeted crack/hole detection** **To monitor/indirect parameter:** Crack/hole -> Increased flow velocity **Technology:** Fibre Optics **Direct Parameter:** Temperature		Implementation monitoring (Deformation) Field trial to show perforated part to fail first (D3)	State-of-the-art material strength design methodoligies	**Scenario T2.1: Calculated material properties (strain properties/strength capacity) are insufficient** D2: Stretch properties of geotextile not properly estimated [V] D3: Insufficient strength capacity against deformation [P]		
		Implementation monitoring (Deformation) (I3) Manufacturability tests for connecting profiles (I4) Corrective measures (I4) Field trial to show low damage probability during implentation (I5)		**Scenario T2.2: Incorrect execution of installation creates a crack/hole in the filter** I3: Excessive deformation [V] I4: Profile runs out of lock [P] I5a: Hole is formed in the closed section [P] I5b: Hole is created in the perforated section [P]		Pipe through  2
[1] **To monitor/indirect parameter:** Vegetation Animal grazing Engravings **Technology:** Infrared **Direct parameter:** Temperature	Detection to repair: vegetation (M3), animal grazing (M4) & soil stirring activities (M5, M6): 1. Inspection **2. Surface monitoring [1]** Dummy elements to periodically check degredation (M7)			**Scenario T2.3: Root growth, animal grazing, soil stirring activities or degradation** M3: Crack by root growth [V] M4: Hole/crack by animal grazing [V + C] M5: Hole/crack by soil stirring activities M6a: Hole forms by soil stirring activities in perforated section [P] M6b: Hole forms by soil stirring activities in closed section [P] M7: Degradation of filter [P]		
				Scenario T3: The granular filter partially erodes or washes away allowing a pipe to form through		
[5] **Non-targeted pipe detection:** **To monitor/indirect parameter:** Pipe -> Increased flow velocity **Technology:** Fibre Optics **Direct Parameter:** Temperature		Quality control (Select & aselect samples) (I6) Strict implementation Protocol & Field trial (I7)	Steep grain distribution curve / Meet criteria for stability (D4)	**Scenario T3.1: Incorrect composition makes filter sand internally unstable** D4: Internaly unstable filter sand [C] I6: Demixing of filter sand [C] I7: Blending of filter sand with surrounding sand [C]		
				Scenario T3.2: Critical heave height has been reached, causing remaining filter sand under slope to succumb to heave		
[6] **Target pipe detection** **To monitor/indirect paramter:** Pipe -> increased flow velocity **Technology:** a. Pore water pressure gauge b. Aquavector **Direct parameter** a. Pore water pressure b. Flow velocity	**Pipe detection monitoring at vulnerable spots [6] (D6)**	Quality control (Sufficient filter sand height) & Corrective measures (I8) Quality control (Sufficient filter sand height) & Corrective measures (I8) Quality control (Compaction) & Corrective measures (I9 & M8)	Representative soil survey (Boundary overburden & aquifer) (D5 & D6) 5m buffer distance normative exit point & filter (D7) Upstream seal not designed with centimetre accuracy (D8)	**Scenario T3.2.1: The effective (remaining) heave height has decreased due too cause other than erosion** D5: No sharp boundary layer between piping-prone sand layer and overburden [C] D6: Boundary layer aquifer is higher upstream [C] D7: Distance barrier to exit point is small allowing an erosion lens [C] D8: Depth of upstream seal is insufficient [C] I8: Insufficient supply of barrier sand during execution [C] I9: Barrier is insufficiently compacted [C] M8: Post-compacting of barrier [C]	 $h_{expected} < h_{reality}$	
[7] **To monitor/indirect parameter:** Settlement overburden **Technology:** Settlement measuring hose **Direct parameter:** Vertical deformation	Detection to repair: **Settlement monitoring [7] (M9)**	Using clay that does not swell strongly (D10)	Representative soil survey (Soil layer composition) (D9) Representative soil survey (Local variation & 3D factor) (D10)	**Scenario T3.2: Erosion process accelerated in barrier due to increase of flow velocity or decrease of erosion resistance** D9a: Highly permeable (gravel) layer below barrier [C] D9b: Intermediate sand layer upstream of barrier not detected [C] D10a: 3D Factor underestimated [C] D10b: Coarse-grained discontinuity in background sand at barrier [C] D10c: Cohesive discontinuity in subsurface at barrier [C] I10: Replenishment clay swells too much in the hollow space [C] M9a: Subsidence of overburden downstream [C] M9b: Subsidence of overburden above barrier [C] M10: Erosion of the coarse sand barrier itself during high tides [C]	 $h_{t0} > h_{t1}$	
		Quality control (Select & aselect samples) (I11) Strict implementation Protocol & Field trial (I11)	Filter sand should match design (D11)	**Scenario T3.2.3: Too low permeability contrast with surrounding sand due to the barrier sand being too fine** D11: Barrier sand is too fine in relation to background sand [C] I11a: De-mixing of barrier sand [C] I11b: Application of wrong material as barrier sand [C] I11c: Blending of barrier sand with background sand [C]	 High Low	

Most General Failure Scenarios		Failure cause scenarios Grouped by the different sub-failure mechanisms Multiple underlying causes of failure per scenario: grouped by life cycle phase (D, I, M)	Failure risk mitigation measures & assumptions (Grouped by Life Cycle Phase) Design (D)	Implementation (I)	Management (M)	Monitoring Options [1] - [7] Monitoring Scenarios* *Can be applicable to different failure cause scenarios 1. Indirect parameter to monitor 2. Suitable technologies/methods to monitor the indirect parameter 3. Direct parameter that is monitored
Pipe behind 		**Scenario BH1: Insufficient finish, connection to piping safe grounds, other piping measures or discontinious produced filter parts** D12: Length of filter along flood defence insufficient D13: Connection of filters / ping measures insufficient	Length conservatively calculated as heave screen (D12)	Strict execution protocols (D13)	**Pipe detection [6]**	**[6]** **Targeted pipe detection** **To monitor/indirect paramter:** Pipe -> increased flow velocity **Technology:** a. Pore water pressure gauge b. Aquavector **Direct parameter** a. Pore water pressure b. Flow velocity **[5]** **Non-targeted pipe detection:** **To monitor/indirect parameter:** Pipe -> Increased flow velocity **Technology:** Fibre Optics **Direct Parameter:** Temperature
OR Pipe below 		**Scenario BL1: Low permeability contrast: Filter/surrounding sand insufficiently permable or too permeable surrounding sand** D18: Trench backfill is finer/less permable than surrounding sand [V] D19: Surrounding sand is coarser/more permeable [P] I16: Smearing of filter perforations [V+P] I17: Soil compaction by ground displacing installation [P] I18: Higher permeability surrounding sand by soil removing [P] installation [P] M14: Clogging of the screen	Heave safe design depth Representative soil survey & soil modelling (Aquifer soil variation) (D18 & D19) Geometrically closed filter rules applied (M14) Include filter sand to the top of closed tubes (M14)	Manufacturability tests & implementation monitoring (I16) Cleaning perforations & strict implementation protocol + monitoring (I16) Compaction estimated to have low influence on flow pattern [Calculations & field trials] (I17)	**Filter permeability monitoring [2]** **Anearobic condition monitoring [3] (M14)** Course soil less susceptible to clogging than surrounding sand (M14)	**[2]** **To monitor/indirect parameter:** Filter permeability/clogging **Technology:** Pump test **Direct parameter:** Hydraulic head difference **[3]** **To monitor/indirect parameter:** Anaerobic conditions **Method:** Scent test **Direct paramter:** Scent of Sulphur
		**Scenario BL2: Filter does not reach the correct depth (anymore)** D20: Filter not designed at correct depth [V+P] D21: Thick or erratic overburden: underside barrier does not extend below overburden [C] D22: Thick or erratic overburden: perforations (partly) in overburden (P) D23: Filter presses up due to upward pressure against filter cap [P] I19: Excavation barrier does not exceed overburden [C] I20: Filter is not installed at correct depth [V+P]	Representative soil survey (Mapping overburden layer) (D20, D21, D22)	Filter cap strenght negligible vs. upwards pressure if installation is correct (Quality control & field trial) (D23) Implementation monitoring (Overburden boundary) (D20, D21, D22, I19, I20)		
		**Scenario BL3: Space around filter due to local variation in aquifer** D20: Local loosened sand layers cause anchoring to be lost [V]	Representative soil survey (Aquifer soil variation) Extra depth	Forced sand replenishment under pressure during implementation		
OR		Variant 1: Pipe grows from above through the filter [C, P] or along the filter [V] Variant 2: Pipe grows from the landside over the filter (VZG, Prolock)				
		**Scenario A1.1: Backfill clay fails and exit point forms directly above the filter allowing pipe through [C] or along [V] the filter (Variant 1)** D14: Clay fill acts as drainage path [C+V] D15a: Normative exit point too close to filter & excessive erosion -> exit point above filter & anchoring geotextile is lost [V] D15b: Combination of normative exit point too close to filter & excessive erosion -> exit point above filter [C] I12a: Backfill clay applied too thinly, too wet and/or contains voids [C+V] I12b: Backfill clay swells too much in the hollow space in the embedment above the coarse sand and will erode [C]	Proper requirements for clay backfill: 1. Erosion-resistant 2. Does not swell too much (D14 & I12) Normative exit point at least 5m from filter (D15)	Strict execution protocols (D14 & I12) Clay is compacted below the water table (D14 & I12) Implementation Monitoring (D14 & I12)	Detection to repair: (Exit points) 1.Clear no burst zone 2. Inspection **3. Surface monitoring** **Settlement measurements [7] (D15)**	**[7]** **To monitor/indirect parameter:** Settlement overburden **Technology:** Settlement measuring hose **Direct parameter:** Vertical deformation
OR Pipe above (2 Variants) 		**Scenario A1.2: Filter cap fails and drainage path & exit point forms directly above the filter allowing pipe through the filter (Variant 1)** D16: Filter cap strenght too weak and is removed by pressure during high water [P] I13: Filter cap not correctly applied [P] M11: Filter cap damaged [P]	Upward pressure relative to filter cap strength insignificant based on tests (D16)	Strict implementation protocol & Quality control (I13 & M11)	Detection to repair: 1.Clear no burst zone 2. Inspection **3. Surface monitoring [1]**	**[1]** **To monitor/indirect parameter:** Surface cracks Exit points **Technology:** Infrared **Direct parameter:** Temperature
		**Scenario A2.1: Pipe can grow above the filter via backfill clay due to weakened backfill clay (Variant 2)** I14:Backfill clay applied too thinly, too wet and/or contains voids -> anchoring fails [V] I15: Vibrating installation adversely affects clay backfill [P] M12: Pipes collapse after high water -> anchoring fails [V] M13: Crack formation in backfill clay [P +???]	Proper requirements for clay backfill: (Erosion-resistant) (I14)	Strict execution protocols (I14 & I15) Clay is compacted below the water table (I14) Implementation Monitoring (I14) Field trial to show low influence on clay overburden (I15)	Detection to repair (Collapsed pipes): 1. Inspection **2. Settlement monitoring [7]** (M12) Detection to repair (Cracks): 1. Inspection **2. Surface monitoring [1]** (M13)	**[7]** **To monitor/indirect parameter:** Settlement overburden **Technology:** Settlement measuring hose **Direct parameter:** Vertical deformation **[1]** **To monitor/indirect parameter:** Surface cracks Exit points **Technology:** Infrared **Direct parameter:** Temperature
		Scenario A2.2: Top of filter (locally) does not reach overburden (Variant 2) D17: Filter not designed at correct depth [V]	Representative soil survey & depth correction based on uncertainties	Implementation monitoring (Overburden boundary)		

Legend / Example Cards

← Specific to General Scenarios

← Monitoring results to failure cause & repair

Monitoring as a part of failure risk reduction →

	Failure cause scenarios Grouped by the different sub-failure mechanisms Multiple underlying causes of failure per scenario: grouped by life cycle phase (D, I, M)	Failure risk reduction measures & assumptions (Grouped by Life Cycle Phase) Design (D)	Implementation (I)	Management (M)	Monitoring Options [1] - [7] Monitoring Scenarios* *Can be applicable to different failure cause scenarios 1. Indirect parameter to monitor 2. Suitable technologies/methods to monitor the indirect parameter 3. Direct parameter that is monitored
General Scenario Sub failure mechanism 1	**Example Scenario 1** The scenario is filter generic and the description can therefore occur for every filter and can cause sub failure mechanism 1. D1: filter specific cause from the design phase, meaning that only for the filters listed this can cause scenario 1 as described [V+P] M1: filter generic cause originating from the management life cycle phase	Filter generic measure only related to one failure cause , meaning this measures is only applicable for preventing this cause from occuring (D1)	Generic measure applicable to all causes of scenario 3	**1. Specific Monitoring Option [1] (D1)** Specifically a monitoring measure suggestion for failure cause D1, the montioring option is with [1] linked to.	**[1]** Possible monitoring option specific for D1 Same monitoring option can occur elswhere for other scenarios. **[3]** This monitoring option is not specifically mentioned under the management section, meaning it is not a direct or targeted option to monitor but can be detected by this monitoring option. An example is DTS: Fibre optics. Using DTS pipes can be detected around the filter, while an underlying cause can not be detected directly by monitoring, while failure can be prevented using this scenario.
	Example Scenario 2 This scenario is specific to Vertically Inserted Geotextile and Prolock and can cause sub-failure mechanism 1 D2: Filter specific cause related to Prolock [P] M2: Filter specific cause [V] M3: Filter specific cause 2 [V+P]	Filter specific measure, only a relevant measure for Prolock indicated by the red color (D2)		1. Measure 1 **2. Filter Specific Monitoring option [2]** Relevant for the whole scenario	**[2]** Possible filter specfic monitoring option
OR Sub failure mechanism 2	**Example Scenario 3** This scenario is specific to the course sand barrier and can cause sub-failure mechanism 2 I1: Filter specific cause I2: Filter specific cause		Filter specific measure, as indicate by color, only relevant for (I2)	1. Measure 1 **2. Filter specific Monitoring option [2]**	**[4]** Possible filter specific monitoring option

Filter Specific Color Indications

Vertically Inserted Geotextile [V]	**Vertically Inserted Geotextile & Prolock [V+P]**	**Prolock [P]**
Vertically Inserted Geotextile & Course Sand Barrier [V+C]	**Course Sand Barrier**	**Prolock & Course Sand Barrier [P + C]**

Filter Generic Color Indication

Filter Generic

B

Appendix B: Filter Failure Scenario's & Risk Mitigation Measures

In this analysis, newly defined failure scenarios are listed, which describe the physical situation in the dike system and the generically described cause of this situation that leads to filter failure. For each failure scenario, which is newly defined, there can be many different failure causes. These root failure causes can be traced back to one of the three life cycle phases of the filter; design, implementation, and management & maintenance. These failure causes were all extracted from the three filters' design & assessment guidelines (Taal et al., 2017; Koelewijn, 2021; Maatkamp et al., 2023). Unless otherwise stated, the information analysed and compared in this appendix is derived from these sources. The schematizations of the failure scenarios are newly made.

B.1. Pipe Through

For all failure scenarios of pipe through, pipe growth from an exit point to the filter must first occur before the failure scenarios can occur. In all cases of pipe through, the filter has lost its filtering effect and can no longer hold back upstream soil. This sub-failure mechanism can be caused by the filter not (or no longer) complying with the filter rules, a hole appearing in the filter, or erosion of the (granular) filter. These scenarios are divided into T1, T2 and T3, respectively.

Faiure scenario T1: The filter itself cannot (no longer) prevent grains of upstream soil from being washed out through it because it does not meet the filter rules for geometrically closed and open filters.

In essence, in this failure scenario T1, one of the six filter conditions according to USACE (2000) is no longer met: preventing upstream grains from flowing through the filter. Filters meet this condition by applying empirically determined filter criteria for geometrically closed filters. These criteria are based on the ratio of the grain size of in-situ sand to the grain size of filter sand or, in the case of a geotextile, the mesh size of perforations in the filter. For the coarse sand barrier, the filter sand provides the filtering action where a filter criteria for granular filters has been applied. In the vertically inserted geotextile, the perforations in the geotextile provide the filter working and a filter criteria for geotextile filters is used for design. In the case of the Prolock filter screen, only the filter sand provides in the filter function; however, here, both filter criteria for granular filters and geotextiles were used, which is also applicable to the plastic material used for Prolock. The size of the perforations (mesh size) in the plastic tubes is designed so that they do not affect the retention of upstream sand (perforations have no filter effect) but do affect the retention of the filter sand and the permeability of the filter screen.

The filter may fail to meet the filter rules if the surroundig sand is relatively too fine relative to the filter. In addition, the filter may also contain too little filter sand. Scenario T1 can be divided into two sub-scenarios T1.1 and T1.2, respectively.

Failure Scenario T1.1: Surrounding sand is too fine relative to (1) the filter sand or (2) the mesh size of the perforations in the filter.

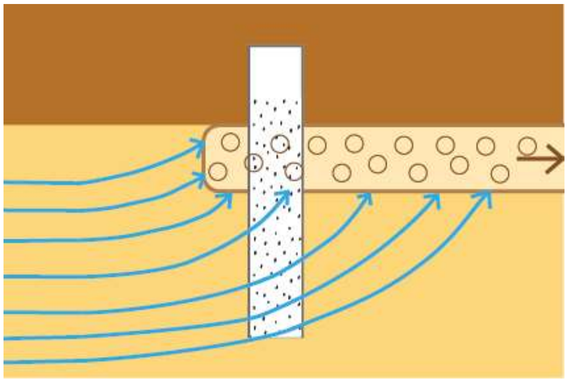


Figure B.1: Failure Scenario T1.1: Surrounding sand is too fine

Here, (1) applies to granular filters such as the coarse sand barrier and the Prolock filter screen and (2) for geotextiles where the filter function relies on the perforations such as the vertically inserted geotextile. It is important to understand that if the failure cause for scenario T.1.1, for example, is that the surrounding sand is estimated to be too fine, this automatically implies that your filter sand is chosen to be too fine and that the mesh size of the geotextile is too large. A failure failure cause for all types of filters of scenario T.1.1 is that the surrounding sand is estimated to be too fine. For the vertically inserted geotextile, ageing may cause the mesh size to increase too much. For the perforations of the Prolock filter screen, this can be ruled out because plastic is used. Furthermore, both granular filters may contain sand that is too coarse due to a design error, de-mixing or using the wrong material when executing, which makes the filter too permeable, and upstream sand may leach out.

#	Failure Cause	Filter		
		VIG	CSB	Prolock
D1	Grain size of surrounding/in-situ sand was estimated too coarsely, resulting in the mesh size of perforations being too large or filter sand being calculated too coarsely	x	x	x
I1a	De-mixing of filter sand, making it too coarse in relation to surrounding / in-situ sand (locally)		x	x
I1b	Application of wrong material as filter sand, making it (locally) too coarse in relation to surrounding / in-situ sand		x	x
M1	Mesh size of geotextile increased due to aging	x		

Table B.1: Failure Scenario T1.1: Surrounding sand is too fine

Risk Mitigation Measures & Monitoring:

For this scenario, the risk is limited when soil testing has been done in accordance with the design guidelines (T1). For this, there must be enough available grain distribution samples to be representative. If these are insufficiently representative and a section with finer piping-sensitive background sand is missed in the soil investigation, there is still a chance that failure will occur as a result. If field tests are performed, similar to the coarse sand barrier pilot, that shows that if surrounding sand can wash through the filter, it can drip through, and if failure does not occur, the risk of scenario T1.1 can be further reduced.

By choosing backfill sand, in the case of a vertically inserted geotextile, with grading so that it functions as an additional filter to cover any variation in grain size from the soil investigation of surrounding sand, this risk can be virtually eliminated. Here, the trench fill functions as an additional filter to cover for any variation in the soil investigation of the surrounding sand.

The risk of scenario T1.1 can be further eliminated if clear implementation protocols have been established and adhered to. For segregation (I1a), this can be eliminated for both granular filters when field tests have shown that segregation does not occur during the pouring of the coarse sand. Although in the pilot, this was demonstrated, it always depends on the design and project-specific conditions. For the application of the wrong material (I1b), it is only a risk when different types of filter sand are used in the design; when different packaging is used, the probability of this failure cause is negligible.

For geotextiles, there is always a chance of damage due to ageing, which increases the mesh size (M1). Although the risk can be reduced by not exposing the geotextile and by defining the durability requirements in design, this can be ruled out with less certainty than the other failure causes by sufficient design and execution. Long-term monitoring of this scenario is most relevant for this in the VIG, where an increase in permeability due to ageing can be monitored.

Failure Scenario T1.2 Filter sand does not reach top of perforations

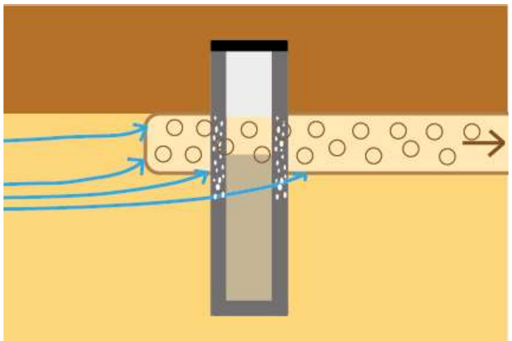


Figure B.2: Failure Scenario T1.2: Filter sand does not reach top of perforations

This failure scenario applies only to granular filters, where (1) applies to the coarse sand barrier and (2) to Prolock. However, for a coarse sand barrier with an indentation, this scenario is very unlikely. In such a scenario, the top of the barrier would extend to the bottom of the overburden, which is highly unlikely and is therefore not included as a cause for pipe above in the design & assessment guideline. However, it remains a theoretical possibility and is therefore included.

#	Failure Cause	Filter		
		VIG	CSB	Prolock
I2	Not enough filter sand is applied so the tube is filled to below the perforations/barrier sand does not extend to the overburden			x
M2	Post-packing filter sand so that tube is filled to below the perforations			x

Table B.2: Failure Scenario T1.2: Filter sand does not reach top of perforations

Risk Mitigation Measures & Monitoring

With a clear implementation protocol, scenario T1.2. can be virtually ruled out. This will have to consist of a clear check per tube or per section in the case of the coarse sand barrier whether the required height of filter sand has been reached (I2). This also applies for post-settlement (M2), including Prolock, since it is not possible for the settlement to exceed the length of the 'blind' section above the perforations. However, quality control suffices so that a long-term risk can be excluded, making long-term monitoring irrelevant for scenario T1.2.

Failure Scenario T2: A crack/hole is created in the filter allowing upstream soil to flow through the crack

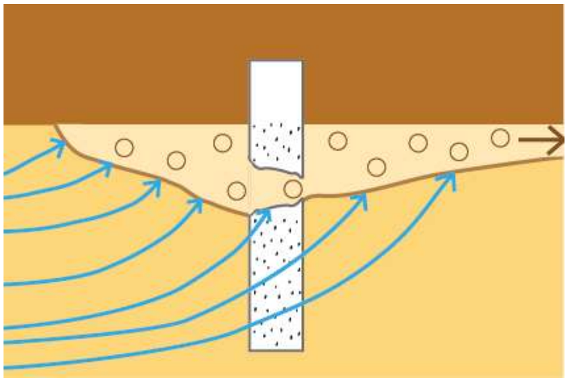


Figure B.3: Failure Scenario T2: A crack/hole has formed in the filter

This failure scenario T2 can be divided into 3 sub-scenarios T2.1, T2.2 & T2.3, each related to the three different life cycle phases of the filter screen, design, implementation and management & maintenance, respectively. In a coarse sand barrier, a hole can only occur due to earth-moving activities. Cracking can theoretically occur when filter sand is used that is highly cohesive; this is very unlikely, and in that case, many other failure paths may lead to failure earlier, given there is no more filter function. In filters made with geotextiles/plastics, weak strength/stretch properties and improper construction can also lead to hole/tear formation in addition to earth-moving activities.

Failure Scenario T2.1: Because the calculated material properties (strain properties/strength capacity) are insufficient, a crack/hole occurs in the filter under deformation

In this scenario, due to a design error, the filter is not sufficiently resistant to the deformation that can be expected in the subsequent life cycle phases. In this scenario, it is likely that the deformation that causes the hole/crack will occur during the implementation phase. However, theoretically, a situation could also occur during the management/maintenance phase where deformation of the filter could occur.

#	Failure Cause	Filter		
		VIG	**CSB**	**Prolock**
D2	Stretch properties of geotextile not properly estimated, resulting in crack forming during or after implementation	x		
D3	Insufficient strength capacity allows the filter profile to break under deformation, creating a hole			x

Table B.3: Failure causes T2.1: Crack/hole formation due to calculated material properties

Risk Mitigation Measures & Monitoring

Scenario T2.1 can be virtually ruled out with sound design and execution. This applies to geotextiles (D2) if the deformation during implementation is constantly monitored and compared with the strength properties used. For the Prolock filter screen, it can be assumed that if the correct PPE/PPL method is used, this is sufficient to exclude the risk. Also, since field tests have shown that the perforated portion of the Prolock filter is more likely to fail, it is assumed that with variations in design, the same result can be expected. In conclusion, for long-term monitoring, scenario T2.1 is not relevant with sound design and implementation.

Failure Scenario T2.2: Incorrect execution of installation creates a crack/hole in the filter

In this scenario, in contrast to T2.1, the material properties are correctly estimated for the deformation expected under normal conditions, but when the installation of the filter is carried out incorrectly in such a way that much more deformation takes place than anticipated, it can still cause a crack/hole. For the Prolock filter screen, it is important to distinguish where the hole/crack occurs. Since the filter screen consists of geometrically closed granular filter tubes (perforated section) interspersed with plastic profiles (closed section) connecting the sleeves together, a distinction must be made as to whether the hole occurs in the perforated or closed section. If a hole arises on one side of the tube, the retention of the filter sand is threatened, but the filter sand, together with the other side of the plastic tube, still provides protection against permeability. A hole on both sides, which is much less likely, still offers protection even if the filter sand can be dumped when executed. So, a hole in the closed part is a greater permeability threat than a hole in the perforated part.

#	Failure Cause	Filter		
		VIG	CSB	Prolock
I3	Cracking during execution construction of a geotextile filter due to excessive deformation	x		
I4	Profile used to connect filter runs out of lock when executed			x
I5a	Hole occurs in closed section filter at execution			x
I5b	Hole occurs in perforated section during execution, jeopardizing retention of filter sand			x

Table B.4: Failure Scenario T2.2: Crack/hole due to incorrect installation

Risk Mitigation Measures & Monitoring

For scenario T2.2, the general rule is that it poses a minimal risk when executed properly. For the VIG (I3), this is assumed to be the case if thorough quality control is carried out during execution in the form of execution monitoring to ensure that not too much deformation takes place. In the case of the Prolock filter screen, it can be stated for connecting profiles (I4) on the basis of manufacturability tests that since only 1 out of 120 tests ran out of lock and the fact that corrective measures are available the probability is low that this was not corrected. Here, it has been assumed that the field tests are representative of another variation on the location-specific design. When this event (I4) occurs and is not noticed, contrary to other failure causes, the probability of flooding is very high. This makes this relevant for long-term monitoring despite the minimal risk. For the Prolock screen, based on field trials, it has been estimated that with careful execution, the probability of such significant damage allowing a through pipe is small (I5). In principle, T2.2 has little relevance for long-term monitoring; however, because of the high risk of flooding when a profile has run out of the lock unnoticed, this is a factor of importance when preparing a monitoring plan.

Failure Scenario T2.3: Root growth, animal engravings or soil stirring activities near the filter or degradation during the filter's lifetime creates a hole in the filter

For scenario T2.3, it depends on the type of the filter and its vulnerability, for which type of subsurface events the filter may form a hole. Because geotextile is woven, a hole can already be created by root growth, whereas the coarse sand barrier can only create a hole with animal digging activities. The Prolock filter screen is only susceptible when humans carry out ground-digging activities. Again, the same distinction can be made between a hole in the closed or perforated part as in T2.2. where a hole in the closed part is a greater permeability threat than in the perforated part. See T2.2. for more details about the closed and perforated parts.

A hole may additionally occur with the Prolock filter screen due to degradation during the life of the filter; since a hole due to degradation can become much smaller than a potential hole caused under deformation/at implementation, only a hole in the closed part poses a pipe-through threat. A small hole in the tube due to degradation is less likely to jeopardize the retention of the filter sand than a larger hole created under deformation, and even then, the other side of the tube still provides protection against pipe through, hence a hole in the closed part is included as a threat.

#	Failure Cause	Filter		
		VIG	CSB	Prolock
M3	Crack occurs due to root growth	x		
M4	Hole/crack created by animal grazing	x	x	
M5	Hole/crack created by human earth moving activities	x	x	x
M6a	Hole created by earth moving activities in closed part filter			x
M6b	Hole created by earth moving activities in perforated part filter			x
M7	Hole occurs in closed part screen due to degradation			x

Table B.5: Failure Scenario T2.3: Crack/hole formation during management/maintenance life cycle phase

Risk Mitigation Measures & Monitoring

For scenario T2.3, the occurrence of a crack remains a significant risk that must be limited by means of inspections as part of the water manager's duty of care, which can be supplemented by long-term monitoring. This makes the chance of an excavation of the coarse sand barrier not being detected in time and posing a threat to piping safety extremely small. For the vertically inserted geotextile (M3), in addition to gravels, the vegetation around the filter should be observed for development over time during inspection/monitoring. For animal burrowing (M4), monitoring is particularly relevant since, for example, beavers or muskrats can dig tunnels tens of meters long, so the burrows are not always easy to detect. In human ground-digging activities (M5/6), the probability of non-temporary detection is lowest, and the need for monitoring may be less. A hole due to degradation (M7) is considered small on a theoretical basis; however, to better cover the risk, dummy elements can be placed for monitoring.

Failure Scenario T3: The granular filter erodes or partially washes away, allowing a through pipe to form

This failure scenario can only occur with the coarse sand barrier as the other filter solutions are not (fully) granular. However, internal instability is also addressed during the design of a Prolock filter as it is partly granular.

Failure Scenario T3.1 Granular filter is (locally) internally unstable due to incorrect composition of filter sand

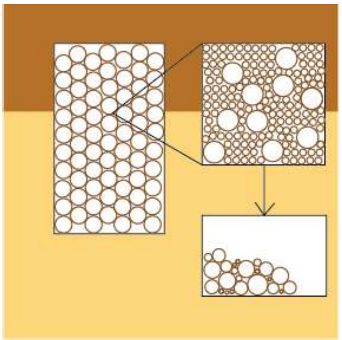


Figure B.4: Failure Scenario T3.1: Filter sand is internally unstable

In scenario T3.1 above, the filter sand consists of internally unstable sand, meaning the sand consists of a coarse and fine fraction with little to no intermediate grain sizes, allowing the finer sand to gradually wash out, possibly resulting in the collapse of the matrix of larger grains. When a pipe has grown up to the filter, the internal stability of the filter allows the filter sand to wash out easily.

#	**Failure Cause**
D4	Barrier sand composition is internally unstable, allowing finer sand to leach out
I6	De-mixing of the barrier sand causes local internal instability and allows the finer fraction of sand to wash out
I7	Mixing of barrier sand with background/in-situ sand causes barrier sand to be locally unstable and allows the finer fraction of sand to wash out

Table B.6: Failure Scenario T3.1: Granular filter is internally unstable

Risk Mitigation Measures & Monitoring

For scenario T3.1, if properly designed and implemented, this scenario can be ruled out. For both the coarse sand barrier and the Prolock filter screen, the filter sand to be applied has a steep grain distribution curve and is, therefore not susceptible to internal instability. This factor (D4) can therefore be ruled out. For segregation (I6), it holds for both filters that if requirements are set for grain distribution in the filter sand actually applied and if these are then met by both randomly taken samples and selectively taken samples, this risk can almost be excluded. For mixing (I7), if done correctly when working in an open excavation in clearly separated steps this risk can be excluded. It can be concluded that scenario T3.1 is not relevant for long-term monitoring.

Failure Scenario T3.2 Critical heave height is reached causing remaining filter sand to succumb to heave, and no more resistance to pipe through can be provided

In the above scenario D3.2, the filter sand has eroded such that the remaining sand in the embankment forms a slope. The vertical distance between the top of the sloped filter sand and the bottom of the overburden on the upstream side of the coarse sand barrier decreases. When the minimum heave height and associated critical slope in the barrier is reached, another small shear will occur on the lower portion of the slope, and then suddenly a larger portion of the upper slope will shear. Then at the upstream edge there is insufficient resistance to heave and collapse by heave occurs there where the filter sand fluidizes and can flow away (Förster & Van Beek, 2021).

The failure scenario T3.2 can be further subdivided into 3 different scenarios, T3.2.1-T3.2.3.

Failure Scenario T3.2.1 reduction in (remaining) effective heave height of the barrier sand due to a cause other than erosion of the filter sand itself

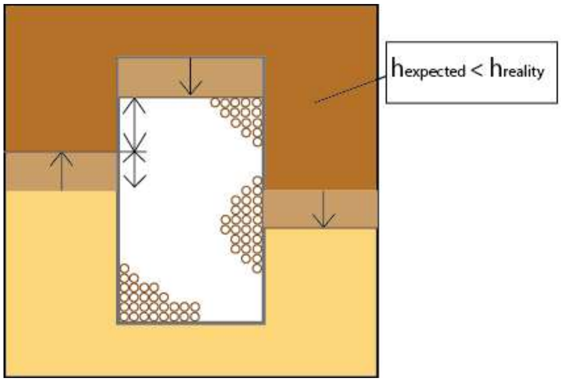


Figure B.5: Failure Scenario T3.2.1: The effective (remaining) heave height has decreased

In this scenario, the (remaining) effective heave height decreases due to a cause other than erosion of the filter sand itself, resulting in less strength against erosion. However, erosion processes in the surrounding sand may cause the effective heave height to eventually decrease in the filter sand.

#	Failure Cause
D5	No sharp boundary layer between piping-sensitive sand layer and the resulting maximum height at which a pipe can occur is underestimated and effective heave height turns out to be lower
D6	Boundary aquifer is higher upstream so effective-heave elevation is lower
D7	Distance barrier to exit point is small creating an erosion lens in which part of the barrier subsequently collapses
D8	Depth of upstream seal to create additional effective heave height is insufficient
I8	Insufficient supply of barrier sand during execution resulting in less effective heave height
I9	Barrier is insufficiently compacted, resulting in later compaction and reduced effective heave height
M8	Post-settlement of barrier reducing effective-heave height

Table B.7: Failure Scenario T3.2.1: Critical heave height has been reached by a cause other than erosion

Risk Mitigation Measures & Monitoring

The risks for scenario T3.2.1 vary greatly for each of the failure causes. The proper mapping of the course of the overburden layer (D5) deserves emphatic attention in the ground investigation to avoid lower effective heave heights in places. An elevated upstream boundary layer between the aquifer and overburden (D6) can also be identified in this way. Depending on the results of the ground investigation, additional attention to this cause of failure may be required: a clay lens (upstream seal) may provide a solution to increase the effective heave height. Long-term monitoring could further monitor remaining vulnerable spots with low effective heave heights.

If the recommended practical size of 5m is kept between the filter and the normative exit point, the risk of collapse of part of the barrier by an erosion lens can be neglected (D7). Furthermore, if through thorough quality control where sections are rebuilt when necessary, the risk of failure due to insufficient supply of barrier sand can be eliminated (I8).

If the application of an upstream seal is necessary because of the variation in the location of the boundary layer (D8), then due to measurement and execution uncertainties, a minimal risk can only be assumed if the depth is set safely and not designed to the centimetre. For the risks concerning compaction of the barrier (I9 & M8), it can be assumed that it is in principle, eliminable when execution is done correctly. A possible scenario is that during the service life, there is a critical situation during extremely high water with little remaining heave height where compaction is stimulated by an emergency measure such as the jacking of a sheet piling. This should be considered very unlikely.

For scenario T3.2.1, there are events where monitoring can be of added value, for example, detecting pipes in the places where the overburden layer has turned out to be thinnest or seepage length the shortest. Another possibility is monitoring the subsidence of the overburden layer. However, the risks can be sufficiently covered even without monitoring if the design is sound.

Failure Scenario T3.2.2 Erosion process is accelerated in barrier due to increase in flow velocity or decrease in erosion resistance

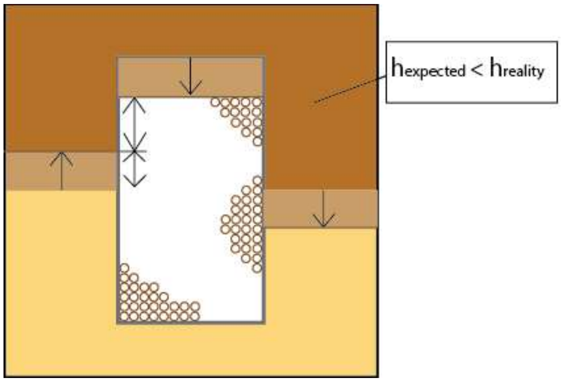


Figure B.6: Failure Scenario T3.2.2: Erosion process is accelerated

In this scenario, the erosion process proceeds faster due to a (local) increase in flow velocity in the barrier or a local decrease in erosion resistance of the filter sand caused by various influencing factors. The erosion process thus proceeds faster than would normally be expected under sustained high water. Flow velocity and erosion resistance mainly determine the degree of erosion. Increases in flow velocity can be caused by an increase in the hydraulic gradient across the dike, a local increase in water inflow/higher flow concentration due to a high permeability contrast, or a non-permeable discontinuity in the aquifer.

The erosion resistance determines under which flow velocity erosion will take place. When erosion resistance decreases, erosion will already be able to take place under a lower flow velocity. In this scenario, there is only one failure path where this is the case: increase in the slope under which the barrier will be located, on a steeper slope, the downstream sand grains have less erosion resistance toward the water flow due to surrounding sand grains.

#	**Failure Cause**
D9a	Highly permeable (gravel) layer at bottom of barrier not detected resulting in more water inflow to barrier than calculated for
D9b	Intermediate sand layer upstream of the barrier not detected resulting in more water inflow to the barrier than calculated resulting in locally increased flow velocity
D10a	3D factor is underestimated, causing locally higher flow concentration than calculated, causing locally increased flow velocity
D10b	Coarse-grained discontinuity in background sand at barrier not accounted for resulting in locally higher flow concentration than calculated and locally increasing flow velocity
D10c	Cohesive discontinuity in subsurface at barrier not accounted for resulting in locally higher flow concentration than calculated resulting in locally increasing flow velocity
I10	Replenishment clay swells too much in the hollow space created above coarse sand, causing a narrowing of the free outlet surface to increase local flow velocity
M9a	Subsidence of cover layer downstream causing pipe to deepen which then forms a steeper slope in the barrier and the critical heave height is reached faster due to less erosion resistance
M9b	Subsidence of overburden above barrier creating a situation similar to a flat coarse sand barrier, but with some heave height and a favorable slope angle.
M10	Erosion of the coarse sand barrier itself at high water due to the presence of a high gradient across the barrier

Table B.8: Failure Scenario T3.2.2 Erosion process is accelerated

Risk Mitigation Measures & Monitoring

Also for scenario T3.2.2, failure causes from the design phase originate in not mapping the subsurface well enough. The risk of an under-calculated water supply to the barrier due to a missed highly permeable gravel layer (D9a) or intermediate sand layer in the overburden upstream of the barrier (D9b), although both of great influence, can be minimized by following the included design work. If additional inputs of water are detected by sufficient soil testing and included in the design, the risk can be virtually eliminated.

The risk of incorrectly estimating the spatial variation in the longitudinal direction of the dike (D10), which will locally lead to higher flow concentrations, also depends on properly conducted soil research. If a correct estimate of the spatial variation and the 3D factor can be made on the basis of thorough soil research, this can virtually eliminate the risk of failure. Furthermore, if clays with high swelling capacity are avoided during execution, the risk of narrowing of the free discharge surface can be excluded (I10).

Subsidence of the covering layer after high water (M9) is a real risk for which long-term monitoring can be applied by means of settlement monitoring. Detection of this is important after each significant flood because targeted action must also be taken. As a risk, however, it is manageable: it occurs only after the end of a significant flood, after which sufficient time will reasonably be available to take appropriate action. If detection and appropriate action follows, then the risk is manageable. Even without failure causes of failure, erosion of the barrier itself is always a risk. Thus, if there are no failure causes of failure, it will lead to failure only when a high water higher than normative occurs. Here, long-term monitoring cannot add anything since a calamity is then involved.

Failure Scenario T3.2.3 Too low permeability contrast with surrounding sand because the barrier sand is too fine so that outflow surface does not increase (much) with further erosion

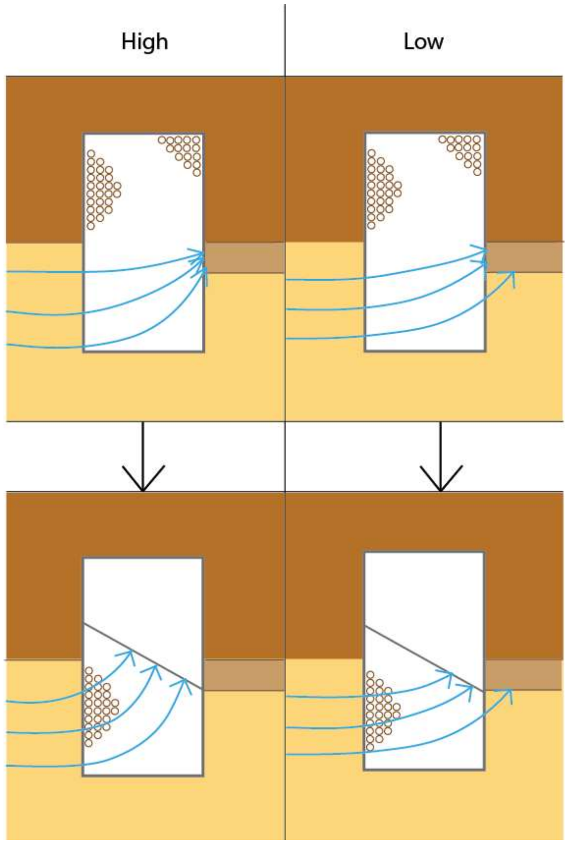


Figure B.7: Failure Scenario T3.2.3: Too low permeability contrast with surrounding sand

With a lower permeability contrast, the outflow at the tip of the pipe in the coarse sand barrier (flat coarse sand barrier) or at the outflow point at the beginning of the pipe at the bottom of the slope (barrier with indentation) will not decrease with further erosion (growing through the pipe/emergence & flattening of the slope). With a desired higher permeability contrast, the outflow at the erosion-sensitive sites near the tip of the pipe and at the bottom of the slope decreases. This occurs as a larger potential outflow surface is created after the pipe grows further into the barrier or the slope in the incision develops a flatter slope. Due to the higher permeability of the barrier relative to the surrounding sand, more water will flow out through this created surface relative to the tip or toe of the slope of the barrier.

#	**Failure Cause**
D11	Barrier sand is too fine in relation to background sand
I11a	Segregation of barrier sand causing barrier sand to be (locally) too fine in relation to background sand
I11b	Application of wrong material as barrier sand making it (locally) too fine in relation to background sand
I11c	Mixing of barrier sand with background sand causing the barrier sand to be (locally) too fine in relation to background sand

Table B.9: Failure Scenario T3.2.3 Too low permeability contrast

Risk Mitigation Measures & Monitoring

The risk of scenario D3.2.3 can be omitted, when clear implementation protocols have been established and adhered to. For segregation (I11a), this can be ruled out for both granular filters when field tests have shown that segregation does not occur with pouring the coarse soil. Although in pilots this has been demonstrated, it always depends on the design- and project specific-conditions. For (I11b) it is a risk when different types of filter sand are used in the design, when different packaging is used the probability of this failure cause is negligible. Mixing (I11c) is mainly a risk with soil displacement installation methods and very precise execution should eliminate the risk. For this entire scenario T.3.2.3, the consequences for the occurrence of this scenario are so disastrous that it must be prevented at all times. This makes the scenario irrelevant for long-term monitoring.

B.2. Pipe Behind

In all cases of pipe behind, the filter placement and/or sizing is (no longer) correct. This is summarized in failure scenario BH1 below.

Failure Scenario BH1: No (proper) finish filter, connection to high soils, connection to other piping measure or discontinuous produced filter parts.

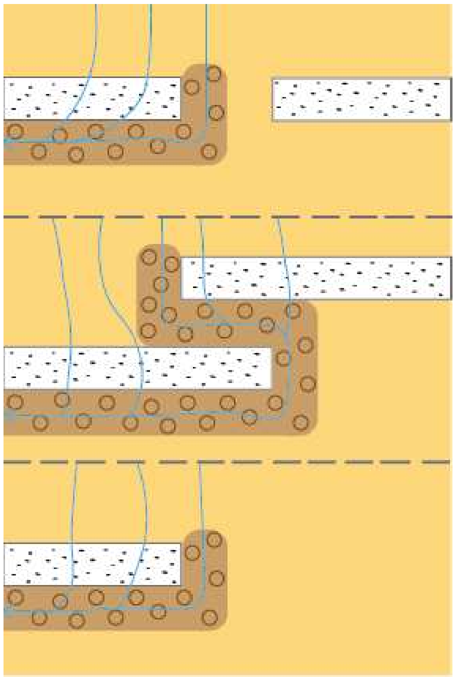


Figure B.8: Failure Scenario BH1: Filter ends are insufficient

For scenario BH1, little distinction can be made for the different filter types in causes for pipe behind specific to a filter type. Both a filter that is designed too short and an incorrect connection to high ground or another piping measure occur for all three filters as a possible cause of pipe behind. However, it is important to mention that with a coarse sand barrier when a lateral pipe is created, the barrier itself is also affected in the extension of the downstream pipe. This leads to an increase in flow from the remaining barrier. Given the limited discharge capacity of the downstream pipe, the flow from the lateral pipe will initially decrease. Further erosion will first cause the downstream pipe to grow in size (Förster et al., 2019). The lateral pipes will start growing again when the downstream pipe can again discharge more flow than before. Whether this happens depends on the increase in gradient and processes surrounding erosion of the coarse sand barrier itself.

#	Failure Cause	Filter		
		VIG	CSB	Prolock
D12	Length of the filter in the longitudinal direction of the water barrier is so short that there is a preferential path around the filter screen	x	x	x
D13	The connection to an already existing piping measure is insufficient, so piping between the screen and the existing measure cannot be prevented.	x	x	x

Table B.10: Failure Scenario BH1: Filter ends are insufficient

Risk Mitigation Measures & Monitoring

For pipe behind, the risk can also be reduced with proper design and, in the case of a connection to another measure, with thorough execution. For the design it may be assumed that the length of the filter screen as a non-permeable sheet piling is conservative design the risk of back-wash is negligible (D12). The connection (D13) is only relevant when other piping measures are present, if existing design rules have been used and the execution has been done according to protocol the risk can be reasonably excluded. Otherwise, monitoring is an option to minimize the failure probability contribution. Long-term monitoring is with pipe behind, a fairly easy failure mechanism to detect as only 2 ends/connections can be monitored with two pore pressure gauges for example.

B.3. Pipe Above

Variant 1: Pipe grows from above through the filter (CSB, Prolock) or along the filter (VIG)

Variant 2: Pipe grows from the landward side over the filter (VIG, Prolock)

For pipe above, two variants can be defined depending on whether the exit point occurs at or near the clay fill above the filter or further downstream. If it arises further downstream, space for the through pipe must be created so that it can continue to grow above the filter. For all causes, either the filter positioning (under the overburden) is not (no longer) correct or the clay fill/overburden is (becoming) weak and possibly in combination with failure closure when the filter is closed at the top.

Failure Cause A1.1: Clay backfill collapses and exit point can form directly above the filter causing pipe through (CSB) or along (VIG) the filter (Variant 1)

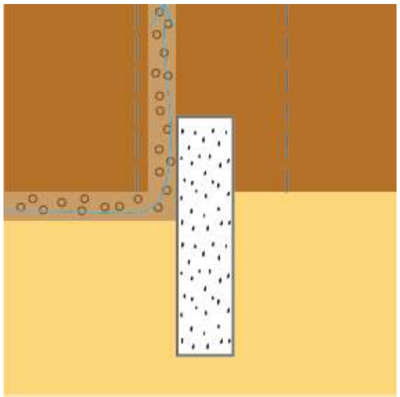


Figure B.9: Failure Scenario A1.1: Backfill clay collapses [VIG]

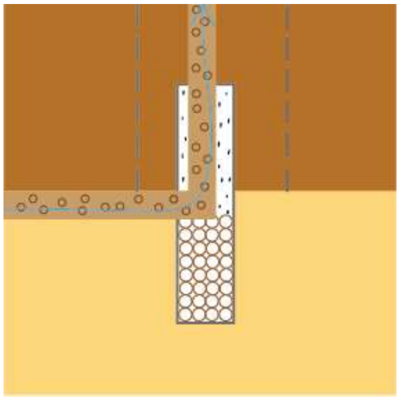


Figure B.10: Failure Scenario A1.1: Backfill clay collapses [CSB]

For failure cause A1, it holds for both granular filters that the filter sand still offers resistance to pipe above; an exit point above the filter does not immediately imply failure due to pipe above. For both filters, if this scenario will lead to failure, the filter sand must also flow out through heave. In the case of the vertically inserted geotextile, however, no more resistance can be provided by the filter after an exit point has been created. Because of the negligible thickness of the vertically inserted geotextile, one could also give this variant the definition of pipe before.

When the clay backfill collapses, it means that the clay fill no longer forms a seal between filter and ground level. Bursting may occur, but this is not necessarily the case; cracking can also result in a failure point because the clay fill collapses without prior bursting. For the Prolock filter screen, in this scenario A1, failure of the cap must also always occur before a through pipe through the sleeve can occur after which filter sand can flow out via heave and a formed exit point. Weak clay fills and excessive erosion combined with a too-close exit point are often a cause for this scenario A1.

#	Failure Cause	Filter		
		VIG	CSB	Prolock
D14	Clay fill acts as a drainage path, collapsing the clay fill and creating an exit point then above filter	x	x	
D15a	Distance from filter to exit point too small and excessive erosion/scaling of the overburden cause the exit point to move into the clay fill, eliminating the anchoring of the geotextile	x		
D15b	Distance from filter to exit point too small and excessive erosion of the overburden causes the exit point to move toward the clay fill, causing it to collapse and create an exit point above the filter		x	
I12a	Backfill clay is applied too thinly, contains voids and/or is inadequately supplied and/or compacted, causing the clay fill to collapse, creating the exit point above the filter.	x	x	
I12b	Replenishment clay swells too much in the hollow space in the inlet above the coarse sand and will erode under the influence of the water flow, subsequently causing the clay fill to collapse and creating the exit point above the filter		x	
I12c	Replenishment clay is prone to erosion / when applied too wet causing the clay fill to erode under the influence of flowing water after which an exit point forms above the filter.		x	

Table B.11: Failure Scenario A1.1: Backfill clay collapses

Risk Mitigation Measures & Monitoring

The risk of scenario A1 can be estimated on the basis of requirements for the clay backfill, the cap in the case of the Prolock filter screen and for the distance from the normative discharge point to the filter in connection with possible excessive erosion. The risk of collapse due to failure of the clay backfill by a cause related to the clay backfill (D14/I12) can largely be excluded provided that sufficient requirements are set for clay backfill (erosion resistant/not too swelling), whereby the clay below the groundwater table is also compacted. This can be demonstrated through site-related implementation monitoring.

The risk concerning excessive erosion (D15) can be minimized by designing the normative discharge point 5 meters from the filter. In this way, soil can be dumped as an emergency measure when this excessive form of erosion occurs. Up to a distance of 5m, this has been deemed practical. Excessive erosion has only been observed as a rarity and not included in piping analyses. This cause of failure is most relevant in thin overburdens and toe ditches.

Failure Cause A1.2: Filter cap fails and exit point can form directly above the filter causing pipe through the filter (Prolock) (Variant 1)

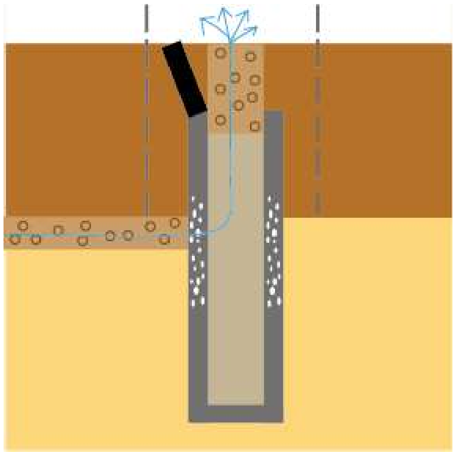


Figure B.11: Failure Scenario A1.2: Filter cap fails

#	Failure Cause	Filter		
		VIG	CSB	Prolock
D16	Cap insufficiently strong causing top to open up. When the load exceeds the strength at high water and the cap fails, a drainage path through the top of the filter occurs including heave causing the grains to wash out			x
I13	Cap not properly fitted, a drainage path through the top of the filter occurs including heave causing the grains to wash out			x
M11	Cap damaged in use phase, a drainage path through the top of the filter occurs including heave causing the grains to wash out			x

Table B.12: Failure Cause A1.2: Filter cap fails

Risk Mitigation Measures & Monitoring

For the risk concerning the loosening of the filter cap, it can be assumed that the design is at least strong enough since the cap and welds together have a strength of 45 meters water column. Because the occurring load at high water will be lower in all cases, this cause of failure does not constitute a real risk (D16). Furthermore, it can be assumed that if the standardized work protocol and recording (with adjustments where necessary) of the data is followed, the probability of flooding as a result is considered not signficant (I13). If the design and implementation are carried out correctly it may be assumed that the failure of the cap during management is very small (M11). Although the consequences of drainage through the tubes are very unlikely, it is expected that in most cases the head is not sufficiently large to cause vertical leaching since drainage will also cause the head to drop again.

Failure Scenario A2: Pipe grows from exit point downstream above the filter to the riverside (Variant 2)

Scenario A2 cannot occur at the coarse sand barrier because a pipe that wants to grow along the top will always be run through by the erosion of the barrier itself because the entire indentation over which the upstream flow path can run erodes with it. The scenario can occur in two ways, a pipe growing through space in the clay backfill over the filter or a pipe growing through space between the bottom of the overburden and above the filter. These scenarios are respectively divided into scenario A2.1 and A2.2

Failure Scenario A2.1: Pipe can grow past & above the filter through due to weakened backfill clay

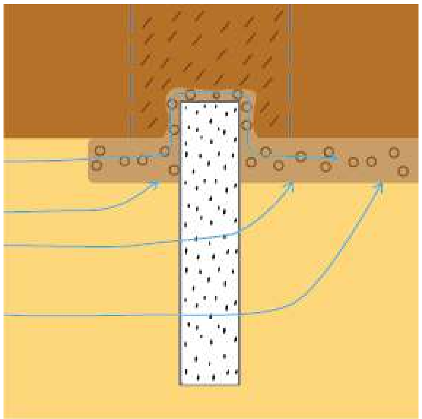


Figure B.12: Failure Scenario A2.1: Weakened backfill clay

In scenario A2, there is space above the filter in the clay backfill that allows a pipe to grow through the clay. With the vertical-sand tight geotextile, this scenario can occur, for example, if the anchoring fails at the top. In this case, the geotextile can create space for pipe above because the clay no longer properly anchors the geotextile. The space in the overburden can occur due to errors in implementation or influencing factors such as collapse of existing pipes and cracking due to drought, for example.

#	Failure Cause	Filter		
		VIG	CSB	Prolock
I14	Backfill clay is applied too thinly, contains voids and/or is inadequately supplied and/or compacted causing the anchoring of the geotextile to loosen and allow a pipe to grow past above the filter	x		
I15	Due to installation effects (vibratory installation), the overburden (and clay fill) has been adversely affected to the extent that there is space around (increased permeability) around the Prolock filter screen allowing a pipe to grow over the filter.			x
M12	Pipes (whether developed in previous floodwaters or not) collapse where a pressure buildup can also collapse the overburden/clay fill after which the anchoring of the geotextile becomes loose	x		
M13	Cracking in the overburden (and clay fill) due to drought, for example, can create spaces in the overburden that allow a pipe to grow past it above the filter	?		x

Table B.13: Failure Scenario A2.1: Weakened backfill clay

Risk Mitigation Measures & Monitoring

The risk concerning loosening of the anchoring (I14) is not significant if good requirements are set for clay filling and clay below the groundwater table is also compacted. This can be demonstrated by means of implementation monitoring. The risk of damage to the overburden by installation effects (I15), subject to comparable implementation methods, can be estimeded using results from field tests that demonstrate that the influence of vibrating installation is limited on the overburden. In addition, if there is damage in the overburden due to vibrating installation, it will be more likely that the overburden will burst just before the filter screen.

The collapse of pipes after high water (M10 & M11) constitutes a realistic risk for which long-term monitoring can be applied, e.g. settlement monitoring. Detection of this is important after each significant flood because targeted action must be taken. As a risk, however, it is manageable: it occurs only after the end of a significant flood, after which sufficient time will reasonably be available to take appropriate action. If detection and appropriate action follows, then the risk is manageable.
For the risk of cracking (M13), it may be assumed that the probability of the presence of (deep) cracks during a flood is limited. The probability of this is further reduced by inspecting for it before a flood and during a drought and, if necessary, taking remedial action.

Failure Scenario A2.2: Filter does not reach into overburden (locally)

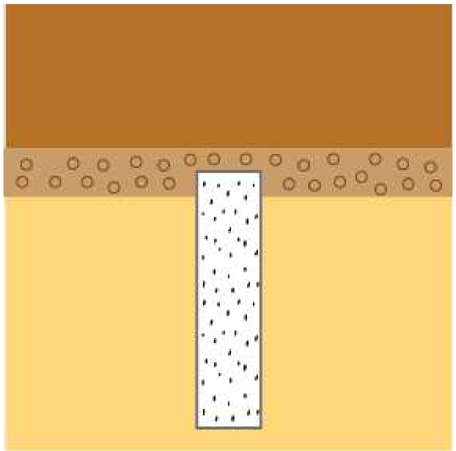


Figure B.13: Failure Scenario A2.2: WFilter does not reach into overburden

For this scenario, the filter does not extend to the overburden, leaving room for a pipe to grow above. This is only a theoretically realistic risk with the vertically inserted geotextile, since a coarse sand barrier and the Prolock filter screen extend higher into the overburden.

#	Failure Cause	Filter		
		VIG	CSB	Prolock
D17	Filter not designed at proper depth allowing a pipe to grow along the top	x		

Table B.14: Failure Scenario A2.2: Filter does not reach into overburden

Risk Mitigation Measures & Monitoring

Assuming that any uncertainties arising from ground investigations are covered by adjusting the length and that the layer transitions are properly monitored during execution, this failure scenario is not realistic. For long-term monitoring, this scenario is not relevant.

B.4. Pipe Below

For pipe below, in all cases, the filter function is no longer adequate due to too low a permeability contrast, or filter positioning/dimensioning is inadequate due to filter depth being insufficient, or local variation in the aquifer. These scenarios are divided into BL1, BL2, BL3, respectively.

Failure Scenario BL1: Too low permeability contrast: The filter/direct surrounding sand is not (no longer) sufficiently permeable or too permeable surrounding sand

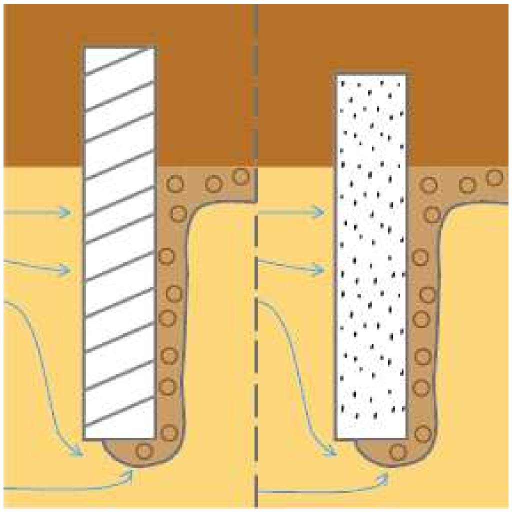


Figure B.14: Failure Scenario BL1: Too low permeability contrast

In this failure scenario, there is a too low permeability contrast, which means that the filter is not (entirely) the preferred flow path, leading to a seepage path below the filter, allowing a pipe to form below and past the filter. The permeability contrast can be negatively affected by both the filter becoming less permeable and the surrounding sand becoming more permeable in relation to the filter. In addition to the permeability decreasing of the filter itself, only the immediate surrounding sand surrounding the filter can also decrease in permeability such that it gives the same effect as a less permeable filter.

#	Failure Cause	Filter		
		VIG	CSB	Prolock
D18	Trench backfill is finer than in-situ sand and less permeable	x		
D19	In-situ sand is more permeable than expected			x
I16	Smearing of filter perforations (with clay) reducing permeability	x		x
I17	Soil compaction (compaction in-situ material) due to soil displacement application technique making in-situ sand less permeable			x
I18	Permeability in-situ sand increases significantly by applying gound-removing installation method.			x
M14	Mechanical / Chemical / Biological blockage	x		x

Table B.15: Failure Scenario BL1: Too low permeability contrast

Risk Mitigation Measures & Monitoring

Also for this scenario, the design-related causes of failure (D18 & D19) can be minimized in terms of risk when the subsurface variation is well mapped. In this case with the help of groundwater modeling. Again, quality control through site-related implementation monitoring can largely eliminate this risk. When the geotextile is also designed considering heave, the risk of failure due to pipe below is negligible.

The risk regarding smearing during installation (I16) varies by filter. For the vertically inserted geotextile, this is a realist risk, even when makeability tests under similar conditions have been performed in conjunction with execution monitoring. This is risk is especially critical when a vertical insertion technique has been used. Especially when the screen is not designed considering heave, smearing is dangerous for pipe below. Monitoring for sufficient permeability is also important during the service life because of this cause of failure. This is where long-term monitoring can play a role. For the Prolock filter screen, this risk (I16) does not contribute to the failure probability when correctly implemented in contrast to the vertically inserted geotextile. If a safe reduction in permeability is correctly taken into account in the design and if the risk of a reduction in permeability is controlled during the implementation phase (by cleaning and adjusting where necessary), the risk can be minimized. However, since clogging of the screen can also originate from other causes of failure, long-term monitoring can still be relevent, especially given the importance of permeability for a filter.

For the risk of soil compaction (I17), it may be assumed with some caution, based on exploratory calculations and field test provided similar conditions are valid, that the flow pattern remains limited under the influence of compaction. In addition, when the screen. Since a soil displacement method was chosen for the Prolock pilot, the risks of increased permeability due to soil relaxation (I18) were not further discussed. If a soil removing method is investigated in the future, this should be further examined.

For the risk regarding clogging (M14), a distinction must be made between the three types of filters and mechanical clogging versus chemical/bacteriological clogging. For the coarse sand barrier, if the requirements for geometrically closed filters are met, then it can be assumed that mechanical blockage is excluded as a risk. However, with the note that this only applies to the Dutch river area where suffosion does not occur. Because it is a granular filter it can be assumed, albeit also only in the context of the Dutch river area, that chemical/bacteriological clogging is not a risk since the background sand has proven to be more sensitive to clogging than the barrier itself.

With the Prolock filter screen, the risk of chemical and biological clogging (M14) is greater because the filter sand is largely enclosed in a tube. There is a risk of threatening anaerobic conditions and clogging. It can be assumed that by completely filling and sealing the shaft the risk of oxygen diffusing to the depth of the perforated section is minimized. The implementation protocol further reduces the likelihood of the risk occurring. Long-term monitoring is relevant to keep the risk and failure probability contribution as low as possible. Here, besides monitoring permeability at critical points, monitoring anaerobic conditions in the tube can also be considered. For mechanical clogging it can be assumed that when the calculation rules for geometrically closed filters and internal stability are properly applied, the risk is covered. However, when monitoring for permeability for chemical and biological blockage, this risk is also further covered and with it the failure probability contribution.

For the vertically inserted geotextile, long-term monitoring is also important to reduce the risk of pipe below. Unlike the vertically inserted geotextile, the filtering effect relies on the perforations. Here, although the risk of clogging is minimized when design rules for geometrically closed filters are applied, periodic permeability measurements might be needed to fully minimize the risk.

In all cases for this scenario, permeability monitoring is more critical when the filter is not (extra) securely designed on heave to eliminate the risk of pipe below due to decreasing permeability.

Failure Scenario BL2: The filter does not reach the proper depth (anymore), allowing a pipe to grow below the filter

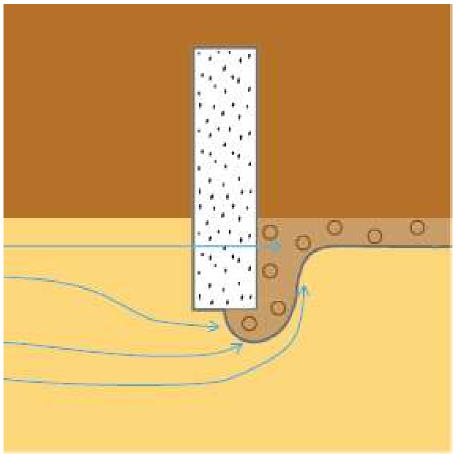


Figure B.15: Failure Scenario BL2: Filter does not reach appropriate depth

For this scenario, for the the vertically inserted geotextile and the Prolock screen, the filter no longer extends to the proper depth if a preferential seepage path under the filter is created. For the coarse sand barrier, the depth is insufficient if it does not extend to the edge of the overburden, and grains may erode at creating a pipe directly below the overburden where no barrier is installed, preventing the barrier from providing any strength.

#	Failure Cause	Filter		
		VIG	**CSB**	**Prolock**
D20	Filter not designed at proper depth so it may sit too high in places causing a pipe under the geotextile	x		x
D21	Thick or erratic overburden so that the underside of the barrier does not extend to the boundary of the overburden		x	
D22	Thick or erratic overlay resulting in part or all of a section with perforations protruding into the overlay			x
D23	Upward water pressure at high water against filter cap is higher than the ground mechanical (tensile) capacity causing the filter to push up and allow a pipe to grow underneath			x
I19	Excavation barrier does not extend to edge of thick cover layer		x	
I20	Filter is not placed at proper depth during installation / machine cannot reach proper depth	x		x

Table B.16: Failure Scenario BL2: Filter does not reach appropriate depth

Risk Mitigation Measures & Monitoring

In scenario BL2 the risks of failure causes from the design phase can also be covered if sufficient soil tests have been carried out. For failure to design at the correct depth of the filter (D20), the risk is limited if the length of the screen is adjusted for any uncertainties arising from the soil investigation and implementation monitoring is done in the form of monitoring the layer transitions between the overburden an aquifer.

For the risk of an erratic overburden layer and therefore a coarse sand barrier or Prolock filter screen placed too high (D21 & D22), it may be assumed that with sufficient soil investigation conducted, and due to the fact that the piping sensitive sand layer and thick overburden can be determined with reasonable certainty, and given that the risk of piping is greatest with a thin overburden layer, the cause of failure may be reasonably excluded because it should always be avoidable.

For the risk regarding the Prolock filter screen being too high due to driving up (D23), it can be assumed that due to field tests which have shown that 80 kN is insufficient to pull the filter screen out of the ground, and since under normative high water approximately an average buoyancy force of approximately 1 kN occurs, that even with a different design or higher normative water this difference is so significantly large that the risk is negligible.

The risk of the coarse sand barrier (I19) being dug too low can be neglected if the boundary layer between aquifer and overburden is monitored during execution. To avoid this problem, it will have to be demonstrated on the basis of monitoring during installation that the piping-sensitive sand layer has been reached. For the vertically inserted geotextile and Prolock filter screen, the risk of inserting the filter too low by machine can be minimized if monitoring is carried out during implementation to ensure that the screen has reached the required depth. For the Prolock filter screen. In the case of the Prolock filter screen, it has been shown that, provided under similar conditions to the field test, the screen is effortlessly inserted to a depth of 8m. The installation of the vertically inserted geotextile is more vulnerable and after implementation monitoring it may turn out that in places the filter does not reach deep enough. This may be included in revisions to the long-term monitoring plan when encounterd.

Failure Scenario BL3: Local variation in the aquifer creates space around the filter allowing a pipe to grow under the filter

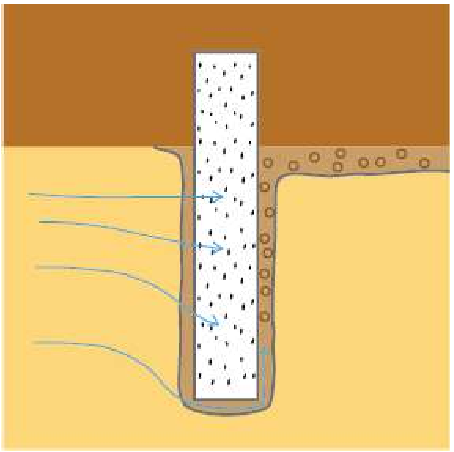


Figure B.16: Failure Scenario BL3: Local variation in aquifer

This failure scenario is only specific to the vertically inserted geotextile where due to local occurrence of loosened sand layers in the aquifer, the anchoring of the geotextile is loosened. This means that the geotextile is no longer properly anchored by the surrounding sand andn that there is room for a pipe to grow below the filter through this space.

#	Failure Cause	Filter		
		VIG	CSB	Prolock
D24	Local occurrence of loosened sand layers in aquifer causing anchoring at the bottom of the geotextile to become loose	x		

Table B.17: Failure Scenario BL3: Local variation in aquifer

Risk Mitigation Measures & Monitoring

The local occurrence of loosened sand layers is a realist risk (D24), especially when it has been missed during soil sampling and in design. When appropriate attention is paid to it by properly covering uncertainty with additional depth and execution, this risk can be covered.

B.5. Pipe Before

Pipe before can lead to failure of the filter, when the exit point occurs upstream of the filter according to two scenarios. In all cases, there is weakness in the thick cover layer or incorrect filter function where pressure buildup occurs upstream due to a decrease in permeability of the filter, categorized as BF1 and BF2, respectively.

Failure Scenario BF1: Exit point forms upstream of filter due to weakness in overburden

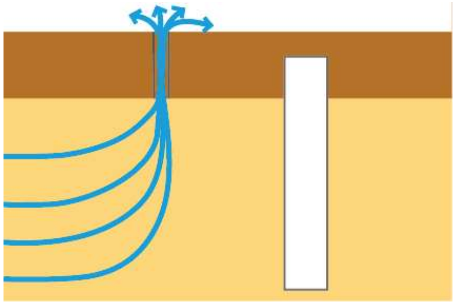


Figure B.17: Failure Scenario BF1: Weakness in overburden leads to bursting upstream

In this failure scenario, damage from installation effects or cracking due to drought creates a weak spot in the overburden layer upstream where an exit point can form. The exit point can also form after bursting when the overburden layer thickness or weight turns out to be less resistant to bursting than assumed during design.

#	Failure Cause	Filter		
		VIG	CSB	Prolock
D25	Normative exit point is located upstream of the filter due to unexpected local variation (overburden thickness & weight) in the subsurface	x	x	x
I21	Overburden leakage due to installation effects (vibrating installation) that damaged the cover layer to the extent that an upstream exit point could occur			x
M15	Cracking of the overburden due to drought, for example, which can cause leakage through the overburden and create an exit point	x	x	x

Table B.18: Failure Scenario BF1: Weakness in overburden leads to bursting upstream

Risk Mitigation Measures & Monitoring

For the bursting upstream of the filter (D25), it is also true that by sufficient soil investigation, the expected variation of overburden thickness & weight can be understood with reasonable certainty. When the design rules are met, the risk of this cause of failure can be reasonably excluded. If during the management phase a clear zoning is defined within which no bursting, digging, etc. may take place, the risk can be further reduced that when it occurs it leads to flooding.

The risk regarding overburden leakage effects due to vibrating installation (I21) can be estimated by means of field tests. Field tests in the pilot have shown that it has a limited influence on the permeability of the overburden layer. For cracking in the overburden layer (M15), the probability of the presence of (deep) cracking during high water is limited. The chance of this occurring is further reduced by inspecting for it before a flood and during drought and, if necessary, taking repair measures.

For scenario BF1, monitoring could mainly play a role in detecting burst points or overburden damages that are upstream of the filter.

Failure Scenario BF2: Exit point may form upstream of the filter due to pressure buildup upstream as a result of decrease in filter permeability

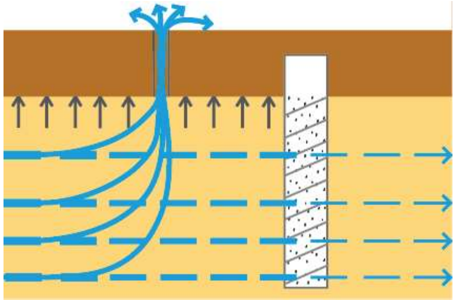


Figure B.18: Failure Scenario BF2: Bursting due too clogging & pressure build-up

For failure scenario BF2, the clogging of the filter causes the pressure build-up upstream to such an extent that bursting upstream may take place. When a soil displacement installation method is used, there is a risk of clamping by tension, causing the immediate surrounding sand of the filter to compact to such an extent that it becomes less permeable and blocks the filter, which can cause upstream pressure buildup. In addition, a clogged filter can lead to this failure scenario. Scenario BF2 is specific to the Prolock filter screen as a coarse sand barrier and vertically inserted geotextile are permeable alonge the entire filter such that no significant pressure buildup can be achieved for this scenario.

#	Failure Cause	Filter		
		VIG	CSB	Prolock
I22	Increased pore pressures in front of screen due to soil displacement installation technique causing the surrounding sand to compact (clamping) and permeability to decrease to such an extent that uplift occurs at the front of the filter after which bursting can take place.			x
I23	Increased pore pressures due to the perforations becoming smeared during installation, causing the permeability to decrease to such an extent that uplift occurs at the front of the filter after which bursting can take place.			x
M16	Mechanical / Chemical / Biological clogging causing the permeability to decrease to such an extent that uplift occurs at the front of the filter after which bursting can take place.			x

Table B.19: Failure Scenarios BF2: Bursting due too clogging & pressure build-up

Risk Mitigation Measures & Monitoring

For the risk of pipe before due to increased pore pressures as a result of clamping by tension as a result of a soil displacement installation (I22), if the design rules for preventing pipe before, additional pressure should be taken into account to account for a decrease in permeability when determining the normative exit point, the probability of this occurring decreases significantly. If it does occur, a timely measure with jacking up is likely and here the failure probability due to this cause is not significant. For the increase in pore water pressures due to smeared perforations (I23), in addition to including decreasing permeability in design rules and timely detection of burst points, it can also be assumed that if during execution the perforations are actively cleaned and adjusted where necessary, this will minimize the risk of failure.

With the Prolock filter screen, the risk of chemical and biological clogging ((14) is present because the filter sand is largely enclosed in a tube. There is a risk that anaerobic conditions will be threatened and clogging will occur. It can be assumed that by completely filling and sealing the shaft the risk of oxygen diffusing to the depth of the perforated section is minimized. The implementation protocol further reduces the likelihood of the risk occurring. Long-term monitoring is important to keep the risk and failure probability contribution as low as possible. Here, besides monitoring permeability at critical points, monitoring anaerobic conditions in the sump can also play a role. For mechanical clogging it can in principle be assumed that when the calculation rules pipe before/bursting are applied with an extra safety built in for pressure build-up due to clogging, the risk is significantly reduced. However, when monitoring for permeability for chemical and biological clogging, this risk is also covered through monitoring and with it the failure probability contribution is reduced.

C

Appendix C: Problem Investigation Interviews

This appendix presents the interviews as part of the problem investigation. First, an interview is conducted with a technical specialist at the target group of this research, HDSR. Secondly, two target group/expert sessions are held on respectively monitoring of innovative measures in dikes and the Prolock Delta filter screen. In the first session, relevant information for the problem investigation has been gained and is summarized in the section C.1. The second session was very specific about the management & maintenance strategy for the Prolock delta filter screen, and did not yield relevant information for the problem investigation. Therefore an additional interview was held afterwards with a member of the asset team flood defences at HDSR.

C.1. Problem Investigation Interview 1

In this section, the interview manual based on van Thiel (2007) and the minutes of the interview conducted with a technical specialist at HDSR are presented. Below in table C.1, the details of the interview are listed. Irrelevant sections of the transcription are left out, for instance, an explanation of this research or an introduction of myself as the researcher.

Name	Eric van der Tas
Job Title	Technical Specialist Geohydrology & Geotechnology
Target Group	HDSR
Expertise of Interest	Groundwater Monitoring
Interview Date	07-03-2023
Language	Dutch [Translated minutes to English]

Table C.1: Interview 1 - Details

0: Summary

Within HDSR, the asset team flood defence is the primary beneficiary of a monitoring strategy to be developed. As an asset team, they own and manage a dike. In the case of the current Sterke Lekdijk project, different contractor combinations are working on dike reinforcements for several dike sections. Several innovations are applied in this process, including thus an anti-piping filter measure Prolock. The asset flood defences would benefit more from a monitoring strategy aimed at creating a monitoring system to demonstrate the effectiveness or proper operation of the innovation of their anti-piping filter measure after construction. A monitoring strategy better serves HDSR if it can help create a monitoring system aimed at monitoring the continued operation of the filter in the future.

Current monitoring at the Strong Lekdijk project aims to understand the system better and consists of monitoring well measurements. After the construction of the innovations, monitoring can be used to determine the change in the system. HDSR does not yet have experience with monitoring new innovations. A better understanding of the system and the collection of input values for the calculation models in the next assessment of the dike can perhaps be combined as measurement goals with the primary goal the strategy aims at. However, it is questionable whether the required measurement locations correspond. A monitoring strategy is of added value within HDSR if it explains, based on scientific knowledge, the promising technologies that can be applied in a monitoring system or are promising to be investigated further.

The respondent also includes reactions to the different sub-monitoring goals that can be set when determining the performance of an anti-piping filter screen according to van Beek (2017) and their feasibility. Further explanation was given on the definitions and operation of monitoring wells, piezometers and pore pressure sensors and considerations in the placements of these sensors. Furthermore, based on his expertise as a geohydrological specialist, the interviewee assessed that new innovative techniques such as glass fibre and Aquavector to measure pore pressures are sufficiently developed for application in an HDSR project.

1: Introduction

Introduction round

I am working within HDSR as a technical specialist in geotechnical engineering, which is the official title, and that has to do with the fact that my background was more in the direction of geotechnical engineering. Still, in the last three to four years, I have been taking up geohydrological projects again, but also, in the last two years, I have been moving more in the geotechnical direction. I hope that I will do more geohydrological projects and fewer geotechnical engineering projects. However, since I do have a total of five or six years of background in geotechnical engineering, I still take on such issues at HDSR because I have relevant knowledge and because that was also what was in the request for my appointment at HDSR.

What is the aim of the study?

The aim of this research is explained and discussed with the respondent.

Does the conversation proceed satisfactorily?

It is made clear that the respondent can indicate if they do not understand a question. Also, it is indicated that the respondent is not obliged to answer or can indicate if they do not have the expertise or background to answer a specific question. Finally, Eric gives permission to record the interview.

2: Questions

The questions consist of two sections: the first section includes questions related to the research's problem investigation, aiming to obtain a firm grasp of the target group's [HDSR] perspective on the problem. Using this perspective, requirements for the to be created monitoring strategy will be set up. The second section includes expert consultation about groundwater monitoring. This is used for theoretical and/or practical recommendations as input for creating a monitoring strategy. This also serves as validation of information included in the literature study.

2.1: Problem Investigation

What are your work duties at HDSR?

- *What is your role as technical specialist geotechnology and geohydrology?*
  Within HDSR, we have the Sterke Lekdijk project, which stretches from Amerongen to Schoonhoven, where 60 kilometres of dike sections will be fully reinforced. I myself work within HDSR's technical team for the project. HDSR has different disciplines: water treatment, water management and flood defences. We are now going to strengthen the flood defences, and in doing so, I am part of the technical team as a technical specialist. So what do we do? We ensure that the principles for strengthening the levee are the same for all subsections. There are six different subsections, one of which is Salmsteke. All six subsections have different engineering contractor combinations. We have three engineering contractor combinations in total, each with two sub-sections. Our goal as an engineering team is to ensure that all those subsections have the same principles. So an

example for determining the height of a dike, we consider an overflow discharge of 5 litres per second per metre for the flood defence. If the embankment does not meet that criterium, it must be raised. That principle is the same for all sub-trajects of the project. This is thus stated in our strategic memorandum for the project.

The Sterke Lekdijk project aims to innovate as much as possible. In doing so, HDSR wants to make CO_2 and nitrogen reductions and create biodiversity. This is to be achieved by applying innovations. Innovations are realised through products such as the Prolock delta filter screen but also by improving calculation rules. Here, we try to look at how the existing calculation rules, which are often fairly conservative because they were drawn up on the basis of empirical relationships and practical tests, can be tightened up. This can save material and is referred to as a calculation rule innovation.

- *Specifically, in what way are you involved in the Sterke Lekdijk project at HDSR?*
  My role within the technical team is to ensure that the various engineering firms and contractors adhere to the same principles and that innovation is promoted and incorporated within HDSR. In this sense, we are also sparring partners with the managers. The asset team flood defences HDSR manages the Lekdijk, provides maintenance and checks the dike during high water. So in that sense, we assist the flood defences asset team, who ultimately manage the dike, with technical advice.

Experience with monitoring of piping relevant parameters?

- *In your role, are you also involved in setting up monitoring plans?*
  The asset team flood defences are to manage the dike. So they preferably want to know the state of the dike at any time. And to do so, monitoring is necessary. So the flood defence asset team will eventually also own the monitoring system. As a technical specialist, I assist the flood defence team in developing a monitoring plan. A monitoring plan may concern groundwater levels, but it may also concern settlements, and it may also concern vibrations during the implementation phase of a measure.

- *As part of the technical team, do you actually get tasked with setting a monitoring plan for the asset team flood defences?*
  Normally, the task lies with the asset team flood defences, where the technical team can provide support. However, the asset team is currently understaffed, so a monitoring plan is then usually outsourced. At the moment, however, they are too busy to outsource it as well, so I have been asked to create an initial start on a monitoring plan for the Sterke Lekdijk. So that is what I am going to get involved with over the next few months. I am going to start soon, it is particularly about groundwater monitoring. Here the aim is to monitor the system. So it is then not so much about seeing whether new innovations actually work. It is then more about insight monitoring needed to check whether innovation actually works as they are applied in the field. So in the case of a filter, check whether the groundwater flow actually continues to flow and whether the filter does not clog up now. And if that is the case, the question remains whether this will still be the case in 20, 30, or 40 years' time. This will also be included in the monitoring plan.

- *Do you have experience with setting up a monitoring plan?*
  Yes, particularly with groundwater monitoring in road construction, I have experience with monitoring plans. But not with innovations in hydraulic engineering, such as innovative anti-piping measures. Of course, I do have an idea of how you could monitor it then. In road infrastructure, monitoring was mainly about determining the baseline situation when constructing a new road. As a result of the work, the environment can be affected, resulting in risks such as subsidence, desiccation, and humidity. And that is something you want insight into when people eventually come forward with a compensation claim. You can then show whether something is a consequence of the work.

Monitoring goals

- *The following life cycle phases of dikes can be distinguished and related to different monitoring goals:*
    - More accurate determination of piping relevant parameters / input calculation models during the assessment
    - Determine correct construction / implementation of measure
    - Management / maintenance
    - Calamities

- *Given these different phases, how do you look at the monitoring question for the new innovative anti-piping measures?*
  This is where the maintenance phase applies, starting with monitoring for a long period. Of course, this also involves eventually reassessing the flood defence. Then you want to know whether the design you made now and the assumptions you made still hold. Ultimately, for example, for piping, you look at how the hydraulic head reacts to the water level in the river Lek. So the water level in the Lek rises at high tide, and the head in the hinterland also rises. And there is a certain relationship there. And that's what we've already been monitoring in recent years. However, it is not the case that because you see a certain response based on one high water, you see the same response at the next high water. You see that there is a certain range in it. So we want to provide insight into the system operation based on ongoing continuous monitoring there. To see whether the system as we present it now is still correct based on new monitoring.

- *Does this then bring together two measurement goals?*
  Yes, here, it is not only about management/maintenance but also about better understanding the system and the design. This can also be useful and related to the next round of assessment of the dyke.

- *Could you then also say that these measurement goals can be linked?*
  Depending on the location, wet spots, for example, are more interesting for management and maintenance in some places. I have not really thought about yet about linking measurement goals. Nevertheless, I think the phreatic groundwater level is particularly important for management and maintenance. The head is going to be particularly important for your design, for your erosion and for the stability of your dike. I think both objectives can come together well in the monitoring system. In what you ultimately want to realise and where exactly the monitoring wells will be, there is always a certain consideration to be made. For instance, you can say there are currently critical points or sensitive spots where you see much seepage. This means there is a higher risk of seepage and piping. That is where you actually want to monitor.

Relevance of Monitoring Strategy

- *How could a monitoring strategy help you prepare a monitoring plan (strategy is the approach to coming up with a monitoring plan that is site and project specific) / What would you like to see reflected in such a monitoring strategy and why?*
  You could go into two monitoring questions. First, you want to know whether the system is working as conceived, which is basically the first thing you want to check. Here you primarily help the innovation teams to demonstrate that their realised system with innovation works. And the second measurement goal is, does it continue to work during the usage phase of that innovation? And that is then more important for HDSR since the asset team flood defences manages the dike. We then assume that the first measurement objective has been achieved and you have demonstrated the operation of a system, and it has been applied in the dyke reinforcement. Then, after completion, management has to monitor that the system continues to work. As a dike manager, you must then be able to see from the monitoring system to what extent the measure is still working.

  Here, I can imagine that it must provide continuous insight, although with a pump test, for example, you cannot get continuous insight, but the monitoring well systems I work with measure the pore pressure in real-time and that is displayed via the Internet of Things telemetry directly in a visualisation programme so that I have immediate insight into the pore pressure. Ideally, I would also like this from a monitoring system for the asset team flood defence HDSR for management/maintenance of a dike with innovative anti-piping measures.

The final product of your research could be useful to us if it indicates, based on the literature review, what might and might not be interesting monitoring methods to investigate further or apply in a monitoring plan. What may also be interesting to investigate is whether promising monitoring methods actually deliver what you want. [This is beyond the scope of the study]

2.2: Expert Consultation

Monitoring Options

- *The following sub-measurement goals can be set when your main monitor goal is monitoring as verification of the operation of anti-piping filter solutions?*
  - Development of a pipe on the outer dike side of the filter screen
  - Closing of a pipe on the inner dike side of the filter screen.
  - Clogging of filter screen (Groundwater flow distribution over depth)

- *Per monitoring goal, you can say something about the feasibility of monitoring these goals by measuring groundwater, and the unknowns and uncertainties involved.*
  - As you pointed out, to detect a pipe, you need many pore pressure gauges, which does not seem feasible. If your pipe is already past the filter screen, detection may no longer seem very relevant to me, except as a warning, perhaps.
  - In the case of siltation of a filter, it does not seem feasible to me to measure this via the groundwater level near the filter, especially since a filter has a limited thickness, even though there is probably a slight drop in the groundwater level, it is probably too small to measure properly. At Salmsteke, you also have a tidal influence, which may allow you to observe damping in this fluctuation due to silting of the filter.
  - There are also new innovative types of sensors that can measure groundwater flow directly, allowing you to measure the decrease in groundwater flow as a result of the filter silting up. There are measurement systems for this that are still under development but, in my view, are already sufficiently developed to be used in these innovations. These include Aquavector technology and Fibreglass technology.
  - Yet another possibility is to measure the permeability of your filter with a well test. You can then place a monitoring well in/near the filter in which you will measure the permeability after lowering the water level in the well pipe. You can do this every other year, for example, and if the permeability decreases, this says something about the permeability of your filter.

Observation Wells & Piezometers

- *When it comes to monitoring wells, piezometers and pore water pressure gauges, different definitions are used interchangeably. Can you explain your definitions?*
  You speak of monitoring well when you are going to drill or press. You can use an auger, or a bailer; in any case, you will remove soil, creating a borehole. And then you are going to put an monitoring well in there, which has a filter of 1 to 2 metres with a blind pipe on top, so a non-perforated pipe. In the monitoring well, you will hang a measuring system that will constantly measure the water level. So that is one possibility. What you can also do is use a CPT vehicle, like a track truck. This actually pushes a casing, a kind of cylinder with a point at the bottom, in the ground. So we are not going to drill, we are not going to remove soil, but we actually push the soil aside, up to a certain layer. Then we place a pressure gauge in the casing. That's roughly the same monitoring well that we put into a borehole. And then we pull that casing back up again. And so then you have a monitoring well where you want it.

  The advantage of having a borehole with monitoring well is that you also know what type of soil it is when you pull the soil up. While here, you are going to push a casing into the ground. And you do have an idea of how hard you have to press to get that thing into the ground. However, you actually have no idea what your subsoil looks like. For me, a borehole is always preferable, but a casing is cheaper. In the monitoring well, you have a 1-2 metres filter. In principle, you never put a filter over the entire length; if you are interested in the aquifer, for example, in the case of piping, it is irrelevant. A pore pressure sensor can also be pushed into the ground via a casing and then accurately measure the pore pressure at that layer. This is what I call a piezometer. But in principle, a monitoring well also contains a pore pressure sensor. With a pore pressure sensor outside a monitoring well, you get the exact pore pressure 10 cm around the filter at that depth and with a monitoring well, you get a coarser picture over the length of the filter.

- *How do you determine where to place point measurements such as observation wells?*
  We now have a lot of monitoring wells along the Sterke Lekdijk, and when those wells have reached their current measurement target for the dike reinforcement, we want to know whether we want to keep monitoring those wells. Monitoring also costs money. So what we have done now is look at the most important properties of the monitoring wells that we want to continue monitoring. The first is sensitive spots, so at seepage or a kolk. A kolk is a type of dike breach. But also at innovations to monitor the long-term operation. Is that going to deteriorate is then also a question? But in addition to sensitive areas, innovations also in works that affect groundwater flow. So, for example, when digging in the foreland or the hinterland. Excavation in the foreland can ensure that if you excavate clay, there is more seepage into the hinterland because more resistance disappears.

  Conversely, if you build a bentonite mat as a piping measure, for example, you will get less seepage. So you get desiccation in the hinterland. These activities affect the groundwater flow and thus can give an environmental risk, such as settlements, drying and wetting. So those are three parameters we want to have insight into for the monitoring well. And then, there is a fourth aspect, which is the spatial distribution of the monitoring wells. If you have a pillar pipe 3-4 kilometres apart, you can ask whether you should have a pillar pipe every kilometre instead. You have to ask the question; when do you need the next data point? We now have the idea here that we need monitoring well every 1 to 1.5 kilometres to get an understanding of mainly the hydraulic head but also the phreatic groundwater level.

3: Closing

- Allow the respondent the chance to react to the interview.
- The respondent is asked if there are points/topics/question which he would like to address again.

C.2. Problem Investigation: HDSR Monitoring Session

In this section, a summary of a monitoring session at HDSR is presented. This session was organized by the asset team flood defences mentioned in the previous interview. As managers of the Sterke Ledkijk dike traject, they are tasked with setting up a management & maintenance strategy for the whole dike trajectory with new innovative anti-piping measures applied. The aim of the session was to discuss possible monitoring techniques suitable for monitoring innovative piping solutions. As a participant in this discussion, this session allowed me to take notes on relevant aspects of the problem investigation, which are presented in summary. Examine the perception of the problem of which the HDSR asset team flood defences is the problem owner: a monitoring strategy for anti-piping innovations is to be developed. Below in table C.2, the session details are listed.

Table C.2: Details of monitoring session HDSR asset team flood defences

No. Participants	?
Job Titles	Advisors & Managers Flood Defences (Asset Team HDSR), Geohydrological Specialist (HDSR), Geotechnical Engineer (Mourik), Consultant Soil & Groundwater (Tauw), Geotechnical Specialist (Antea HDSR) Professor Geo-environmental engineering
Date	14-03-23

Summary & Interpretation

For the asset team flood defences, the starting point for the management and maintenance plan with regard to monitoring is: being able to unambiguously demonstrate the permanent functioning of the product innovation at low costs during its life cycle. Here, limited effort means not having to carry out a separate long-term project to implement monitoring. Unambiguous refers to having a uniform method to set up a monitoring system for the various innovations, preferably using mainly comparable techniques. A monitoring strategy should consider the whole lifetime of the embankment.

During the session, a geotechnical engineer on behalf of Mourik briefly explained their findings in preparing a monitoring plan. Their starting point was to monitor as little as possible, only the necessary monitoring to ensure the functionality of the Prolock screen. The monitoring plan was prepared using the failure path analysis. Dominant failure paths are chosen to monitor, where the failure probability contribution can be reduced by monitoring.

A geo-environmental engineering professor further noted that for the management & maintenance plan, a clearer distinction should be made by the asset team flood defences between the different phases in the life cycle of the embankment. Applicable here are construction, completion and management/maintenance. Here, delivery is a new phase that can be defined and one that has not yet emerged from the literature review. Delivery is specifically applicable to product innovations; this includes a period after delivery, to be defined, in which monitoring can be used to demonstrate the operation of the innovation. In all likelihood, this requires more intensive monitoring than in the management/maintenance phase in the longer term, where the lasting effect of the innovation needs to be monitored. This was also mentioned in the previous interview. It is, therefore, important to distinguish this phase and the associated monitoring objectives. Based on the first problem investigation interview, and which is confirmed in the second interview, the focus of this research should remain on the management life cycle phase.

C.3. Problem Investigation Interview 2

In this section, and minutes of the interview conducted are presented. The interview manual was based on van Thiel (2007). To avoid repetition, the subsections introduction and closing are left out. Below in table C.3, the details of the interview are listed. Due to the limited time available for this interview, only the most important questions were included, for instance, preferably some context about the role of advisor flood defences was asked for.

Name	Ruud Weijs
Job Title	Advisor Flood Defences
Target Group	HDSR
Expertise of Interest	Asset Team Flood Defences
Interview Date	16-03-2023
Language	Dutch [Translated minutes to English]

Table C.3: Interview 2 - Details

0: Summary & Interpretation

During the interview it was indicated that HDSR assumes that implementation monitoring is correctly implemented, the working principle is demonstrated before delivery to HDSR, as these tasks are the responsibility of the contractor, and therefore, the focus of a monitoring strategy for HDSR is on monitoring functionality of a filter long-term. In the previous monitoring session, it was noted that delivery should be regarded as a separate life cycle phase where the filter is intensively monitored. While, the Prolock has a different monitoring approach by only monitoring a minimal necessary amount, this life cycle phase is considered in another form by HDSR and the contractor and called aftercare. During this phase the contractor remains responsible for the operation of the filter and performs finishing works. After this phase, the dike is handed back to HDSR's asset team flood defences as manager. The management and maintenance phase overlaps with the aftercare phase. However, the difference lies mainly in the different monitoring objectives, demonstrating the long-term durability of the filter versus checking for the correct implementation and demonstrating the working principle in the field. Installing your monitoring system, taking baseline measurements and determining signal values can occur during the after-care phase. In the case of the Strong Lekdijk project, this is also the case.

The montioring that except for a few choices, the management and maintenance plan for monitoring has already been realized. This will be integrated into the Sterke Lekdijk management and maintenance plan, where resources will be allocated, schedules made, and details worked out. One aspect that needs further elaboration, for example, is the processing and interpretation of monitor results, preferably defining scenarios that describe the state of the filter screen and can be linked to results in your monitor data. The interviewee indicated that it would be valuable for HDSR if this could be addressed further in the monitoring strategy to be designed. Given HDSR's uniformity principle mentioned in the first monitoring session, it was also indicated in the interview that for the management and maintenance plan of the Sterke Lekdijk, HDSR preferably has a uniform method for monitoring filter screens.

Response Interviewee 1

In the first interview, the interviewee talked about making an initial start on a monitoring strategy. Since it also talked about monitoring filter screens, one could imply that this is part of the HDSR management & maintenance plan. However, that would contradict this interview, where only the adoption and further development of the management and maintenance plan of the innovations within the larger management and maintenance plan was mentioned. For accuracy, the first interviewee was asked for a comment, and it can be concluded from his terms of reference that it matches the picture outlined in this interview.

The monitoring plan for the entire Strong Lekdijk should provide insight into:

- Long-term monitoring of the system. Are the assumptions we adopted in the design actually correct? We can use the monitoring data collected when assessing whether the assumptions hold up;
- Long-term monitoring of innovations. The various teams write an OBOR (design, management and maintenance guideline). This will also include a monitoring plan for the specific innovation. This will have to be implemented in the Strong Lekdijk monitoring plan;
- Before- during and shortly after implementation (several years) Assess identified environmental risks regarding implementation, longitudinal structures and innovations based on measurements;

2: Questions

Besides exploring the perception of the problem (demand for a monitoring strategy) by the target group (HDSR, specifically asset team flood defences) with this interview, questions were asked to understand the difference between HDSR's management and maintenance plan and the product innovations. In monitoring session 2, a monitoring strategy designed by the Prolock team consisting of monitoring techniques per dominant failure path and associated frequency was presented and discussed; this strategy is part of the Prolock management and maintenance plan.

- ***My research is already focused on filter screens and with the monitoring aim to monitor the operation of the innovative measure. However, there is still an important distinction to be made between the life phase of delivery or aftercare and management/maintenance. In delivery, the focus is on demonstrating the working principle and, in all likelihood, requires more intensive monitoring. In management, the focus is on monitoring the continued operation of the filter screen. Is that the case with the monitoring strategy of the management/maintenance plan of the Prolock filter screen?***

  I see it as follows: you put your innovation in the ground and use monitoring at the aftercare stage to demonstrate that something works. You have already had the previous phase, execution monitoring, where you ask, are you getting the screen into the ground in a good way? So is the screen in the ground as it should be? Are they still complete, or are they deformed or compressed by whatever circumstances? We have seen a few to a number of those filters in a trial that was compressed or broken. Then in the aftercare phase, the contractor starts working on demonstrating the screen's operation before the dike is transferred back to the asset team flood defences of HDSR. The asset team is responsible for the management/maintenance plan where the long-term operation is demonstrated. The last monitoring session [Monitoring Session 1] discussed monitoring for filter screens in a broader sense, and today specifically discussed the management/maintenance plan for the Prolock.

- ***Is the management and maintenance plan provided by the Prolock team to be adopted 1-to-1 by HDSR in their management and maintenance plan for all sub-sections of the Sterke Lekdijk project?***

  We wish that there is eventually one management and maintenance plan for all six subsections. At some point, you will need to link the specific management and maintenance plans for the subsections, but for now, it is a plan for each subsection, but HDSR wants to have a single management and maintenance plan with, as part of it or possibly as an appendix, the management and maintenance plans for the product innovation, such as Prolock. So now we are describing that management and maintenance plan for Prolock, which should become an appendix to the management and maintenance plan for the Salmsteke section, which includes other things besides Prolock. We want to translate such a maintenance plan into the larger one in the same style, which you need in seven years for the entire Lekdijk when all subsections are completed. So there can be quite a bit of insertion or changes there. But the basis you already have in place will mostly be applied in a broader sense.

- ***So does the specific Prolock management/maintenance plan change in terms of implementation when it is integrated into a larger management and maintenance plan?***

  In principle, it does not change; you place it in a wider environment. The measurements and frequencies will remain the same. For example, with the pump tests as part of Prolock's management/maintenance plan, those tests have to be integrated into our maintenance management system (OBS). It is integrated into the planning, and a link must be made between the execution and required resources. So for that pump test, for example, you also look at what can be done by HDSR or what an external agency needs to be hired for. An aspect of this is also, for example, the processing and interpretation of the results. An example is the H2S smell test that can be carried out at Prolock for checking anaerobic conditions as an indicator of filter clogging. As you further develop the management and maintenance plan, you need to think about how to conduct this test correctly and carefully and how to compare and process results.

To summarize, in the final management and maintenance plan, the principles of the management and maintenance plan of the product innovations will be elaborated. Here we paste together the basic elements of the various management and maintenance plans. From the basic elements, we then refer to the specific management and maintenance plans as an appendix with further explanation. This is then a kind of staircase of activities.

- ***To what extent does such a management and maintenance plan correspond with the asset team flood defences' premise of applying a unified monitoring strategy and method for the various filter structures?***

  This has not been mentioned in the monitoring session on the management and maintenance plan for Prolock so far. However, the uniformity of a method will be an argument as one of the deciding factors in a discussion for choosing a particular method for a specific monitoring purpose, such as screen permeability. One method was mentioned where you use the tube of filter sand from the Prolock filter. However, this is not possible for a coarse sand barrier. So methods that can be uniformly applied will be preferred, but it is not a hard requirement. What also factors into this is the number of measurements; 1 or 2 measurements for a different type of filter is less of an issue than if you have to measure seven different things for each type of filter screen.

- ***How long do the contractor combinations remain responsible for the aftercare/delivery of the product innovations before the handover to HDSR's asset team flood defences occurs?***

  That is not quite clear yet. The entire Sterke Lekdijk project has an aftercare phase of three years. Previously it was always a 1-year phase, but with this, it was sometimes unclear whether the aftercare was complete. A possible question, for example, could be if the turf were already mature or not. Also, with issues such as subsidence, a 1-year period often leaves work to be done. Therefore the aftercare period was set to 3 years. With product innovations, however, the question is whether 3 years is sufficient because the focus is also on demonstrating how your innovation works. And so then the question is whether three years for this is sufficient to demonstrate this for transfer.

- ***Is the aftercare phase included in the management/maintenance plan as discussed, for example, in for the Prolock filter screen at the monitoring session?***

  No, that mainly concerns the management and maintenance after the aftercare phase. During the aftercare phase, the baseline measurements are done, such as checking whether the pump test included in the management and maintenance plan works as intended. And when that is further crystallized, you can also determine whether you are getting reliable measurement data. You can look further at the signal values compared to the baseline measurements. So in the asset team's management/maintenance plan, you will see a tightening of the management/maintenance plan of the product innovation. This includes defined scenarios of the state of the filter screen that can be linked to the monitor results.

- ***Can a to-be-designed monitoring strategy for HDSR assume that implementation monitoring and aftercare has been done correctly?***

  Yes, this is, in fact, the task of the contractor. For us, for example, it is very interesting how we end up linking monitor results to defined scenarios that describe the state of functioning of the filter screen, furthermore, how you proceed from an observed degradation scenario to measures. For the management and maintenance strategy you then come to the next question that has been put on the table before by HDSR's asset team flood defences. What do you want to monitor, and how will you do it? But the underlying question is to monitor this uniformly. So every filter construction is monitored in the same way. And then the question is where you end up; which monitoring approach is suitable to apply unambiguously to filter screen constructions?

D

Appendix D: Expert Opinion Validation Interviews

This chapter contains the reports of the two expert opinion interviews. In section D.5, the summary that was sent to both experts can be found, including validation goals and interview protocol. An interim version of the final monitoring diagram (which can be found in appendix A) as an attachment was also sent. The validation goals are referred to in the summary and the interview reports. Both experts were approached because of their relevant experience and expertise in dike engineering and monitoring. Since neither expert was able to delve into the submitted work in detail, the sub-questions of the validation goals were omitted, but the validation goals themselves were discussed.

D.1. Validation Interview 1

Name	Andre Koelewijn
Job Title	Research and development specialist

Andre Koelewijn studied civil engineering in Delft, followed by a doctorate in born tunnels. At the end of 1999, he started working at Geo Delft in the department of dikes, roads and railroads. After several years, he began to specialize in dikes. Geo Delft merged in 2008 with the hydraulic engineering laboratory and a number of departments of Rijkswaterstaat and TNO to form Deltares. During the past 23 years, he worked a lot on large-scale field tests with different failure mechanisms. Between the field tests, which included monitoring, he gave advice to water boards and the Department of Waterways and Public Works. Furthermore, for about five years, he worked on the application of artificial intelligence in hydraulic engineering.

Summary

Regarding the relevance of the research and the chosen research goal, the interviewee agrees with the relevance. Also, based on the submitted work, generally, it can be stated that the final result does meet the stated research goal, which meets validation goal 1. The main criticism dealt with the practical usefulness of the research result at the current moment, which touches on the second validation goal: the application of the final result in the intended problem context. A significant number of monitoring options that are a result of the research will, according to the interviewee's estimation based on his experience, be discarded in practice for two reasons mentioned: a measurement uncertainty that is too high or an unfavourable cost-benefit ratio. However, this does not mean that the second validation goal is not met at all. The interviewee indicated that technological breakthroughs could greatly improve the costs and benefits as well as ease of use and measurement accuracy of technologies. In conclusion, validation goal 2 can thus be partially met since, in the future, the practical usefulness in the intended problem context can increase significantly. For the entire interview report, see section D.3.

Theoretical recommendations

- Take into account that when the monitoring options are implemented in practice, many options will be discarded at the current time due to unfavourable costs and benefits or the measurement accuracy available with current technology being inadequate. Keep in mind that this, therefore, detracts from the practicality of the end result.
- Technological breakthroughs can greatly improve the cost-benefit ratio or measurement accuracy of technologies in a short time, which would greatly improve the practicality of the end result.
- Targeted pipe detection at critical locations is not beneficial for the course sand barrier as gravel is placed in such a way in the course sand barrier that this can be found at the exit point of an existing pipe. This means that by taking a sample of the exit point, it can be determined if this pipe has reached the barrier. This method should be added to the monitoring options, while targeted pipe detection should be removed for the course sand barrier.

Practical recommendations

- Water managers in the report should be named dike managers or water authorities with levees.
- Piping in English refers to what is called Micro Instability in Dutch; this can be solved by stating at the beginning of the report that piping refers to backward erosion piping.

D.2. Validation Interview 2

Name	Martin van der Meer
Job Title	Water Services & Geo Risk Management Specialist at Fugro

Martin van der Meer works at Fugro as a Water Services and Geo Risk Management specialist. Martin has been active in the hydraulic engineering sector for 35 years and is, in particular, involved with dikes. Martin has gained relevant knowledge about dike monitoring throughout the years. He is also a part-time lecturer in Geo Risk Management at Delft University.

Summary

Of the relevance of the study, the interviewee is very convinced. Especially as comparing the different filters in terms of monitoring also says something about the robustness and corresponding risk profiles of the different filter solutions. No definite answer could be given about the validation goals. The main improvement points are to make the risk profiles more concrete and to clarify the failure sensitivity by using figures for the sub-failure mechanisms and failure scenarios. It is therefore implied from the conversation that with these improvements, validation goal 1 is met. Especially as the interviewee was positive about the diagram itself. To test validation goal 2, the interviewee needed a concrete monitoring plan with figures to be able to give a proper answer. This validation goal, therefore, remains inconclusive based on this interview. However, this is not feasible, given the scope and time frame of this study.

Theoretical Recommendations.

- Emphasize that comparing different filters for monitoring purposes also says something about the robustness of a filter solution as a risk mitigation measure. With this fact, it is important to make the risk profiles more evident in the final result.
- It is very important to make the vulnerabilities of the different filters very clear to a dike manager. With this fact, it is recommended to clarify the sub-failure mechanisms and failure scenarios using clear figures.

Practical Recommendations

- Try to avoid making statements about monitoring related aspects that are outside the scope of your research.

D.3. Validation Interview Report 1

Comments by interviewer added for clarification in cursive and underlined

Interview Report is read, edited and approved by the interviewee

Specifically, in relation to this research, the interviewee worked on the coarse sand barrier. This included his involvement in a working group of different people in terms of background. As part of this working group, they explored how a coarse sand barrier could be monitored. It is known from lab tests that the concept itself works. When the implementation is done correctly, which we know through implementation monitoring, meaning the barrier is basically just there where it should be. Sand in the subsurface has no tendency to disappear spontaneously. And then, when the barrier is tested for what it was made for, how can you properly measure that in a way that you could still intervene? Because otherwise, you're only collecting data for the disaster committee. This is also relevant, of course, to avoid disasters elsewhere in the future. But preferably, you collect data and make observations when you can do something with the observations at the moment itself. And the result of the working group at the time was: monitoring this just doesn't work currently.

When you then look at the diagram as the final product of your research, it is a nice and complete diagram that makes sense, but in terms of monitoring options, it does not include measurement accuracy, for instance. Many options listed in the diagram would turn out not to be feasible in practice because of this. The following example is given of this:

For example, when you want to measure a head difference with pore pressure measurements across the VIG during gradient increase across the dike. When the head difference increases more than proportionally, the filter is clogging, and when it actually decreases, the resistance decreases, and a hole is forming. So you have a dike system with the high outside water on one side of the dike and the low-lying polder on the other. In between is a system with a lot of flow resistance. There is a sand layer under the dike where the VIG is installed, which offers virtually no flow resistance but does hold back the sand grains. When a pipe is formed downstream, it provides less flow resistance and just behind the fabric, the head is equalized with the head at the ditch. You obviously have some resistance in the pipe, but it is relatively small. But you mainly want to know something about the VIG itself. So when you put two pore pressure gauges on either side of the VIG, which is very thin and permeable, you're not going to measure a difference across since the accuracy of pore pressure gauges is a few centimetres of water column. Since you also have to deal with placement accuracy, you can get a higher head upstream of the filter than downstream, which is obviously not correct. For example, the coarse sand barrier has a much higher permeability than the surrounding sand. Then you're not going to measure a difference with pore pressure measurements. You're not going to measure a difference in head measurements there either. *Although this is not a monitoring option that has been included in the final diagram and table, it does illustrate how:* something can be a good story conceptually and theoretically, but when it is applied in practice, it lands in the category of practically not feasible.

Then another example of measurement accuracy was given by the interviewee about a monitoring option that is included in the diagram: targeted pipe detection For example, when you're going to use pore pressure gauges for targeted detection of a pipe then you're going to monitor this underground. Whereas in the hinterland, you can see water flowing up there, and at some point, it forms a sand-carrying well. So, from the exit point, you have a limited range of possibilities where the pipe is exactly under the dike. So, with this, you have a reasonably accurate location indication of the pipe, and the existence of the pipe is thus also known.

About the situation in Gameren: Here, a fairly large gradient is needed to get a pipe to grow to the coarse sand barrier. Depending on how the safety factors work out in practice, the water may get over the dike before a pipe reaches the barrier. So you're working with a distribution of strength parameters, and if this distribution is already around the mean, which is the expected value, then the water will flow over the dike. If you happen to have a somewhat weaker section, then the barrier is reached earlier by a pipe. Then, if you consider the barrier as a cross-section, only the right-hand corner of the barrier, as typically depicted in cross-sectional schematic figures of the coarse sand barrier, is affected. Then, a slope is formed in the coarse sand barrier. However, it takes three to five times as much gradient to get the coarse sand barrier to collapse. So then, very often, you will have the situation that the water is already flowing over the dike. In the distant future, it may be a different story. But for now, certainly, at Gameren, it will be the case, and then you should also consider it is also a relatively unfavourable situation. When the water comes over the dike, your problem is obviously bigger than a piping problem.

But when you do have the situation that a right upper corner has eroded out of the coarse sand barrier, then it will thus post settle, either faster or slower. During the initial flood, this does not cause any problems. Afterwards, this does not cause problems immediately either because the flood is gone by then. If there is a new high water, then the barrier only has about 70, maybe 80 per cent of its original strength left. And because of all the different safety factors in the situation at Gameren, the barrier will fall below the set safety requirements if any of those factors are not adjusted to a more favourable value in the future. And adjustments to unfavourable values are rather unlikely, the way they are adjusted for Gameren. You don't want to get into trouble by further insight, but by further insight, we can benefit. If we don't know very well, we just have to be careful. And therefore, before high water occurs again, you have to fix that upper right corner. At Gameren, the barrier is not that deep, so then you have to dig it open. And then where do you have to dig it open? You look where the big pipes have been. You can simply observe that in the hinterland. There's a pile of sand there. You take a sample there, and you look for some kind of tennis court gravel. That is because, in the barrier, there is also mixed in a layer of that kind of gravel in such a location that if something is wrong, if that upper right corner is thus so gone, then those gravel stones will be in the debris cone. If you come across those, then you just know for sure that you have to repair the barrier. If you do not come across any, then maybe your sample was wrong. Or it has indeed not been affected. Our advice is to make a test hole in the first situation and maybe also in the case of the second and third situations. And then just dig the last bit very carefully and then take a good look at what happened. It is expected that it could be several decades before that situation even occurs at Gameren. Let alone that failure becomes an issue.

At Gameren, however, there was however, a wish to implement monitoring. Consideration was given, for example, to laying a fibre optic cable. But you have to read the resulting data. Not permanently, but during high water. To do this, you have to do annual maintenance at the end of the cable to which you connect the measuring equipment. And you have to connect the measuring equipment during high water. This measurement box is also quite expensive. And maybe you have to deploy it in all kinds of other places as well during high water. So that also gave uncertainty and annual maintenance costs while no high waters have occurred. That was quite budgetary. It also gave very little added value compared to what was applied with the gravel.

For clogging, a study by Acacia Water in 2020 for the VIG concluded that under Dutch conditions, you can rule out clogging. And with the reasoning is that a coarse sand barrier is much more permeable and less susceptible to clogging vertically sand-tight geotextile, so this also applies to the coarse sand barrier.

Summarizing and relating back to the stated validation goals: so the research goal is certainly relevant (control question), and with the research conducted, the stated goal is met (validation goal 1). But when you start to actually implement the measurement options, many options get bogged down by practicality/measurement accuracy or a poor cost/benefit ratio.

In many cases, it is thus either not measurable in practice or it is relatively expensive. However, technological breakthroughs might solve the problems of unfavourable costs and benefits relatively quickly. That may sound as very distant in the future, but during the IJkdijk tests, a technological breakthrough was also experienced. That involved slope measuring tubes that have become a factor of 10 cheaper and also easier to use. The technology has gone from rarely used to almost a standard application in a short period of time.

D.4. Validation Interview Report 2:

Comments by interviewer added for clarification in cursive and underlined

Interview Report is read and approved by the interviewee

After introducing the interview, the first thing the interviewee indicated was that he missed clear figures in the diagram and report.

There is mainly a lot of text, and also, in the diagram, for example, a picture of the sub-failure mechanisms would be very helpful. Technical diagrams are very important; without these, you cannot respond properly in terms of content. Thereby, the fundamental characteristics of the three filter solutions are missing. And then, what are the failure paths or failure effects you might see in your design? Where does that manifest itself? In what place? The interviewee indicated that he was also very curious about what the characteristic differences are with regard to the safety and robustness of the various filter solutions. Where is the Achilles heel of each solution and how that leads to a very different approach to monitoring and risk management? So, for measurement options, it is important to know what reliability should be placed on the solutions to that measurement question. And when you compare filters, I would also like to see the differences and similarities in the risk profile of the three solutions. So you want to know how by implementing monitoring the risk profile changes, what remains, and is that acceptable? Ultimately, monitoring is a means of reducing your risk profile. To summarize, two aspects are missing: what determines the risk profile and clear indications of failure modes using diagrams. If you then look at the diagram as a result of the study, it is mostly good, but if you make people aware of where the risk is with each filter solution and by adding clear figures of the failure modes, the most important improvements have been made.

Returning to the first validation question with the goal of separating any criticism of the research objective itself and its relevance from criticism of the results of the study, the interviewee indicated:

I think it is a very good question because the best way to think about things is to also look at different solutions and contrast them. So I think it is a very relevant question. Piping is besides a very relevant failure mechanism.

About validation goals 1 and 2, the interviewee indicated the following:

That interviewee found it difficult to answer this because he did not have the time to look at the details precisely. Based on just flipping through the report, this could not be said, and then there should actually also be a concrete monitoring plan with pictures. After a brief side path about costs and benefits, the interviewee recommended that the report should not make recommendations about something that is not within the scope of the research. About the summary that was sent, it was mentioned that it is a clear problem statement. About the diagram, the interviewee is of the opinion that if you also show what the failure sensitivity of the system is, in combination with the schematizations, the issues raised are mostly solved. About the added value of the study, the interviewee says that the comparison between the filters is especially relevant for thinking about the question: what is the risk profile of the solution for a water manager with dikes?

The costs and benefits of monitoring were also briefly discussed

You indicate that you did look at the risks associated with the filters, which is good but make it even more concrete. And also show that, ultimately, it makes sense that part of the cost of the solution goes into information and monitoring. But that also has its limits. If I am going to spend 100% of my costs from the budget on measurement and monitoring, I have 0 euros left to construct something. So, it definitely makes sense that there is a limit. If, at some point, I start spending more on measurement than on building the solution, is it really such a good solution?

In conclusion, there was further discussion of the relationship between monitoring, filter solution risk profiles and the comfort of use for a manager

As indicated earlier, the comparison of the three different solutions is to better consider, what is the risk profile of the solution relevant to the water manager with dikes. This includes the question of how to get this risk under control and how monitoring can play a role in this. And what is the monitoring effort compared to those three different solutions? It is also important to note that there is a difference in comfort for the manager. One solution is intrinsically just less prone to failure than the other. With or without monitoring. So, with that, it is important for a manager to have confidence in the solution that monitoring helps with. But if a lot of monitoring is required, then you do not have more confidence as a manager. So, the more monitoring you need, the less you are going to believe in a solution. You can think of it as confirming a robust design. So, the simpler the monitoring solution can be, there is more confirmation that you are working with a good design and solution. Because the monitoring also has to be done and understood in the managers' time. So, if you overcomplicate the monitoring, there is a good chance it will go wrong. It has to be logical, especially for the manager. Because the manager also has to use it and has to be able to react to it.

D.5. Expert Opinion Summary

Introduction & Research Goal:

An iterative design methodology is used to create a measurement & monitoring strategy for innovative anti-piping filter solutions. A measurement and monitoring strategy should be able to provide insight into the continued functionality with regard to the piping of the filter screen during the management life cycle. The research is requested by HDSR and is, therefore, the primary stakeholder of this research. The target group, in general, is water managers of dikes (to be) reinforced with an anti-piping filter screen. HDSR is a part of this target group as currently, the Sterke Lekdijk is to be reinforced with a new filter screen solution, Prolock. This study is requested by HDSR as a second opinion for the designed monitoring plan while they also wish to gain insight into the different filter solutions available and differences in monitoring these filters: Vertically Inserted Geotextile, Course Sand Barrier, Prolock.

It was stated they would ideally be able to unambiguously demonstrate the permanent functioning of the product innovation at low costs during its life cycle. Here, unambiguous refers to having a uniform method to set up a monitoring system for the various innovations, preferably using mainly comparable techniques. The following research goals have been formulated:

Research Goal: To design a measurement & monitoring strategy to assist the intended target group of water managers within its intended problem context: creating measurement & monitoring plans to monitor the continued functionality of a filter as an anti-piping measure during the management life cycle phase of a dike.

Here a measurement & monitoring strategy is defined as a tool to aid in creating a monitoring plan that, unlike the strategy itself, is specific to a filter and location. Given the stated research goal and the chosen iterative design cycle methodology, two knowledge questions can be posed, and three sub-goals each related to the phases of the design cycles: problem exploration, design and validation. Knowledge questions:

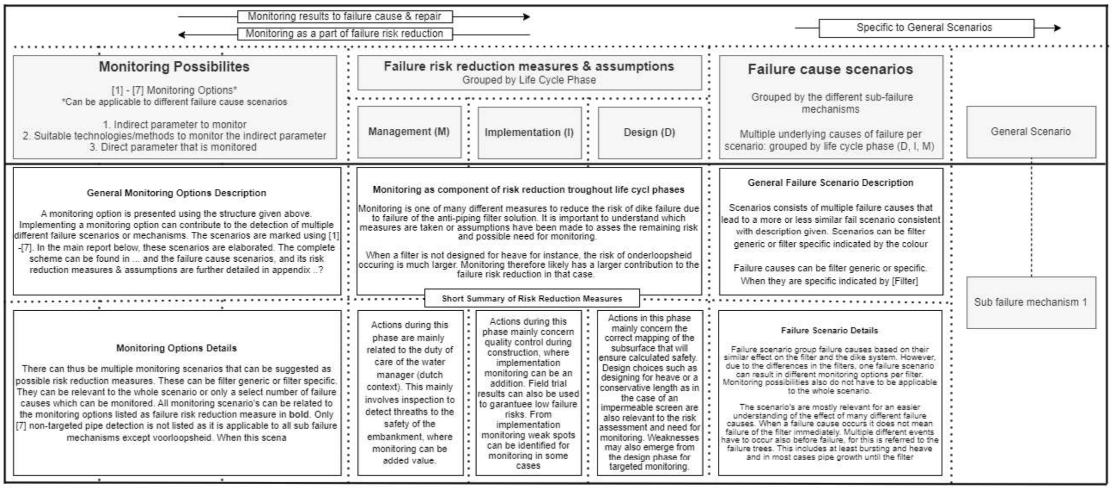
1. How do the various filters work in their function to prevent dike failure by piping, and what could cause these filters to fail in this?
2. How can monitoring provide insight into the functionality of a filter, thereby reducing the risk of dike failure due to failure of a filter, and how does this differ for each filter?

Sub-design goals:

- To investigate the requirements of measurement & monitoring strategy within its intended problem context: *creating location and filter specific measurement & monitoring plans for innovative anti-piping solutions by the target group (water managers).*
- To integrate current knowledge about the different filters and monitoring in a general measurement & monitoring strategy that can be used in its intended problem context.
- To verify and validate the measurement & monitoring strategy for its intended problem context.

Results (Final Product):

The final result can be captured in one large diagram. The essence of this diagram is that when assessing possible monitoring options, these are measures part of many different measures taken or assumptions made to decrease the failure of the filter. With consideration of all these measures/assumptions that may or may not have been taken, and the project and site-specific circumstances, a well-considered decision can be made for implementing a monitoring option. The diagram shows for which causes of failure monitoring can contribute to their risk reduction, as well as insight into the differences and similarities between the three different filters. The failure scenarios are also a way of making many different causes of failure, such as those found in the failure trees comprehendible; many causes can lead to more or less a similar situations such as clogging or disruption of filter rules allowing upstream sand to flow through the filter. Creating these failure scenario's also a mean to make comparisons between the filters without reading through all the documentation or having extensive knowledge of all three filters. Below, the structure of the extensive diagram can be found. There are different boxes explaining some concepts to understand the diagram. There is a distinction made between the two most basic failure scenario distinction: a pipe passes the filter, and a pipe forms upstream of the filter. Furthermore, the sub-failure mechanisms are included. Then, the diagram can primarily be read from the failure scenario to the most important risk reduction measures per life cycle phase and then the resulting monitoring options. However, it could be read in the opposite direction when a monitoring option is implemented to assist in determining the underlying cause of failure of the filter based on monitoring results, as understanding of the complete life cycle and functioning of the filter is very important.



A monitoring option is presented using the structure given above. Implementing a monitoring option can contribute to the detection of multiple different failure scenarios or mechanisms. The scenarios are marked using [1] -[7]. In the main report below, these scenarios are elaborated. The complete scheme can be found in ... and the failure cause scenarios, and its risk reduction measures & assumptions are further detailed in appendix ..?

Monitoring is one of many different measures to reduce the risk of dike failure due to failure of the anti-piping filter solution. It is important to understand which measures are taken or assumptions have been made to asses the remaining risk and possible need for monitoring.

When a filter is not designed for heave for instance, the risk of onderloopsheid occuring is much larger. Monitoring therefore likely has a larger contribution to the failure risk reduction in that case.

Scenarios consists of multiple failure causes that lead to a more or less similar fail scenario consistent with description given. Scenarios can be filter generic or filter specific indicated by the colour

Failure causes can be filter generic or specific. When they are specific indicated by [Filter]

There can thus be multiple monitoring scenarios that can be suggested as possible risk reduction measures. These can be filter generic or filter specific. They can be relevant to the whole scenario or only a select number of failure causes which can be monitored. All monitoring scenario's can be related to the monitoring options listed as failure risk reduction measure in **bold**. Only [7] non-targeted pipe detection is not listed as it is applicable to all sub failure mechanisms except voorloopsheid. When this scena

Actions during this phase are mainly related to the duty of care of the water manager (dutch context). This mainly involves inspection to detect threaths to the safety of the embankment, where monitoring can be added value.

Actions during this phase mainly concern quality control during construction, where implementation monitoring can be an addition. Field trial results can also be used to garantuee low failure risks. From implementation monitoring weak spots can be identified for monitoring in some cases

Actions in this phase mainly concern the correct mapping of the subsurface that will ensure calculated safety. Design choices such as designing for heave or a conservative length as in the case of an impermeable screen are also relevant to the risk assessment and need for monitoring. Weaknesses may also emerge from the design phase for targeted monitoring.

Failure scenario group failure causes based on their similar effect on the filter and the dike system. However, due to the differences in the filters, one failure scenario can result in different monitoring options per filter. Monitoring possibilities also do not have to be applicable to the whole scenario.

The scenario's are mostly relevant for an easier understanding of the effect of many different failure causes. When a failure cause occurs it does not mean failure of the filter immediately. Multiple different events have to occur also before failure, for this is referred to the failure trees. This includes at least bursting and heave and in most cases pipe growth until the filter

Figure D.1: Conceptual Explanation of Monitoring Diagram

From the complete diagram, the following monitoring options are derived and listed below in table D.3.

Table D.3: Monitoring Options found in Appendix A

#	Monitoring Option	Indirect Parameter	Technology	Direct Parameter	Related Sub Failure Mechanism	Filter Generic / Specific
1.	Surface Monitoring	Exit Points Surface Cracks	Infrared	Temperature	Voorloopsheid	Generic
		Vegetation, Engravings / Animal Grazing			Doorloopsheid	Generic
		Exit Points Surface Cracks			Bovenloopsheid	Prolock
2.	Filter permeability	Clogging	Pump test	Hydraulic Head Difference	Onderloopsheid	VIG + Prolock
					Voorloopsheid	Prolock
3.	Anaerobic conditions	Clogging (bacterial/chemical)	Scent	Sulphur Scent	Onderloopsheid	Prolock
					Voorloopsheid	Prolock
4.	Non-targeted crack/hole detection	Crack/hole - Increase in flow velocity	DTS: Fibre Optics	Temperature	Doorloopsheid	VIC + Prolock
5.	Non-targeted pipe detection	Pipe - Increase in flow velocity		Temperature	All but Voorloopsheid	Generic
6.	Targeted Pipe Detection	Pipe - Increase in flow velocity	Pore pressure gauge	Pore water pressure	Doorloopsheid, Achterloopsheid	CSB, Generic
			Aquavector	Flow velocity		
7.	Settlement Monitoring	Settlement overburden	Settlement measuring hose	Vertical deformation	Doorloopsheid	CSB
					Bovenloopsheid	VIC + Prolock

See the next page for validation goals and the interview protocol.

Validation Goals:

Two goals can be identified for validation of the results of the design phase. The first goal is to justify that the delivered product would contribute to target group goals in its intended problem context when implemented. Secondly, the goal of validation is to predict how the result will interact in its context without actually observing an implemented measurement & monitoring strategy in a real-world context (Wieringa, 2014). For the first goal, both target satisfaction & expert opinion interviews are held. The second validation goal is only relevant to expert opinion.

Expert Opinion Interview:

Introduction:

- Opening statements
  - Permission to record? Recording is removed afterwards, minutes included in the report after permission and review/comments. Final the report will be sent when finished.
  - Not obliged to answer, indicate if something is unclear or no knowledge to answer a question.
- Brief introduction round
- Brief explanation research

Opinion on Research Goal & Relevance

To avoid the intermingling of a judgement on the chosen research goal and its relevance and the validation of the research the following questions are discussed first:

a. Can you comment on the relevance of this research, given the chosen research goal?

Validation Goal 1: Justify that the final product would contribute to meeting the research goal stated and, therefore can be used in its intended context.

a. Does the final product meet the stated research goal in your opinion?

   Final product: See the results section and explanation given during introduction.

   Research goal: *To design a measurement & monitoring strategy to assist the intended target group of water managers within its intended problem context: creating measurement & monitoring plans to monitor the continued functionality of a filter as an anti-piping measure during the management life cycle phase of a dike.*

b. Are the knowledge questions sufficiently answered by the final product?

   Final product: See the results section and explanation given during introduction.

   Knowledge questions:

1. How do the various filters work in their function to prevent dike failure by piping, and what could cause these filters to fail in this?
2. How can monitoring provide insight into the functionality of a filter, thereby reducing the risk of dike failure due to failure of a filter, and how does this differ for each filter?

Validation Goal 2: Predict how a monitoring plan created with help of this study's result will perform in its intended context.

a. Can you comment on the final product, its content and accuracy?
b. Can you comment on the final product and whether this structure / approach is logical?
c. Can you comment on whether you think the monitoring options listed are in a general sense appropriate, not considering project-specific circumstances.
   a. Do you miss monitoring options or have ideas for possible additional monitoring options?

Final Statements & Thank You

- Allow the respondent the chance to react to the interview.
- Are there any points/topics/questions you want to come back to?