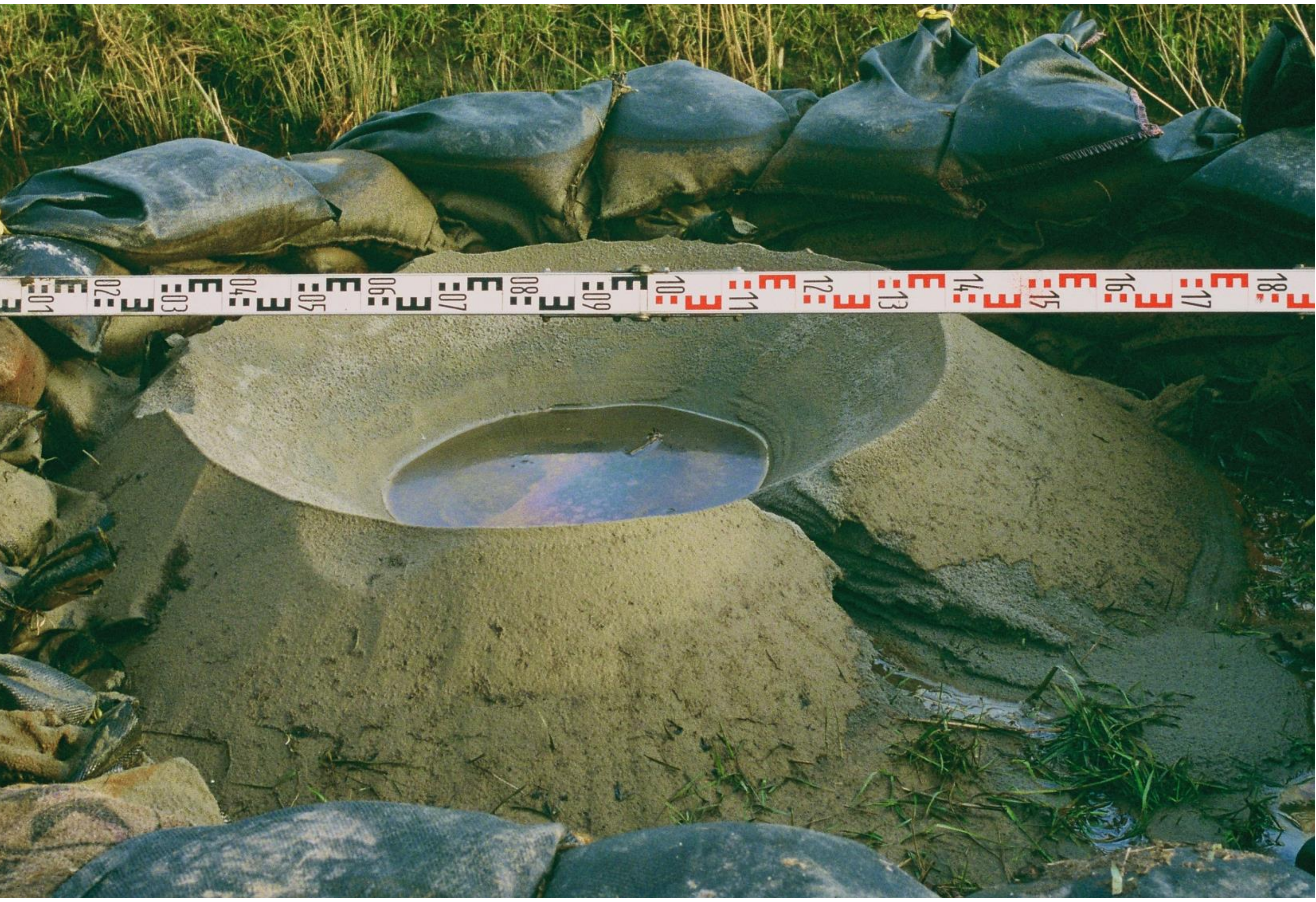

Bachelor thesis Civil Engineering:

Finding safe boundary conditions in D-Geo Flow to assess the failure mechanism of piping: insights from two case studies

A thorough analysis of the effect of several geohydrological boundary conditions on the critical head and pipe calculation in D-Geo Flow based on two case studies.

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PREFACE

This thesis is written as a final research assignment to complete my bachelor Civil Engineering at the University of Twente. The research is executed under supervision and in collaboration with Witteveen+Bos. Witteveen+Bos is a Dutch consultancy and engineering firm for water, infrastructure, environmental and construction related projects. For the duration of my thesis, I worked most of the time from their main office in Deventer, and on occasion also from their office in Utrecht.

Doing this thesis project, I learned a lot about the Dutch water safety, and specifically their assessment method for primary flood defences. As a follow-up on module 5 of the bachelor I learned in more detail about the failure mechanism of piping, and how to assess a dike's safety against it. Specifically, I learned about the pipe assessment software D-Geo Flow, made by Deltares, and what boundary conditions are important to consider when performing a pipe assessment.

Of course, I could not have done this alone and therefore I first want to thank my supervisor from Witteveen+Bos ir. Laura Halbmeijer who was always ready to help me when I had questions, or to discuss my results with. I also want to thank her for introducing me to the world of dike assessment in the Netherlands. Besides her I also want to thank ir. Niek van der Leer for providing experience and knowledge on theoretical questions in this thesis, and for supervising me during Laura's absence. I also want to thank the department of flood defences in Deventer who, not per se for my thesis, but for my time at the office provided a welcoming environment at Witteveen+Bos and took me along to fun activities besides the thesis work. Last but not least, I want to thank my supervisor from the University of Twente dr. Han Su, for being very attentive to my mails and questions, and never letting me wait when I needed help or information.

Daan Gestel

Enschede, July 2024

SUMMARY

One of the important failure mechanisms within the safety assessment of dikes is piping or backward erosion. Piping is the failure mechanism where due to a high head difference between the river and the polder, groundwater starts to stream through the under the dike laying aquifer towards the hinterland behind the polder, where because of high effective stresses from the groundwater the covering layer bursts, resulting in heave which is the sub-mechanism of piping where liquefied sand flows up onto the surface in a sand boil through the bursting channel. With a strong enough seepage flow the pipe will continue growing from the heave towards the river, to potentially grow progressive and reach the river causing short-circuiting. When the pipe reaches the river the stream velocity in the pipe will grow exponentially, resulting in more transportation of water and sand from the aquifer to the sand boil, which in turn results in subsidence of the crest and possibly the dike losing its flood retaining function. In the Netherlands, dikes are assessed on their safety against piping periodically.

Primary flood defence safety in the Netherlands has undergone changes in assessment over the past decade, and in 2024 the current assessment method is the BOI. Under the BOI, regional water authorities are given the task to assess their primary flood defences based on nationwide assessment rules, but also to incorporate regional characteristics. In case of piping, the presence of a poorly permeable foreland is important to consider in the assessment of the safety of the dike, because they might be of great significance to the sensitivity of the dike to piping. One of the assessment tools for piping in the BOI is D-Geo Flow. D-Geo Flow is a software developed by Deltares to calculate the pipe length for a given river head. In the BOI, D-Geo Flow is used to calculate whether a pipe grows longer than the dike base, in which case a further pipe analysis for the dike should be performed. Another function of D-Geo Flow is to calculate the critical pipe length and head for different schematizations, however this is not yet incorporated in the BOI. One of the reasons for this is that it is not yet known how a dike's foreland and hinterland should be schematized in D-Geo Flow, and what boundary conditions are important to follow in setting up these schematizations.

In this thesis the main geohydrological boundary conditions are determined to be the schematization of the heave boundary, the hinterland and the foreland, all three for an open / closed hinterland. In D-Geo Flow a closed hinterland assumes that all the groundwater leaves the system via the heave boundary, which is very conservative, because in reality a part of the groundwater will stream land inward. The results shows that the heave boundary should be schematized as two times the covering layer thickness; the hinterland should be set open and should be schematized land inward for a certain distance based on the specific schematization; and the foreland, if poorly permeable, should be schematized until the entry point of the pipe, but without the rest of the foreland or riverbed. When these three main geohydrological boundaries are kept in mind, it is possible to simulate more realistic results on the critical head and pipe. In further research it is recommended to investigate the influence of the aquifer thickness on the results to check if the conclusions still hold. Furthermore, it is recommended to perform calculations on the pipe length based on a given river head to see what effect the schematizations have on the calculated pipe length for a consistent head level. This could provide interesting insight in how D-Geo Flow simulates the influence of the initiation or progression dominated critical head, due to change in schematization. Results from these future projects could help in providing even more insight into the workings of D-Geo Flow.

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1 INTRODUCTION

This section discusses the context of the thesis project, the problem statement, the research objective, the corresponding research questions and an overall thesis outline.

1.1 Context

1.1.1 Water safety in the Netherlands

The Netherlands has been prone to flooding since ancient times. The water is a threat not only from the sea but also from the inflowing rivers, like the Meuse, Schelde, and the Rhine. Through the centuries, the Dutch have built dikes, dams, polders, and all kinds of other water defences to protect themselves against the water.

The most common primary flood defence in the Netherlands is a dike. Under BOI2023 dikes are assessed along trajectories, which are assigned signal values. Figure 1 shows a map of the Netherlands with its dike trajectories, along with their assigned signal values. These signal values represent a probability of flooding per year. Areas with high population densities are assigned a higher safety norm than other dikes. In general, every inhabitant in the Netherlands has the probability of dying due to flooding 1/100.000 per year.

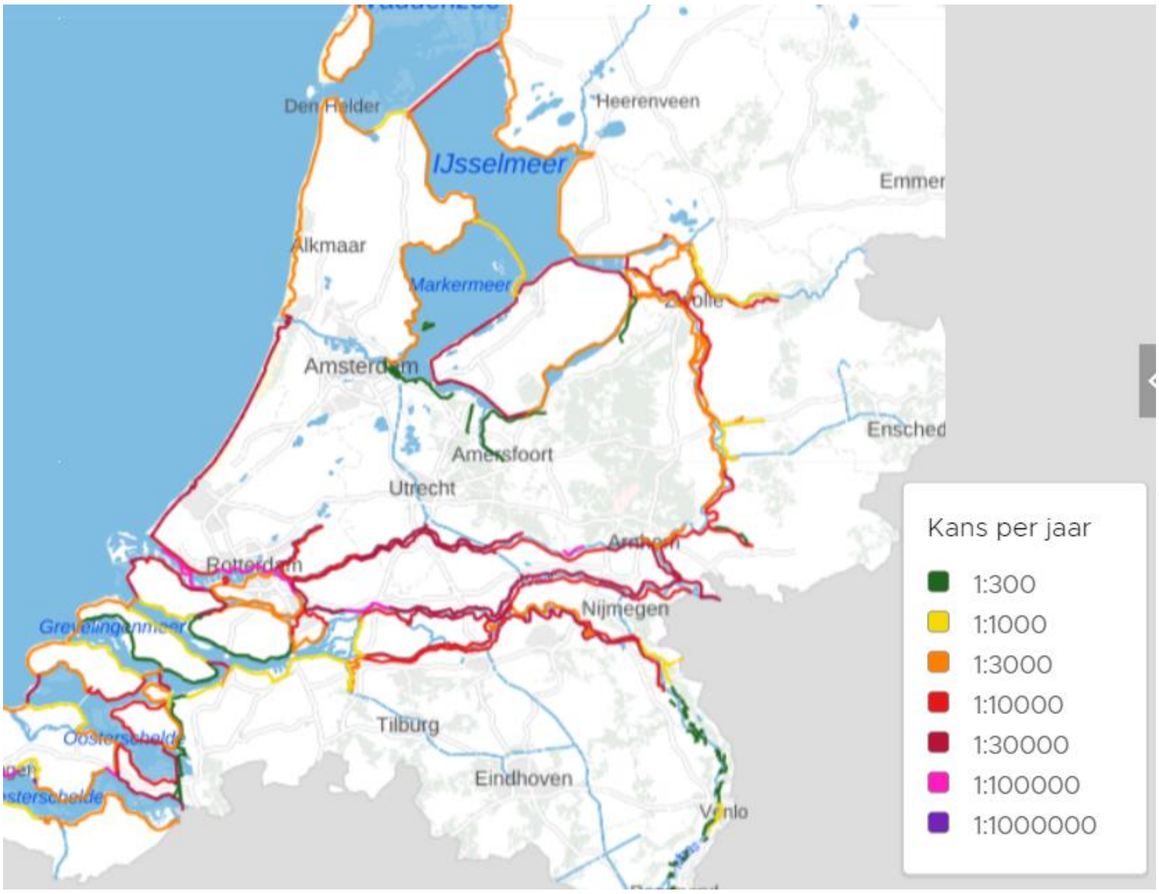


Figure 1 - Signal values for the dike trajectories (waterveiligheidsportaal, 2024)

Dikes can fail their flood retaining function due to several failure mechanisms. One example of a failure mechanism is piping. Each failure mechanism has to follow the assessment procedure from BOI 2023, on which more information will follow in 1.1.3 Change from WBI to BOI.

1.1.2 Piping

This section provides a short introduction into the failure mechanism of piping. A more in detail elaboration on the failure mechanism is given in section 2.2 Piping.

Piping is one of the main failure mechanisms of a river dike, and can best be described as the failure mechanism by which ground water moves from the river through a permeable ground layer underneath the dike to the lower laying polder in the hinterland. For piping to occur a big enough head level difference between the riverside and landside is necessary, combined with a soil composition that is sensitive for piping. In general, a dike needs to be built upon a non-permeable covering clay layer, above a permeable sand layer; the aquifer. One of the crucial aspects for piping is the occurrence of heave at the landside of the dike in the form of a sand boil flowing up though the covering clay layer. Figure 2 shows the failure mechanism piping, in the case of a ditch in the hinterland, where bursting and heave have taken place.

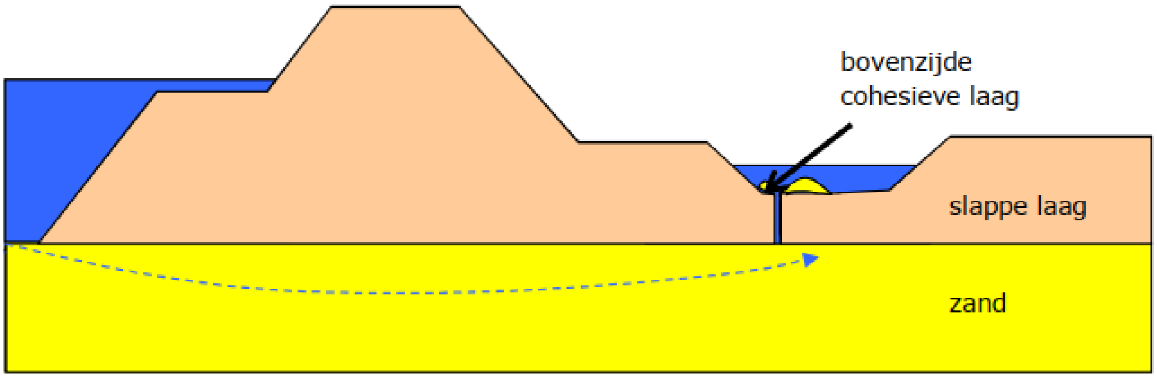


Figure 2 - Failure mechanism piping with a sand boil in the ditch (Rijkswaterstaat, 2021)

Ever since the high water levels in 1993 and 1995 in the main rivers in the Netherlands, the research behind the piping failure mechanism has increased. One of the reasons for this, was that at around 180 different places sand boils were found, indicating the presence of backward erosion or piping. Many of these sand boils have been appointed the main reason behind the subsidence and/or breaching of levees due to the high water levels at that time (Druk op de dijken, 1995).

1.1.3 Change from WBI to BOI

By law, the primary flood defences are assessed and judged every twelve years by (regional) water authorities. Because of expected changes in climate and population density the Ministry of Infrastructure and Water Management set strict rules for the assessment, to ensure all our primary flood defences (dikes, sluices, pumping stations) are prepared for the expected situation in 2050 (Rijkswaterstaat, 2023).

In 2017, the first National Assessment Round of Flood Probability (LBO1) started, which continued for six years until 2023. The differences in assessment between 2017 and before, are that: primary flood defences since 2017 are assessed on the probability of flooding, whereas before 2017 the primary flood defences were assessed based on an exceedance probability of the water level. In the years before 2017, the assessment method was called WTI and for designing OI was used. The assessment method that was used since 2017 takes into account: the effects of climate change; the effects of flooding of the hinterland on residents; and the economic value and is called WBI2017 (Ministerie van Infrastructuur en Waterstaat, 2019). The WBI2017 has been developed for years and was completed in 2017. From 2017 until 2023 (regional) water authorities have assessed the primary flood defences using these new rules. The results from the LBO1 are now used for the LBO2 which began in 2023 and will last for twelve years until 2035 (Rijksoverheid helpdeskwater, 2023).

For the second National Assessment Round of Flood Probability (LBO2), BOI was developed. One of the reasons for the change from WBI and OI to BOI is that experts found the WBI to be too fixed. The assessments on water defences were mainly done according to theoretical tools that were developed nationwide. Experts found that many of these assessment rules were too general, and non-specific for their regional water defences. This resulted in many water defences being assessed as unsafe with a high failure probability, because their regional characteristics were not taken into account, while regional experts felt that the water defences were much safer. For example, according to the WBI some dikes had a failure probability of once every ten years for certain dike profiles, which is unlikely, because some of those dikes had been standing there for a much longer period. This (together with other factors) called for the need of a new assessment method, which became BOI. This assessment method is based on the results from WTI, OI and WBI. The redevelopment of WBI into BOI took place under the architecture of IWEA-kaders. The BOI brings more freedom-of-choice with it, which is positive because now local characteristics can be accounted for, however nationwide it might result in inconsistency, because of the freedom-of-choice. Together with this development there was also a change from the Waterwet into the Omgevingswet.

At the end of LBO1 in 2022, 38% of all primary flood defences already met the more stringent standards of 2050 based on WBI2017. The other 62% is currently also safe, however those do not meet the standards that are required by 2050 (Unie van Waterschappen, 2023). A potential reason for this high percentage of unsafe water defences is that WBI ignored regional characteristics, as already explained earlier. One example for this is how piping should be assessed for different water defences. Piping is one of the main failure mechanics of a dike and can be described as the situation where an underground pipe has formed in the upperpart of the aquifer between the open water and the hinterland underneath a dike, resulting in the collapse of the dike. Under WBI2017, piping was assessed using Sellmeijer's mathematical calculation rule, which included many simplifications. More on this will be explained in section 2.4 on Sellmeijer. One simplification is that Sellmeijer's rule does not take into account the effect of a foreland on piping.

1.1.4 D-Geo Flow

Since 2017 Deltares has been developing the software called D-Geo Flow. D-Geo Flow is a Finite Element Model (FEM), which means that it breaks down the model (e.g. the schematization of a dike) in a finite amount of elements. In D-Geo Flow it is possible to set the size of these elements at any desired value within a certain range. In the FEM, the calculation model of Sellmeijer is coupled with a groundwater flow model (Darcy's model). Through this combination of both models, it is possible to calculate the pipe length for different scenarios or schematizations of a dike. The software was in prototype until 2023 and is now in official use. Under the BOI, D-Geo Flow is used to calculate the pipe length for a head level corresponding with the norm of the dike. Furthermore, D-Geo flow can calculate at what water level the pipe's length will become critical (progressive), thus unstoppable.

1.2 Problem statement

Currently, D-Geo Flow is only used under BOI to calculate the pipe length, however it has the potential to help in assessing whether a dike is safe from the failure mechanism piping. The change from the analytical calculation rule to the FEM-model brought some uncertainty with it on how to schematize a dike, and what geohydrological boundary conditions to follow/ use. D-Geo Flow provides many possibilities in schematizing a dike and what choices to make for water boundaries, however this freedom-of-choice also brings a lot of uncertainty with it, on what choices to make. For example, should only the dike's foundation width be used, or also a foreland? And what is the effect of having a ditch in the fore- and hinterland of a dike? What is the influence of an aquifer head or heave boundary on the system? What are safe values for these boundary conditions, and when are they true or not? Because the software has only been in official use recently at Witteveen+Bos these questions remain unanswered. In the following sections, a research framework will follow providing more information on the background of this thesis.

1.3 Research objective

The aim of this research is to provide Witteveen+Bos with a set of educated rules-of-thumb to follow in future projects that use D-Geo Flow simulations for the analysis of primary flood defences on piping. This research should give insight into what geohydrological boundary conditions to implement under certain conditions or scenarios. The objective is to create an overview of different dike-assessment scenarios, combined with their respective rules-of-thumb for the use of D-Geo Flow. Next to that, a clear overview of all ranked boundary conditions and their respective effect on the piping failure mechanism will be provided. The purpose of this overview is to provide clarity on the effect each boundary condition has on the system, and how strongly it affects the system compared with other boundary conditions. All combined, this 'instruction manual' for D-Geo Flow should help Witteveen+Bos in their assessment of future projects.

1.4 Research questions

In order to lead this research in a distinct direction the methodology will try to answer the main question, by going step-for-step through the sub-questions. The results from each sub-question will thereafter be used to answer the next sub-question, until the main research question can be answered

1.4.1 Main research question

In order to obtain the research objective, the main research question for this thesis is stated as follows:

"What are safe values for boundary conditions in D-Geo Flow to produce realistic results regarding piping, and when are these values legitimate?"

Here "safe" means that the chosen boundary conditions are conservative, and not too optimistic; "realistic" means that the pipe behaves according to the phenomenological definition as stated by Deltares, which can be read in section 2.2 Piping.

1.4.2 Sub-questions

In order to answer the main research question, five corresponding sub-questions have been formulated to help in answering the main question. The sub-questions are formulated as follows:

1. *What boundary conditions in D-Geo Flow are important to consider in this research?*
2. *What effect does the choice for heave boundary for both an open and closed hinterland have on the critical pipe and head in the piping failure mechanism, and when is this value legitimate?*
3. *What effect does the schematization of the hinterland for both an open and closed hinterland have on the critical pipe and head in the piping failure mechanism, and when is this value legitimate?*
4. *What effect does the schematization of the foreland for both an open and closed hinterland have on the critical pipe and head in the piping failure mechanism, and when is this value legitimate?*
5. *To what extent can the new safe values be implemented in other projects?*

1.5 Thesis outline

This section is written to provide clarity on the overall structure of the thesis. Section 2 gives background information on some important aspects of this thesis. Namely, the case studies are specified, a background on piping is given, the basic functioning of Sellmeijer is explained, the effect of accounting for a foreland and hinterland in dike assessment in previous assessments is given, some information on the basic functioning of D-Geo Flow is provided together with the possibilities on choice in geohydrological boundary conditions and an explanation of the different boundary conditions. Thereafter follows section 3 which provides some technical background information which is used to analyse the results. Section 4 is the set-up of the analysis, including information on the input variables, the methodology and a sensitivity analysis. Section 5 displays the results of the methodology, and follows the same structure as the methodology. Subsequently in section 6 a discussion is provided that functions as an evaluation of the methodology and the overall thesis project and the functioning of D-Geo Flow. Section 7 concludes the results and shows when some results are legitimate and can be used in future projects and under which circumstances. Lastly, in section 8 recommendations for future projects are given, which could not be handled in this project.

2 BACKGROUND

2.1 Case studies

For this research two case studies are used as schematizations in D-Geo Flow, namely and a segment of the Grebbedijk and a segment of the Zwolle-Olst dike. It was chosen to use two different cases, because this will help in identifying different results for the same researches. In the following part both case studies will be elaborated upon, and their characteristics which might influence the results are described.

2.1.1 Grebbedijk

The first case study that will be elaborated upon is that of the Grebbedijk, called dike trajectory 45-1. The Grebbedijk is a river dike located on the north bank of the Nederrijn close to Wageningen and it has a trajectory length of 5.54 km. The Grebbedijk protects 250.000 people in the Gelderse vallei from flooding and has been assigned a lower limit flood probability norm of 1:30.000 per year and a signal value of 1:100.000 per year, and is therefore a primary flood defence (waterveiligheidsportaal, 2024). Figure 3 shows the dike segment on a map.

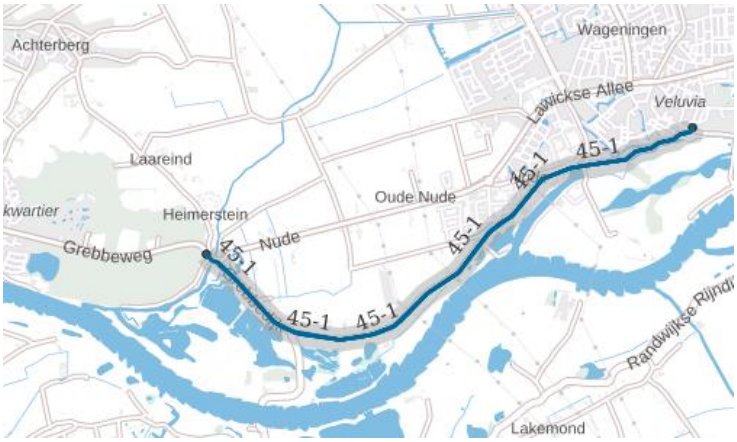


Figure 3 - Dike trajectory 45-1: the Grebbedijk (waterveiligheidsportaal, 2024)

For the schematisation in D-Geo flow, the schematisation made by Witteveen+Bos is used, which can be seen in Figure 4. This schematisation shows the average geometry of the Grebbedijk from 3B: DP 34+00 till DP 35+80. The schematisation includes from left to right: the ditch that lies perpendicular to the dike, a small hinterland, the embankment, the foreland, a ditch, more foreland and lastly the river itself.

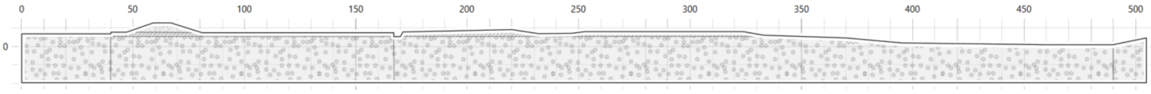


Figure 4 - Schematization of the Grebbedijk in D-Geo Flow

In Table 2.1 the names of the different soil layers and their respective permeability is given.

Table 2.1 - Soil layers of the Grebbedijk and their respective permeability

Soil layer:	Name:	Permeability [m/day]:
Levee	Embankment old	0,01
Covering layer	Clay, shallow	0,05
Aquifer	WVP1	41,00

Figure 5 shows the different layers of the Grebbedijk.

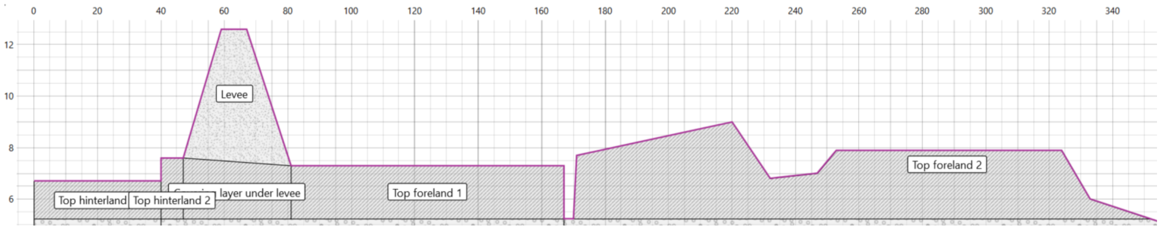


Figure 5 - Schematization of the layers of the Grebbedijk

In Table 2.2 the geometrical dimensions of the layers are provided. In Table 2.4 the same table has been made for the Zwolle Olst dike for comparison.

Table 2.2 - Geometrical dimensions of the different characteristics of the Grebbedijk

Name:	Horizontal length [m]:	Vertical length [m]:
Levee	34,00	5,60 (outside toe)
Ditch	40,00	1,47
Hinterland	7.,00	2,37
Foreland	270,00	2,02 (smallest)
Aquifer	505,00	25,23

2.1.2 Zwolle Olst

The second case study is the dike Zwolle Olst, called dike trajectory 53-2. The Zwolle Olst dike is a river dike located on the eastern bank of the IJssel between Zwolle and Olst, and it has a trajectory length of 28.88 km. The Zwolle Olst dike segment has been assigned a lower limit flood probability norm of 1:3.000 per year and a signal value of 1:10.000 per year, making it a primary flood defence as well (waterveiligheidsportaal, 2024). Figure 6 shows the dike segment on a map.

Figure 6 - Dike trajectory 53-2: the Zwolle Olst dike (waterveiligheidsportaal, 2024)

For the schematisation in D-Geo Flow, the public data from AHN was used to schematize for a self-chosen dike cross section in this dike segment at 53-2780, i.e. the dike at location DP 27,80 km. Data on the soil characteristics was provided by Witteveen+Bos, and together this formed the schematization in Figure 7.

From left to right the figure includes: the river, the foreland, the levee, a small hinterland, the ditch and the rest of the hinterland.

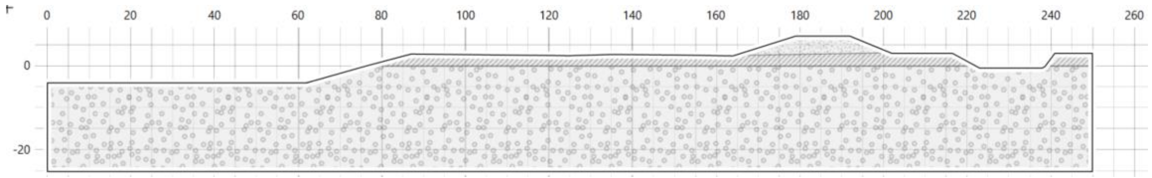


Figure 7 - Schematization of the Zwolle Olst dike in D-Geo Flow

Figure 8 shows the geometrical schematization of only the covering layer and dike in more detail. As can be seen in this figure, the levee is built upon the covering layer, which itself lays upon the aquifer.

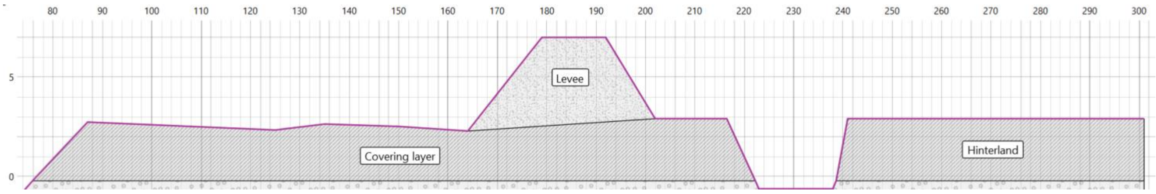


Figure 8 - Schematization of the layers of the Grebbedijk

In Table 2.3 the names of the different soil layers and their respective permeability is given.

Table 2.3 - Soil layers of the Zwolle Olst dike and their respective permeability

Soil layer:	**Name:**	**Permeability [m/day]:**
Levee	Embankment old	0,01
Covering layer	Clay, shallow	0,05
Aquifer	Sand, permeable	41,00

In Table 2.4 the geometrical dimensions of the layers are provided.

Table 2.4 - Geometrical dimensions of the different characteristics of the Zwolle Olst dike

Name:	**Horizontal length [m]:**	**Vertical length [m]:**
Foreland	91,15	2,50
Levee	38,00	4,70
Hinterland 1	14,00	3,12
Ditch	24,50	3,52
Hinterland 2	60,00	3,12
Aquifer	301,00	25,23

2.2 Piping

In this section the failure mechanism of piping will be elaborated upon. Piping is one of the main failure mechanisms of a dike, and in some cases may lead to the dike losing its water retaining function. Under the WBI approximately 62% of the primary flood defences in the Netherlands do not demonstrably meet legal requirements that are set for the piping failure mechanism (Unie van Waterschappen, 2023). It is thought that this is partly due to the fact that only the dike’s width (from landside dike toe to riverside dike toe that is) plus 1x the dike width in the foreland is used in calculating the safety against piping, whilst accounting for more foreland could potentially have an impact on the dike’s safety against piping. In the following text a more detailed elaboration on piping is given.

In the Netherlands the failure mechanism of piping can occur at dikes that exist out of an embankment that is settled upon a aquitard layer of clay or peat called the covering layer, under which the erosion-prone sand layer lies, called the aquifer (Deltares, 2012). See Figure 9 for a neat schematization of a dike's cross section with an impermeable covering layer (brown in the figure) on top of an aquifer where piping occurs.

Before piping can occur there needs to be a groundwater flow in the aquifer from the outside to the inside of the embankment. The discharge of the groundwater flow is dependent on the thickness and permeability of the aquifer and the head difference between the in- and outside of the dike. Piping might occur when high water levels occur on the river side, resulting in a bigger head difference.

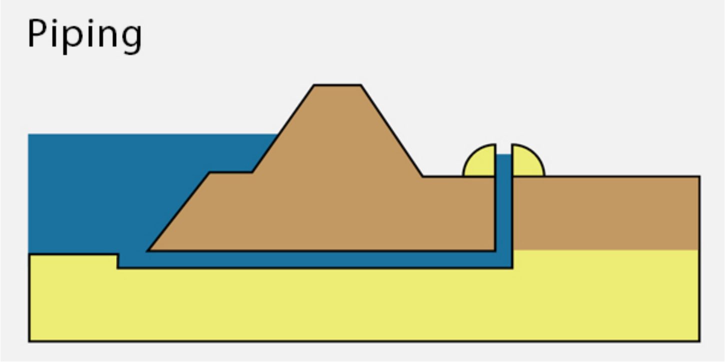


Figure 9 - Schematization of a dike's material decomposition (Meanderendemaas, 2024)

The failure trajectory of piping can be stated as follows, namely: bursting, heave and backward erosion possibly resulting in the collapse of a dike body. Figure 11 provides the most common failure trajectory of piping.

The first sub-mechanism is bursting. In this sub-mechanism the cohesive ground layer behind the dike bursts due to high water levels in the river that increase the water pressure in the aquifer. When the water pressure under the cohesive layer is higher than the weight of the covering layer, the layer might burst, creating an open connection from the aquifer to the ground layer behind the dike. The burst results in holes or cracks in the surface layer, through which water can rise.

The second sub-mechanism of piping is heave. The inflow of water into the bursting channel causes high flow velocities near the exit point. Due to the seepage flow occurring from the sand layer, sand particles are transported from this layer to ground level. The burst channel is filled with a sand-water mixture. This is called heave. At this point, two possibilities arise: 1) The flow velocity decreases so much due to friction in the burst channel, that the erosion process stops. A well that delivers clean water emerges. 2) A second possibility is that a sand-carrying well is created, with sand flowing through the well from the sand layer to ground level. For this, the heave criterion must be met, which means that the vertical groundwater flow in the direction of the exit point as a result of the vertical head (i.e., the water pressure difference across the layer thickness) is so great that the effective stresses in the soil are reduced to zero and the sand grains are transported upward from the aquifer to the exit point. Only when the sand is flushed upward can an erosion channel also form under the covering layer and dike. The outflow of sand from the well is called a sand boil. Figure 10 shows an example of a sand boil. The figure shows how a crater of sand is formed around the sand boil.

Figure 10 - Example of a sand boil (Druk op de dijken, 1995)

The third sub-mechanism is the formation of the backward erosion or piping. When the horizontal hydraulic gradients are great enough to erode sand particles, and the sub-mechanisms of bursting and piping have already happened, the backward erosion will start to take form. One or multiple erosion channels can form, which are generally growing in an upstream direction i.e., to the riverside. These channels, or pipes, are very shallow cavities (only a few particle diameters deep) on top of the aquifer. The covering layer or the levee form the 'roof' of the pipe so to say. A pipe cannot form when it has no cohesive roof, like for example sand, because than the roof would collapse when a pipe is forming. The backward erosion pipe will grow when the particles at the head of the pipe are eroded and transported though the pipe towards the heave. When the length of the pipe has become critical its growth will become progressive, and even a lowered head will not stop the pipe from growing (Handleiding overstromingskansanalyse dijken/dammen deel 2, 2023).

The subsequent-mechanism is the enlargement of the piping channel and collapse of the dike body. Under WTI the rule-of-thumb is that the moment the piping channel is halfway between the sand boil and the outside water, the growth becomes progressive. Before this point the pipe growth can stop when the river head drops or even when the head difference remains the same, because an equilibrium is reached. When the growth becomes progressive it will continue growing, even if the river head drops. When the channel has reached the entry point of the water e.g., the river, an open connection between outside water and well is created and thus short-circuiting occurs, allowing flow velocity and erosion in the channel to increase. The channel then widens and deepens in the direction of the exit point, that is, toward the inner dike side. As a result, the dike will be slowly submerged, creating hollow spaces under the barrier. Over time, these spaces collapse, and subsidence of the crest occurs; the dike body collapses. If the outside water level consequently becomes higher than the crest height, overflow and thus breach growth will occur: the flood defending function will fail (Hart, 2018) In Figure 11 a clear overview of the most common trajectory for piping is depicted. In English it says: *High hydraulic pressure: 1. Riverside water levels rise, 2. Water pressure in the aquifer rises* and secondly *The initial mechanism commences: 3. Bursting, 4. Heave, 5. Backward erosion* and thirdly *Subsequent mechanisms commence: 6. Hydraulic short-circuit, 7. Widening and deepening of the erosion channel, 8. Crest subsidence* and lastly *Crest subsidence and breach growth result in flooding: 9. Breach growth*.

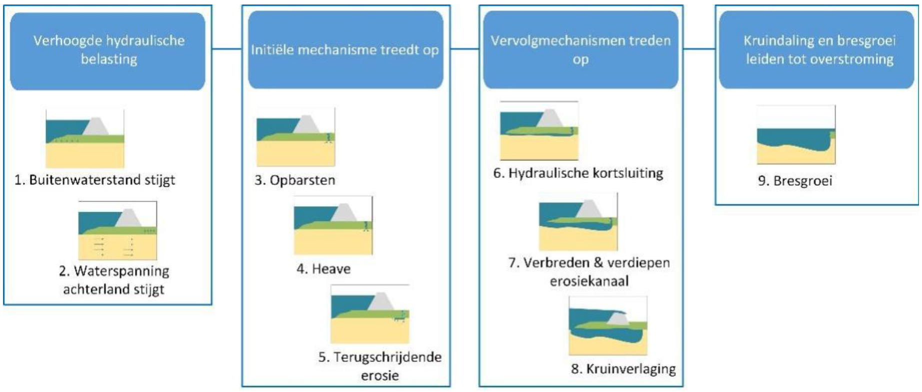


Figure 11 - Most common trajectory of the failure mechanism of piping (Rijkswaterstaat, 2021)

2.3 Sellmeijer

The rule of Sellmeijer was first introduced in 1988 as a mathematical model for calculating backward erosion. The calculation model was very simplified and could only be used under standard configurations, as can be seen in Figure 12, which also demonstrates the exact geometry that had to be used for this model (Deltares, 2009).

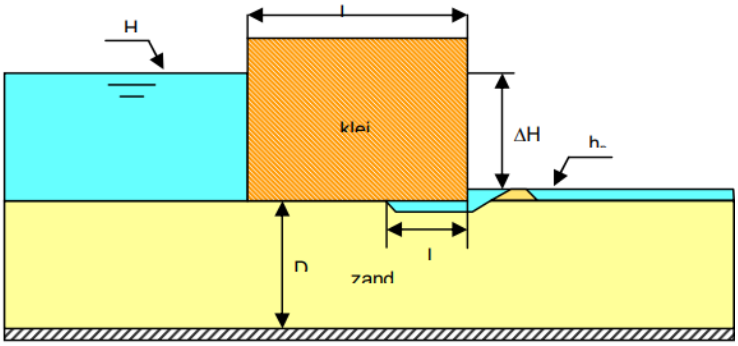


Figure 12 - Calculation model of Sellmeijer (Deltares, 2009)

Hand in hand with the calculation model a more simplified calculation rule was introduced. This analytical calculation rule is based on the mathematical model but is a very much simplified piping analysis. The calculation rule is based on the numerical calculations from Sellmeijer, and thereafter fitted on an analytical formula. The calculation rule was then extensively calibrated, taking into account uncertainties and fitting the standard. Thus, suitable for application (with safety factors) at the flood probability (Deltares, 2012).

Since 2005 a numerical model for piping has become available. The added value of this numerical model was that it also considers the effects from a non-homogenous aquifer. Furthermore, the forces that work on sand particles in the pipe were reduced from four (two horizontal and two vertical drag forces and flow pressures) to only two drag forces, one horizontal and the other vertical, as it was found that the flow pressures were negligible (Deltares, 2012).

In the WBI2017, the analytical Sellmeijer calculation rule was first introduced nationwide in the assessment plans of flood defence structures. However, the analytical calculation rule of Sellmeijer does come with a few simplifications, that could make the results less broadly applicable. For example, Sellmeijer's rule can only be used for green dikes, and not for other flood defences. The reason for this is that Sellmeijer assumes the simplification that the seepage only exists horizontally, however for other flood defences this is not always the case because they could make use of seepage screens, in which case the seepage is partly vertically oriented.

Furthermore, it is not validated for situations in which water penetrates the surface layer of the foreland, in other words it assumes an impermeable foreland when included in the schematization. This gives shape to another rule-of-thumb that is used for the assessment of backward erosion piping, namely that in Sellmeijer the seepage path length that is used to assess piping has a maximum length of two times the dike base from toe to toe. This is because it is assumed that only the dike is impermeable and that the pipe growth becomes progressive at ½ the seepage path length. When two times the dike base is used as the seepage path length the calculated pipe will always be under the dike, because otherwise its growth would have been progressive.

Another important simplification is that Sellmeijer assumes that there is only one entrance point for the aquifer whilst in D-Geo Flow it is possible to set a permeability for the foreland through which water can enter the seepage path as well (Rijkswaterstaat, 2021). Sellmeijer's rule is an analytical approach that represents the backward erosion part of the failure mechanism piping. It describes the relation between the critical head difference and several dike and subsoil characteristics. The formula covers three essential areas: the groundwater flow through the subsoil, pipe flow through the erosion channel, and limit equilibrium of sand particles at the bottom of the erosion channel (Hans Sellmeijer, 2011).

2.4 Foreland and hinterland

The foreland is the land between the levee and the river, or other open water body, which is most often a flat grassland (Hart, 2018). During periods of high water levels the foreland will flood and form extra room for the river. The hinterland is the land behind the levee. The hinterland can have several functions, like grassland for cattle, but also urban planning is possible. As explained in section 2.3, the Sellmeijer model is only validated for scenarios with an impermeable foreland or hinterland. In other words, when the foreland is to be included in the piping analysis using the Sellmeijer numerical model, it must first be proved that the foreland is indeed completely impermeable, because otherwise the underground pipe will have extra influx of water through the covering layer of the foreland, whilst the model assumes that all water enters the system via the entry point. As explained in section 1.1.3 Change from WBI to BOI, 62% of the primary flood defences currently do not meet the standards that are required by 2050. Part of the reason for that is that the assessment rules in the WBI for piping are too stringent, because almost no foreland or hinterland is taken into account. However, the presence of a foreland has a huge positive impact on the piping assessment, thus it is most certainly interesting to investigate when a foreland can be included, and if so, how. The following examples will try to illustrate what other options for an entry and exit point are possible.

The seepage path length is the distance between the entry point for groundwater flow through the aquifer sand layer on the river side and the exit point on the landside, or in other words the potential pipe length from entry to exit point. The longer the seepage path length is, the higher a critical head is needed to form a pipe that can traverse that distance. Sometimes these points can be indicated naturally, like for example in Figure 13 where there is no covering layer in the hinterland, thus the dike toe is taken as the exit point, because that gives the shortest seepage path length.

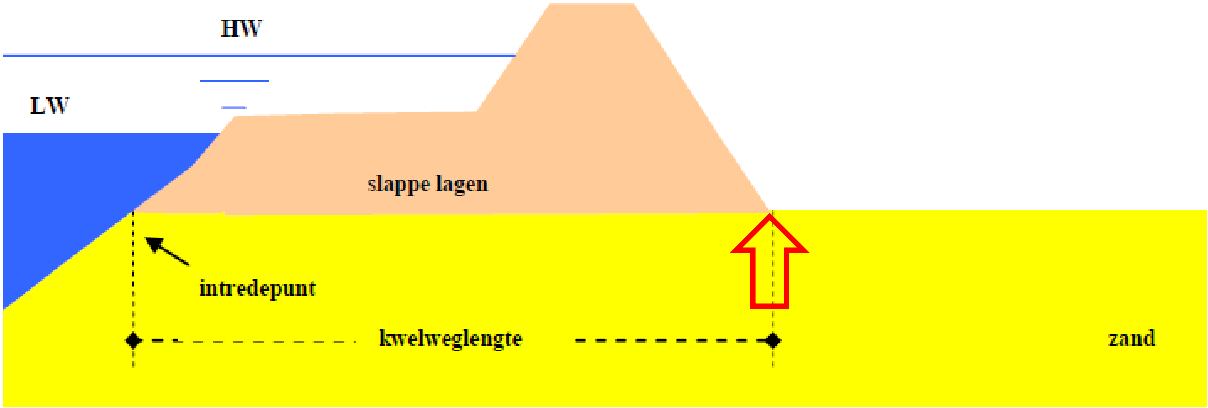


Figure 13 - No covering layer at inside, meaning that there is also no bursting (Deltares, 2012)

On the other hand when there is a covering layer, the place where bursting takes place is not certain. Depending on the geometrical characteristics of the situation this might either be in the ditch as indicated in Figure 14 or perhaps at the dike toe, as shown in Figure 13. This makes it harder to indicate where the pipe will burst though the covering layer.

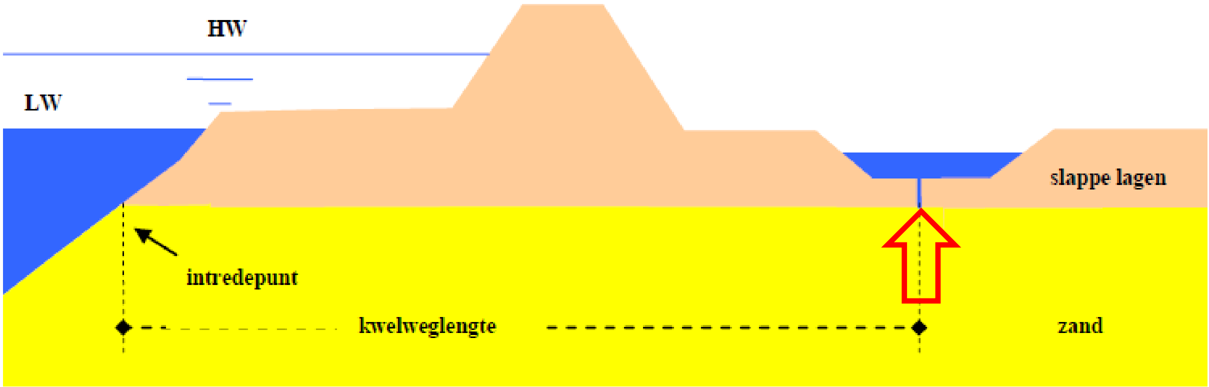


Figure 14 - Covering layer on inside, resulting in burst (under ditch) (Deltares, 2012)

The choice of the entry point depends on the presence of foreland on the riverside of the barrier, and on the presence of ditches, holes or other objects that might interfere with the water-repellent function of the foreland. In a situation where a dike has a foreland it can only be included in the assessment when it is proven that the foreland is impermeable, and does not feed the underneath laying pipe with more water. Sellmeijer is namely only validated for an impermeable covering layer and dike, and when the pipe is fed water from a point that lies closer to the dike than the entry point does, the results will become to optimistic, because the seepage path length is actually shorter.

Examples of situations in which a pipe could start in the foreland are the presence of ditches, trees with roots, deep holes, or other objects that might penetrate the covering layer. Figure 15 is an example of a foreland with a ditch in it. In this scenario it would be safe to set the entry point at the ditch, assuming that piping will not start even closer to the dike somewhere under the covering layer of the foreland.

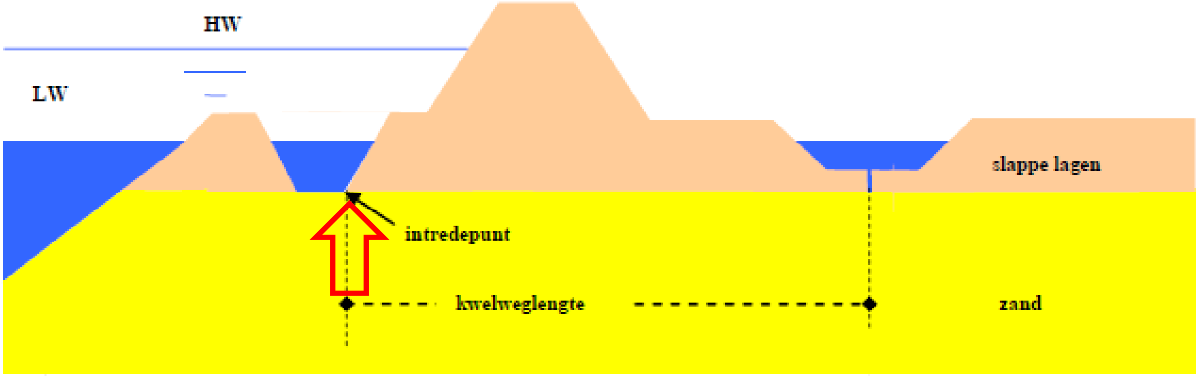


Figure 15 - Potential seepage path length with a ditch in the foreland (Deltares, 2012)

For sheardikes or dikes without a foreland, the location where the outer embankment line and the aquifer sand layer incise with the river is chosen as entry point.

2.5 D-Geo Flow

D-Geo Flow has been developed to assess complex calculations on dike safety, specifically on the failure mechanism of piping. The software includes a Finite Element piping analysis, based on the Sellmeijer model, to assess whether piping can occur given a specific water level progression (D-Geo Flow | Deltares, n.d.). In the software Sellmeijer's numerical calculation model (i.e. without the simplifications) is linked to a groundwater flow model by Darcy. So, using D-Geo Flow, it is possible to execute numerical calculations with help of the underlying calculation model. More elaboration on the underlying models is given in section 3 Technical details.

Furthermore, D-Geo Flow contains the following features: calculation of 2D groundwater flow, the (modified) Sellmeijer rule for predicting the occurrence of piping, ability to set up complex, multi-layered soil schematizations and graphical and numerical presentation of groundwater calculation results and pipe development. Most importantly, in D-Geo Flow the simplifications that are used in Sellmeijer are no longer needed, meaning that D-Geo Flow is more broadly applicable. Figure 16 shows a snapshot of the tutorial of D-Geo Flow, including the critical water head and the pipe from the Results tab.

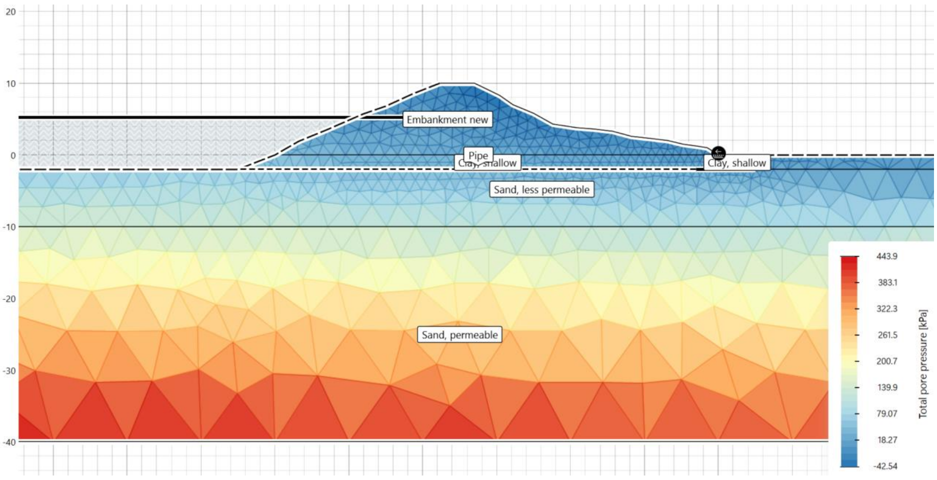


Figure 16 – Snapshot of the D-Geo Flow tutorial

However, at this point D-Geo Flow is not calibrated extensively enough for the specific application of determining flood probabilities, which is why there is much uncertainty around the input data and boundary conditions at Witteveen+Bos. Therefore, it cannot yet be used for calculating flood probabilities. In the BOI2023 D-Geo Flow is not presented as a "replacement" for the analytical calculation rule, but only meant to calculate piping lengths (Handleiding Overstromingskansanalyse dijken/dammen deel 2: piping, 2023).

2.5.1 Geohydrological boundary conditions in D-Geo Flow

As input D-Geo Flow needs a 2D schematization of the cross section of a dike. After schematizing the desired geometrical shape for the dike, the next step is to indicate the soil characteristics for all the different layers. In Figure 17 the tutorial model from Deltares is depicted with the different soil layers clearly visible.

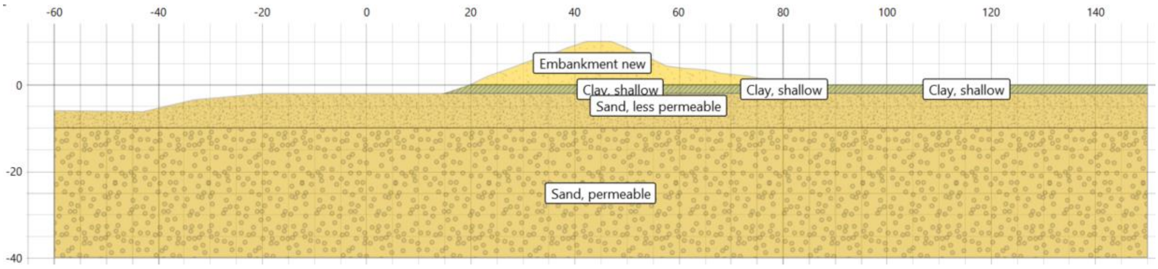


Figure 17 - Example schematization of the different soil layers in the tutorial provided by Deltares

At this point the geometrical shape represents a closed ‘body’ without in- or outflux of water. The next step is to set the water boundaries through which (ground)water can enter and exit the system. It is important to notice that the boundaries between layers inside the system are already open (Deltares, 2023). For this research the following water boundaries, as can be seen in Figure 18 will be created when applicable for that specific schematization, namely the river head, surface head, aquifer head and the heave potential.

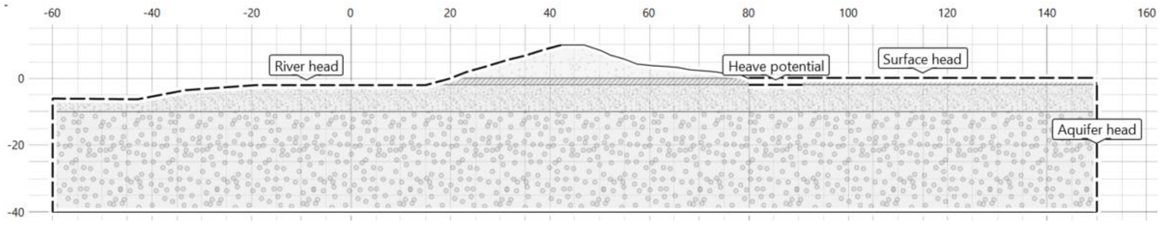


Figure 18 - Water boundary conditions in D-Geo Flow

The river head is the boundary condition on the riverside of the dike starting at the crest of the dike and ending at the end of the schematization. This could either be vertically or horizontally. The river head boundary can be schematized over the entire foreland, if present, or only over the embankment or even over the riverbed. After a choice has been made for the schematization of this boundary, a head needs to be appointed on which the pipe length calculation will be based. Next to that, the critical head calculation is based on the river head, namely by appointing the river head as critical in D-Geo Flow, and subsequently defining a search area between a minimum and maximum head level and a step size along which D-Geo Flow will calculate the pipe for every step until the critical head is found along the river head. It is important to notice that the output for the critical head in D-Geo Flow can be higher than the actual levee. The reason for this is that D-Geo Flow does not take the geometrical shape of the levee into account for its piping assessment.

The next boundary condition is the surface head. The surface head is schematized from the landside dike toe until a point in the hinterland. In this research the surface head will only be schematized directly above the heave boundary, however it also possible to schematize it until the end of the hinterland. This does not change the outcome of the model significantly. The head level that needs to be appointed to the surface head is the z-level of the surface. Here it is assumed that a fully saturated ground is present before piping occurs.

The aquifer head is a vertical boundary condition in the hinterland. By schematizing the aquifer head in the hinterland, the hinterland is in fact opened. In other words, when an aquifer head is present a certain amount of the ground water will not resurface through the heave, but in fact flow land inwards through the aquifer. In this research the head level is set at the z-level of the bottom of the covering layer. It is also possible to not include the aquifer head level, resulting in a closed system. More on this will be explained in section 4 the methodology.

The fourth and last boundary condition that is used in this research is the heave potential. The heave potential is in fact the bottom of the heave, or burst channel, through which the groundwater must travel before entering the burst channel. In the schematization it is drawn between the covering layer and the aquifer, starting at the die toe, or another location where heave is expected, like a ditch. The effect of the heave potential on the system will be investigated in this research by changing the width of the heave potential, or in other words the heave boundary. The corresponding head level for the heave potential is calculated according to the 0.3d-rule (Deltares, 2019). The equation for this rule is stated as follows:

Equation 1 - 0,3d-rule

$$Hh = Hs + 0{,}3 * d$$

In which Hh is the heave potential, Hs the surface head, and d the thickness of the covering layer in meters.

2.6 Boundary conditions

As explained before in the section 2.5.1 Geohydrological boundary conditions in D-Geo Flow, it is important to define the correct boundary conditions in D-Geo Flow to ensure that it describes the outside situation properly and behaves accordingly. In this section it will be elaborated in more detail what the different boundary conditions are and what impact they have on the model's outcomes.

For starters, the most important boundary conditions concerning piping according to (Rijkswaterstaat, 2023) are:

1. The head level difference between the outside and inside of the dike (head gradient across the dike).
2. The soil composition of the fore- and hinterland and underneath the embankment (the covering layer and the erosion-prone layer).
3. The geohydrological boundary conditions that determine the seepage path length (depending on the entry and exit point in respectively the fore- and hinterland).

In the following sub-sections these three main boundary conditions will be elaborated upon, after which in more detail a elaboration on the geohydrological boundary conditions will follow.

2.6.1 Head level difference

The head level difference ΔH is the difference between the riverside water level (high-water level for rivers (WBN)), and the landside water level of the flood defence at the exit point if a free water surface is present. If there is no free water surface at the exit point or the burst location, the surface level can be used for calculation, taking into account any ground level subsidence. However, this is only the case during high water levels, when the hinterland is completely saturated. Otherwise, in 'normal' conditions, the water level might be below the ground level. The expected sea level rise and land subsidence to be taken into account depend on the plan period used for design or on the legal period of 6 years between two safety tests. The values to be used for sea level rise can be found in the HR-database, however all data for water levels will be provided by Witteveen+Bos. In Figure 19 the head level difference between the river- and landside of a dike is depicted. The dark blue line represents the initial head before the forming of the pipe. The light blue line shows the local head, affected by the pipe-forming. Channel growth is readily observable in changes in head, however, in practice there is no real-time data on the water head in the dike. A decrease in head indicates channel formation. When backward erosion occurs, the head at the upstream side of a piping channel is higher than in the situation without a channel and at the location of the channel front the head is lower. The channel has a greater permeability than the sand and so this will pull the water towards it. This gives a somewhat higher total flow. On the upstream side of that channel, the sand layer is still undisturbed, but that is where the higher flow rate has to pass through and so there is a higher head there as well (Deltares, 2012). For piping to occur the head difference must be big for a longer period of time (Rijkswaterstaat, 2023).

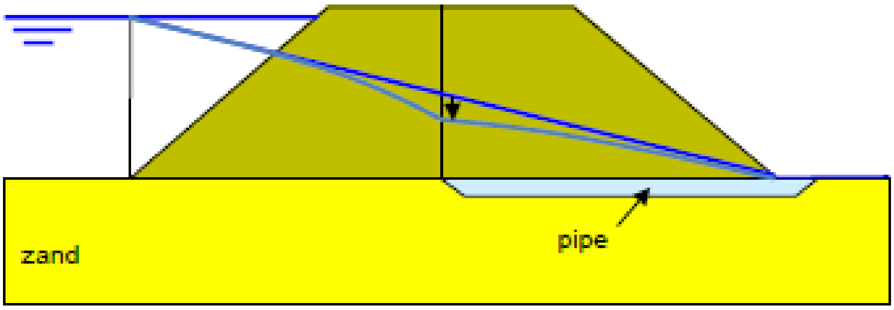


Figure 19 - The head level difference shown through a dike with the blue line being the initial hydraulic pressure

For this research two different sorts of calculations will be performed in D-Geo Flow, namely:

1) Calculating the pipe length based on a given head level (WBN) for a schematization.
2) Calculating the critical head and its corresponding critical pipe length for a schematization. This calculation is preformed through iteration by giving a search area for minimum/ maximum head level, and searching via a specified step size for the pipe to become progressive.

2.6.2 Soil composition

As already mentioned in section 2.5.1 Geohydrological boundary conditions in D-Geo Flow, the soil characteristics of the different layers is very important for pipe assessment using D-Geo Flow. Depending on the calculation model used for piping control, the required information on the material composition and configuration of the sand layer is more or less extensive. In D-Geo Flow it is possible to set values for:

- the permeability of the aquifer and other layers;
- the 70-percentile value of the grain distribution (d70);
- the thickness of the aquifer and its course under and next to the barrier.

In addition, this calculation method requires specific parameter indications, namely the drag force factor and the rolling resistance angle. These parameters cannot be determined via simple experiments. In the calculation model, nominally prescribed values are used for these, which were determined partly on the basis of laboratory tests carried out to verify the calculation model (Deltares, 2012). Default values have been determined for this in the WBI/BOI. For this research the exact soil composition is assumed as given. Only the thickness of the aquifer will be altered to check the results.

2.6.3 Geohydrological boundary conditions

The third important boundary condition is the effect of the schematization of the geohydrological boundary conditions on the piping failure mechanism. As explained in section 2.5.1 Geohydrological boundary conditions in D-Geo Flow, D-Geo Flow's user interface gives the user a lot of freedom regarding the choice on exactly what to schematize and what not. In this paragraph there will be elaborated upon what choices on schematization of boundary conditions can be done, and how this will be done generally. In section 4.1 the methodology will follow-up on this section by going into detail in how this will be implemented in D-Geo Flow step-by-step.

In this section the following three geohydrological boundary conditions will be elaborated upon, namely the schematization of the heave boundary, the hinterland and the foreland. Furthermore, the role of the vertical aquifer head and the thickness of the aquifer will be elaborated upon, and how they might influence each other.

Thickness of the aquifer

The thickness of the aquifer depends on the soil characteristics of the location or cross-section. How the aquifer is exactly schematized has a great influence on the critical head. That is also the reason that between different calculations the thickness of the aquifer will remain consistent, in order for the results to remain viable. I.e. not introducing another uncertainty by changing the thickness of the aquifer, whilst the schematization of other geohydrological boundary conditions has also been varied.

The effect of the vertical aquifer head

As explained in section 2.5.1 the aquifer head is a vertical boundary condition that is drawn at the end of the hinterland schematization. Its function is to create a scenario where not all water in the pipe flows out at the heave, but some flows through to the hinterland, as described by Darcy's formula in section 3.2. Its head is determined as an equilibrium where the covering layer in the hinterland does not break due to uplift from the groundwater. Schematizing the aquifer head in the calculations does have a significant impact on the critical pipe, thus it will be accounted for in this research. This will be done by making all calculation with both an open and a closed hinterland.

Heave boundary

The first main geohydrological boundary condition that will be assessed is the heave boundary. The heave boundary is in fact a value for the width that is linked to the location of the bottom of the heave channel. In Figure 20 the heave boundary is shown as a horizontal line on the bottom of the covering layer. The heave channel is the channel through which the pipe bursts (heave), possibly resulting in water and sand boil on the ground surface. The vertical length of the channel is equal to the thickness of the covering layer. As a standard it is taken that this heave/burst channel has a width of two times the thickness of the covering layer.

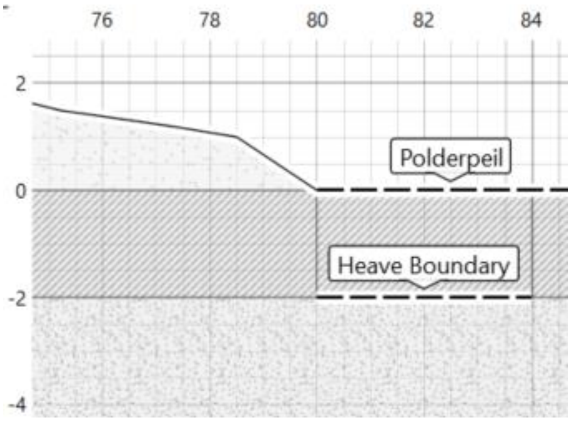


Figure 20 - Heave boundary (also heave potential) drawn in D-Geo Flow, in this case for 4 meters.

Schematization of the hinterland

The second main geohydrological boundary condition that will be assessed is the schematization of the hinterland. How far should the hinterland be schematized, and what is the effect of this on the critical head and pipe. Of course, the most realistic schematization would be to schematize as much of the hinterland as possible, because the model becomes a better reflection of the real world. In this research the effect of the hinterland will be compared for both an open and a closed hinterland.

Schematization of the foreland

The third and last main geohydrological boundary condition that will be assessed is the schematization of the foreland. As explained earlier in section 2.4, is important to incorporate the foreland because it might influence the results on critical head and pipe calculations significantly. A longer foreland will namely result in a longer seepage path length. Especially interesting to do research on is the effect of schematizing the river in D-Geo Flow, creating a horizontal boundary between the water and the aquifer. Figure 21 shows the schematization of the Zwolle Olst segment with the river head boundary schematized along the river bottom.

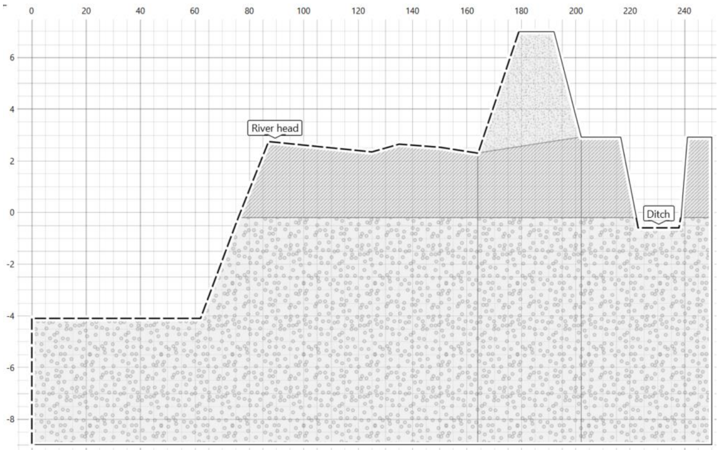


Figure 21 - Zwolle Olst schematization with horizontal boundary condition in the river

3 TECHNICAL DETAILS

This chapter provides some technical details on initiation/progression dominated critical head and Sellmeijer and Darcy. It is separated from section 2, the background, because many conclusions from the results will be referenced to this section.

3.1 Initiation and progression dominated critical head

For the piping process it is important to know the theoretical background of the process, and how it is influenced by the environment around the pipe. An important factor in describing the behaviour of the pipe growth is the geometrical form of the exit point. The exit point determines the formation of the critical head and pipe, and what the influence of a change in head difference is on the system (Pol, Time-dependent development of Backward Erosion Piping, 2022). In general there are two possible processes that determine the type critical head and pipe. The critical head and pipe can namely be initiation or progression dominated.

Piping initiation is marked by the change from an intact sand bed to a small pipe (Pol, Time-dependent development of Backward Erosion Piping, 2022). This process is initiated when the covering layer has already burst due to high pressure differences, and the gradient near the exit point exceeds a critical gradient (head difference), resulting in sand transporting out of the sand layer. This initiation can lead to an ongoing erosion process, where the flow in and towards the pipe increases with increasing pipe length (Pol, Time-dependent development of Backward Erosion Piping, 2022).

On the other hand, piping progression is marked by erosion processes that reach an equilibrium at a certain pipe length, and further pipe lengthening only occurs after more head increase (Pol, Time-dependent development of Backward Erosion Piping, 2022).

In other words, the difference between initiation and progression dominated critical heads is that an initiation dominated process occurs directly when the critical gradient at the exit point is exceeded, and a lowered equilibrium head will still result in pipe growth, whereas in a progression dominated erosion process the pipe has already formed at an equilibrium head, and growth of the pipe can only occur when the gradient increases until the critical head is reached, after which a lowering of the gradient will still result in a pipe growth.

In Figure 22 the initiation dominated and progression dominated equilibrium curves are shown, with the pipe length (l) on the x-axis, and the equilibrium head (H_{eq}) on the y-axis. Th critical head (H_c)is the maximum equilibrium head for either curves, and (L_c) is the corresponding critical pipe length. In case of the initiation dominated curve, the critical head is found at lc is zero, or in other words directly at the point the pipe starts forming. As can be seen when following the blue line, a decrease in head difference (the equilibrium head) still results in the growth of the pipe. In case of the progression dominated curve, the critical head is only reached after a certain increase in the equilibrium head, resulting in a growth of the pipe as well. The length of the pipe when the critical head is reached is the critical pipe length. After this point, a decrease in the equilibrium head (thus a lower head level difference) will still result in a longer pipe. Therefore, when the critical pipe is reached, the pipe will continue growing, even if the equilibrium head decreases. In the graph this is shown with the dotted line, separating the regressive and the progressive phase.

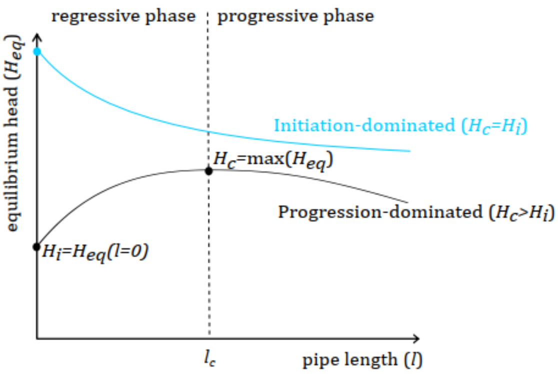


Figure 22 - Initiation dominated and progression dominated equilibrium curves; equilibrium head Heq as function of pipe length l (Pol, Time-dependent development of Backward Erosion Piping, 2022)

To determine what cases are initiation dominated, and what cases are progression dominated, one must observe the type of exit point. In general, smaller exit points like holes in the covering layer are progression dominated, because the flow in the small hole is initially strongly concentrated, which relatively quickly leads to the initiation of the pipe. However, when the pipe grows, the concentration decreases, which means that the head difference must increase in order to maintain the same amount of concentration, and thus pipe growth, otherwise the pipe will stop growing. After a certain critical head is reached, the pipe will have a critical length as well, and will continue growing, even when the head difference drops. On the other hand, bigger exit points, like ditches, slopes, or planes are generally initiation dominated, because the flow is initially spread over a larger area, thus resulting in a lower initial concentration. This low concentration means that there is no initial pipe growth, and only after a big enough head difference has been reached, the concentration will have increased enough to start forming a pipe from the exit point. In this case the growth of the pipe will result in even higher concentrations around the pipe, thus assuring the growth of the pipe even with a lowered head difference. This means that the critical head is reached at the moment the pipe's formation is initiated, thus the critical pipe length is zero. All the information that is given in the text above is summarized in the two separate tables below.

Table 3.1 shows the process of both the process types.

Table 3.1 - The process for the progression and initiation dominated critical heads.

Process type	**General size of exit point compared with the other.**	**Initial concentration compared with the other**	**Pipe initiation starts at a lower or higher head difference**	**Change in concentration due to pipe growth**
Progression dominated	Smaller	Higher	Lower	Decrease
Initiation dominated	Bigger	Lower	Higher	Increase

And Table 3.2 summarizes the location of the critical head and the critical pipe, as shown in Figure 22.

Table 3.2 - Location of the critical head and pipe compared with the initiation.

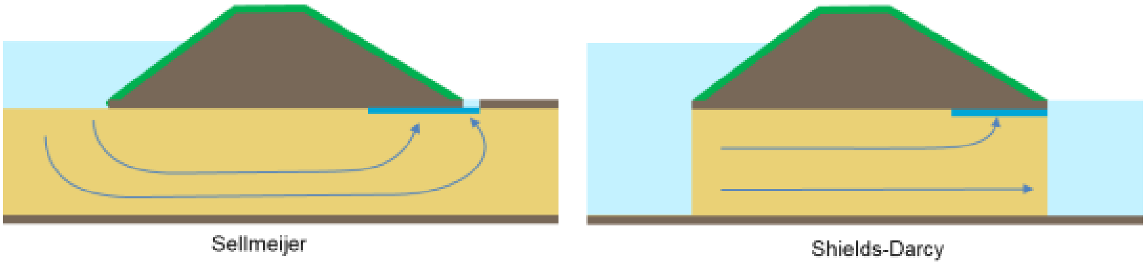
Process type	**Critical head against initial head**	**Pipe length at critical head**
Progression dominated	Only after enough increase in equilibrium head after the pipe initiation, the critical head is reached (Hc>Hi)	Only after growth of the pipe, thus Lc>0
Initiation dominated	At the initiation of the pipe growth (the initial head) the critical head is directly reached (Hc=Hi)	It is directly reached, thus Lc=0

3.2 Sellmeijer and Shields-Darcy

As already explained in section 2.5 D-Geo Flow is a combination of the calculation rule of Sellmeijer and a groundwater stream model. D-Geo Flow can be used to calculate the pipe length for a given river head, or to calculate the critical head and pipe length for a given schematization. Next to D-Geo Flow there are also two other methods to calculate this, namely the Sellmeijer calculation rule itself, and the Shields-Darcy model.

As already explained in section 2.3 the Sellmeijer calculation rule assumes one entry and exit point for the pipe, meaning that in between those two points no water enters or leaves the pipe (Hans Sellmeijer, 2011). Shields-Darcy is in principle the same, and it can also calculate the pipe length, however the groundwater stream model differs from Sellmeijer (Pol, 2020)

The difference between these two methods is that Sellmeijer assumes that all the water leave the system via the heave, whereas Shields-Darcy has the possibility for groundwater to leave the system through the hinterland (Pol, 2020). In Figure 23 two schematizations for both methods are shown, visualizing the water stream in their respective piping calculation methods.



Sellmeijer

Shields-Darcy

Figure 23 - Schematization of the groundwater stream of the Sellmeijer and Shields-Darcy model.

In D-Geo Flow it is possible to choose whether a water boundary is set in the hinterland. This water boundary, called the aquifer head in this research, can be schematized ate the end of the hinterland with a fixed head. Schematizing the aquifer head let the model behave according to the Shields-Darcy method, because the aquifer head pulls water into the hinterland. On the contrary, the absence of a aquifer head makes the model behave more like the Sellmeijer calculation rule, because all the water must leave the system via the heave. Which method is correct and whether the aquifer head should be schematized or not depends on the geometrical characteristics of the location, however in all cases the Shields-Darcy method results in higher critical heads (meaning a safer dike), because not all water leaves the system via the heave, but some is pulled into the hinterland, which is possibly more realistic (Pol, 2020).

4 SET-UP OF THE ANALYSIS

This section describes the set-up of the research. First a comprehensive methodology will elaborate on a step-by-step level what choices were made in the research and why they were made. Thereafter follows a subsection in which the choices on global input variables and settings is explained. The combination of the methodology and the subsection on input variables should provide enough information for anyone to conduct the same research.

4.1 Methodology

In order to answer the research question, and its sub-questions this methodology has been developed that elaborates on the approach that should be taken to answer the questions. The goal of this methodology is to provide a clear overview of what steps are to be taken to help answering the main research question. The main research question is stated as follows:

"What are safe values for boundary conditions in D-Geo Flow to produce realistic results regarding piping, and when are these values legitimate?"

More elaboration on the main research question and the sub-questions is to be found in section 1.4 Research questions.

4.1.1 Schematisation of the dike cross sections in Excel

The first step in this process was to acquire two data sets on the elevation levels of the two dike cross sections of the Grebbedijk and the Zwolle Olst dike. Together with the elevation data Witteveen+Bos also provided data on the soil composition. The next step was to combine all the data to make two schematizations for the Grebbedijk and the Zwolle Olst dike. Both geometries consist of a non-permeable embankment upon a non-permeable covering layer upon a permeable sand layer. The difference between the two cross sections lies in the location of ditches, and their geometry. More information on the schematisation is to be found in section 2.1 Case studies. In the next section first the Grebbedijk, and thereafter the Zwolle Olst dike will be shown.

Grebbedijk

In Figure 24 the profile schematization of the Grebbedijk can be seen. The Grebbedijk has a long foreland (i.e. 270.00 meters) with a small ditch (i.e. 4.00 meters in width) halfway in between the levee and the river. The ditch lies upon the aquifer. The levee has a base width of 34.00 meter on top of the covering layer. Directly behind the levee is a small stripe of hinterland with a width of 7.00 meter, after which a ditch that lies perpendicular to the levee is located. The ditch lies 0.90 meters lower than the hinterland, and is filled with water.

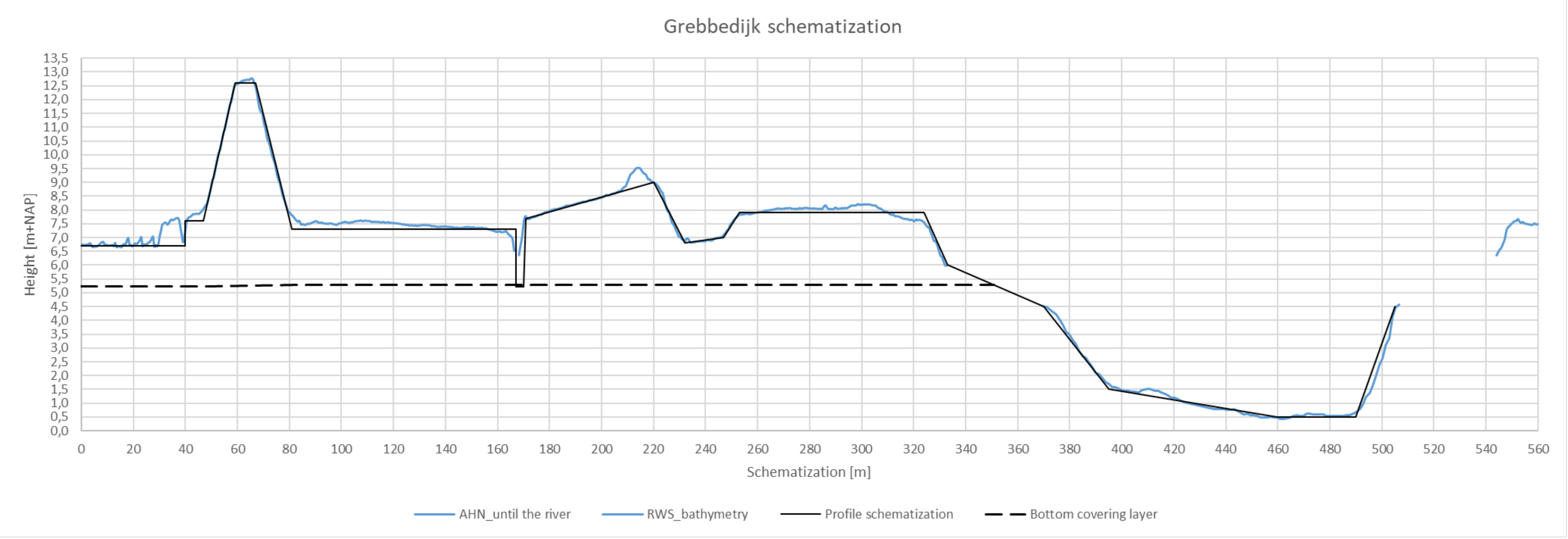


Figure 24 - The Excel schematization of the Grebbedijk, including the AHN, the Bathymetry, the covering layer and the profile schematization.

Zwolle Olst dike

In Figure 25 the profile schematization of the Zwolle Olst dike can be seen. The Zwolle Olst dike has a smaller foreland of 91.15 meter, without a ditch in the foreland. The levee has a base width of 38 meter on top of the covering layer. Directly behind the levee lies the hinterland for another 14.00 meter where a ditch with a width of 24.50 meter is located. The bottom of the ditch lies 3.52 meter under the surface, in the aquifer. After the ditch the hinterland continues on the same height as before the ditch.

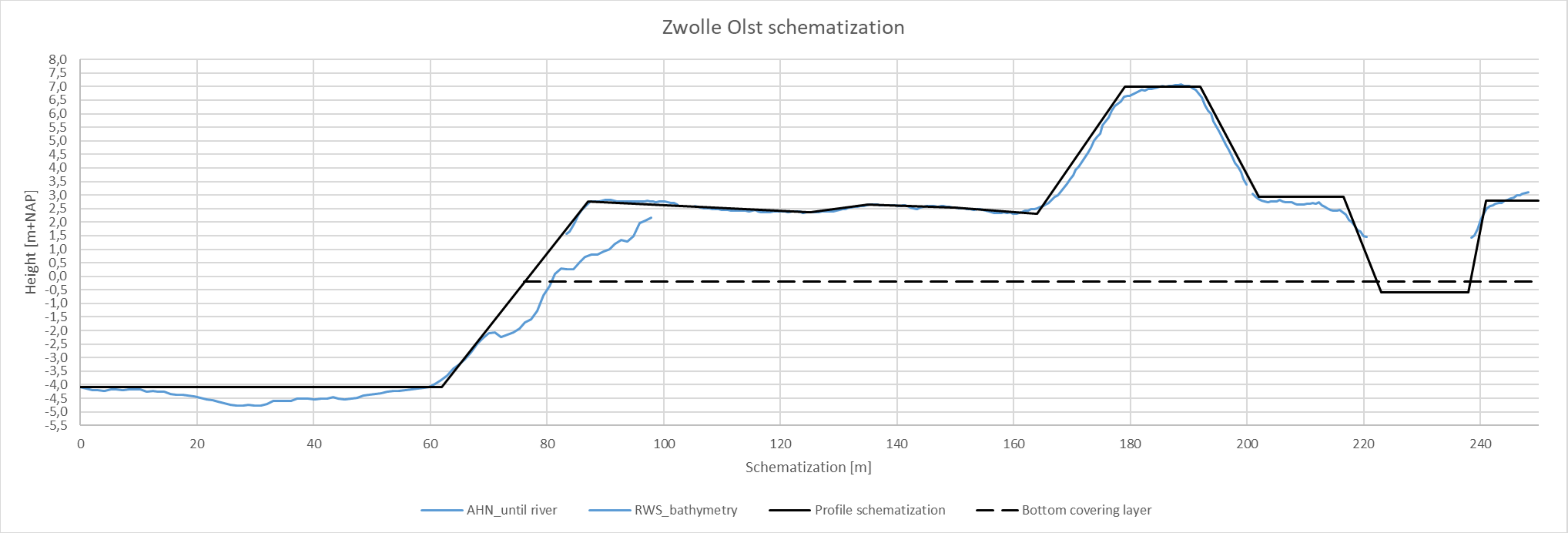


Figure 25 - The Excel schematization of the Zwolle Olst dike, including the AHN, the Bathymetry, the covering layer and the profile schematization.

4.1.2 Modelling of the schematisation in D-Geo Flow

After completing the basic schematization of the dikes in Excel, they have to be schematized in D-Geo Flow. Because the user interface of D-Geo Flow is very intuitive, this is not a difficult step in the whole progress, however it consumes a lot of time, which will be further discussed upon in section 6 Discussion. To summarize it in a few steps, the schematization is done as follows:

1. The geometry is copied by hand in D-Geo Flow using the Draw function. Using the Point function can help in setting the edges of layers on the exact location i.e., in centimetres or millimetres precise.
2. Thereafter all different layers are assigned material properties, like clay or sand. From the provided soil data it is possible to assign specific permeabilities to different layers.
3. The third step is to assign the water boundaries. As already explained in section 2.5.1 Geohydrological boundary conditions in D-Geo Flow, there are several options to choose from. For both dike cross sections the following water boundaries were set:

Grebbedijk

The Grebbedijk was assigned a river head from the crest of the levee, over the foreland, until the riverbed. The surface head was set on the bottom of the ditch in the hinterland and the heave potential on the bottom of the covering layer, directly under the surface head. The width of the heave potential (the heave boundary) will be researched in section 4.1.4 of the methodology. Lastly, the aquifer head is a vertical boundary condition at the end of the hinterland, schematized on the aquifer only. The schematization of the open hinterland can be seen in Figure 26.

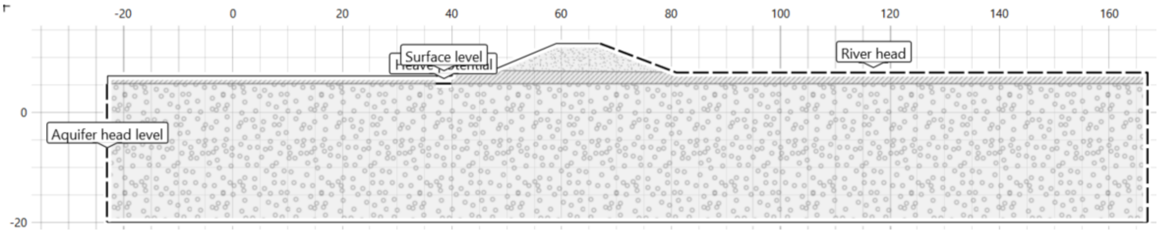


Figure 26 - Schematization of the Grebbedijk with an open hinterland

The schematization of the Grebbedijk with a closed hinterland can be seen in Figure 27. The difference with the open hinterland schematization is that here no aquifer head is schematized.

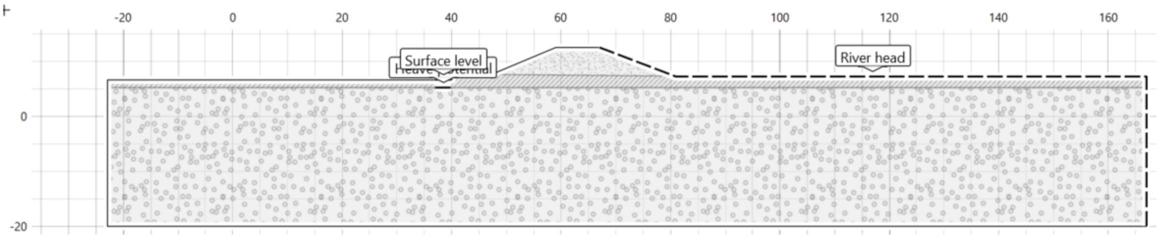


Figure 27 - Schematization of the Grebbedijk with a closed hinterland

In Figure 28 the zoom-in of the heave potential and surface level is provided, because in the previous figures it is not clear.

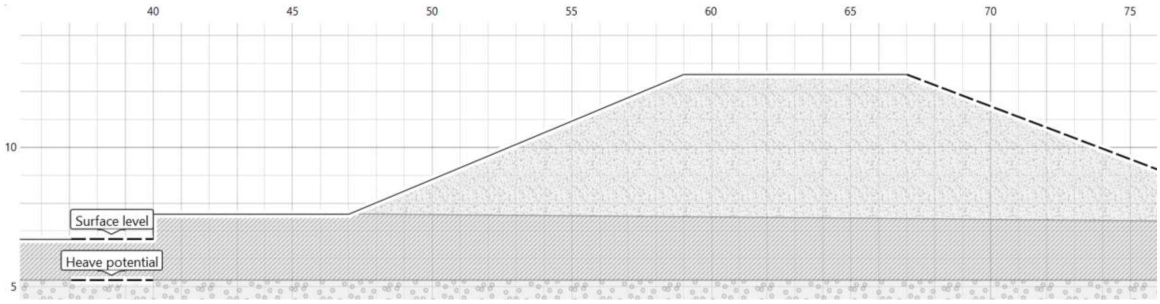


Figure 28 - Zoom-in of the heave potential and surface level

Zwolle Olst dike

The Zwolle Olst dike was assigned a river head from the crest of the levee, over the foreland, until the riverbed. The surface head was set on the bottom of the ditch. Because the bottom of the ditch directly touched the aquifer, no heave could occur, thus no heave potential was schematized. In D-Geo Flow the surface head is called ditch. Lastly, the aquifer head is a vertical boundary condition at the end of the hinterland, schematized on the aquifer only. The schematization of the open hinterland is provided in Figure 29.

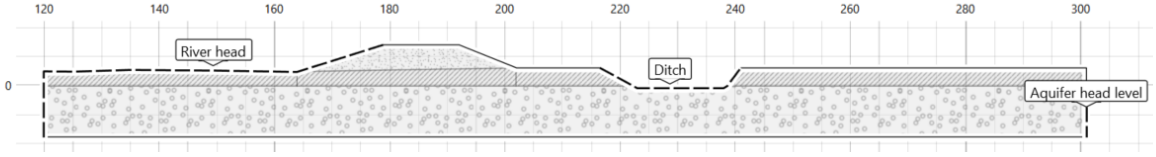


Figure 29 - Schematization of the Zwolle Olst dike with an open hinterland

The schematization of the Zwolle Olst dike with a closed hinterland can be seen in Figure 30. The difference with the open hinterland schematization is that here no aquifer head is schematized.

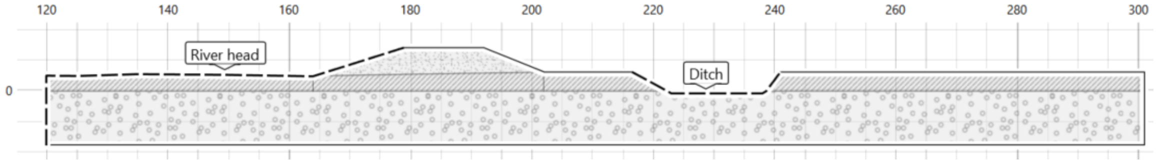


Figure 30 - Schematization of the Zwolle Olst dike with a closed hinterland

Using these schematizations the effect of the geohydrological boundary conditions can be researched. The structure in the next part of this methodology will follow the sub-questions step-by-step.

Sub-question 1 is stated as follows:

'What boundary conditions in D-Geo Flow are important to consider in this research?'

In section 2.6 Boundary conditions the main boundary conditions concerning piping are listed as follows:

1. The head level difference between the outside and inside of the dike (head gradient across the dike).
2. The soil composition of the fore- and hinterland and underneath the embankment (the covering layer and the erosion-prone layer).
3. The geohydrological boundary conditions that determine the seepage path length (depending on the entry and exit point in respectively the fore- and hinterland).

These three boundary conditions are most important for the failure mechanism of piping. As explained earlier boundary condition 1. 'the head level difference' is the first and most important boundary condition. A longer period of high water levels, resulting in a high water head gradient across the levee is essential for piping to occur. In this research the water levels are assumed to be given, following from historical data. Via D-Geo Flow it is possible to calculate the critical head level difference for different geohydrological boundary conditions.

The second boundary condition is the soil composition underneath the embankment. This boundary condition influences the formation of the pipe and thus the dike's stability, however it cannot be altered, so it is assumed as a given value in this research. For completeness sake, the conclusions will be tested on different thicknesses for the aquifer sand layer.

The third main boundary condition is the schematization of the geohydrological boundary conditions. How the dike cross section, along with the water boundaries is schematized in D-Geo Flow greatly influences the results of the critical head and pipe. In order to examine this, three geohydrological boundary conditions are specified in section 2.6.3 Geohydrological boundary conditions, namely:

1. the heave boundary;
2. the schematization of the hinterland and
3. the schematization of the foreland and a horizontal river head.

Next to these three boundary conditions, the effect of a open or closed hinterland will be investigated for all three the boundary conditions. The thickness of the aquifer has a great influence on the results as well, and therefore it will remain constant during the examination of above mentioned boundary condition. Afterwards, the conclusions will be checked on their robustness by changing the thickness of the aquifer.

Before any calculations can be done, first the input variables have to be determined in order to ascertain that all calculation use the same input variables, or at least have clear what is changed as a variable.

4.1.3 Global input variables and settings

As already explained before in section 2.5 D-Geo Flow the mesh size of the layers, the element sizes around the (critical) pipe and lastly the step size for the critical head affect the results from D-Geo Flow, and moreover influence the duration the model needs to run calculations. During the calculations a lot of different choices on these input variables and settings were made. In order to keep a clear overview of what choices were made and what reasoning was used for these choices, a table is provided for each schematization (Tutorial, Grebbedijk and Zwolle Olst dike). Next to that the choice on head level in the water boundaries is provided, together with some reasoning.

Tutorial

For the calculations on the heave boundary the tutorial schematization is used. In Table 4.1 the mesh sizes for the different layers can be found. Reasoning for the choice on input values is as follows: the mesh sizes were chosen based on the trade-off simulation duration against preciseness. Only the layers that directly touch the pipe trajectory should have sufficiently small mesh sizes, and therefore the Top hinterland, Revetment and the Coarse sand were assigned mesh sizes of 2.0, 4.0 and 10.0 meters respectively. The covering layer underneath the revetment, called the Top under, was assigned a mesh size of 1.0 meter in accordance with the pipe trajectory element size of 1.0 meter. The layer that consists of the burst channel is assigned a mesh size of 0.5 meter, because its area is small, thus it will not consume much simulation running time.

Table 4.1 - input mesh sizes Tutorial

Layer	Mesh size [m]
Levee	4,0
Top under	1,0
Top heave	0,5
Top hinterland	2,0
Fine sand	2,0

Layer	Mesh size [m]
Coarse sand	10,0

The next input values that have to be determined are the element sizes for the calculation of the pipe trajectory together with the corresponding erosion direction and particle size. Especially the element size heavily influences the duration time the model needs to run. After running it for both 0.5 and 1.0 meters it was decided that the element size should be 1.0 meter, because it reduces the duration by 50%, and moreover the calculated pipe trajectory only differed a maximum of 10 centimetres, which was determined to be sufficiently small. For the calculation of the critical head the same element size, erosion direction and particle size should be chosen, in order for the results to be comparable. Furthermore, the step size was set at 0.05 based on the standard value used in the D-Geo Flow tutorial. The low and high level for the head were set at 5 and 6 meters respectively, because it was known that the critical head would lie in between the two. Lower/higher values is also possible, however that would result in the same critical head and it would take longer to calculate. In Table 4.2 a clear overview of these choices is provided.

Table 4.2 - input (critical) pipe and head calculations Tutorial

Calculation	Element size [m]	Erosion direction	Particle size d70 [mm]	Step size[m]	Head level low [m+NAP]	Head level high [m+NAP]
Pipe length	1,0	Right to left	0,1	-	-	-
Critical head	1,0	Right to left	0,1	0,05	5,0 (and 2,0 for closed)	6,0

Finaly, the water boundary conditions were determined as follows: the riverhead was set at 5.0 meter +NAP for the open hinterland, and 2.0 meter +NAP for the closed hinterland. The reason for this difference is that with a river head of 5.0 meter +NAP the closed hinterland simulation would result in a progressive pipe for all schematizations of the heave boundary. The surface head was set at 0 +NAP meter, and the heave potential is determined according to the 0.3d-rule which is explained in section 2.5.1 which lead to a head of 0.6 meter. The aquifer head was set at the z-level of the bottom of the covering layer, in accordance with the D-Geo Flow manual (Deltares, 2023), thus -2.0 meter.

Table 4.3 - input head levels in water boundaries Tutorial

Water boundary	Head level [m+NAP]
River head	5,0 (or 2,0 for the closed hinterland)
Heave potential	0,6
Surface head	0,0
Aquifer head (only for open hinterland)	-2,0

Grebbedijk

The schematization of the Grebbedijk will be used for both the hinterland and foreland calculations. This paragraph will elaborate on the choices that were made for the different input variables, namely the mesh sizes, the critical pipe and head variables and the water boundary head levels.

As shown in section 4.1.2 the Grebbedijk consists of a levee, covering layer (including hinterland until ditch), top foreland (after the ditch) and the aquifer. In Table 4.4 the chosen mesh sizes can be found. The different sizes are based on the size of the layer, and whether it directly touches the pipe. Larger layers have a smaller size, and layers directly touching the pipe have a smaller size, except for the aquifer. These sizes for the meshes are the same for both the hinterland and foreland calculations, except that the hinterland calculations makes no use of the Top foreland layer.

Table 4.4 - input mesh sizes Grebbedijk

Layer	Mesh size [m]
Levee	4,0
Covering layer	1,0
Top foreland (only for foreland calculations)	4,0
Aquifer	10,0

Secondly, the input variables for the calculation of the critical head and pipe have to be determined. As explained earlier, especially the element size influences the simulation running time significantly. The reason for these specific variables is given in the section above, Tutorial. In Table 4.5 the input variables for the Grebbedijk are given.

Table 4.5 - input critical head and pipe calculations Grebbedijk

Calculation	Element size [m]	Erosion direction	Particle size d70 [mm]	Step size [m]	Head level low [m+NAP]	Head level high [m+NAP]
Grebbedijk	1,0	Left to right	0,1	0,05	8,0	20,0

And lastly the head levels in the water boundaries are set at the following values for both an open and closed hinterland and for both the hinterland and foreland calculations, as can be seen in Table 4.6.

Table 4.6 - input head level in water boundaries Grebbedijk

Water boundary	Head level [m+NAP]
River head	12,88
Heave potential	7,64
Surface head	7,2
Aquifer head (only for open hinterland)	5,23

Zwolle Olst dike

The schematization of the Zwolle Olst dike will, just like the Grebbedijk be used for both the hinterland and foreland calculations. This paragraph will elaborate on the choices that were made for the different input variables, namely the mesh sizes, the critical pipe and head variables and the water boundary head levels.

As shown in section 4.1.2 the Zwolle Olst dike consists of a levee, covering layer (including foreland, layer under levee, and the hinterland until the ditch), the hinterland (directly after the ditch) and the aquifer. In Table 4.7 the chosen mesh sizes can be found. The different sizes are based on the size of the layer, and whether it directly touches the pipe. Larger layers have a smaller size, and layers directly touching the pipe have a smaller size, except for the aquifer. These sizes for the meshes are the same for both the hinterland and foreland calculations, except that the hinterland calculations makes no use of the Top foreland layer.

Table 4.7 - input mesh sizes Zwolle Olst dike

Layer	Mesh size [m]
Levee	4,0
Covering layer	1,0
Hinterland	4,0
Aquifer	10,0

Just like for the Tutorial and Grebbedijk schematizations the input variables for the critical head and pipe calculation significantly influence the simulation running time for the Zwolle Olst dike. Reasoning for the specific variables is given in Tutorial. In Table 4.8 the specific variables for Zwolle Olst can be found.

Table 4.8 - input critical head and pipe calculations Zwolle Olst dike

Calculation	Element size [m]	Erosion direction	Particle size d70 [mm]	Step size	Head level low [m]	Head level high [m]
Zwolle Olst	1,0	Right to left	0,1	0,05	5,0	20,0

Lastly, the head levels in the water boundaries are set at the following values for both an open and closed hinterland and for both the hinterland and foreland calculations, as can be seen in Table 4.9.

Table 4.9 - input head levels in water boundaries Zwolle Olst dike

Water boundary	Head level [m]
River head	2,0
Ditch	2,92
Aquifer head (only for open hinterland)	-0,2

4.1.4 Heave boundary

Sub-question 2 is stated as follows:

What effect does the choice for heave boundary for both an open and closed hinterland have on the critical pipe and head in the piping failure mechanism, and when is this value legitimate?

To start-off with the first sub-boundary condition: the heave boundary. Before experimenting on the effect of the schematization of the hinterland and foreland can start first a safe value for the heave boundary must be found. As explained earlier, the heave boundary describes the horizontal bottom of the burst channel where a certain head level is connected to the horizontal heave boundary. Here the question arises how wide the heave boundary should be schematized, ranging from one grid cell or the entire burst zone width, e.g. two times the thickness of the covering layer, or even wider. In order to determine what value for the width should be chosen, it is first important to find the effect of the heave boundary on the piping failure mechanism. When the effect is known, conclusions can be stated on what safe choices for the heave boundary should be. In order to find the safest value for the heave boundary different widths, ranging from 0.5 to 8 meter will be modelled in D-Geo flow.

With all the input variables known the different schematisations in D-Geo Flow can be made. For the modelling of the heave boundary the Deltares schematization from the tutorial (Deltares, 2023) was chosen, because this schematization is definitely correct, and moreover fairly easily adaptable for different heave boundaries. The standard schematization used in the D-Geo Flow tutorial can be seen in Figure 31.

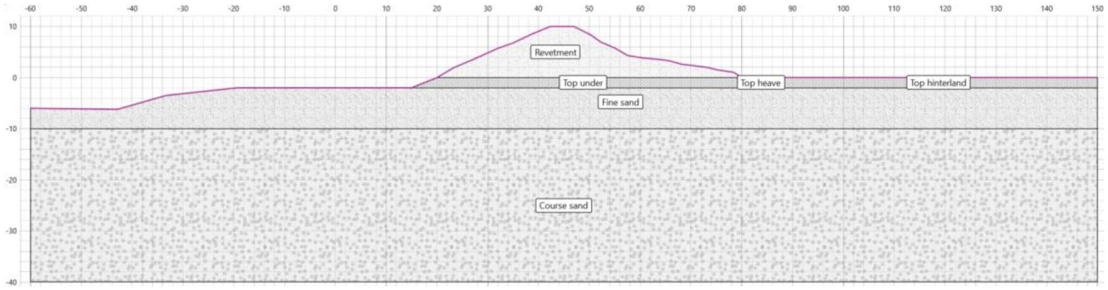


Figure 31 - D-Geo Flow tutorial dike schematization

The standard water boundaries in the tutorial were placed as follows: the river head is placed from the crest over the foreland, till the bottom of the aquifer, as can be seen in Figure 32. The surface head is schematized on top of the surface for the entire hinterland. The aquifer head is schematized as a vertical boundary on the aquifer.

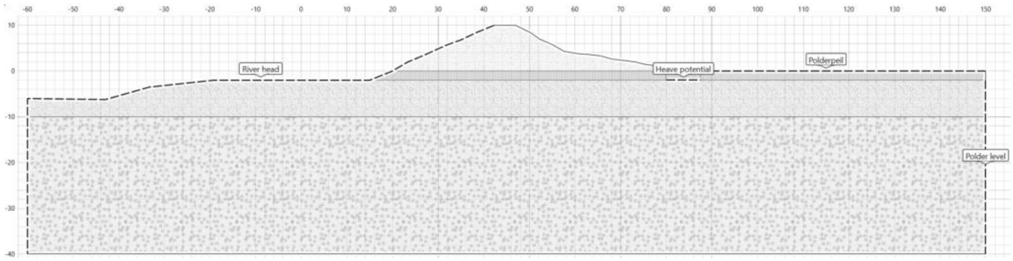


Figure 32 - Water boundaries in the tutorial

As said earlier, it was chosen to vary the heave boundary from 0.5 to 8.0 meters. To elaborate on this: as a standard 2 times the covering layer thickness is used for determining the heave boundary. In this schematization, that means 2 times 2.0 meters, thus 4.0 meters. To verify this rule of thumb the heave boundary was simulated in D-Geo Flow for four meters above and under it, to see if any unexpected trends would appear.

The same steps were followed for the Tutorial schematization without the aquifer head, thus creating a closed hinterland.

The complete list of all the performed calculations can be found in Table 4.10.

Table 4.10 - list of all performed calculations for the heave boundary

Schematization	Segment	Open or closed	Heave boundary [m]
1	Tutorial	Open	0,5
2	Tutorial	Open	1,0
3	Tutorial	Open	1,5
4	Tutorial	Open	2,0
5	Tutorial	Open	2,5
6	Tutorial	Open	3,0
7	Tutorial	Open	3,5
8	Tutorial	Open	4,0
9	Tutorial	Open	4,5
10	Tutorial	Open	5,0
11	Tutorial	Open	5,5
12	Tutorial	Open	6,0
13	Tutorial	Open	6,5
14	Tutorial	Open	7,0
15	Tutorial	Open	7,5
16	Tutorial	Open	8,0
17	Tutorial	Closed	0,5
18	Tutorial	Closed	1,0
19	Tutorial	Closed	1,5
20	Tutorial	Closed	2,0

Schematization	Segment	Open or closed	Heave boundary [m]
21	Tutorial	Closed	2,5
22	Tutorial	Closed	3,0
23	Tutorial	Closed	3,5
24	Tutorial	Closed	4,0
25	Tutorial	Closed	4,5
26	Tutorial	Closed	5,0
27	Tutorial	Closed	5,5
28	Tutorial	Closed	6,0
29	Tutorial	Closed	6,5
30	Tutorial	Closed	7,0
31	Tutorial	Closed	7,5
32	Tutorial	Closed	8,0
33	Tutorial	Closed	10,0
34	Tutorial	Closed	10,5
35	Tutorial	Closed	11,0

4.1.5 Hinterland

The third sub-question is stated as follows:

What effect does the schematization of the hinterland for both an open and closed hinterland have on the critical pipe and head in the piping failure mechanism, and when is this value legitimate?

The second geohydrological boundary condition that will be investigated is the effect of the schematization of the hinterland for both an open and closed hinterland. Using the predefined rule-of-thumb for the heave boundary, namely taking two times the covering layer as heave boundary width, the hinterland could now be investigated. This investigation was repeated for both the Grebbedijk and the Zwolle Olst dike. For both cross sections an open and closed hinterland was schematized, in order to compare the results. For the schematization of the hinterland it was chosen to schematize the hinterland further from the heave boundary in steps of 20 meters, ranging from 0 to 120 meter, and an extra schematization at 10 meter to investigate start-up errors in the model. All the input variables can be found in section 4.1.3. This approach was repeated for a closed hinterland without the aquifer head. In order to visualize this better the schematizations of the hinterland are shown in Figure 33.

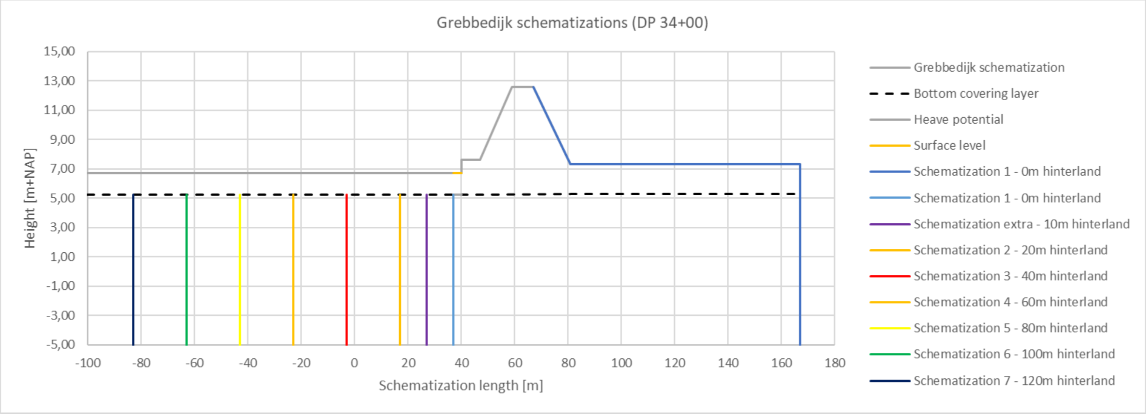


Figure 33 - Visualization of the hinterland schematizations for the Grebbedijk

The exact same approach was also used for the Zwolle Olst dike segment for both an open and closed hinterland. This is visualized in Figure 34.

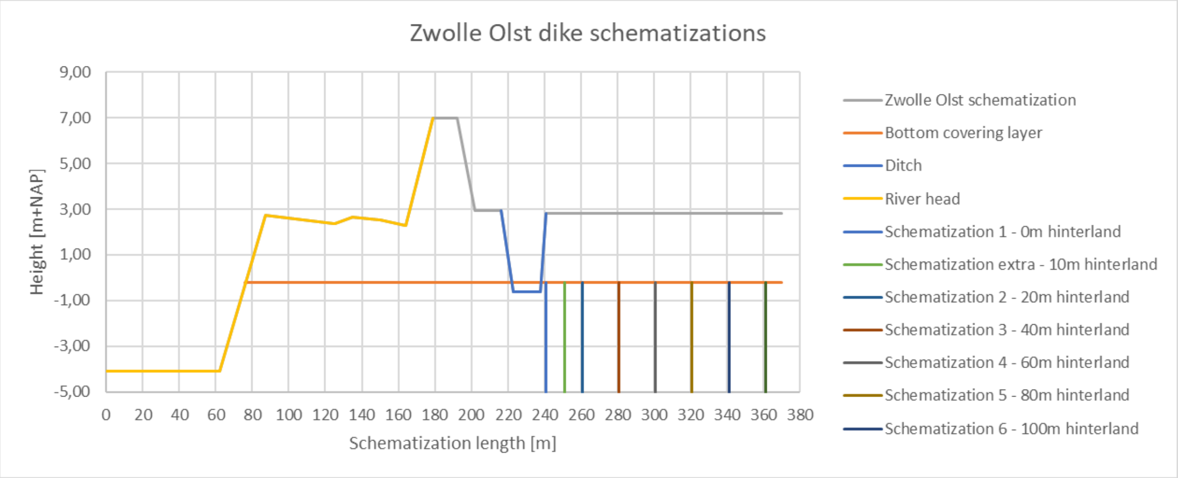


Figure 34 - Visualization of the hinterland schematizations for the Grebbedijk

Because this calculation was repeated for both the Grebbedijk and the Zwolle Olst dike for both an open and closed hinterland for a range from 0 to 120 meter in steps of 20 meter and an extra schematization of 10 meter for all scenarios this resulted in 32 calculations on the hinterland. In Table 4.11 all the calculations can be seen.

Table 4.11 - list of all performed calculations for the hinterland

Calculation	Segment	Open or closed	Distance from heave [m]
1	Grebbedijk	Open	0
2	Grebbedijk	Open	10
3	Grebbedijk	Open	20
4	Grebbedijk	Open	40
5	Grebbedijk	Open	60
6	Grebbedijk	Open	80
7	Grebbedijk	Open	100
8	Grebbedijk	Open	120
9	Grebbedijk	Closed	0
10	Grebbedijk	Closed	10
11	Grebbedijk	Closed	20
12	Grebbedijk	Closed	40
13	Grebbedijk	Closed	60
14	Grebbedijk	Closed	80
15	Grebbedijk	Closed	100
16	Grebbedijk	Closed	120
17	Zwolle Olst	Open	0
18	Zwolle Olst	Open	10
19	Zwolle Olst	Open	20
20	Zwolle Olst	Open	40
21	Zwolle Olst	Open	60
22	Zwolle Olst	Open	80
23	Zwolle Olst	Open	100

Calculation	Segment	Open or closed	Distance from heave [m]
24	Zwolle Olst	Open	120
25	Zwolle Olst	Closed	0
26	Zwolle Olst	Closed	10
27	Zwolle Olst	Closed	20
28	Zwolle Olst	Closed	40
29	Zwolle Olst	Closed	60
30	Zwolle Olst	Closed	80
31	Zwolle Olst	Closed	100
32	Zwolle Olst	Closed	120

4.1.6 Foreland and horizontal water boundary

The fourth sub-question is stated as follows:

What effect does the schematization of the foreland for both an open and closed hinterland have on the critical pipe and head in the piping failure mechanism, and when is this value legitimate?

The third and last main geohydrological boundary condition that will be investigated is the effect of the schematization of the foreland. What effect does a ditch in between the levee and the river have on the critical head and pipe, and what is the effect of schematizing a horizontal water boundary in the riverbed, instead of the standard vertical boundary condition.

Specific schematization

Both the Grebbedijk and the Zwolle Olst dike will have the general schematization as shown in section 4.1.1. Again all schematizations will follow the rule-of-thumb for the heave boundary, namely two times the covering layer thickness. Furthermore, both the Grebbedijk and the Zwolle Olst dike will include a hinterland with a length of 60 meter directly starting after the heave boundary.

The Grebbedijk will have 16 schematizations, namely 8 for an open hinterland and 8 for a closed hinterland. These 8 schematizations with description can be found in Table 4.12.

Table 4.12 - Grebbedijk schematizations

Schematization	Total foreland length [m]	Description
1	0	No foreland.
2	85	Foreland until ditch at 85 meter from dike.
3	271	All foreland until the river.
4	289	All foreland plus the riverbed for 18 meter.
5	314	All foreland plus the riverbed for 43 meter.
6	379	All foreland plus the riverbed for 108 meter.
7	410	All foreland plus the riverbed ending horizontally.
8	410	All foreland plus the riverbed ending vertically at 410 meter from the dike.

The Zwolle Olst dike initially has four extra schematizations in the riverbed. Two for both an open and closed hinterland. The total of 10 schematizations with description can be found in Table 4.13.

Table 4.13 - Zwolle Olst schematizations

Schematization	Total foreland length [m]	Description
1	0	No foreland.
2	44	Foreland schematized for half of the entire length.
3	88	All foreland until the river.
4	123	All foreland plus the riverbed for 35 meter.
5	128	All foreland plus the riverbed for 40 meter.
6	133	All foreland plus the riverbed for 45 meter.
7	164	All foreland plus the riverbed ending horizontally.
8	164	All foreland plus the riverbed for 76 meter.
9	144	All foreland plus the riverbed for 56 meter.
10	154	All foreland plus the riverbed for 66 meter.

In order to visualize this better the schematizations of the foreland and riverbed for the Grebbedijk are shown in Figure 35.

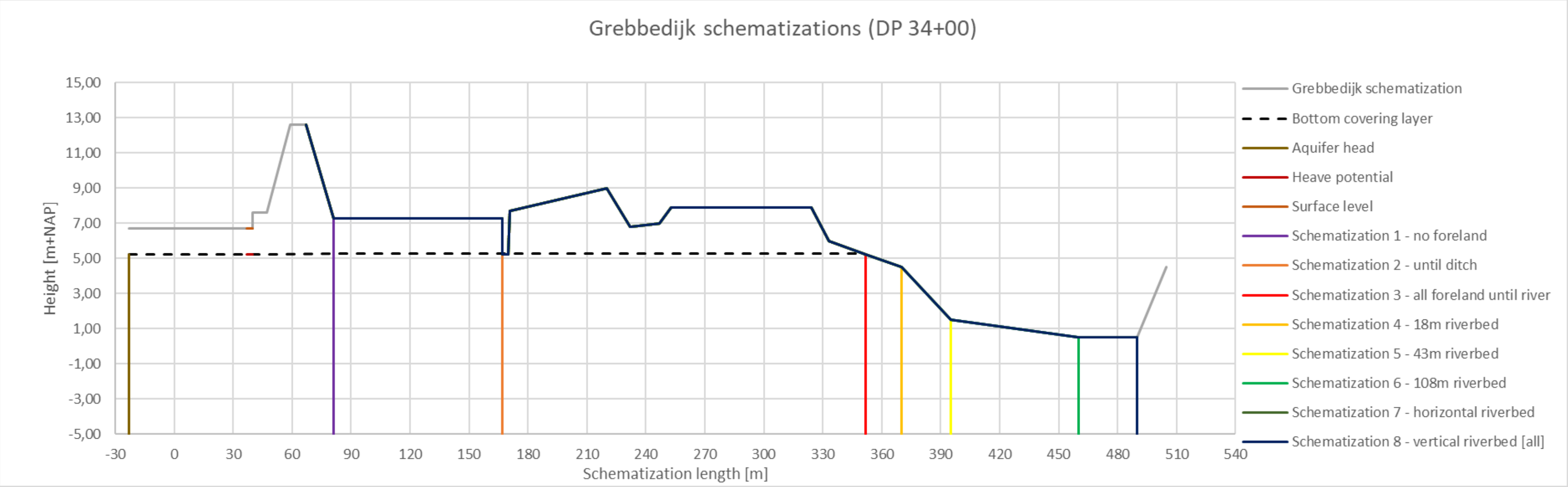


Figure 35 - Visualization of the foreland and riverbed schematizations for the Grebbedijk

It must be noted that that Schematization 7 “horizontal riverbed” cannot be seen in Figure 35, because it ends horizontally at around schematization length 480 meter, and is thus overtopped by Schematization 8 “vertical riverbed [all]” which has the exact same schematization, except that it ends vertically in the aquifer.

And the same is done in order to visualize the schematizations of the foreland and riverbed for the Zwolle Olst dike as shown in Figure 36.

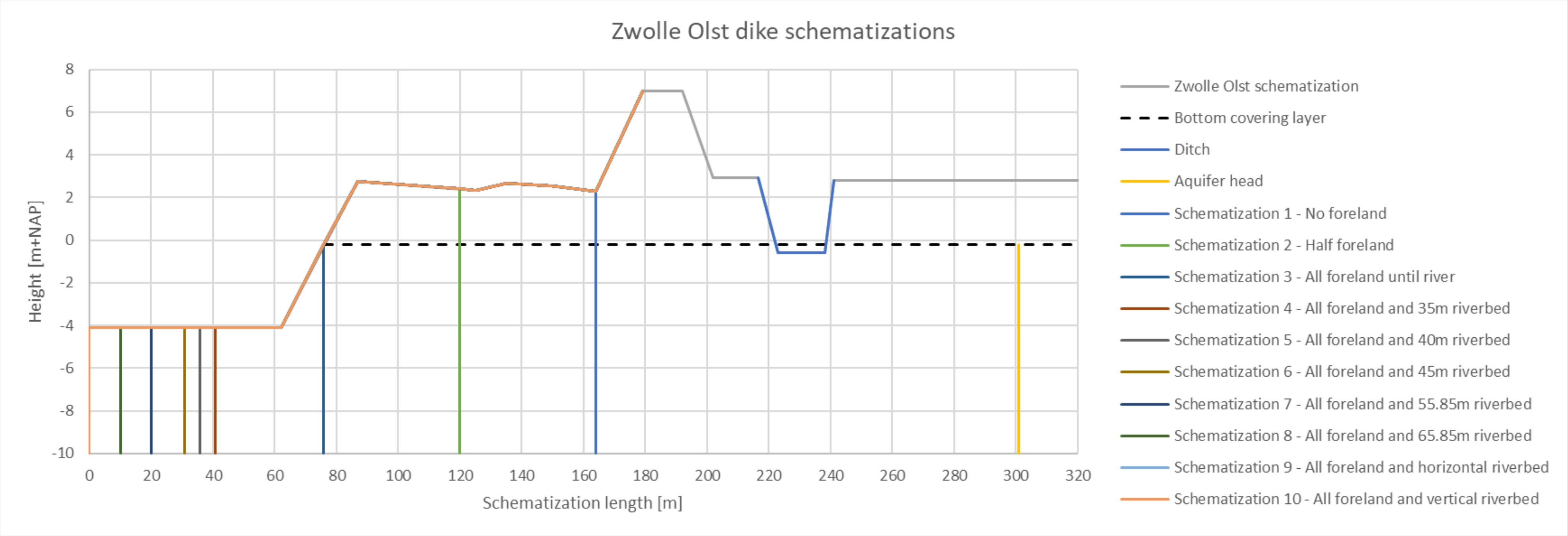


Figure 36 - Visualization of the foreland and riverbed schematizations for the Zwolle Olst dike

Again it must be noted that Schematization 9 “All foreland and horizontal riverbed” cannot be seen in Figure 36, because it ends horizontally at schematization length 0 meter, and is thus overtopped by Schematization 10 “All foreland and vertical riverbed”, which follows the exact same schematization, except that it ends vertically in the aquifer.

4.1.7 Overview of difference between schematizations

In order to provide more clarity on what has, and has not changed between different schematizations this section was added.

In Table 4.14 and Table 4.15 the changes in input variables and schematizations between calculations is shown.

Table 4.14 - Changes in input variables between the open/ closed heave boundary schematizations

Schematization changes heave boundary	Change in mesh sizes?	Change in input (critical) pipe and head calculations?	Change in input head levels water boundaries?	Change in schematization?
Open hinterland	No	Lower boundary critical head is 5.0 meter.	River head is 5, and there is a aquifer head.	No, both schematizations performed the same calculations for different widths of the heave boundary.
Closed hinterland	No	Lower boundary critical head is 2.0 meter.	River head is 2, and there is no aquifer head.	No, both schematizations performed the same calculations for different widths of the heave boundary.

Table 4.15 - Changes in input variables between the open/ closed foreland schematizations

Schematization changes foreland	Change in mesh sizes?	Change in input (critical) pipe and head calculations?	Change in input head levels water boundaries?	Change in schematization?
Open hinterland Grebbedijk	No	Erosion direction Grebbedijk is left to right. Lower boundary critical head is 8.0 meter.	The Grebbedijk has a surface head (7.2) and heave potential (7.64). Open hinterland has an aquifer head (5.23)	Difference between Grebbedijk and Zwolle Olst dike is explained in section 4.1.2. In between open and closed no change except removal aquifer head.
Closed hinterland Grebbedijk	no	Erosion direction Grebbedijk is left to right. Lower boundary critical head is 8.0 meter.	The Grebbedijk has a surface head (7.2) and heave potential (7.64).	Difference between Grebbedijk and Zwolle Olst dike is explained in section 4.1.2. In between open and closed no change except removal aquifer head.
Open hinterland Zwolle Olst dike	No	Erosion direction Zwolle Olst dike is right to left. Lower boundary critical head is 5.0 meter.	The Zwolle Olst dike no surface head or heave potential, but instead a ditch (2.92). Open hinterland has an aquifer head (-0.2)	Difference between Grebbedijk and Zwolle Olst dike is explained in section 4.1.2. In between open and closed no change except removal aquifer head.
Closed hinterland Zwolle Olst dike	No	Erosion direction Zwolle Olst dike is right to left. Lower boundary critical head is 5.0 meter.	The Zwolle Olst dike no surface head or heave potential, but instead a ditch (2.92).	Difference between Grebbedijk and Zwolle Olst dike is explained in section 4.1.2. In between open and closed no change except removal aquifer head.

For the foreland calculations the same schematisations are used as in Table 4.15, but now with a consistent hinterland of 60 meter and a changing foreland schematization.

5 RESULTS

In this section the results will be shown and directly discussed upon. The structure will be the same as that of the methodology, namely the effect of the schematization of: first the heave boundary, than the hinterland, and thirdly the foreland. All results come in twofold, namely for an open and closed hinterland. The results for the foreland and hinterland will come in fourfold, because they are tested on both the Grebbedijk and the Zwolle Olst dike for both an open and closed hinterland. All the results in table form are to be found in section 10.1, the results section from the appendices.

5.1 Heave boundary

In this sub-section the effect of the schematization of the heave boundary on the (critical) pipe and head is shown. Both for an open as well as a closed hinterland. In section 4.1.3 all the input variables are given and elaborated upon. The heave boundary is schematized for a range of 0,5 meter until 8,0 meter with an interval of 0,5 meter. Again it must be noted that the heave boundary is tested using the Tutorial schematization from Deltares, because this is the most general schematization, and therefore functions well as an example for other dike schematizations (Deltares, 2023). The rule-of-thumb states that the heave boundary should be set at two times the covering layer thickness, which is in this case a width of 4,0 meter. In this section the rule-of-thumb will be tested.

5.1.1 Open hinterland

First the results from the open hinterland schematization are discussed.

In Figure 37 the effect from the schematization of the heave boundary on the pipe length for a given river head of 5,0 meter +NAP for an open hinterland is presented.

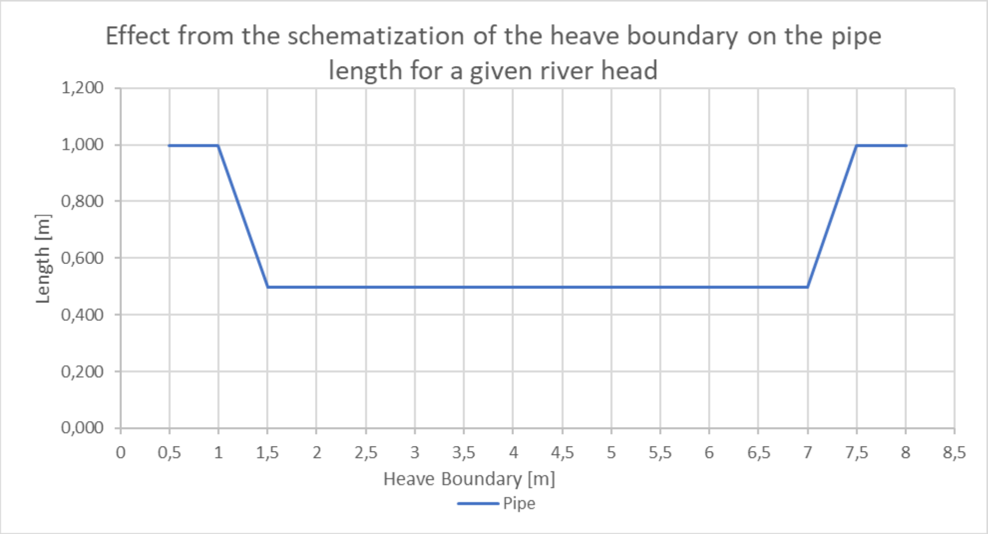


Figure 37 - The effect from the schematization of the heave boundary on the pipe length for a given river head

In Figure 37 it can be seen that the calculated pipe length for a given river head of 5,0 meter +NAP is 1,0 meter when the heave boundary is schematized as 1,0 meter or less and when it is schematized as 7,5 meter or more. Between 1,5 and 7,0 meter the calculated pipe length is circa 0,5 meter. This agrees with the theory in section 3.1 that a wider heave boundary leads to a lower concentration of groundwater in the heave, thus resulting in a shorter pipe. However, it is peculiar that the calculated pipe length increases again when the heave boundary is more than 7,0 meter.

In Figure 38 the effect of the schematization of the heave boundary on the critical head and pipe is presented.

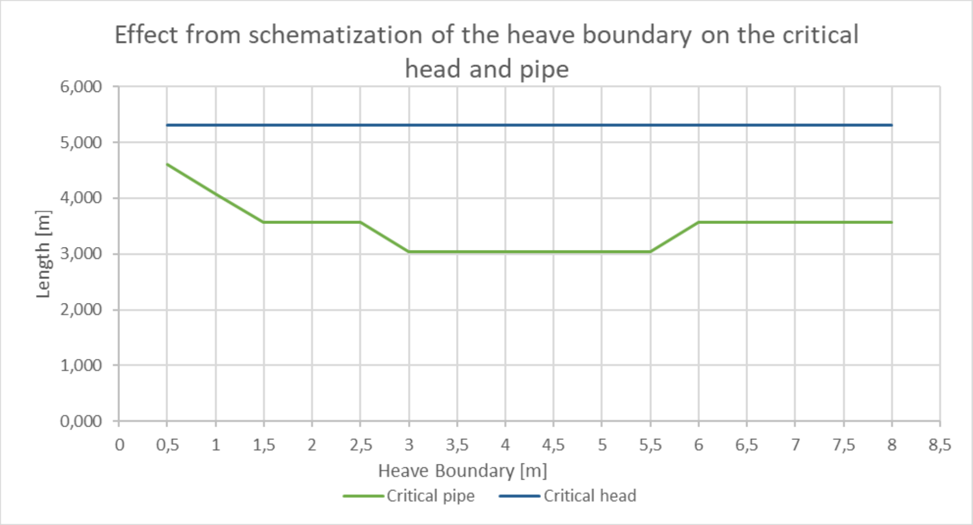


Figure 38 - Effect from schematization of the heave boundary on the critical head and pipe

In Figure 38 it can be seen that a small heave boundary (i.e. < 3,0 meter) leads to a longer critical pipe, however the critical head remains unchanged. When the heave boundary lies between 3,0 and 5,5 meters the critical pipe is the lowest. A shorter critical pipe means that the pipe's length is reached sooner i.e., at a lower critical head, thus the shortest critical pipe is the most conservative scenario. This agrees with the rule-of-thumb that the heave boundary should be drawn as two times the covering layer thickness (which is 2,0 meters), meaning that this rule is safe/ conservative.

5.1.2 Closed hinterland

For comparison the same analysis is made with a closed hinterland, meaning that there is no aquifer head drawn at the end of the hinterland, and thus all the ground water is forced to leave the system via the heave. Important to notice is that the river head is set at 2,0 meter +NAP, because when a higher river head is used (like 5,0 meter +NAP like in the open hinterland schematization) all the calculated pipes will grow progressively and reach the riverside and thus cause short-circuiting. However, the results on pipe length are still comparable, because what is interesting is the behaviour of the pipe length, which can still be compared. The same schematizations as for the open hinterland scenario i.e., for a range of 0,5 meter until 8,0 meter with an interval of 0,5 meter are used with the addition of three extra calculations for a heave boundary of 10,0, 10,5 and 11,0 meter.

In Figure 39 the effect of the schematization of the heave boundary on the calculated pipe length for a given river head of 2,0 meter +NAP for a closed hinterland is presented.

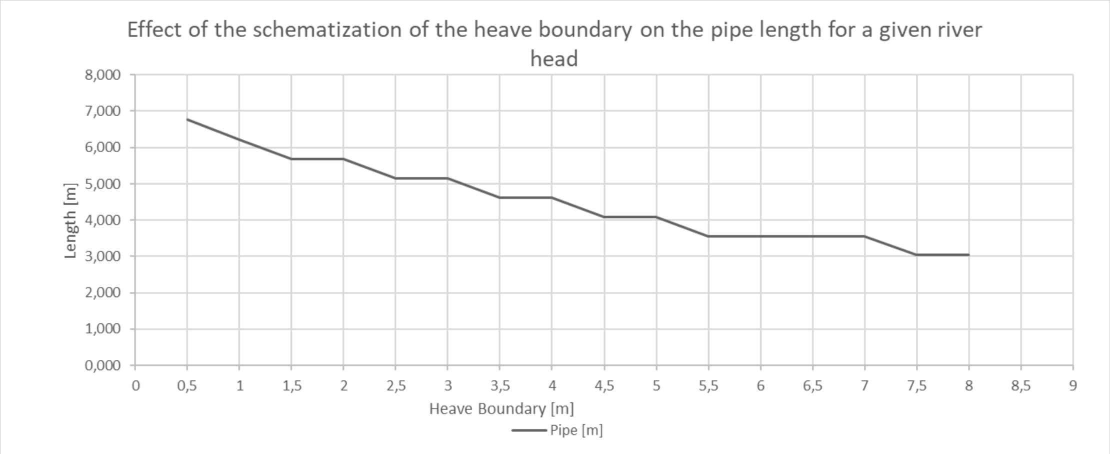


Figure 39 - Effect of the schematization of the heave boundary on the pipe length for a given river head

In Figure 39 it can be seen that the calculated pipe length with a given river head of 2,0 m +NAP has a negative trend when the heave boundary width increases. This can be explained using the theory behind the initiation or progression dominated pipe, as explained in section 3.1. The following should be considered, namely the fact that this scenario has a closed hinterland, thus all groundwater must leave the system via the heave. By increasing the width of the heave boundary the water pressure in the heave decreases, resulting in a slower groundwater stream around the heave, and thus a smaller pipe.

In Figure 40 the effect of the schematization of the heave boundary on the critical head is presented.

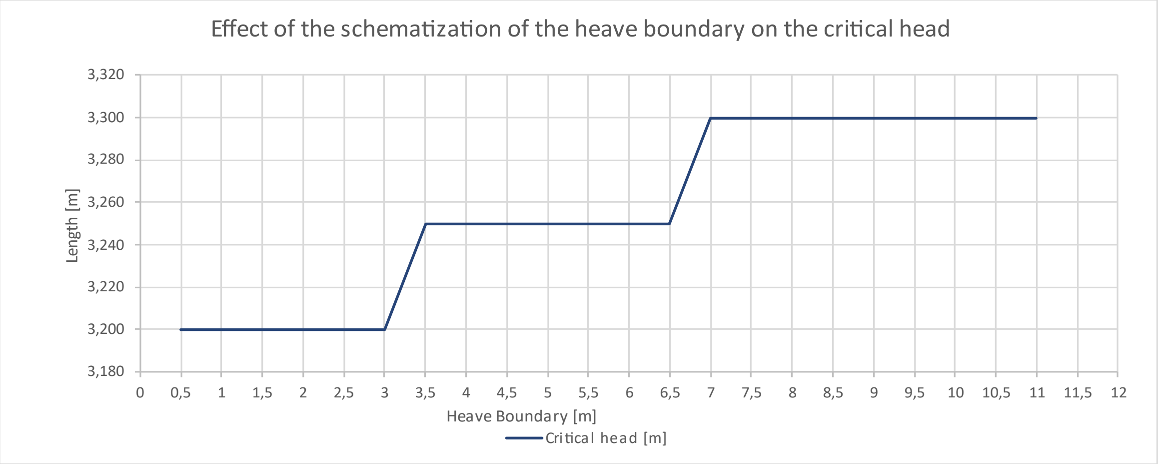


Figure 40 - Effect of the schematization of the heave boundary on the critical head

In Figure 40 it can be seen that the calculated critical head increases stepwise when the heave boundary is increased. At a heave boundary width of 3,0 meter and 6,5 meter the critical head increases by 0,05 meter.

Comparing Figure 38 with Figure 40 it can be seen that the critical head is lower for the closed hinterland than for the open hinterland (3,2 meter +NAP and 5,2 meter +NAP respectively). The reason for this is that the system behaves differently with a closed hinterland. As already explained in section 2.6.3, the model is initially closed on all the edges, however using the water boundaries, it is possible to mark boundaries as open, with a fixed head level. In this case with a closed hinterland, all the water entering the system from the river must leave the system again via the heave, contributing to a higher concentration of water in the pipe, thus a lower critical head because the stream in the pipe is more concentrated and will thus transport more sand and water with it.

In Figure 41 the effect of the schematization of the heave boundary on the critical pipe is presented.

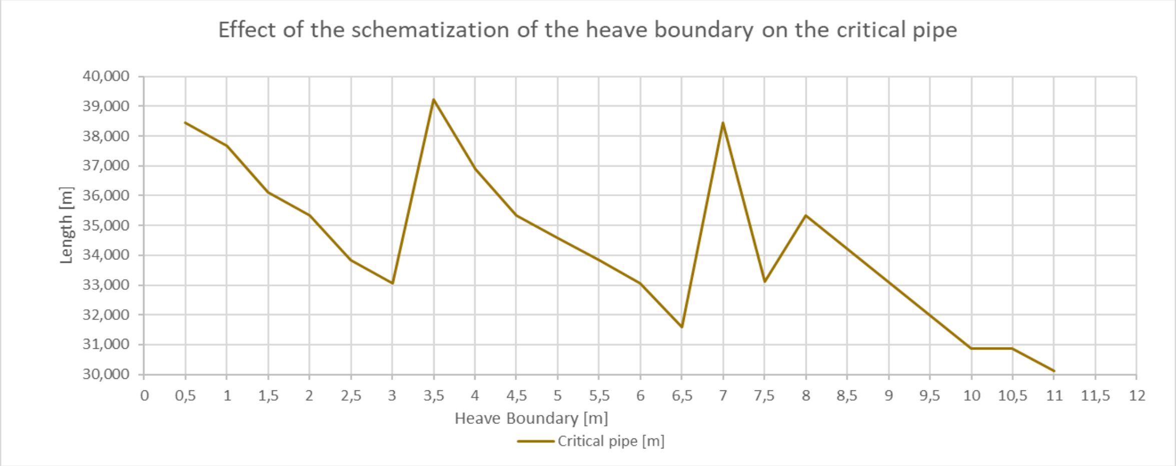


Figure 41 - Effect of the schematization of the heave boundary on the critical pipe

As can be seen in Figure 41 the calculated critical pipe decreases when the width of the heave boundary increases. This is a peculiar result, because it is expected that with the increase of the width of the heave boundary the concentration of groundwater in the pipe would decrease, thus resulting in a longer critical pipe. Furthermore, peaks are observable at the heave boundary widths of 3,5 and 7,0 meter. This can be explained by comparing it with Figure 40, where it can be seen that the critical head has increased at 3,5 and 7,0 meter as well. Comparing Figure 38 with Figure 41 shows that the calculated critical pipe for a closed hinterland scenario is much longer than for a open hinterland scenario. This is again a peculiar result, because as explained before it is expected that the critical pipe would be shorter than for the open hinterland scenario.

5.1.3 Heave boundary results summary

As seen in section 5.1.2, the results of the critical pipe calculations behave peculiar in the closed hinterland schematization. Furthermore, the closed hinterland scenario is a very conservative calculation method, because it assumes that all the water leaves the system via the heave, which is not realistic, because at least some groundwater will also stream into the hinterland. Because of these two reasons it is chosen that the open hinterland scenario is safer to use, as its results behave according to the literature, and an open hinterland is moreover more realistic. Furthermore, the rule-of-thumb for the heave boundary is accepted, because it results in the shortest critical pipe in the open hinterland scenario. Notice that the shortest critical pipe represents the most conservative schematization, because this pipe is reached with a lower critical head.

5.2 Hinterland and aquifer head

For the analysis of this boundary condition the comparison between the dike segment Grebbedijk and Zwolle Olst is made. On one hand the Grebbedijk schematization has a relatively small exit point, namely only the heave boundary which was set at two times the covering layer thickness, i.e. 2,94 meter. On the other hand the schematization that is used for Zwolle Olst has a ditch that lies parallel to the levee, and which also lies directly on the aquifer, meaning that no heave will occur. This ditch has a width of 24.5 meter, and thus an exit width which is roughly ten times the size of that of the Grebbedijk. Following the theory from section 3.1, the Grebbedijk schematization is likely progression dominated, because it has a smaller exit point, and the Zwolle Olst dike is perhaps initiation dominated. For both segments the same analysis with an open and closed hinterland was performed, using the same input variables as mentioned in section 4.1.3.

5.2.1 Grebbedijk

First the analysis is made for the Grebbedijk. Here the results for the critical head for both an open/ closed hinterland are compared, and thereafter the same is done for the critical pipe.

Figure 42 shows the critical head against the schematization of the (open/closed) hinterland, and Figure 43 shows the critical pipe against the schematization of the (open/closed) hinterland.

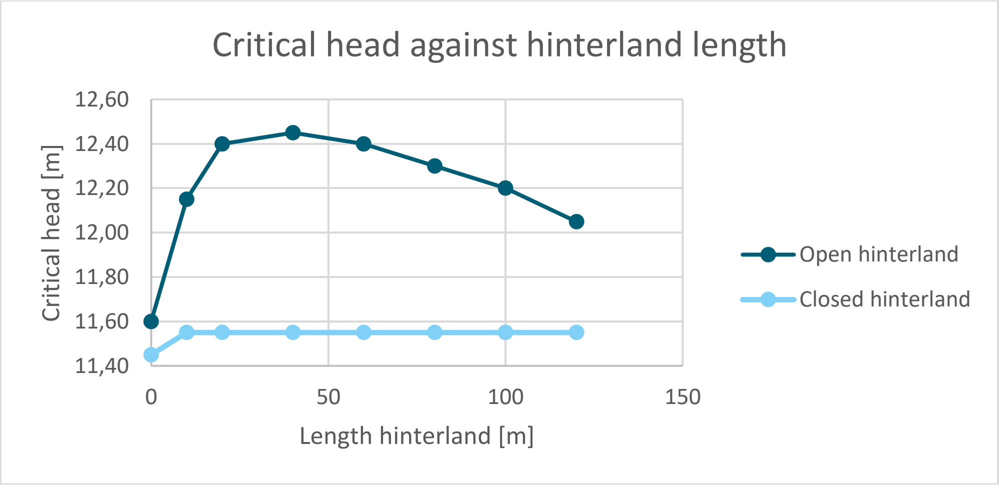


Figure 42 - The effect of change of hinterland length on the critical head for both an open and closed hinterland for the Grebbedijk.

From Figure 42 it can be concluded that the critical head in a closed hinterland is barely sensitive to a change in schematization of the hinterland length. This can be explained as follows: in the closed hinterland scenario all the groundwater that leaves the system, does so via heave. Whether the hinterland boundary is schematized nearby or further land inward does not alter the groundwater flow, because no groundwater is pulled towards the end of the schematization.

On the other hand, the critical head in the scenario with an open hinterland is very much affected by the schematization of the hinterland. In case of an open hinterland, an aquifer head is schematized as a vertical boundary in the aquifer at the hinterland boundary. This aquifer head is assigned a certain head level, thus pulling ground water towards it. If this boundary is schematized further land inward, thus further away from the heave potential, the groundwater in the system will have to travel larger distances before reaching the boundary compared to the heave potential, which lies almost directly behind the dike. In other words, when the hinterland length is schematized relatively small (e.g. 20 meter from the heave) it will pull a lot of groundwater towards it, thus leaving less groundwater to leave the system via the heave, thus a pipe with a lower concentration of groundwater, thus a higher critical head. A higher critical head is in this case needed to compensate for the percentage of groundwater that is pulled land inward. When the hinterland is schematized further land inward, this percentage flowing land inward will become smaller, thus resulting in more groundwater leaving the system via the heave, resulting in lower critical heads. The reason for the increase in critical head in the open hinterland scenario for the first 20 meters, is not yet known but might be partially caused by simulation errors.

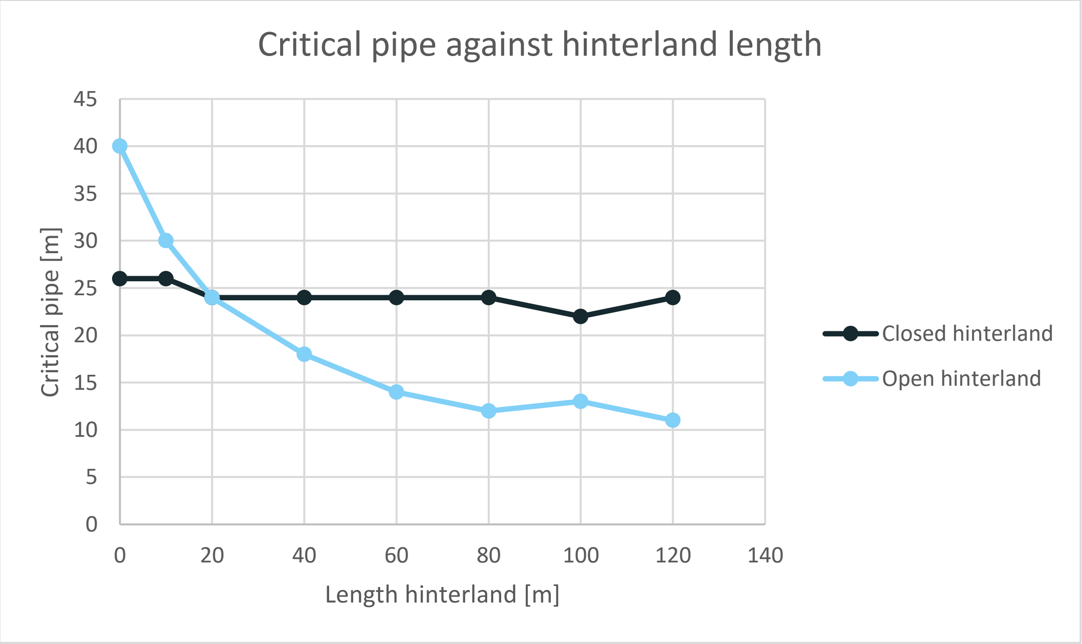


Figure 43 - The effect of change of hinterland length on the critical pipe for both an open and closed hinterland for the Grebbedijk.

From Figure 43 it can again be concluded that the closed hinterland scenario is not very sensitive to a change in schematization of the hinterland, as the critical pipe ranges between 22 and 26 meter.

Interesting to see is that the critical pipe in the open hinterland scenario is very sensitive to the schematization of the hinterland length (range between 40 and 10 meter critical pipe length). This can be explained by the same theory as before that the further land inward the hinterland is schematized, the less groundwater is pulled to that boundary condition. In other words, when the hinterland is schematized very close to the heave, it will attract more groundwater. This results in less groundwater leaving the system via the heave, and thus a lower concentration of groundwater in the pipe. A lower concentration means that a longer pipe is needed before it has the same discharge as a smaller pipe with a higher discharge.

5.2.2 Zwolle Olst

In this section the same analysis is done, but now for the Zwolle Olst dike. Figure 44 shows the critical head against the hinterland schematization, and Figure 45 shows the critical pipe against the hinterland schematization for both an open/ closed hinterland scenario.

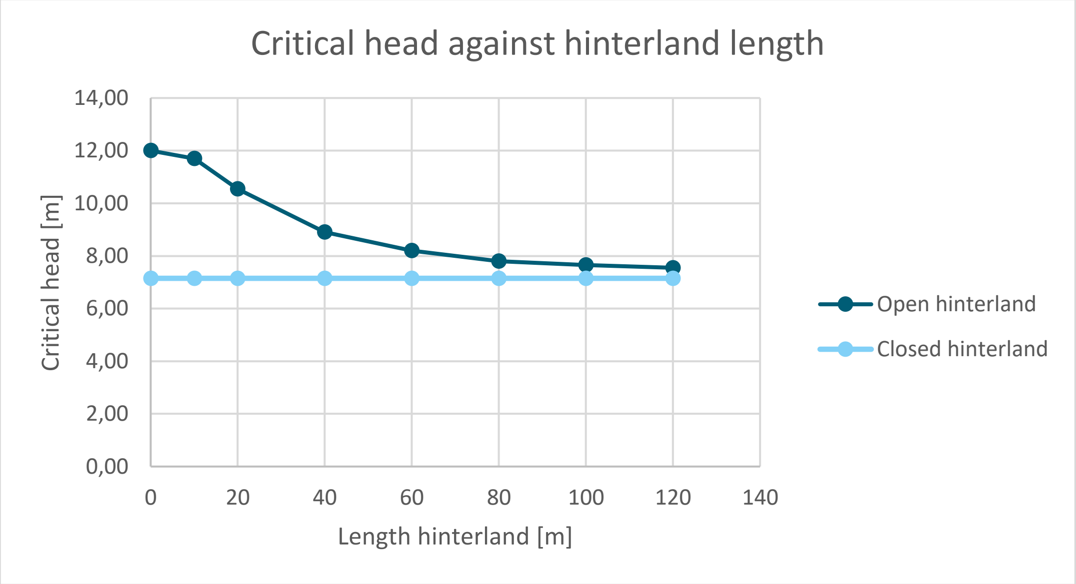


Figure 44 - The effect of change of hinterland length on the critical head for both an open and closed hinterland for the Zwolle Olst dike.

The same as in section 5.2.1, the critical head in the closed hinterland scenario is not sensitive to the change in schematization of the hinterland. The reasoning for this is explained in the same section.

Next to that, it seems that the assumption made in section 5.2.1 that the critical head is affected by the schematization of the open hinterland, and that the closer it is schematized to the heave the more groundwater is leaving the system into the hinterland instead of the heave is also true for the Zwolle Olst schematization. The only difference is that the Zwolle Olst dike does not have the same start-up phase as the Grebbedijk schematization, where the critical head only has its peak after 40 meter, as can be seen in Figure 42. Whereas, the Zwolle Olst dike has its critical head peak at the hinterland length of 0 meter.

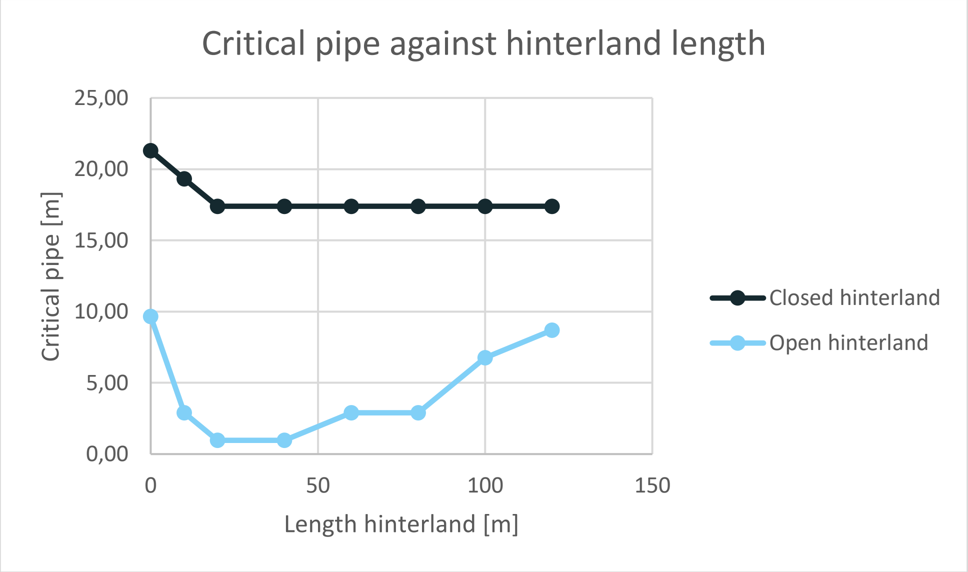


Figure 45 - The effect of change of hinterland length on the critical pipe for both an open and closed hinterland for the Zwolle Olst dike.

From Figure 45 it can be concluded that the closed hinterland scenario is again not very sensitive to a change in hinterland schematization, just like the Grebbedijk. Only for the hinterland range from 0 to 20 meter, its critical pipe is longer, however this is a difference of just 3,70 meter on a total pipe trajectory of 146,4 meter for the Zwolle Olst dike.

On the other hand, the open hinterland scenario is much more sensitive to the schematization of the hinterland, having critical pipe values ranging from 0,97 to 10 meter. An interesting aspect to notice here is that the critical pipe, initially relatively long at 10 meter, drops when the hinterland schematization is moved more land inward, only to become longer again after 40 meter of hinterland schematization. This suggests that when more than 40 meter of hinterland is schematized, the critical pipe becomes longer, or in other words a longer pipe is needed before the pipe becomes critical, the further the hinterland is schematized.

5.2.3 Hinterland results summary

In general it can be concluded that the schematization of more hinterland for the open hinterland scenario leads to a closer approximation of the critical head in the closed scenario, because the further land inward the aquifer head is schematized, the less water will be pulled towards that head, thus more water leaving the system via the heave (approximating the closed hinterland scenario). For the Zwolle Olst dike approximately 60 meter of (open) hinterland is enough to equal the closed hinterland. For the Grebbedijk this value is larger, but the exact value is unknown because it was only schematized for 120 meter. It is important to note that this value is possibly very sensitive to the head level in the aquifer, because that determines how much groundwater is pulled land inwards. Furthermore, the critical pipe length is very sensitive to the schematization of the hinterland, especially in the case of the Grebbedijk. At least 60 meter of hinterland should be schematized, because otherwise the aquifer head will pull to much groundwater land inwards, creating a longer critical pipe.

5.3 Foreland and horizontal boundary condition

The third main boundary condition that is researched is what effect the choice on vertical and horizontal schematization of the foreland has on the critical pipe and head in the piping failure mechanism. To investigate this effect both schematizations of the Grebbedijk and Zwolle Olst dike were analysed; both with a standard heave boundary and a hinterland of 60 meters, starting directly after the exit point of the pipe. For visualization: the Grebbedijk has in this analysis a small hinterland between the dike and the ditch, followed by the heave boundary, and thereafter a hinterland in the ditch for 60 meter long. The Zwolle Olst dike has a relatively longer hinterland between the dike and the ditch, followed by the wide ditch (which touches the aquifer), and thereafter a hinterland for 60 meter long.

5.3.1 Grebbedijk

As shown in the methodology, in section 4.1.6, 16 schematizations, namely 8 schematizations for both an open and closed hinterland, have been made for the Grebbedijk. A clear visualization of the foreland schematizations of the Grebbedijk can be found in Figure 35, but for clarity a smaller version is included here in Figure 46. Notice that Schematization 7 is horizontal, and can thus not be seen as Schematization 8 is drawn over it.

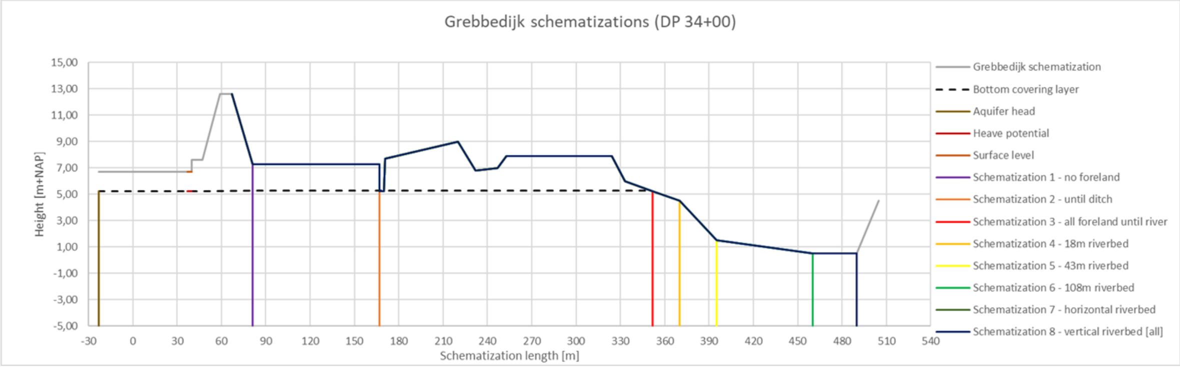


Figure 46 - Visualization of the foreland schematization of the Grebbedijk.

Figure 47 shows the critical head against the foreland length for specific schematizations for both an open and closed hinterland, and Figure 48 shows the critical pipe against the foreland length for specific schematizations, for both an open and closed hinterland.

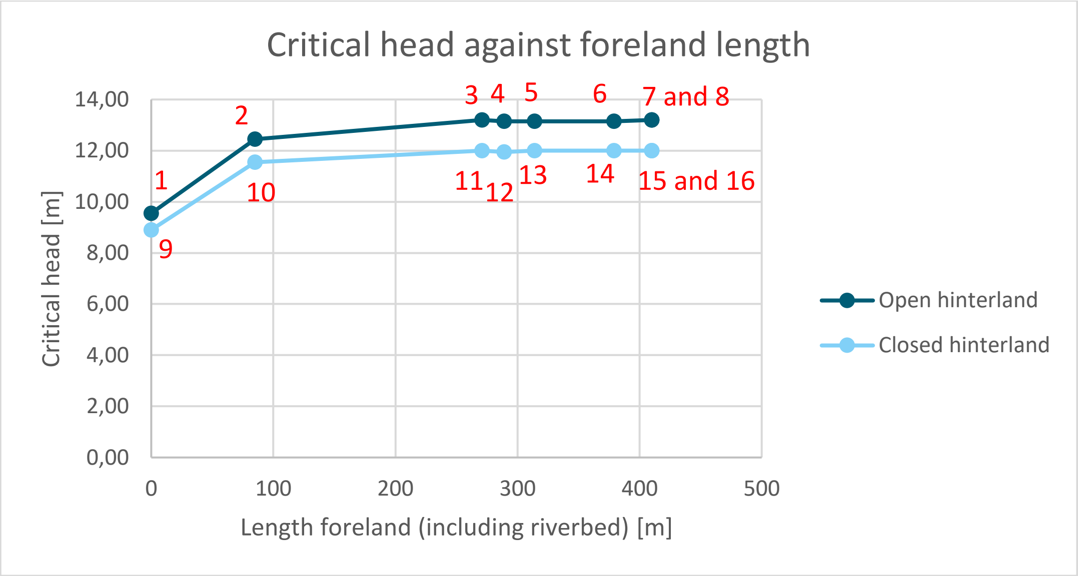


Figure 47 - The effect of change of schematization of the vertical/horizontal foreland on the critical head for both an open and closed hinterland for the Grebbedijk.

As expected the critical head for both the open and closed hinterland increases when the foreland is schematized more towards the river. As explained in section 2.4, the longer the seepage length is (assuming little water will penetrate through the covering layer and the levee), the higher the head level must become for the pipe to travel the whole seepage length.

What is interesting to see is that the critical head still increases after schematizing more foreland after the ditch. For example, in Figure 47 it can be seen that the highest critical head is found when circa 300 meter of the foreland is schematized at schematization 3. After this point (i.e. when all of the foreland is schematized) the critical head does not change significantly anymore, which can be seen in Figure 47 by the fact that the graph becomes almost flat after this point. What exactly the reason is that the critical head increases when all of the foreland is schematized instead of only the part before the ditch is not certain.

Another interesting observation is that the scenario with the open hinterland has a bigger critical head, than the closed hinterland schematization, namely a difference of around 1,1 meter on average. This again confirms the assumption that in the open hinterland schematization more groundwater flows into the hinterland, instead of the heave, thus resulting in a smaller concentration of water in the pipe, and thus a higher critical head.

Also evident from these results is that the difference between the vertical and horizontal schematization on the riverbed cannot be seen in the results in critical head and piping, for these specific input variables, and these dike segments. This is not surprising, because the entrance point for the pipe still lies at the ditch, and the seepage length is the main boundary condition for the critical head calculation.

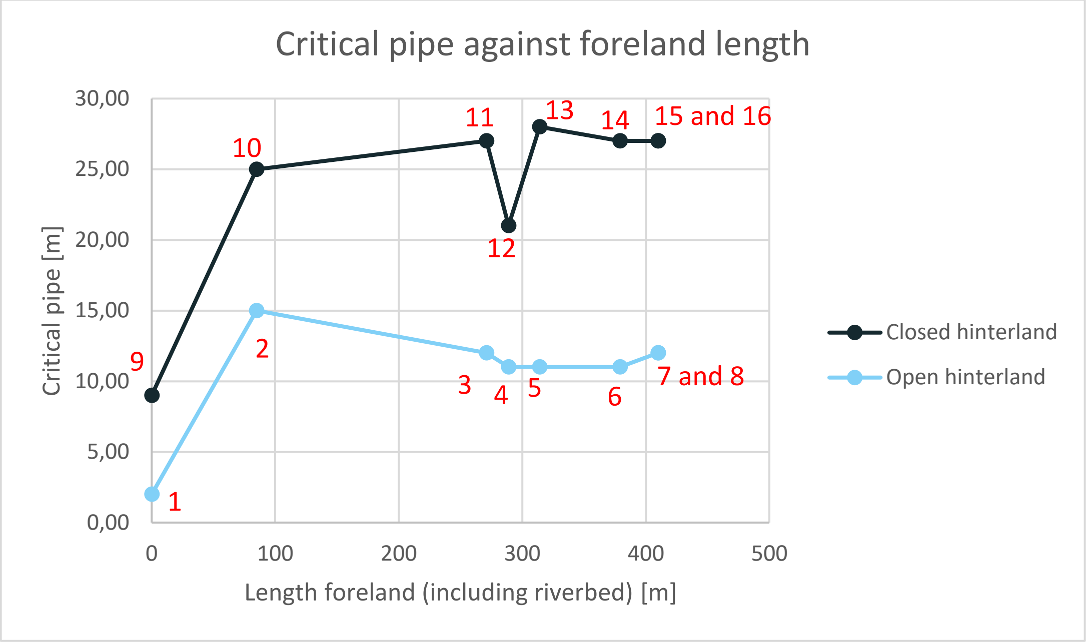


Figure 48 - The effect of change of schematization of the vertical/horizontal foreland on the critical pipe for both an open and closed hinterland for the Grebbedijk.

From Figure 48 it can be concluded that the critical pipe for both a closed/ open hinterland are affected by a change in schematization of the foreland. First of all, the critical pipe length increases rapidly between schematization 1 and 2 (no foreland, and foreland until ditch respectively), because the seepage path length is increased. After this point it becomes interesting because both scenarios react differently to the further schematization of the foreland and riverbed. For instance, for the open hinterland scenario the critical pipe length decreases when more foreland is schematized. On the other hand, for the closed hinterland scenario the critical pipe length increases when more foreland is schematized. Schematization 12 of the closed hinterland scenario has a notable hiccup in the trend, however this caused by the small change in critical head for the same calculation, as can be seen in Table 10.5. However, the changes in critical pipe for both scenarios do not alter significantly more after the ditch is schematized. An interesting conclusion that can be drawn however is that there is not visible difference between the vertical and horizontal schematization of the riverbed, which can be seen in Figure 48 at schematization 7 and 8 for the open hinterland and at schematization 15 and 16 for the closed hinterland.

5.3.2 Zwolle Olst dike

The same analysis has been made for the Zwolle Olst dike, however with 4 extra schematizations, 2 for both an open and closed hinterland in the riverbed in order to find more results for the riverbed. In Table 10.6 all schematizations along with their specific results for the critical head and pipe are shown for both the open and closed hinterland. Furthermore, it should be noted that for the foreland analysis for the schematization of the Zwolle Olst dike again a hinterland length of 60 meter was used, as a result of the hinterland analysis in section 5.2.2. The reason for this was that after schematizing 60 meter of open hinterland, the resulting critical head was halfway in between the too optimistic, small open hinterland of 20 meter, and the too conservative closed hinterland.

A clear visualization of the foreland schematizations of the Zwolle Olst dike can be found in Figure 36, but for clarity a smaller version is included here in Figure 49 . Notice that Schematization 9 is horizontal, and can thus not be seen as Schematization 10 is drawn over it.

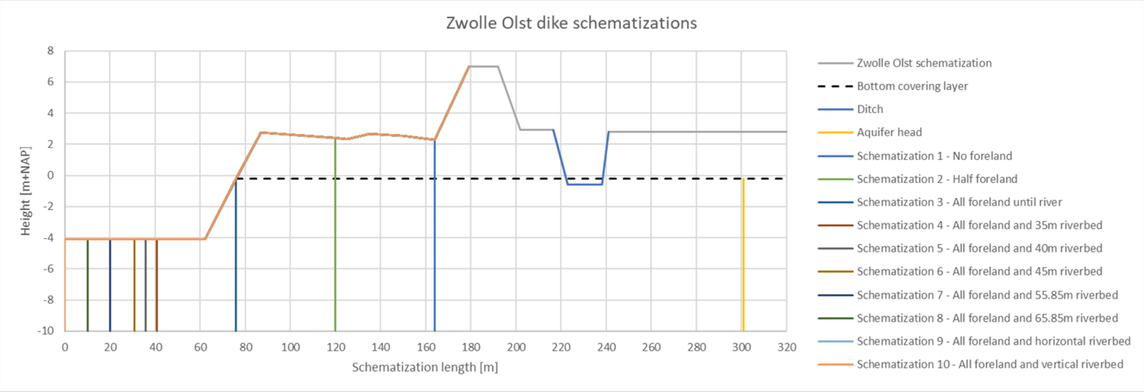


Figure 49 - Visualization of the foreland schematization of the Zwolle Olst dike.

The results are drawn in two graphs again. Figure 50 shows the critical head against the foreland length for specific schematizations for both an open and closed hinterland, and Figure 51 shows the critical pipe against the foreland length for specific schematizations, for both an open and closed hinterland.

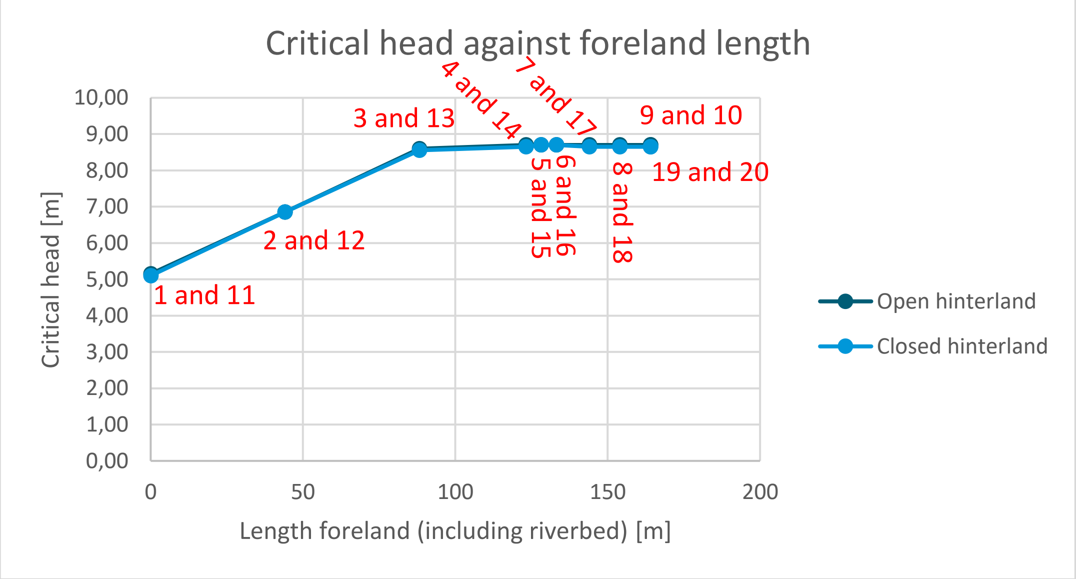


Figure 50 - The effect of change of schematization of the vertical/horizontal foreland on the critical head for both an open and closed hinterland for the Zwolle Olst dike.

In Figure 50 it can be seen that for the Zwolle Olst dike the critical heads stay almost the same for the open/closed schematization. When looking at Table 10.6 however, it can be seen that critical head for the open hinterland scenario lies circa 0,05 meter higher than for the closed hinterland scenario. This difference is negligible, however this difference is caused by the fact that for the open hinterland scenario more groundwater streams into the hinterland, resulting in a higher critical head.

Interesting to see is that for the Zwolle Olst dike the critical head does not alter significantly comparing the schematizations that include all foreland excluding the riverbed (schematization 3 and 13) with the schematization that do include the riverbed as well. This agrees with the results for the Grebbedijk that the critical head does not change significantly when the riverbed is schematized. Neither do the schematizations of the horizontal riverbed (schematization 9 and 19) differ from the vertical schematizations (10 and 20), which again confirms the conclusion that it does not matter whether the riverbed is schematized vertically or horizontally.

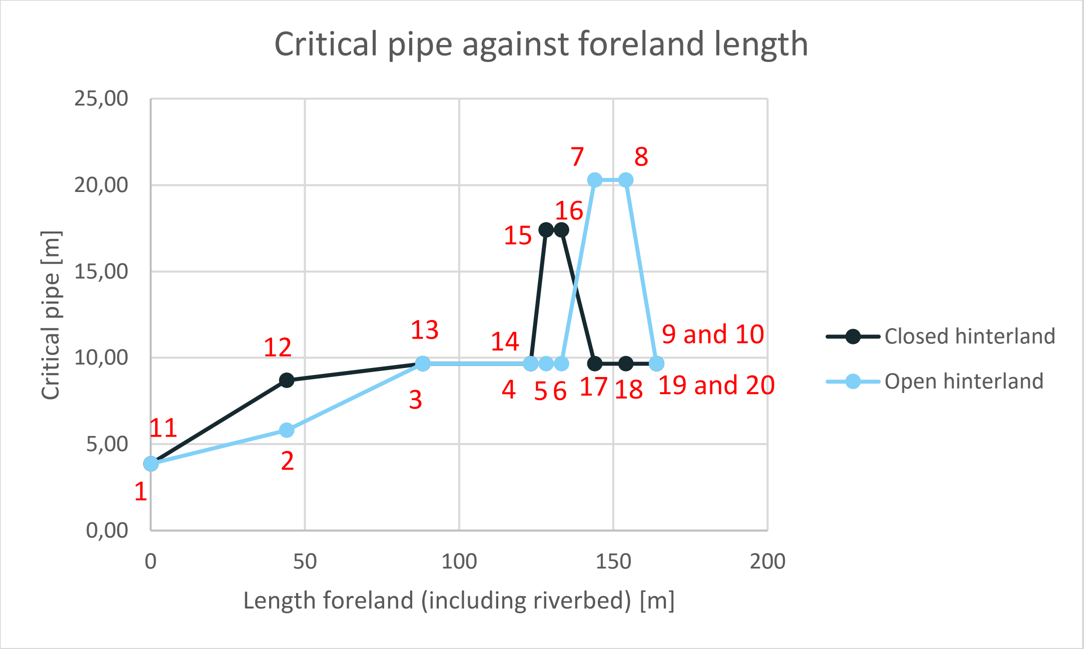


Figure 51 -The effect of change of schematization of the vertical/horizontal foreland on the critical pipe for both an open and closed hinterland for the Zwolle Olst dike.

In Figure 51 it can be seen that the open/ closed scenarios do react differently to the change in foreland schematization. Interesting to see is that again the calculated critical pipe length does not differ for either the vertical/ horizontal schematization for the open hinterland (schematization 9 and 10 respectively) and the closed hinterland (19 and 20 respectively).

It is also interesting to see that for the schematization of no foreland there is no difference between the open / closed schematization (1 and 11 respectively). However, when half of the foreland is schematized they do differ significantly (schematization 2 and 12). It is not certain why this happens exactly.

Last but not least, the calculated critical pipe length starts to behave very unpredictable when more riverbed is schematized i.e. all the calculations with more than 100 meter foreland. This can be seen in Figure 51 in the peculiar peaks that take shape around 150 meter foreland.

5.3.3 Foreland results summary

The general conclusion that can be drawn from the results of the Grebbedijk and Zwolle Olst dike is that an increase of the seepage path length also increases the critical head level, for both an open and closed hinterland. For the Grebbedijk, the critical head results are sensitive to the schematization of the rest of the foreland, in case of a ditch, or even the schematization of the riverbed, for both an open/ closed hinterland. However, schematizing the riverbed does not change the results significantly. Furthermore, the critical pipe lengths also increases when more seepage path length is schematized, however the behaviour of the critical pipe length when more foreland after a ditch is schematized is not yet clear, and behaves apparently quite random sometimes. Furthermore, the schematization of a vertical/ horizontal riverbed as riverhead does not give different results for the critical head and pipe.

6 DISCUSSION

In this section the discussions by the results will be denoted. The discussion will discuss the input variables, assumptions that were made, the uncertainty of the results, and the overall uncertainty behind D-Geo Flow.

To start off with an overall discussion on the working method for this research. The initial method provided in the proposal only handled the foreland schematizations, and only later it was found that two other geohydrological boundary conditions should be handled as well, namely the heave boundary and the open/ closed hinterland. Because of this delay in knowing what to do research on exactly, it took longer before a sufficient working method was established for the whole thesis. Not to undermine the method that is now used, because it has very interesting conclusions, however some interesting aspects that were only partly or not at all handled in this method are for example the aquifer thickness level, and the effect of schematization of the foreland and hinterland on the calculated pipe length for a given river head. Although this was still performed partially, more could have been tested if it was incorporated in the working method in an earlier stage. This would have provided more interesting results on the matter. Furthermore, the results from each sub-question were used as input for answering the next sub-question, which worked very well, however not always the results were tested thoroughly enough, resulting in sometimes not the best fitted input variables for subsequent sub-questions. Take for example the hinterland length schematization which was set at 60 meter for the Grebbedijk, but which could better have been set at a longer distance. In the following points the flaws and potential improvements are discussed.

- One input value that might also be set at a different value is the aquifer head. During all the calculations this variable was set according to the same rule, it should namely be the z-level of the bottom of the covering layer upon the aquifer in the hinterland, as this was how it is done in the D-Geo Flow manual. However, during the process it was found that this value should perhaps not be set the same as the bottom of the covering layer. More logically would it be to set it the same as the surface head, as the water presses against the covering layer, because it is assumed that the hinterland is completely saturated. Sadly, changing this value for all calculations was no longer possible due to time restrictions, however some logical reasoning might help. In all cases this leads to a higher value for the head in the aquifer, thus a stronger attraction of groundwater land inward in an open hinterland. This would mean that less water would leave the system via the heave, thus resulting in higher critical heads and possibly longer critical pipes.
- A peculiar observation was also made in the results in section 5.2.1 for the effect of the schematization of the open hinterland on the Grebbedijk. Here it can be seen that the calculated critical head increases when the hinterland is schematized from 0 to 40 meter. Following the theory in section 3.1 it would be logical to have a relatively high critical head at first, before it gets lower due to the lengthening of the hinterland. Perhaps this is happening because of the initiation/ progression dominated critical head, but it cannot be said for sure. Sadly, because no extra tests were performed for the hinterland analysis on the pipe length for a given river head, it is not possible to see how the schematization behaves with a consistent river head and a changing hinterland schematization.
- Another result that seems to be unpredictable at times is the critical pipe length. In general, the theory from section 3.1 suffices, saying that a stronger concentration of water leads to a shorter critical pipe length, however for three schematizations this was not the case. For example, Figure 41 shows a negative trend in the critical pipe length when the heave boundary increases, however a wider heave boundary suggests a lower concentration of water in the pipe, and thus a longer critical pipe. Another example can be seen in Figure 45, which displays the effect of the schematization of an open/ closed hinterland on the critical pipe for the Zwolle Olst dike. As explained before a lower concentration of water in the pipe would lead to a longer critical pipe, so the other way around is also true, namely that a higher concentration of water in the pipe leads to a shorter critical pipe. However, in this example the critical pipe length first drops as expected when the hinterland length is increased from 0 to 40 meter, however after 40 meter it increases again when more hinterland is schematized. This is unexpected because an increase in hinterland length should lead to a higher concentration of water around the pipe, thus a lower critical pipe. Last but not least, the critical pipe starts to behave unpredictable when the riverbed is included in the schematization of the foreland for some reason. In order to draw conclusions on this behaviour of

the critical pipe more research should be performed on what exactly determines the critical pipe length in D-Geo Flow. It seems that more than just the concentration of water around the pipe influences the critical pipe length.

- Another improvement in the schematization of the dike was found for the Grebbedijk. During the calculations on the foreland, a hinterland of 60 meters was used to stay in line with the Zwolle Olst dike, however after analysing the results from the hinterland analysis on the Grebbedijk, it was found that in that case a hinterland of approximately 120 meter would have suited better. This value was found using the hinterland length calculation method as explained in section 5.2.3. Sadly, there was no time to do the same calculations again for this schematization. However, doing this would probably have led to a decrease in critical head and critical pipe length, because more groundwater would have left the system via the heave instead of the hinterland, because the hinterland schematization is schematized further away from the heave. This also explains the gap between the open/ closed hinterland results for the critical pipe and critical head for the Grebbedijk as can be seen in Figure 47 and Figure 48.

This paragraph will consist of a general discussion on the use of D-Geo Flow, both its flaws and advantages. Starting with the flaws, D-Geo Flow is a very time-consuming programme to use when one is not already familiar with it. Although the user interface is very understandable and clear, the instruction on how everything works and what effect it has on the model is not clear for a new user. There is a manual, but it is very general, and only provides limited information about the software. After a period, when the workings of D-Geo Flow have become clearer, the running of multiple simulations will still consume much time. The running time for each separate calculation took circa 5 minutes, which is not that much, however the schematizing and setting up of calculations correctly in D-Geo Flow were time-consuming. Running multiple simulations at once is a more efficient work method, and is certainly advised for future users. Other than that, the user interface of D-Geo Flow was very pleasing to work with, when one knew how to use it exactly. One final issue with D-Geo Flow remains that, even after doing research on it for some time, it still remains a black-box at times, for which it is not always known why it behaves in a certain manner, and why at times results differed from results that were calculated using the same input.

7 CONCLUSION

The conclusion will follow the same steps as the methodology, namely going through the sub-questions one by one, before answering the main research question. Intermediate results obtained in section 5 'the results' will also be summarized in this section, in order to have a clear overview of all the results, and how the conclusions are drawn from them.

Sub-question 1. What boundary conditions in D-Geo Flow are important to consider in this research?

In sections 2.6 and 4.1.2, this sub-question was already answered based on literature review. To summarize, Rijkswaterstaat (Rijkswaterstaat, 2023) states that the piping failure mechanism knows three main boundary conditions that are the most important factors in determining whether piping occurs or not. These three boundary conditions are: a head level difference that lasts for a longer period of time, the right soil composition, and the right geohydrological boundary conditions which determine the seepage path length under the dike, foreland and hinterland.

A head level difference that lasts for a longer period of time is crucial for piping to occur, because without a persistent underground water flow, due to the head difference, no pipe will form.

The soil composition is very important for piping as well, because piping can only happen when a (thick) aquifer layer lies underneath an aquitard covering layer, on which the levee is build. In case of a sand dike or dune, no piping can occur, because a pipe cannot form without an aquitard.

The geohydrological boundary conditions that determine the seepage path length have a great influence on the pipe formation, and where its entry and exit point are located, and thus whether the pipe has the potential to grow to a critical length. In this research the following three geohydrological boundary conditions are examined, namely the effect of the schematization of the heave boundary, the hinterland and the vertical/ horizontal foreland boundary. All three boundary conditions will also be subject to a sensitivity analysis for an open/ closed hinterland.

Sub-question 2. What effect does the choice for heave boundary for both an open and closed hinterland have on the critical pipe and head in the piping failure mechanism, and when is this value legitimate?

In section 5.1 the results of the heave boundary have been examined. After analysing the width of the heave boundary on a range from 0,5 till 8,0 meter with an interval of 0,5 meter for both an open and closed hinterland, the following conclusions can be drawn.

First the open hinterland scenario. As can be seen in Figure 38, the critical head is not sensitive to a change in the width of the heave boundary for the open hinterland. However, the calculated (critical) pipe is sensitive to the schematization of the heave boundary, as can be seen in Figure 37 and Figure 38. In general, the critical pipe is expected to grow longer with an increase in heave boundary width (which decreases the concentration of water around the pipe) because a lower concentration around the pipe results in the need of a longer pipe before it becomes critical. However, from the results it seems that the calculated (critical) pipe decreases when the width of the heave boundary increases for the open hinterland scenario, which contradicts with the previous statement. Notice that a shorter critical pipe in general means that the critical pipe is reached sooner, i.e. with a lower head level difference. However, in the case of the heave boundary, the critical head is not affected by the schematization, meaning that the pressure in the aquifer on the covering layer remains the same. Combining the fact that the water pressure in the aquifer remains the same (no critical head level change), whilst the heave boundary increases (creating a longer area for the pipe to rest on, and thus the concentration of water around the pipe decreasing) which subsequently leads to a decrease of the critical pipe length, it can be concluded that the widening of the heave boundary attracts more water towards it resulting in the need of a shorter critical pipe.

In the closed hinterland scenario, the critical head increases when the heave boundary is schematized wider, and the (critical) pipe length decreases. Remembering that in the closed hinterland scenario all the water must leave the system via the heave, it seems logical that the critical head increases with the increase in the width of the heave boundary, because the water pressure is divided over a wider heave, resulting in a lower concentration around the heave and thus a smaller pipe. The closed hinterland scenario is however very conservative, and therefore not the best schematization, because it results in a very low critical head. Furthermore, the increase of critical head in the open hinterland is insignificant i.e. only 10 centimeters.

In conclusion, the rule-of-thumb for the heave boundary width should be adhered to, because in case of the open hinterland scenario, it results in the shortest critical pipe, whilst having a consistent critical head level.

Sub-question 3. What effect does the schematization of the hinterland for both an open and closed hinterland have on the critical pipe and head in the piping failure mechanism, and when is this value legitimate?

To answer this sub-question two dike segments were analysed, namely the Grebbedijk and the Zwolle Olst dike. The first has a very long foreland, with a ditch halfway through, and the other has a smaller foreland, with a deep and wide ditch in the hinterland lying parallel to the levee.
First of all, it can be concluded that the critical head is not sensitive to the schematization of the closed hinterland for both the Grebbedijk and the Zwolle Olst dike. The critical head is however very sensitive to the schematization of the open hinterland for both dikes. The further away the open hinterland is schematized, the closer the critical head approximates the result for critical head for the closed hinterland. Again, a closed hinterland is very conservative, because it assumes that all the groundwater leaves the system via the heave, which is realistically not the case. Therefore, it can be concluded that for sure the open hinterland should be schematized for a specific length, because otherwise the system gets too optimistic. In case of the Grebbedijk this should be around 120 meter and for the Zwolle Olst dike 60 meter. For other dike segments, one should test what the critical head is for only 20 meter of open(optimistic)/ closed(conservative) hinterland. Subsequently, the open hinterland should be schematized in such a way that the critical head lies halfway in between the optimistic and conservative result.

To visualize this, take a look at Figure 52, where for the Zwolle Olst dike the critical head against the hinterland length is schematized. As explained before, the closed hinterland is too conservative, and thus a specific schematization of the open hinterland should be used. When the open hinterland is schematized very close to the heave, it will attract more groundwater to its aquifer head, than when it is schematized further away. In Figure 52 it can be seen that the open hinterland results (asymptotically) approach the closed hinterland results when the schematization length is increased. In order to find the best length, a possible rule-of-thumb is to calculate the critical head for both the open/ closed hinterland at 20 meter. A good schematization of the hinterland should have its critical head value somewhere between these two values, so the open hinterland schematization that has this critical head as a result should be used, which in this case is at 60 meter. A short schematization of the open hinterland is possibly too optimistic (having a high critical head value), and thus the open hinterland should be schematized further away. The most realistic schematization would be to schematize an infinite open hinterland length, however this would make the calculation time very time-consuming / impossible. In Figure 52 the best fit open hinterland schematization is found at 60 meter.

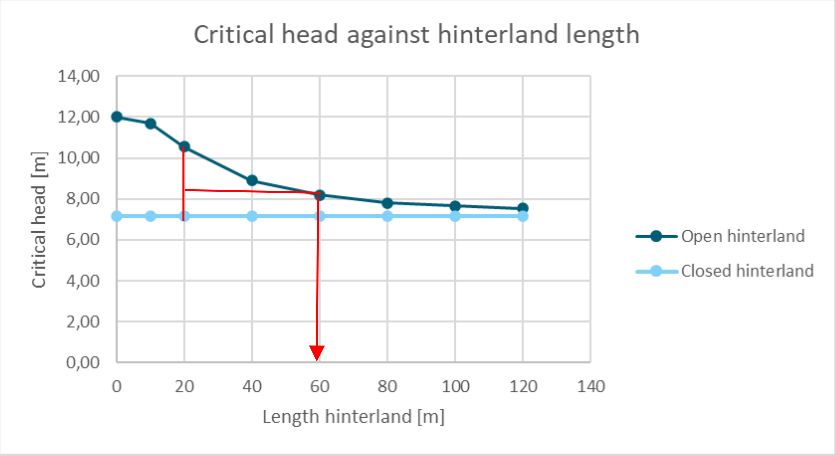


Figure 52 - Visualization of the hinterland schematization best fit.

The critical pipe is not sensitive to the schematization of the closed hinterland for both the Grebbedijk and the Zwolle Olst dike. Next to that, the critical pipe is too long (too optimistic) when the open hinterland is not schematized long enough. So, again one must do the same test as mentioned above and in section 5.2.3 to find a safe value in between the optimistic and conservative choice.

Sub-question 4. What effect does the schematization of the foreland for both an open and closed hinterland have on the critical pipe and head in the piping failure mechanism, and when is this value legitimate?

The results in section 5.3 verify the literature that indeed the longer a seepage path length is schematized, the more optimistic the results for a critical head and pipe become. How exactly the foreland should be schematized is already handled in literature, however to summarize the literature: before any foreland can be included in the piping analysis it should first be verified that no other large entry point for the pipe exists in the foreland on any other place than the entry point that is used. Because, if this is the case than the dike analysis is performed too optimistic, because it assumes a longer seepage path length, than what is realistic.

From the results it can also be concluded that the critical head is not sensitive to any changes in the foreland/ riverbed that do not alter the seepage path length. Even a change in vertical/ horizontal schematization has no significant influence on the critical head for both an open/ closed hinterland.

Interesting to see is that the critical pipe length starts to behave peculiar when more foreland or riverbed is schematized than just the seepage path length. Therefore, it is advised not to schematize any foreland and or riverbed that does not influence the seepage path length of the pipe, because it makes the results of the model unpredictable.

Sub-question 5. To what extent can the new safe values be implemented in other projects?

To start off with the rule-of-thumb for the heave boundary. This rule has been verified for the Tutorial schematization of D-Geo Flow, and it also proved to present realistic results for the Grebbedijk, so generally the rule-of-thumb as described in section 5.1.3 should be accepted and used for other projects as well. However, not all projects use a heave boundary, like in the case of the Zwolle Olst dike, so it is not obligatory to use it. Furthermore, for an open hinterland the heave boundary could also be taken wider, because the results will not differ significantly. For a closed hinterland the heave boundary should not be taken more than the rule-of-thumb, because the critical pipe length drops significantly.

Next, the hinterland schematization can be used for various dike analysis projects. Using the newly created rule-of-thumb, as mentioned in section 5.2.3, the safe value for an open hinterland length can easily be found. The safe value for the open hinterland length schematization should have a critical head value that lies between the optimistic critical head value when the open hinterland is schematized nearby the heave, and the conservative critical head value that is calculated by the closed hinterland. Furthermore, the hinterland should always be schematized as open in order to make realistic results, because otherwise the results will be very conservative.

For the foreland there is no correct schematization that always provides realistic results. However, it is always important to consider the effect of including the foreland in the schematization, and whether this is safe to do. It is possible to schematize more foreland after the entry point, however take into consideration that this might increase the critical head, as it did with the Grebbedijk in Figure 47. The critical pipe length will also change when more foreland is schematized after the entry point, however how it changes is not defined, because the change in calculated critical pipe length differed for both the Grebbedijk and the Zwolle Olst dike for an open/ closed hinterland. For sure, it can be concluded that the riverbed should not be included, either vertically or horizontally, as it makes the critical pipe behave unpredictable, an does not alter the critical head.

"What are safe values for boundary conditions in D-Geo Flow to produce realistic results regarding piping, and when are these values legitimate?"

When one wishes to analyse the piping failure mechanism on a dike using D-Geo Flow, there are some important boundary conditions to keep in mind while schematizing the dike configuration. Next to all the mandatory requirements stated by D-Geo Flow, like the fact that the software is not validated for non-horizontal seepage paths, the following list of rules or helping methods should be kept in mind:

- If applicable, the heave boundary should be set according to the rule-of-thumb, which states that the heave boundary width is two times the covering layer thickness.
- In order to obtain realistic results that are not too conservative one should always schematize an open hinterland.
- In order to find a safe open hinterland length, one should calculate the critical head for both an open and closed hinterland for a hinterland length of 20 meter from the surface level or heave if applicable. The results obtained for the critical head at 20 meter should be compared and the safe critical head should lie in between those two. Trial and error the open hinterland for various lengths until it gives the earlier found critical head as a new critical head for that schematization of the open hinterland. This is a safe and not too conservative schematization of the open hinterland.
- Only schematize the foreland when it can be verified that no entry point for the pipe exists between the entry point of the pipe and the dike itself. If it does, schematize the foreland only until that infiltration point, and set it as the entry point, and again check if no other infiltration point in between exists. If other infiltration points may exist, only schematize the dike base itself. This is the most conservative schematization, however also the safest. When it can actually be proven that there are no infiltration points between the dike and the entry point of the dike, this whole part of the foreland should be schematized, in order to produce the most realistic results regarding piping. Do not schematize any possible foreland behind the entry point of the pipe, and also do not schematize the riverbed either vertically or horizontally, because it makes the critical pipe calculations unpredictable and possibly too optimistic.
- Schematize the river head along the levee (and if proven safe over the foreland until the entry point of the pipe), and then schematize it vertically through the aquifer. The heave potential should follow the 0.3d-rule, and the surface head should be set at the surface level, or at the water level, when the surface level lies on the bottom of a water body e.g. a ditch.

In order to rank the different boundary conditions on how much they affect the critical head and pipe a list has been made sorted from most impact to less impact, namely:

1. Setting the right head levels;
2. Open/ closed hinterland schematization;
3. Seepage path length in the foreland;
4. Schematizing the hinterland length correctly for an open hinterland;
5. The heave boundary.

8

RECOMMENDATIONS

From the results of this research, it is concluded that an open hinterland is more realistic and that the heave boundary is safe to set according to the rule of thumb, namely two times the covering layer thickness. Furthermore, the schematization length of the hinterland should be determined by trial and error through calculating the result in critical head for the open hinterland, and thereby finding a safe value that lies between the optimistic and conservative values. Last but not least, the foreland should be schematized at least until the entry point when that point is determined, and otherwise just the dike base. If more foreland is present behind this entry point it should not be schematized because it makes the results for the critical head too optimistic, and the critical pipe results unpredictable. Next to all these conclusions more insight into D-Geo Flow could be obtained in future research by examining the following subjects:

- First of all, it is recommended that a sensitivity analysis is performed on the results from this research by changing the thickness of the aquifer and testing whether the results behave the same, or if perhaps certain conclusions do not hold anymore.
- Furthermore, it is recommended to perform pipe length calculations based on a given river head, next to the critical pipe and head calculations. It could be interesting to see what pattern the calculated pipe has when the head level remains consistent, as is the case with the pipe length calculation. Results from this could be used to test whether certain dike schematizations are initiation or progression dominated, or whether they change from type due to a change in schematization.
- Another interesting follow-up research to perform is to test the hinterland length calculation, as stated in the conclusion. As of now, this test is more trial and error than focussed searching for certain schematization lengths. It could for example be interesting to find if there’s a pattern between dike schematizations and their optimal hinterland length schematization.
- D-Geo Flow calculations also provided information on the maximal pipe height. In this research that output data was not used, but in follow-up researches it could be interesting to obtain more maximal pipe height data and compare it between schematizations and their calculated (critical) pipe, to see whether there lies a pattern there. It could for example be possible that the maximal pipe height influences the critical pipe length heavily, or maybe the other way around.
- In this research only three different dike segments were examined, namely the Tutorial segment, the Grebbedijk and the Zwolle Olst dike. None of these dikes had a ditch in the foreland that almost touched the aquifer, so it might be interesting to examine what effect this might have on the seepage path, the critical head and the critical pipe results.

9

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10 APPENDICES

10.1 Results

In this appendix section all the results in table form will be shown.

10.1.1 Heave boundary

Here the results for the heave boundary analysis are shown.

Table 10.1 - results of the calculations of the schematization of the heave boundary on the (critical) pipe and head for an open hinterland

Heave boundary	Pipe [m]	Critical pipe [m]	Critical head [m+NAP]
0,5	0,998	4,612	5,300
1	0,998	4,084	5,300
1,5	0,497	3,560	5,300
2	0,497	3,560	5,300
2,5	0,497	3,560	5,300
3	0,497	3,040	5,300
3,5	0,497	3,040	5,300
4	0,497	3,040	5,300
4,5	0,497	3,040	5,300
5	0,497	3,040	5,300
5,5	0,497	3,040	5,300
6	0,497	3,560	5,300
6,5	0,497	3,560	5,300
7	0,497	3,560	5,300
7,5	0,998	3,560	5,300
8	0,998	3,560	5,300

Table 10.2 - results of the calculations of the schematization of the heave boundary on the (critical) pipe and head for a closed hinterland

Heave boundary	Pipe [m]	Critical pipe [m]	Critical head [m+NAP]
0,5	6,766	38,443	3,200
1	6,221	37,658	3,200
1,5	5,681	36,106	3,200
2	5,681	35,339	3,200
2,5	5,144	33,822	3,200
3	5,144	33,072	3,200
3,5	4,612	39,234	3,250
4	4,612	36,880	3,250
4,5	4,084	35,339	3,250
5	4,084	34,578	3,250

Heave boundary	Pipe [m]	Critical pipe [m]	Critical head [m+NAP]
5,5	3,560	33,822	3,250
6	3,560	33,072	3,250
6,5	3,560	31,590	3,250
7	3,560	38,443	3,300
7,5	3,040	33,106	3,300
8	3,040	35,339	3,300
10	-	30,857	3,300
10,5	-	30,857	3,300
11	-	30,129	3,300

10.1.2 Hinterland

Table 10.3 - Results of the calculations of the schematization of the hinterland on the (critical) pipe and head for an open and closed hinterland for the Grebbedijk

		Open			Closed		
Length hinterland [m]	Description	Schematization	Critical head [m+NAP]	Critical pipe [m]	Schematization	Critical head [m+NAP]	Critical pipe [m]
0	Only heave	1	11,60	40,00	8	11,45	26,00
10	10 meter hinterland	extra	12,15	30,00	extra	11,55	26,00
20	20 meter hinterland	2	12,40	24,00	9	11,55	24,00
40	30 meter hinterland	3	12,45	18,00	10	11,55	24,00
60	40 meter hinterland	4	12,40	14,00	11	11,55	24,00
80	50 meter hinterland	5	12,30	12,00	12	11,55	24,00
100	60 meter hinterland	6	12,20	13,00	13	11,55	22,00
120	70 meter hinterland	7	12,05	11,00	14	11,55	24,00

Table 10.4 - Results of the calculations of the schematization of the hinterland on the (critical) pipe and head for an open and closed hinterland for the Zwolle Olst dike

		Open			Closed		
Length hinterland [m]	Description	Schematization	Critical head [m+NAP]	Critical pipe [m]	Schematization	Critical head [m+NAP]	Critical pipe [m]
0	Only heave	1	12,00	9,67	8	7,15	21,30
10	10 meter hinterland	extra	11,70	2,90	extra	7,15	19,33
20	20 meter hinterland	2	10,55	0,97	9	7,15	17,40
40	30 meter hinterland	3	8,90	0,97	10	7,15	17,40

		Open			Closed		
60	40 meter hinterland	4	8,20	2,90	11	7,15	17,40
80	50 meter hinterland	5	7,80	2,90	12	7,15	17,40
100	60 meter hinterland	6	7,65	6,77	13	7,15	17,40
120	70 meter hinterland	7	7,55	8,70	14	7,15	17,40

10.1.3 Foreland and horizontal boundary condition

Table 10.5 - Results of the calculations of the vertical/horizontal schematization of the foreland on the (critical) pipe and head for an open and closed hinterland for the Grebbedijk.

		Open			Closed		
Length foreland (including riverbed) [m]	**Description**	**Schematization**	**Critical head [m+NAP]**	**Critical pipe [m]**	**Schematization**	**Critical head [m+NAP]**	**Critical pipe [m]**
0	No foreland	1	9,55	2,00	9	8,9	9,00
85	Foreland until ditch	2	12,45	15,00	10	11,55	25,00
271	All foreland until river	3	13,20	12,00	11	12	27,00
289	All foreland and 18 m riverbed	4	13,15	11,00	12	11,95	21,00
314	All foreland and 43 m riverbed	5	13,15	11,00	13	12	28,00
379	All foreland and 108 m riverbed	6	13,15	11,00	14	12	27,00
410	All foreland and horizontal riverbed	7	13,20	12,00	15	12	27,00
410	All foreland and all the riverbed	8	13,20	12,00	16	12	27,00

Table 10.6 - Results of the calculations of the vertical/horizontal schematization of the foreland on the (critical) pipe and head for an open and closed hinterland for the Zwolle Olst dike.

		Open			Closed		
Length foreland (including riverbed) [m]	**Description**	**Schematization**	**Critical head [m+NAP]**	**Critical pipe [m]**	**Schematization**	**Critical head [m+NAP]**	**Critical pipe [m]**
0	No foreland	1	5,15	3,87	11	5,1	3,87
44,075	Half foreland	2	6,85	5,80	12	6,85	8,70
88,15	All foreland	3	8,60	9,67	13	8,55	9,67
123,15	All foreland plus 35 meters riverbed	4	8,70	9,67	14	8,65	9,67
128,15	All foreland plus 40 meters riverbed	5	8,70	9,67	15	8,7	17,40

133,15	All foreland plus 45 meters riverbed	6	8,70	9,67	16	8,7	17,40
144	foreland and riverbed minus 20	7 extra	8,70	20,30	17 extra	8,65	9,67
154	foreland and riverbed minus 10	8 extra	8,70	20,30	18 extra	8,65	9,67
164	All foreland and no vertical	9	8,70	9,67	19	8,65	9,67
164	All foreland and riverbed	10	8,70	9,67	20	8,65	9,67

10.2 Library

Library

This thesis contains a lot of technical jargon, or words that are translated from Dutch (abbreviations). The most used words are listed in this small library.

Tabel 7 - Translation library (Kennisbank Waterbouw, sd)

Dutch term	English translation	Meaning
Achterland	Hinterland	The land behind the dike, that is to be protected from flooding.
Slecht waterdoorlatende laag	Aquitard	Soil layer that is not very permeable.
Bezwijkkans	Failure probability	The probability that a structure will fail under its load (is not equal to the 'faalkans' in Dutch)
Bres	Breach	Hole in levee, after which the levee body fails.
Damwand	Sheet pile	Vertical construction inside a levee to stop underground water streams.
Debiet	Discharge	Amount of water flowed through per unit time (i.e. in m3/s).
Dijk	Dike (dyke)	Water barrier consisting of a body of soil.
Dijk	Levee	River dike; body of land along river to protect hinterland during peak river discharges (in US near New Orleans also Sea Dike).
Dijk, kade	Embankment	Water barrier consisting of a body of soil.
Doorlatend	Permeable	Construction that allows water to pass through, but usually needs to be sand-tight.
Doorlatendheid	Permeability	Availability to let water pass through it (i.e. in m/day).
Faalkans	Failure probability	The probability that a structure can no longer perform its function (is not equal to the failure probability in Dutch).
Faalmechanisme	Failure mechanism	

Grens potentiaal	Aquifer head	Vertical boundary condition for certain head level in the hinterland.
Greppel/ sloot	Ditch	
Heave	Heave	Unstable sand due to water flowing upward, causes quicksand.
Infrastructuur en Waterstaat Enterprise Architectuur	Infrastructure and water management Enterprise Architecture	IWEA-kaders. Specially developed governmental team that among others were responsible for the development of BOI.
Intredepunt	Entrance point / entry point	Entry point of the pipe, where the water enters the aquifer.
Keren	Retain	
Kritisch stijghoogteverschil	Critical head difference	
Kruin	Crest	Top of a structure, e.g. the crest of a dike or harbour dam.
Kwel	Seepage	Leaking groundwater.
Kwellengte	Seepage length	Distance, which water must travel through the ground to flow out of the ground at the inside of a water barrier.
Kwelscherm	Seepage screen	An impermeable, generally vertical, structure for the extension of the seepage path.
Kwelsloot	Toe ditch	A ditch on the inside of the dike whose purpose is to collect and drain seepage water.
Kwelweg	Seepage path	A possible path in the ground that seepage water travels, from entry point to exit point.
Macro instabiliteit	Macro instability	
Micro instabiliteit	Micro instability	
Ministerie van infrastructuur en waterstaat	Ministry of infrastructure and water management	The ministry that is among others responsible for the water safety in the Netherlands.
Niet poreus, ondoorlatend	Impermeable	
OI: Ontwerp Instrumentarium	Design instruments	Designing method used before 2023. Replaced by BOI in 2023.
Ondergrond	Subsoil	
Ontwerpstorm	Design storm	Storm whose parameters (e.g., H, T, duration) are used for structural design. is often related to a return time.
Ontwerpwaterstand	Design water level	Water level to be used for the design, normally a water level that has some given return probability.
Opbarsten	Bursting	Cohesive covering layer on the landside of the dike burst due to high water pressure in the aquifer underneath it.
Opdrijven	Heave	Pushing up the capping (soil) package by reaching the boundary potential.

Opkisten		Apply a coffin around a sand entrained well.
Opwaartse druk	Uplift	Water pressure seeking to lift a body of soil or structure.
Overbelasting	Overload	
Overloop	Overflow	
Overschrijdingskans	Probability of exceedance	
Overslag	Overtopping	The amount of water overtopping a structure (e.g., a dike) due to wave action.
Overstromingsrisico	Flood risk	
Piping (pijpvorming)	Piping	The phenomenon of creating a hollow, pipe-like space under a dam due to the failure of the erosion process of a sand entrained well to stop.
Primaire waterkering	Primary flood defence	Water barrier that provides protection against flooding from the sea or major rivers is regulated through the Water Act.
Randvoorwaarde	Boundary condition	
Regionale waterkering	Regional flood defence	Non-primary water barrier, managed by water board and regulated by provincial decree.
Schaardijk	Sheardike	Levee that is directly placed next to the water body, thus without a foreland in between.
Steenzetting, bekleding	Revetment	Lining a bank (with stony material) to prevent its erosion by currents and waves.
Stijghoogte	Head	
Stijghoogte	Phreatic level	
Stijghoogteverschil	Head difference	
Stormvloed	Storm surge	Extreme elevation of the water level (above the astronomical tide) by wind (higher than the level reached once every two years).
Stroomgebied	Catchment	The area that drains naturally at a particular location in a river.
Stroomlijn	Stream line	
Terugschrijdende erosie	Backward erosion	The technical term for the piping process.
Toetsing	Safety assessment	
Toplaag	Cover layer	Topmost layer of a (fractured stone) protection of a structure to protect against hydraulic loading.
Uittreegradient	Exit gradient	
Uittreepunt	Exit point	
Veiligheidsfactor	Factor of safety	
Veiligheidsnorm	Safety standard	
Verzadigd	Saturated	
Volumegewicht	Volumetric weight	
Voorland	Foreland	Land between the dike and the water body.

Voorlandkering		Regional flood defence located outside the diked areas.
Waterkering	Flood defence	
Waterkering beheerders	Water authorities	Government entities that manage the (primary) flood defences
Waterschap	Water board	
Waterstand bij norm (WBN)	Normative water levels	WBN is the datasheet with normative water levels for the Netherlands, based on historical data.
Waterspanning	Pore water pressure	
Watervoerend pakket	Aquifer	Permeable (sand) layer, through which ground water moves freely.
Wel	Well	Place where water (usually vertical) flows with some velocity concentrated from the soil.
Wel	Sand boil	Sand boil is a synonym for well in English.
Wet op de waterkering	Flood defence act	This law has since been incorporated into the Water Act.
WTI: Wettelijk Toetsing Instrumentarium	Legal review instruments	Assessment method that was used in NL before 2017. Replaced by WBI and thereafter BOI.
Zand meevoerende wel	Sand boil	Erosion phenomenon in which seepage water washes out sand; a well that carries sand from the subsurface and can become so uncontrollable that it leads to piping.
Zetten (van grond)	Settlement	
Zettingsvloeiing	Liquefaction	The phenomenon of a saturated sand mass behaving like a liquid due to the loss of grain tension.