Bachelor thesis Civil Engineering:

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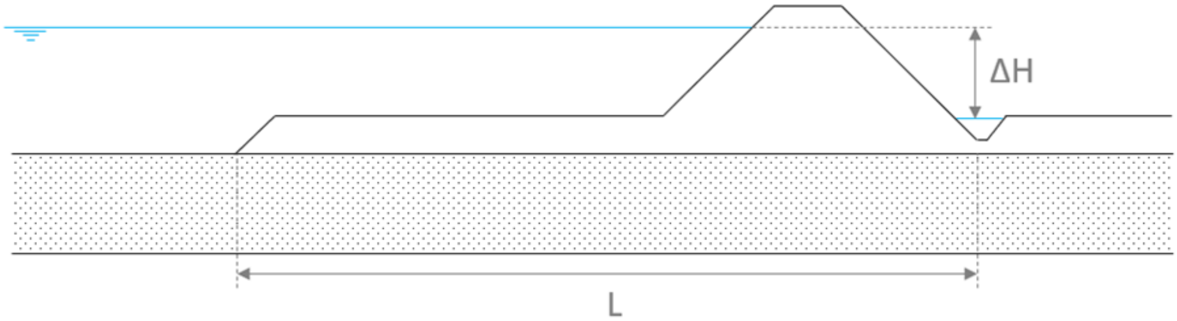
A comparison between the rule of Sellmeijer and D-Geo Flow software for a piping assessment of river dikes with a foreland



Floris Couwenberg

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Preface

This thesis is written 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 consultancy and engineering firm for water, infrastructure, environmental and construction related projects. During the research I learned a lot about the topic of my research: the failure mechanism piping, the application and background of the rule of Sellmeijer, the use and background of the D-Geo Flow software and the assessment of dikes. Besides that I gained knowledge about the engineering practice, projects and tenders.

At start of the thesis the partial lockdown was proclaimed. During the thesis this partial lockdown was transformed into a full lockdown. At the end the even a curfew was introduced to cope with the second wave of the covid-19 crisis. Therefore I had to work from home and do meetings via Microsoft teams for the entire thesis period. Despite these extraordinary circumstances, I enjoyed the experience. I want to thank everyone for his adaptability to the new normal. Because of this I was able to execute my research.

First of all I want to thank ir. David Barmentloo for his supervision, help, advice and feedback for the research. Besides that I want to thank him for the look into the work field of dike assessments. For the support with the D-Geo Flow software I want to thank ir. Guido van Rinsum. I appreciated his clear explanation and practical tips of the D-Geo Flow software. I also want to thank the department of flood defences Deventer for the fun and interesting teams meetings. Finally I want to thank my supervisor from the university of Twente dr. ir. J.H. Damveld for his advice, feedback and help.

Floris Couwenberg

Enschede, January 2021

Summary

Piping or backwards erosion is an important failure mechanism within the safety assessment of the Dutch dikes. The failure mechanism occurs by high water levels, which causes a channel(pipe) under the dike due to the strong seepage flow. For the assessment of this failure mechanism the adjusted rule of Sellmeijer is prescribed to calculate the failure probability of the dikes. However, the adjusted rule of Sellmeijer and several other changes in the safety assessment has led to higher failure probabilities. As a result more dike sections fail to comply with the norms. More advanced piping assessment methods such as the D-Geo Flow software of Deltares can refine this failure probabilities.

The presence of foreland with poorly permeable top layer has a dampening effect on the failure mechanism of piping. The rule of Sellmeijer and D-Geo Flow software have a different approach towards the inclusion of a foreland in the assessment of piping. Therefore it is expected that these differences lead to different outcomes for the piping assessment. In the rule of Sellmeijer formula the foreland is included by an extension of the seepage length. In D-Geo Flow the entire groundwater flow through the foreland is modelled.

For researching the influence of the foreland on the different outcomes between both methods, a standard dike configuration with a foreland is generated. With this standard dike configuration the influence of different parameters on the results of both methods is analysed. The researched parameters are: the foreland length, the conductivity of the piping sensitive layer, the conductivity of the foreland top layer and the thickness of the piping sensitive layer. The results show that D-Geo Flow in general provides more optimistic outcomes than the rule of Sellmeijer. However, this is not the case for low foreland top layer conductivities, there the rule of Sellmeijer is less conservative. The differences are the largest for small piping sensitive layers and long forelands. In further research it is recommended to research the d70 parameters as well in order to improve the results for the conductivity of the piping sensitive layer. Besides that it would be useful to research the effect of the differences between both methods on the failure probability for practical examples. With this the added value of an assessment with D-Geo Flow could be further confirmed.

Table of content

1. Introduction

This section discusses the context, the problem statement, the research questions and methodology of the research.

1.1 Context

1.1.1 Water safety within the Netherlands

Dikes are the most common flood defences within Dutch delta. In order to guarantee and maintain the water safety within the Netherlands, the dikes must be assessed whether they still meet the safety standards. Recently, those standards are adjusted due to environmental and societal changes such as climate change, sea-level rise and economic expanse, but also by new insights and methods to assess dike safety. The safety standards prescribe the flood probability per dike area and are based on the impact of a flooding in that dike area. Hereby the basic safety for every inhabitant a chance 1/100.000 per year dying due to flooding is normative (Rijkswaterstaat, Normen, 2020). Besides that, the standards take the economic value/impact of/on a dike area and groups risk into account. These safety standards are laid down in the water law and oblige the water authorities to assess their dikes every 12 years (Rijksoverheid, 2020). If the dike does not comply with the standard measures are taken in the HWBP (High water protective program) by the Rijkswaterstaat and water authorities (Rijksoverheid, 2020).

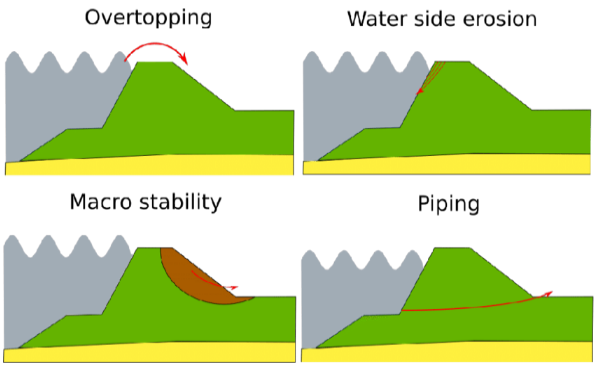

Figure 1 Four important failure mechanisms of dikes (kumar, 2017)

Dikes can fail due to several so-called failure mechanisms. The main four failure mechanisms are overtopping, piping, instability and erosion (Deltares, Faalmechanisme, 2020). These failure mechanisms are depicted in Figure 1. For each failure mechanism the assessment has to follow the procedure from the WBI (Wettelijk Beoordelingsinstrumentarium/Statutory Assessment Instruments) provided by the ministry of infrastructure and environment/Waterstaat. Research institution Deltares is a supplier of the technical content and software for the WBI (Deltares, Wettelijk Beoordelingsinstrumentarium (WBI), 2020). The WBI assessment procedure develops over time, due to new researches, new norms and shift in approach. Currently the WBI 2017 version is operative. In this version the flood probabilities are leading instead of exceedance probabilities within the old version. Hereby the norms shifted a from maximum safe water level to a maximum flooding probability. This shift required knowledge from the first damage till total failure of the flood defense (Deltares, Wettelijk Beoordelingsinstrumentarium (WBI), 2020).

1.1.2 Piping

After the high-water levels in the main rivers in 1993 and 1995 the awareness of the failure mechanism piping raised. The high-water levels showed that piping is an important failure mechanism within the Dutch delta (Hasselt, Everdingen, & partners, 1995). Piping is a type of backwards erosion due to groundwater flow. The groundwater flow creates a pipe under the dike by flushing soil particles in the hinterland of a dike. If this process continuous for too long the dike will collapse, because the flow becomes too strong and the bearing soil of the dike is flushed away. Therefore, more research focused on the failure probability due to piping and the preservation measures for piping. Since then, piping has a more prominent role within the dike assessment criteria. Despite this, VNK 2 research (Dutch safety analysis) revealed that the problem of piping was underestimated (Vergouwe, 2014). Hereby the research indicated that the soil composition of the dike and subsoil is an important factor for dike failure (Rijkswaterstaat, Veiligheid Nederland in Kaart, 2020). In the Netherlands piping prone situations are very common (Förster, van den Ham, Calle, & Kruse, 2012).

1.1.3 Piping assessment in the WBI 2017

The WBI 2017 prescribes the procedure for a pipping assessment of a dike. This procedure contains several steps before a conclusion can be drawn if a dike meets the standard. These steps have an order from broad to refined. The number of steps in this procedure depends on outcome of the intermediate steps, such that unnecessary research is limited to a minimum. The conception in this procedure is: simple when it can and detailed when it has to. In Table 1 the different levels and steps of the assessment procedure can be found.

Table 1 Steps in the piping assessment procedure (Rijkswaterstaat, Schematiseringshandleiding piping, 2019)

Level of detail	Description and application
Simple assessment	This is more a relevance test whether piping is a possible failure mechanism or not. This relevance test contains three components: • The soil composition of the flood defense and sublayer • The duration of the high-water level • The geometry of the flood defense If the soil composition is suitable for piping, the duration of the high-water level is long enough for piping and dimensions or not sufficient the refined assessment is required. If not, the chance of piping is negligible small.
Refined assessment	In the refined assessment the whole failure mechanism of piping is analysed. This includes three different sub-fail mechanisms: burst of the top layer, heave and receding or backwards erosion. These different sub parts have to assessed according a detailed and strict procedure to perform the calculations. These calculations determine whether the dike meets the standards of the WBI, such that the dike is safe enough.
Custom assessment	In case of complex situations or insecurities more appropriated tools, models and calculations can be used to assess piping. In some cases, this is an option when the refined assessment is estimated to be conservative.

In the refined assessment the rule of Sellmeijer is prescribed to assess piping. The rule of Sellmeijer is an equation which describes the relation between the critical water level difference and the dike characteristics, such as dimensions and soil composition. The water level difference is the difference across the dike between the water level in the river and in the polder/hinterland. When the water level difference at a dike exceeds critical water level difference piping is likely to occur. In case this value lower than the critical value piping is not likely to occur (Förster, van den Ham, Calle, & Kruse, 2012). This equation is based on the two forces piping model of Sellmeijer.

> *“Due to several changes in the backward erosion safety assessment in the recent years, such as the inclusion of the length effect, the transition from dikes regulated by the probability of a flood level to a probability of flooding per section of each dike ring, the abandoning of Bligh’s rule and an adjustment in the Sellmeijer rule, more dike sections fail the new (detailed) assessment” (van Beek & Hoffmans, 2017).*

The rule of Sellmeijer in combination with the changes in safety assessment and uncertainty in input parameters results thus in higher failure probabilities. Therefore more advanced and accurate piping assessment methods are necessary (van Beek & Hoffmans, 2017).

1.1.4 Custom assessment

In some cases, more sophisticated methods and models shows that the dikes are safer than the Sellmeijer formula indicates. To preserve unnecessary and costly dike reinforcements, custom made assessments are possible within WBI 2017 to prove the dike safety meets the standards. An example of such a more sophisticated model is the D-Geo Flow software. This software package is also based on the model of Sellmeijer. Furthermore, D-Geo Flow has more advanced features than the rule of Sellmeijer. In D-Geo Flow it is possible to calculate with time depended hydraulic load and more subsoil parameters (Deltares, D-Geo Flow, 2020)& (Deltares, Achtergrond D-Geo Flow, 2020). Besides that, this model has a different approach towards a foreland/floodplain than the rule of Sellmeijer. In D-Geo Flow the whole groundwater flow is modeled by dividing the subsoil into small pieces (Stoop, 2017), but in the rule of Sellmeijer this groundwater flow is further simplified to one entrée and exit point (Rijkswaterstaat, Schematiseringshandleiding piping, 2019). This means that in D-Geo Flow the whole modeled foreland is included in the analysis, but the rule of Sellmeijer changes only the entrée point based on some calculations. Another important difference between the rule of Sellmeijer and D-Geo flow is that the rule of Sellmeijer is fitted for a standard dike configuration (Rijkswaterstaat, Het aangepaste rekenmodel van Sellmeijer - Rekenmodellen en rekenregels, 2020) and in D-Geo Flow a dike can be more customized. Therefore, it is expected that these methods result in different failure probabilities of piping.

1.2 Problem statement

The current assessment methodology of Sellmeijer and the uncertainty in input parameters in combination with the national safety philosophy can result in higher failure probabilities due to piping (van Beek & Hoffmans, 2017)& (Deltares, Achtergrond D-Geo Flow, 2020). Sophisticated models such as D-Geo Flow provide more refined results, which may include lower failure probabilities. Both methods have a different approach towards a foreland, therefore it is expected that this leads to different outcomes in the piping assessment. How large the outcome differences between the rule of Sellmeijer and D-Geo flow are in case of foreland is unknown. Also for which dike situations these differences occur is not clear at the moment.

1.3 Research objective

The aim of this research is to obtain insight into the differences of failure probabilities between rule of Sellmeijer from the WBI 2017 and the D-Geo Flow model for assessing piping in case of a river dike with a foreland/floodplain. The objective is an overview for which situations a customized piping assessment with D-Geo Flow model results in different failure probabilities for piping than the rule of Sellmeijer in case of a river dike with a foreland/floodplain. The purpose of this overview is to indicate if further analysis with the D-Geo Flow software is meaningful to do for reaching the safety standards in case a dike section with a foreland/floodplain does not comply with the safety standards by the Sellmeijer rule. Hereby unnecessary costs in dike assessments as well as in dike reinforcement could be prevented. This overview will consist out of a sensitivity analysis of the important foreland parameters, limitations, simplifications and other technical details of both models. The content of this overview must provide insight for which dike situations with a foreland D-Geo Flow provides less conservative results than the rule of Sellmeijer.

1.4 Research questions

1.4.1 Research question

In order to obtain the research objective the main research question is formulated as follows:

"Too what extent does the critical head from the D-Geo Flow model deviate from the calculated critical head by the rule of Sellmeijer for a dike with a foreland and can this difference be explained by the different approach towards a foreland?"

1.4.2 Sub questions

Besides this main question several sub questions are formulated to sustain the main question and narrow down the scope of the research. These sub questions are as follows:

1. *What are the technical differences between the rule of Sellmeijer from the WBI 2017 and the D-Geo Flow model?*
2. *What is an appropriate dike configuration for this research and which parameters are important for a foreland?*
3. *Which differences can be observed between the results of the rule of Sellmeijer and D-Geo Flow model?*
4. *How can the differences between the results of the rule of Sellmeijer and D-Geo Flow model be explained?*

1.5 Thesis outline

This section describes the structure and methodology of the thesis. In section 2 the background is given about the used concepts, models and methods. The first sub question is answered in section 3 by a literature research to the scientific background of both methods. Than in section 4 the standard dike configuration and set up of the analysis is discussed. Based on section 3 and 4 the second question can be answered. The input for this question exists out of the results from question 1 and meetings with experts on dike assessments. In order to answer question 3 different calculations with both methods are executed. The results in section 5 answers the third question. Also the fourth question is partly answered by section 5 and partly in the conclusion in section 6. Hereby the answers and results of sub question 1 and 3 are used to answer this question. At the end the main question is answered in 0 the conclusion. In section 6 the findings have been discussed and in section 8 the recommendations are presented for further research

2. Background

This section elaborates on the failure mechanism piping. First of all the applied concept of piping in the research is explained. Afterwards the conditions in which piping occurs are indicated and the process of piping is described. Then the background of the piping assessment tools the rule of Sellmeijer and D-Geo Flow is given.

2.1 The failure mechanism piping

2.1.1 Definition

Internationally all internal erosion due to seepage flow is called piping. Hereby four types internal erosion are distinguished: backwards erosion, suffusion, contact erosion and erosion by rifts within the cohesive layer (`t Hart, De Bruijn, & de Vries, 2016). In Table 2 there is a description what each type is. However, in the Netherlands the term piping is only used in case of backwards erosion through the dike, because this type is relevant within the Netherlands. The other types are not likely to occur, due to the soil and dike characteristics in the Netherlands (`t Hart, De Bruijn, & de Vries, 2016). In this research will focus only on backwards erosion. Therefore, the term piping signifies backwards erosion in this report

Table 2 Description of the four types of internal erosion (`t Hart, De Bruijn, & de Vries, 2016)

Type of erosion	description
Backwards erosion	This erosion occurs due to a concentrated seepage flow through a dam or dike that carries sand particles with it. The erosion starts at the downstream part and creates a channel or pip towards the flow direction
Suffusion	The smaller particles are washed out the skeleton of larger particles. The skeleton of larger particles remains intact. This type of erosion is only possible when there is a highly non-uniform grain distribution.
Contact Erosion	This erosion occurs when a layer of coarse material is in contact with a layer of fine material. Hereby the layers are exposed to groundwater flow that washed the fine layer through the coarse layer away.
Erosion by rifts within the cohesive layer	The rift can enhance the groundwater flow due to the concentration of flow patterns through the rift. This may lead to erosion and further widening of the rifts. However, this type of erosion is also possible when a split below the flood defense is present.

2.1.2 Piping conditions

Piping is a failure mechanism that occurs during high water levels by dikes and dams that are poorly permeable or not permeable at all, but also have a permeable sandy subsoil layer beneath them. This sublayer is called an aquifer or piping prone layer, because the seepage will flow through this layer and is able to cause some backwards erosion within this layer. However, this seepage flow and backwards erosion is only possible when there are so called exit and entrée points. The entrée point is the point where the aquifer layer is in touch with the water. This is the spot where also large part of the inflow of the seepage takes place. The exit point is where the seepage flow meets the surface of the hinterland, mostly a burst into the ground level or the bottom of a ditch. At this location the water must be able to flow into the hinterland and deposit the sediments from the sand layer (`t Hart, De Bruijn, & de Vries, 2016). The entrée and exit points define the seepage length which is an parameter for how likely it is that piping occurs. The presence of foreland can extend the location of the entrée point, so the seepage length increases. Therefore, a foreland can have a reducing effect on the chance of piping, but cannot be an exclusion when the aforementioned conditions apply. Since these specific conditions must be present for piping, not all dikes or flood defenses are piping prone, for example sand dikes and dunes (Förster, van den Ham, Calle, & Kruse, 2012).

2.1.3 The mechanism of piping

The backwards erosion or piping is not one process. It takes several steps and conditions before a real pipe evolves. First of all, the conditions as early mentioned must be present.

1. When all the aforementioned conditions are present the ground water or seepage flow must be strong enough to burst the (poorly permeable) top layer of the hinterland open. This occurs when the pore pressures in the sublayer exceed the weight of the top layer (`t Hart, De Bruijn, & de Vries, 2016).
2. Through this first burst water streams towards ground level of the hinterland. This is the result of the pore pressure from the sub layer and the lower conductivity of the top layer (`t Hart, De Bruijn, & de Vries, 2016). This burst is called the exit point.
3. When this stream is strong enough it causes erosion in the sub layer. Sand will be transported towards the ground level of the hinterland. This results in a sand boil within the hinterland (`t Hart, De Bruijn, & de Vries, 2016).

4. If this erosion is still continuing for some time the erosion migrates towards the source of the seepage, the so-called entrée point. The migrating erosion creates a pipe or erosion channel beneath the dike (`t Hart, De Bruijn, & de Vries, 2016).
5. After some time, the pipe or erosion channel becomes so large that it is connected towards the water of the river. The erosion channel will become larger and larger. The dike will be flushed away or collapses due to this stream (`t Hart, De Bruijn, & de Vries, 2016).

Phase 1: seepage *Phase 3: widening of pipe*

Phase 2: backward erosion *Phase 4: failure of the levee*

Phase 2: backward erosion *Phase 4: breakthrough*

Figure 2 Visual display of the piping process (Andrew Robbins & van Beek, 2015)

These steps form briefly the whole mechanism of piping. However, piping could be subdivided in smaller mechanisms. Step 1 and 2 are also known as eruption. Step 3 is called heave and step 4 and 5 are called backwards erosion. These three sub mechanisms must be assessed separately, despite it seems to be one mechanism. However, the sub mechanisms are technically very different. The mechanisms are dependent on each other. If eruption is not possible than heave will not occur. The same counts for if heave will not occur receding erosion is not possible. Therefore, it is also useful to assess them separately.

2.2 The rule of Sellmeijer

In order to estimate whether piping will occur or not several calculation methods have been developed. However, some of them are not relevant, applicable or sufficient accurate anymore. Therefore, the rule of Bligh is abandoned and replaced by the adjusted Sellmeijer rule in the WBI 2017 (van Beek & Hoffmans, 2017). The rule of Sellmeijer represents the backwards erosion part of the failure mechanism piping. It describes the relation between the critical head difference and the 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 (Sellmeijer, de la Cruz, van Beek, & Knoeff, 2011). This equation is constructed by executing a large number of calculations with the numerical variant of the Sellmeijer model for several relevant parameters. The results of these calculations were used to derive a formula that approximates the results, by using a precise curve fitting method. This formula is validated for standard Dutch dike configuration (Förster, van den Ham, Calle, & Kruse, 2012).

In the piping model of Sellmeijer it is assumed that the backwards erosion process is dominated by the sediment transport conditions in the bottom of the pipe. The model could be described as an equilibrium model which calculates the critical head. When the critical head is not exceeded the piping channel reaches an equilibrium. If the critical head is exceeded the process of piping will progressively increase until failure (Stoop, 2017). The original conceptual model considers four forces. Two horizontal ones: the drag force and horizontal flow force. The two vertical ones consist out of the weight of a particle and the vertical flow force (Sellmeijer, de la Cruz, van Beek, & Knoeff, 2011). This model is only valid when a soil particle is embedded between other particles. In case of a pipe or erosion channel in a dike this is no longer valid. The horizontal and vertical flow force are not relevant in that situation. Therefore, the model is changed into a two forces model. Due to this modification the formula is modified as well. This adjusted rule of Sellmeijer is calibrated by small-scale, medium-scale and IJkdijk experiments (Sellmeijer, de la Cruz, van Beek, & Knoeff, 2011) Hereby several changes are added and validation for Dutch soil is used in order to comply with the Dutch practice, because the exact physics is not understood (Förster, van den Ham, Calle, & Kruse, 2012). This calibrated and adjusted version is within the WBI 2017.

2.3 D-Geo Flow

Different adjustments and tightening in the safety assessment provoked a need for more advanced piping assessment methods (Deltares, Achtergrond D-Geo Flow, 2020). In order to assess these complex situations the D-Geo Flow software is developed by Deltares in collaboration with Rijkswaterstaat (Rosenbrand & van Beek, 2017). D-Geo Flow is a graphical user interface for 2D groundwater flow calculations based on the DGFlow calculation platform (Deltares, Achtergrond D-Geo Flow, 2020). For those groundwater calculations the software makes use finite element method (FEM). The finite element method is a numerical method for solving engineering problems. It divides the problem domain in triangular elements with nodes, for each node a set of requirements or equations that must be solved (Stoop, 2017). The software contains a piping module based on Sellmeijer, which is able to determine the critical water head for a certain water level. The D-Geo Flow is able to perform transient and steady state calculations. Also it is possible to include time dependent hydraulic load, different subsoil layers, compressibility of the soil, compressibility of the groundwater and change of the phreatic line (Deltares, D-Geo Flow, 2020)& (Deltares, Achtergrond D-Geo Flow, 2020).

3. Technical Details

This chapter focusses on the technical aspects of both methods. It discusses their parameters, drawbacks, applicability, simplifications, assumptions and limitations.

3.1 The rule of Sellmeijer formula

The rule of Sellmeijer formula based on the two force model described by Sellmeijer is depicted below in equations 1, 2, 3 & 4. The formula considers a homogeneous sandy sublayer with a constant depth. This formula is valid for a standard dike configuration as depicted in Figure 3. The seepage length is determined by the horizontal distance by the dike toe and the exit point see Figure 3. The exit point is on the spot where it is the most likely that soil bursts under the water pressure. The formula consists out of three factors, the resistance factor, the scale factor and the geometry factor. The first factor describes the equilibrium of the sand particles on the bottom of the pipe. The second factor reflects the ratio between the scale of the particle transport mechanism and the scale of the groundwater flow, which drives this mechanism. The third factor describes the influence of the geometry of the subsoil on the groundwater flow.

$$\frac{H_c}{L} = F_{resistance} F_{scale} F_{geometry} \qquad \text{Equation 1}$$

$$F_{resistance} = \frac{\gamma'_p}{\gamma_w} \eta \tan(\theta)$$

Equation 2

$$F_{scale} = \frac{d_{70m}}{\sqrt[3]{\kappa L}} \left(\frac{d_{70}}{d_{70m}}\right)^{0,4}, \kappa = \frac{v}{g} * k$$

Equation 3

$$F_{geometry} = 0{,}91 \cdot \left(\frac{D}{L}\right)^{\frac{0,28}{\left(\frac{D}{L}\right)^{2,8} - 1} + 0,04}$$

Equation 4

Table 3 Parameters of the rule of Sellmeijer and their units (Rijkswaterstaat, Schematiseringshandleiding piping, 2019)

Parameters	description
H_c	critical head across the flood defense [m]
γ'_p	(probable) volume weight of sand particles below water [kN/m^3]
γ_w	volume weight of water [kN/m^3]
θ	rolling resistance angle of sand particles [°]
η	coefficient of White [-]
κ	intrinsic permeability of the piping sensitive sand layer [m^2]
d_{70}	70 percentile value of the grain size distribution [m]
d_{70m}	average d_{70} of the small-scale experiments (2,08 E-4 m)
D	thickness of sand layer [m]
L	seepage length horizontal [m]
k	Darcy conductivity of the piping sensitive layer [m/s]
v	Kinematic viscosity [m^2/s]
g	Gravitational constant [m/s^2]

3.1.1 Foreland and fictitious entry point

This formula for the standard situation does not incorporate a foreland. A foreland with poorly permeable top layer has reducing effect on piping, because it can prolong the seepage length and can reduce the inflow towards the piping sensitive layer. In order to include this within Sellmeijer the seepage length can be increased within the rule of Sellmeijer. The size of this extension of the seepage length can be determined by the equation 5 & 6 in the WBI 2017. These formulas describe where the so-called fictitious entry point is, based on the soil characteristics of the foreland. Important parameters for the fictitious entry point are the length foreland, the thickness and conductivity of the top layer. Depending on the foreland characteristics the whole or a part of the foreland is added to the seepage length. In this way the rule of Sellmeijer takes the strength and the uncertainty of the foreland with a homogenous poorly permeable layer into account.

$$L'_v = \lambda_1 \tanh\left(\frac{L_v}{\lambda_1}\right)$$

Equation 5

$$\lambda_1 = \sqrt{\mathrm{kDd_1/k_1}}$$

Equation 6

$$In\ case\ of\ \frac{L_v}{\lambda_1} < 0{,}5 \quad L'_v \approx L_v$$

$$In\ case\ of\ \frac{L_v}{\lambda_1} > 2 \quad L'_v \approx \lambda_1$$

Table 4 Parameters and their units for the Leak length and fictitious entry point equations

Parameters	Description
$\boldsymbol{L'_v}$	Prolongation of the seepage length in direction of the outside water [m]
$\boldsymbol{L_v}$	Seepage length [m]
$\boldsymbol{\lambda_1}$	Leak length [m]
D	Thickness of the permeable sublayer [m]
k	Conductivity of sublayer [m/day]
$\mathbf{d_1}$	Thickness of the poorly permeable top layer of the foreland [m]
$\mathbf{k_1}$	Conductivity of the poorly permeable top layer of the foreland [m/day]

3.1.2 0,3d rule

In situations with a poorly permeable top layer on a piping sensitive layer a vertical burst channel is present. This vertical burst channel arise after bursting and heave. This burst channel is described as the exit point and forms the start of the seepage channel. The rule of Sellmeijer only assess the horizontal backwards erosion in the aquifer layer. To account for resistance due to the fluidized sand particles in the vertical burst channel, the head drop across the flood defence can be lowered by a factor of 0,3d for the assessment. The d stands for the thickness of the top layer at the exit point. This reduction is known as 0,3d rule (Förster, van den Ham, Calle, & Kruse, 2012).

3.1.3 Converting critical head into failure probability

In the Dutch water safety policy the failure probability and corresponding risks are leading. Therefore, the calculated critical head have to converted to a failure probability. For this purpose the stability factor must be derived first by using equation 7. This factor determines whether piping will occur or not.

$$F_p = \frac{\Delta H_c}{\left(h - h_{exit} - r_c D_{toplayer}\right)}$$

Equation 7

With the correlation in equation 8 the stability factor for a scenario can be converted into a failure probability.

$$P_{f,p} = \Phi\left(\frac{\ln\left(\frac{F_p}{1.04}\right) + 0.43\beta_{norm}}{0.37}\right)$$

Equation 8

Table 5 Description and units of the parameters for calculating the failure probability and stability factor

Parameters	description
$\boldsymbol{F_p}$	Stability factor for backwards erosion [-]
$\boldsymbol{\Delta H_c}$	Critical head [m]
$\boldsymbol{h}$	Water level in the river relative to NAP with a probability equal to the norm [m]
$\boldsymbol{h_{exit}}$	Phreatic level, or height of the ground level, at the exit point relative to NAP [m]
$\boldsymbol{r_c}$	Reduction factor for the resistance at the exit point [0,3]
$\boldsymbol{D_{toplayer}}$	Thickness of the top layer at the exit point [m]
$\boldsymbol{\beta_{norm}}$	Reliability index of the dike trajectory [-]
$\boldsymbol{P_{f,p}}$	Failure probability for backwards erosion [1/year]
$\boldsymbol{\Phi}()$	Standard (cumulative) normal distribution [1/year]

3.2 Limitations and assumptions of the rule of Sellmeijer

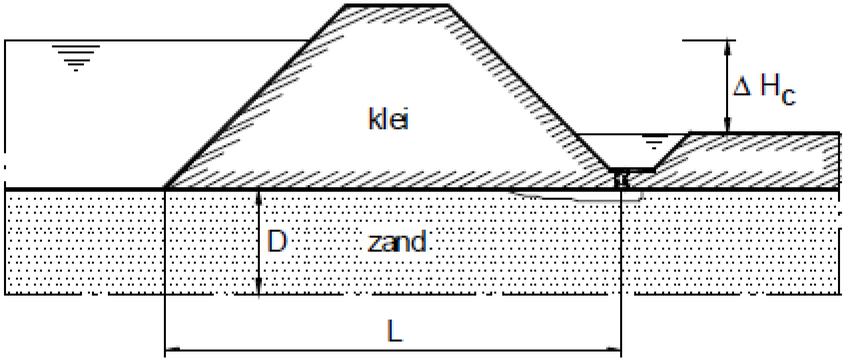

Figure 3 Standard dike configuration for the rule of Sellmeijer (Förster, van den Ham, Calle, & Kruse, 2012)

The analytical piping model of Sellmeijer simplified the piping problem, by considering a relative simple geometry with a homogeneous aquifer, beneath and impermeable (clay) dike, constant head boundaries at both sides of the dike and steady state flow (Stoop, 2017).This assumptions resulted in a standard dike configuration for which the rule of Sellmeijer is constructed and validated. Therefore, this empirical formula is only valid for range in which the formula is tested (Förster, van den Ham, Calle, & Kruse, 2012). The formula performs well for these conditions, however for more advanced configurations it must be taken into account that this formula is less appropriate. An important example for this research is that the formula of Sellmeijer is not validated when the inflow into the pipe is via the top layer of the foreland. Because, the formulas that describe the influence of the foreland are no longer valid when the pip grows beneath the top layer of the foreland. For this problem a rule of thumb is used to determine whether the full fictitious foreland length can be included or not in the piping assessment. This rule of thumb says that when seepage length exceeds two times the Dike base more checks and field work is required to include the full fictitious foreland length. These checks can consist out of monitoring well measurements of the flooded foreland from which can be concluded that there will be no inflow into the pipe or with groundwater flow models, which include the mechanism of piping (Rijkswaterstaat, Schematiseringshandleiding piping, 2019).

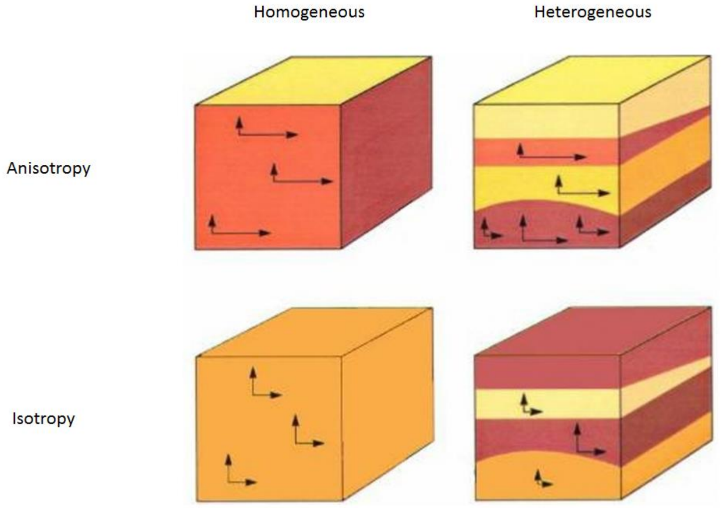

Figure 4 overview of anisotropy, isotropy, heterogeneity and homogeneity (Stoop, 2017)

Besides this standard dike configuration the rule of Sellmeijer has more underlying assumptions and simplifications from the Sellmeijer model. The Sellmeijer model uses equations for laminar and incompressible flow in the pipe (van Beek & Hoffmans, 2017). As earlier mentioned in 2.2 the model behind the rule of Sellmeijer assumes that the backwards erosion process is dominated by the sediment transport conditions at the bottom of the pipe. Another important assumption or simplification in the rule of Sellmeijer is that the soil layers are homogenous but also are isotropic. Isotropy means that the physical properties are not directional dependent, which is different than homogeneity that describes a difference in physical properties between two or more elements or layers (Stoop, 2017). The opposites anisotropy and heterogeneity in the soil layers are not included within the rule of Sellmeijer. In Figure 4 a clarification is depicted of homogeneity, heterogeneity, isotropy and anisotropy of soil layers. The rule of Sellmeijer also assumes that the pipe progresses in straight horizontal line.

3.3 Scientific background of D-Geo Flow

3.3.1 Boundary along the erosion channel

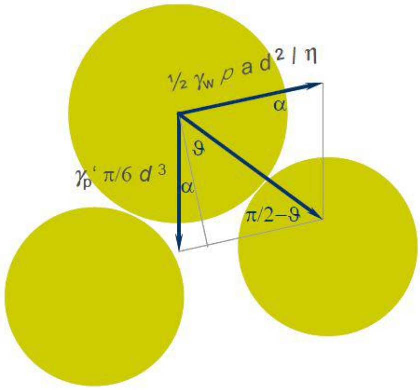

Figure 5 Two force balance on the top grain (Sellmeijer J.)

The piping module in D-Geo Flow is also based on the same model of Sellmeijer as the rule of Sellmeijer, which considers a force balance at the bottom of the erosion channel. However the application in this software is different than in the rule of Sellmeijer. In D-Geo Flow the boundary along the pipe equation (Equation 9) written by (Sellmeijer J.) is used to describe this force balance at the bottom of the erosion channel. This expression for the boundary condition along the erosion channel considers the continuity condition in the erosion channel and the limited stress state of the bottom particle. The condition of limiting stress state imposes a balance between the shear stress force along the channel and the weight of a spherical particle according Sellmeijer (Stoop, 2017).

$$\sqrt[3]{\frac{Q}{kL}p_c^2} = \frac{\pi}{3}\eta\frac{\sin(\theta+\phi)}{\cos(\theta)}\frac{d}{\sqrt[3]{12\kappa L}} \qquad \text{Equation 9}$$

Table 6 Variables and their units in the boundary along the pipe equation (Stoop, 2017)

Variable	Description
$\boldsymbol{Q}$	Erosion channel discharge [m^2/s]
$\boldsymbol{p_c}$	Erosion channel gradient [-]
$\boldsymbol{\theta}$	Bedding angle [°]
$\boldsymbol{\phi}$	Slope of the channel [°]
$\boldsymbol{d}$	Particle diameter [m]
$\boldsymbol{L}$	Dike width [m]
$\boldsymbol{\eta}$	Whites coefficient [-]
$\boldsymbol{\kappa}$	Intrinsic permeability [m^2]

3.3.2 Subsurface flow

Another important equation implemented in D-Geo Flow describes the groundwater flow. The subsurface flow equation (equation 10) in D-Geo flow describes the flow through a partly saturated porous medium. This equation considers the conservation of mass and a generalization of Darcy's law. This equation is also known as the storage equation. The problem definition is completed by two types of boundary conditions; the Dirichlet and the Von Neumann boundary conditions. The Dirichlet boundary conditions prescribe the pressure on parts of the boundary and Von Neumann boundary conditions prescribe the derivative of the pressure or flux on the boundary (Deltares, Finite Element Model DGFlow in Delta Shell manual, 2018).

$$(\alpha + n\beta)S\frac{\delta p}{\delta t} + n\frac{dS}{dp}\frac{\delta p}{\delta t} + \frac{\delta q_i}{\delta x_i} = 0 \text{ on } \Omega^p$$

Equation 10

$$\alpha = \frac{1}{\lambda + 2v}$$

$$q_i = -\frac{k_r \kappa_{ij}}{\mu}\left(\frac{\delta p}{\delta x_i} - \rho^l g_j\right)$$

Table 7 Variables and units of the subsurface flow equation (Stoop, 2017)

Variable	Description
$\boldsymbol{\alpha}$	the compressibility of the soil skeleton [m^2/N]
$\boldsymbol{\beta}$	the compressibility of the pore water [m^2/N]
$\boldsymbol{n}$	porosity [-]
$\boldsymbol{S}$	the degree of saturation of the liquid phase in the void space [-]
$\boldsymbol{p}$	pore pressure [m^2/N]
$\boldsymbol{\lambda, v}$	Lame's constant [N/m^2]
$\boldsymbol{q_i}$	specific discharge [m/s]
$\boldsymbol{k_r}$	elative permeability [-]
$\boldsymbol{\kappa_{ij}}$	intrinsic permeability [m^2]
$\boldsymbol{\mu}$	the dynamic viscosity of liquid [kg/(m·s)]
$\boldsymbol{\rho^l}$	the density of liquid [kg/m^3]
$\boldsymbol{g_j}$	gravitation acceleration in y-direction [m^2 s]
$\boldsymbol{t}$	time [s]
$\boldsymbol{\Omega}$	the flow domain [m^2]

3.3.3 Finite Element Method

This implemented groundwater equation in the mathematical model is solved by the finite element method. As earlier mentioned in section 2.3 The method divides the system into triangular elements, hereby every triangular element is defined by three nodes, one at each corner. With this the method is able to solve a set of algebraic equations in which the unknowns are the heads at finite numbers of nodal points. In this system the nodes are computed within the problem domain. In order to obtain the value within each element the nodal heads are interpolated. When the unknowns are defined the values will be computed. In Figure 6 an example is given of the finite element grid in D-Geo Flow.

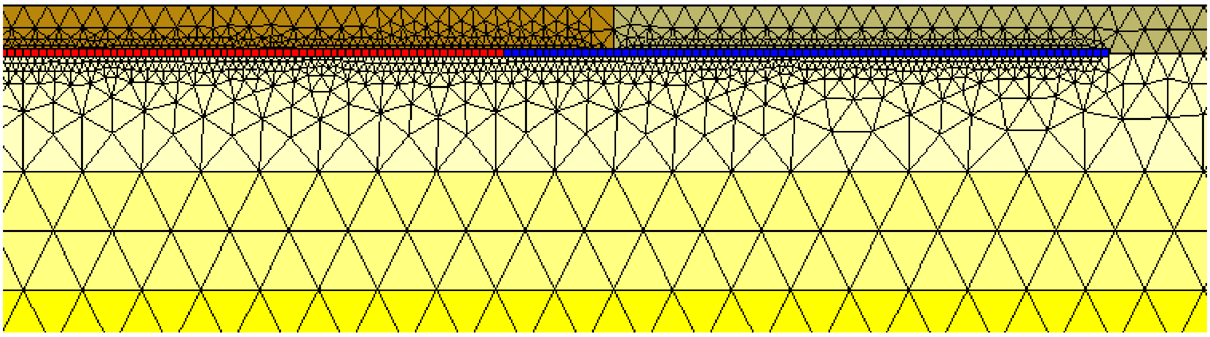

Figure 6 Cross section in D-Geo Flow with grid and pipe

3.3.4 Piping module

The piping module has different approach than the finite element method. The software divides the defined pipe into small square elements. The equilibrium for each element is calculated by the software in order to check whether a pipe arises within the element. When an element is not in equilibrium, the element will change into a pipe. If an element is changed into a pipe the software proceeds to the next time step where it continues with the next element. When an element is in equilibrium, the element will not change into the pipe, but the software still continues to the next time step. In this next step the software will calculate the equilibrium of the element again and continues to the next element if necessary. This process continues until the pipe growth reaches the critical head. Then the pipe will continue to grow in one step to the entry point in the foreland or outside dike toe (van Klaarbergen, 2019). In Figure 6 the pipe in D-Geo Flow can be seen, the red squares indicate the parts that are still in equilibrium and the blue parts indicate the evolved pipe.

3.3.5 Application of the 0,3 rule within D-Geo Flow

In D-Geo Flow the top layer is physically included and the burst channel can be physically modelled by a gap in the top layer in the hinterland. This difference pertaining to the rule of Sellmeijer affects how the 0,3d rule must be applied. For several situations the modelling of the burst channel by a gap is not appropriate enough, because the model will not respond correctly to these situations. Therefore it is proposed to include 0,3d rule by using the heave boundary conditions in D-Geo Flow (Van Beek, 2019). This heave boundary is defined in equations 11 & 12.

$$p_i < P \Longrightarrow Q_i = 0$$ *Equation 11*

$$Q_i > 0 \Longrightarrow p_i = P$$ *Equation 12*

Table 8 Description of the variables in the heave boundary

Variables	description
$\boldsymbol{Q_i}$	Flow [m^2/s]
$\boldsymbol{p_i}$	Pressure [N/m^2]
$\boldsymbol{P}$	User defined pressure [N/m^2]

This heave boundary closes the nodes to which the boundary is assigned if the nodal pressure is smaller than the user defined pressure. However when the pressure is higher than the user defined pressure P, water flow is allowed and the pressure is equal to the value of P. This heave boundary prevents water flow towards the river when the water head in the hinterland is higher. Besides the upwards flow through the burst channel and top layer is correctly distributed by this boundary. With this boundary it is not necessary to model the burst channel by a gap in top layer (Van Beek, 2019). The value of P represents the resistance in the burst channel, which can be determined by equation 13 (Van Beek, 2019).

$$P = \rho g(h_{exit} - z) + 0.3D_{deklaag}\rho g$$ *Equation 13*

Table 9 Variables to calculate the user defined pressure

Variables	description
$\boldsymbol{P}$	User defined pressure [N/m^2]
$\boldsymbol{\rho}$	Water density [kg/m^3]
$\boldsymbol{g}$	Gravitational acceleration [m/s^2]
$\boldsymbol{h_{exit}}$	Polder level [m]
$\boldsymbol{z}$	Level of the heave boundary [m]
$\boldsymbol{D_{deklaag}}$	Thickness of polder blanket layer [m]

3.3.6 From D-Geo Flow model to failure probability

The output of D-Geo Flow is an equilibrium head drop, which is the head drop with a corresponding pipe length. These results are depicted in a graph. The critical head drop is the last head drop before the pipe reaches its maximum length beneath the whole dike and foreland. This critical head drop can be converted into a failure probability in the same way as the critical head of Sellmeijer in section 3.1.3.

3.4 Limitations and sidenotes for D-Geo Flow

Despite that D-Geo Flow has more features and applicability's for assessing piping than the rule of Sellmeijer, it has still some practical as well as theoretical limitations and drawbacks.

- The pipe can only be located beneath the poorly permeable dike and foreland on top of the aquifer layer in D-Geo Flow. Besides, it is not possible to calculate vertical erosion. This makes D-Geo Flow only useful and reliable when the pipe progresses in a straight line (Stoop, 2017).
- The user interface of D-Geo Flow is relativity simple and therefore easy to operate. On the contrary the implementation of advanced and complex situations is very time-consuming or still even impossible (Stoop, 2017).
- D-Geo Flow performs as an black box, because the performed calculations of the model are not visible. Only the input and output can be viewed. This makes it hard to detect and observe errors (Stoop, 2017).
- D-Geo Flow can only perform 2D groundwater flow calculations. So, the effect of variation over length is cannot be included in the calculations.
- It is in D-Geo Flow impossible to operate the model by coding in a programming language. This can speed up the process and contributes to automation (van Rees, 2019).
- D-Geo Flow will not provide relevant output, when the inputted water level is not high enough to reach critical water height. Therefore unrealistic or not normative values have to be used to obtain the critical water height (van Klaarbergen, 2019).
- The software has long run times. Especially when accuracy or the size of the model increases. This is not convenient for dike assessments with a large foreland, because an assessment with large foreland requires a larger model to include this foreland. A larger model increases the number of calculations and iterations. Accuracy requires run time therefore a tradeoff must be made between the accuracy and the run time.

4. Set-up of the analysis

This section describes the research set up of the quantitative aspect of the research. It describes the configurations that are used within the analysis. Also in this section is explained how these configurations are modelled in D-Geo Flow and which settings are used for this. In addition this section provides an overview which parameters are used in the analysis for the rule of Sellmeijer as well as D-Geo Flow.

4.1 Methodology of the analysis

The purpose of this analysis is to have insight for which parameters the outcome of rule of Sellmeijer deviates from D-Geo Flow. For this purpose a standard dike configuration with a foreland is constructed, where the difference between D-Geo Flow and Sellmeijer is minimal. For this situation D-Geo Flow is verified by the rule of Sellmeijer, such that the model will perform correctly. This is done to preserve that the different outcomes of both methods rely on modelling or input defects in D-Geo Flow. This constructed standard situation is used to test the influence of the parameters on the outcome. Hereby the input or model is adapted to obtain the results for the different values of a certain parameter.

The researched parameters are: the thickness of the piping sensitive sand layer, the conductive of the piping sensitive sand layer, the conductivity of the foreland top clay layer and the length of the foreland. The thickness of the clay layer is for this research out of scope since this overlaps with the results of the conductivity of the clay layer, because in the rule of Sellmeijer the increasing the thickness of the top layer has the same effect as decreasing the conductivity of the clay layer. These parameters are inversely proportional, an increase by 2 times the conductivity of clay will have the same effect as an decrease 2 times the thickness of the layer. For D-Geo Flow more or less the same applies, therefore this is not included on the analysis.

4.2 Global input variables and settings

D-geo flow and Sellmeijer have a number of parameters and settings that are not particular for a foreland and therefore not further analysed within this research. Most of these parameters are standard physic properties. These standard physic properties are valid for the Dutch dikes and recommend by the schematization manual piping (Rijkswaterstaat, Schematiseringshandleiding piping, 2019). Besides D-Geo Flow has several settings that determine the accuracy of the outcome, but also affect the run time.

4.2.1 Standard values within dike assessments

In Table 10 the standard physic values for this analysis are depicted. These values are recommended by the schematization manual and are valid for the standard dike configuration. These values are the same for the rule of Sellmeijer and D-Geo Flow. However, D-Geo Flow uses different units, therefore the values have to converted to other units.

Table 10 Standard values within dike assessments

Parameters	Description	Value	Unit
$\boldsymbol{\eta}$	Coefficient of White	0.25	-
$\boldsymbol{\gamma_w}$	Volumetric weight of water	10	kN/m^3
$\boldsymbol{\theta}$	Bedding angle	37	°
$\boldsymbol{v}$	Viscosity of water	$1.33*10^{-6}$	m^2/s
$\boldsymbol{g}$	Gravitational constant	9.81	m/s^2
$\boldsymbol{d_{70m}}$	Average d70 value	$2.08*10^{-4}$	m

4.2.2 Standard D-Geo Flow settings

The following settings and standard values are used within D-Geo Flow.

- **Mpicard value:** This value controls the step size by which the pipe height is adjusted to achieve an equilibrium in the pipe. The higher this value the higher the accuracy, which also results in longer calculation times. A Mpicard value of 1000 is recommended by (Deltares, Finite Element Model DGFlow in Delta Shell manual, 2018). This value is the optimum between the run time and required accuracy, therefore used within this research. A less accurate pipe height results in a lower critical head, that is unnecessary conservative. The step size of the can be derived as follows: $step\ size = 100 * \frac{d70}{Mpicard}$ (Rosenbrand & van Beek, 2017)
- **Advanced mode:** If this mode is on true the model is able to implement the heave boundary as described in section 3.3.5. If this mode is on false the exit point can be modelled by a gap in the top layer or by ditch. In this research the heave boundary is used, because it is easy to implement and it models the exit point appropriate for this research. Therefore the advanced mode was set on true.
- **Time steps:** Time steps is also a parameter for accuracy within D-Geo Flow. It determines step size for the water level raise in the river. For this parameter also counts the more steps the higher the accuracy, but it increases the run length too. The amount of time steps is set to 50, this is also tradeoff between accuracy and run times. In this

research also the Rule of Sellmeijer used to determine the critical head. This already provides an indication of the outcome of D-Geo Flow. Therefore, implemented the water level input was already in the range of the critical head. This saves calculation time since less time steps are required to obtain a certain accuracy due the smaller range of the water levels. Because, the smaller range requires less time steps than a bigger range for the same accuracy.

- **Output step interval:** This value determines how often output is denoted. This value was set to 1. Otherwise the amount of data points will be lower which is not favorable for the analysis

4.3 Standard dike configuration

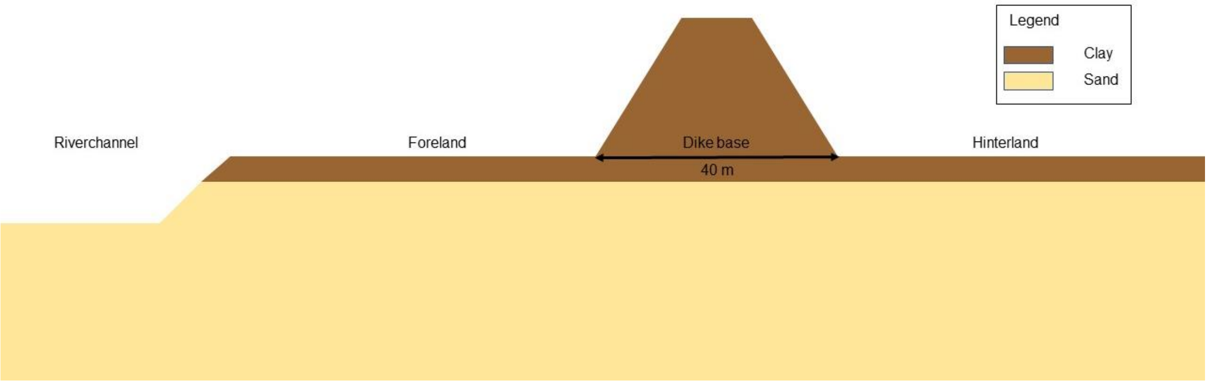

Figure 7 Standard dike configuration with a foreland

As can be seen in Figure 7 a standard dike configuration with a foreland is depicted for the sensitivity analysis. In this configuration a dike base of the 40 m is used roughly derived from the Figure 8, which is an average geometry of Dutch river dikes. This average is determined by the HKV profielengenerator. The HKV profielengenerator uses the Actueel Hoogtebestand Nederland(current height file of the Netherlands) to generate dike geometries. The Actueel Hoogtebestand Nederland is a database that contains the elevation data of the Netherlands. The selection for the average geometry is not based on any random dike, but is based on likelihood that piping will occur at that location (Stoop, 2017).

The used data is filtered on:

- the presence of a piping sensitive region.
- the absence of relative wide inland berm and foreshore.

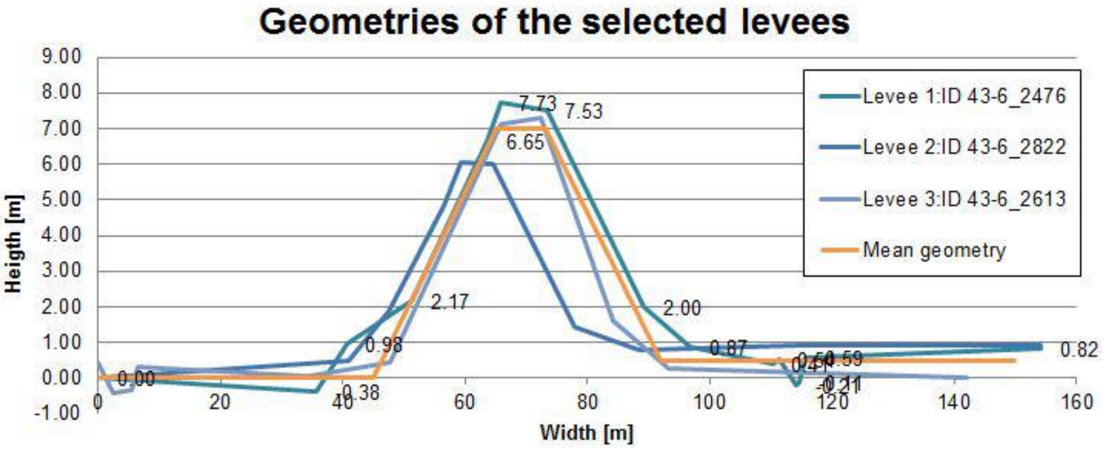

Figure 8 Geometries generated by the profielen generator of HKV (Stoop, 2017)

For the standard dike configuration a sand layer thickness of 30 is used. This is representative value for a standard dike configuration according to (Stoop, 2017)& (van Rees, 2019). The standard foreland length is set 50 meters. This value is chosen to include a significant foreland for which the run times are limited. The thickness of the foreland top layer is set to 2 meters, which is considered to be an representative value. This value is often used in researches with D-Geo Flow. The volume weight of the sand particles below water of 16,5 kN/m^3 is derived from the schematization manual of piping (Rijkswaterstaat, Schematiseringshandleiding piping, 2019). This value is standard applicable for the Netherlands. The standard conductivity of the foreland top layer and the piping sensitive layer is set to 0.00652 and 6.52 m/day respectively. The d_{70} value is set to 0.0002 m. The permeabilities and the d_{70} value are default values in D-Geo Flow, for which is expected that the difference between the rule of Sellmeijer and D-Geo Flow is minimal.

Table 11 Overview of the used parameters for the standard dike configuration with foreland

Parameters	Description	Value	Unit
γ'_p	(probable) volume weight of sand particles below water	16.5	kN/m^3
d_{70}	70 percentile value of the grain size distribution	0.0002	m
$\mathbf{d_1}$	Thickness of clay top layer	2	m
D	Thickness of the sand layer	30	m
L_v	Length of the foreland	50	m
$\mathbf{k}$	Conductivity of piping sensitive layer	6.52	m/day
$\mathbf{k_1}$	Conductivity of the poorly permeable top layer of the foreland	0.00652	m/day

4.4 Modelling of the standard dike within D-Geo Flow

This section describes how the standard dike configuration is modelled in D-Geo Flow. In D-Geo Flow parameters are differently implemented than in the rule of Sellmeijer, because Sellmeijer is empirical formula and D-Geo Flow a groundwater flow model. Besides D-Geo Flow has more advanced settings than the rule of Sellmeijer which are not used for this research, because the research focuses on the influence of the foreland. These advanced settings are not considered by the rule of Sellmeijer and will lead to different outcomes. Therefore, only steady state flow independent from time is modelled, hereby the compressibility soil and water is in D-Geo Flow set to 0 for this purpose. Also the soil is considered to be isotropic model, this means that the vertical and horizontal Conductivity in D-Geo Flow are equal.

Another issue in D-Geo Flow is that parameter are slightly different implemented than in the rule of Sellmeijer. An example of this in D-Geo Flow is that only the density can be implemented and not the (probable) volume weight of weight of the soil. Therefore an equivalent value of 2650 kg/m^3 is used. Hereby the saturation degree is set to saturated to account for the submerged conditions of the soil.

4.4.1 Cross section

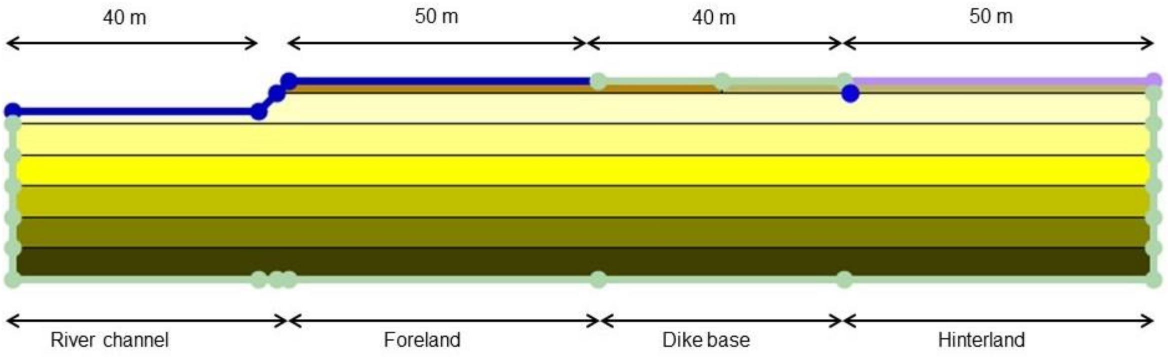

Figure 9 Cross section with dimensions of the D-Geo Flow model

The standard dike configuration for the sensitivity analysis is constructed as follows in D-Geo Flow see Figure 9. First of all the dike is for this analysis modelled as an no flow boundary of 40 wide, the reason for this is that a clay dike does not conduct a significant amount of seepage and in this way the run time is reduced. The hinterland has length of 50 meters this value is not very important for assessing piping. Therefore this value is not too large ether to reduce the run time. However, this length should be increased to 3 times the leak length for groundwater flow purposes. The river channel has an width of 40 meters which is a chosen representative value. A longer value has little or even no effect on the performance of the model and the outcome of the critical water height. In contradiction, a significant smaller width has a large impact on the performance, which results in a unsafe higher critical head difference. The cause of this is that the inflow in the sand layer is too low and not realistic.

Figure 10 Subsoil in the D-Geo Flow model

Figure 11 indicates that there are multiple sand layers within the model. These layers have all the same characteristics, so this means that it is actually one layer such as the standard configuration for the sensitivity analysis in Figure 7. The reason that this is modelled as 6 separate layers is for the sensitivity analysis. In D-Geo Flow it is hard to alternate the thickness of a certain soil layer. If the thickness must be changed the whole model must be rebuild. To avoid this several layers are implemented for which easily the conductivity can be changed, such that the piping sensitive sand layer becomes smaller. For that reason as well the foreland and hinterland have separate top layer such that alterations can be

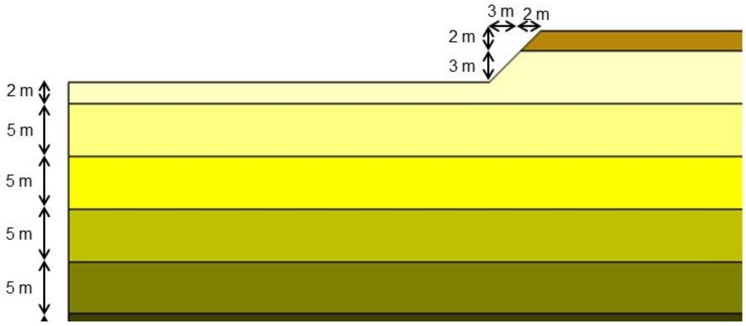

Figure 11 Dimensions of the soil layers and the river incision

easily applied and specified to one side of the dikes. This also excludes the influence of the hinterland on the results.

4.4.2 Boundary conditions

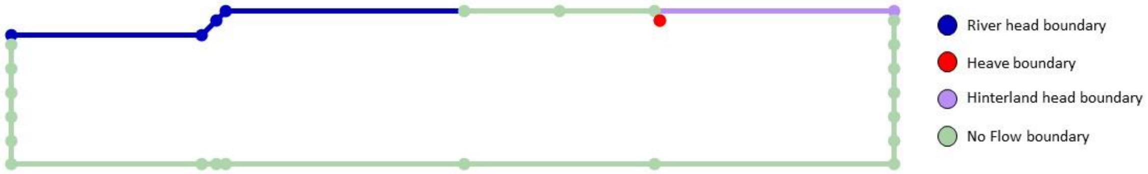

Figure 12 Overview of the applied boundary conditions in D-Geo Flow

In D-Geo Flow boundary conditions must be defined to model the groundwater flow. In this model four boundaries are applied. The no flow boundary is used for the simplifications of the model. The no flow bounder does not allow flow, but has minimal effect on the model. The hinterland head boundary defines the ground water level in the hinterland. This boundary is set to ground level of the hinterland, so the groundwater level in the hinterland is equal to the ground level in this model. The riverhead boundary defines actually the river water level, therefore this boundary is assigned to the foreland and river channel. The riverhead curve for this boundary is determined based on the results of Sellmeijer, because this requires a smaller step size to obtain a higher accuracy. At last the earlier mentioned heave boundary is assigned at the end of the pipe at the expected burst location. For this situation a pressure of 25506 N/m^2 is used to accommodate 0.3 d rule for a top layer of 2 meters.

4.4.3 The grid size

D-Geo Flow solves the groundwater problem by the finite element method. For this method a grid must be generated. The grid must be fine enough to perform accurate calculations, but high resolution also increases the run time. It is recommended to use a grid size that is small enough, such that one layer is two triangles thick. For the sand layers a grid size of 2.5 meters is chosen. For the top layers a grid size of 1 meter is chosen, because this layer is smaller. Around the pipe the grid size can be further refined by a factor. The grid size around the pipe becomes 3 times as small as the default value in the model. In this research a factor 3 is used, that means that around the pipe the grid size is three times as small as 2.5 meter.

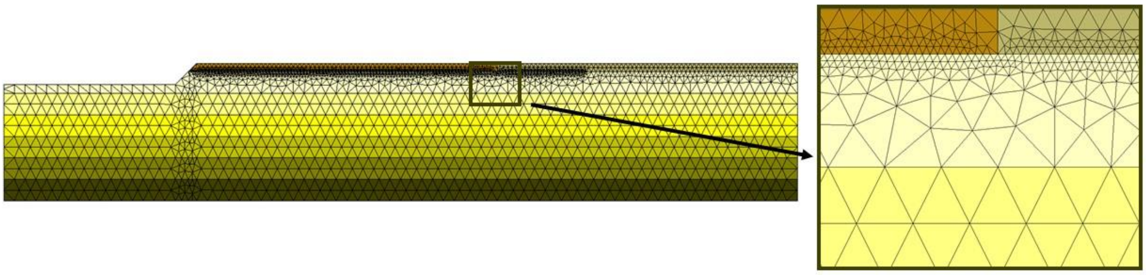

Figure 13 D-Geo Flow model cross section with the grid

4.5 Input values for the analysis

This section describes which input values are used for the researched parameters in the analysis. It defines the range for which the analysis is executed. The range is important for the validity of the results, since unrealistic inputs provide useless results. In Table 12 conductivities and the classification of types of sand are depicted. For the influence of the sand conductivity analysis values between 0.5 and 50 are used, because higher values are less common (doorlatendheid k, 2020).

Table 12 Conductivity of several sand types (k-waarde, 2020)

Type of sand	Conductivity [m/day]	Classification of Conductivity
Very fine	0.2 - 0.5	Poorly permeable
Medium fine	1 - 5	Permeable
Coarse	10 - 50	Very permeable
Very Coarse	80 - 200	Very permeable

For the influence of the top layer clay conductivity range of 0.002 – 0.2 is used. Researching lower conductivities is not very useful for the comparison to rule of Sellmeijer, because for these values the entire foreland length is included, which means that the maximum critical head for the rule of Sellmeijer is reached. For the same reason a longer foreland of 100 meters is used instead of the standard 50 meters to obtain the results for the clay conductivity, such that the differences become more clear. In Table 13 the conductivities for several types of clay is depicted as well as their conductivity classification.

Table 13 Conductivity of several clay types (k-waarde, 2020)& (doorlatendheid k, 2020)

Type of clay	Conductivity [m/day]	Classification of conductivity
Heavy clay	0.0001	Very poorly permeable
Pottery clay	0.001	Very poorly permeable
Medium heavy clay	0.01	Poorly permeable
Sandy clay	0.05	Permeable

The thickness of the piping sensitive layer is adapted between the 5 and 30 meters. Above the 30 meters the influence of the thickness on the critical heads decreases and therefore less differences are expected. The range of the foreland length is 25 to 200 meters. Smaller forelands have limited effect on the critical head and larger forelands are rarely common.

5. Results

This section contains the result of the quantitative analysis of the difference between the rule of Sellmeijer and D-Geo Flow in case of a foreland for several important parameters. The result are dependent on the input parameters and therefore not unambiguously. One method provides not always a higher critical head. The results for each parameter are depicted in the next sections.

5.1 Conductivity of the piping sensitive sand layer

In Figure 14, the relationship between the critical head difference and the hydraulic conductivity of the sand can be found, determined using the two earlier mentioned methods of Sellmeijer and the D-Geo Flow. The critical head difference decreases with increasing conductivity in a similar way for both methods. The conductivity of the sand is an important factor in the piping process, because it affects the groundwater flow and particle transport in the erosion channel. The similarities between the results of the two methods regarding this parameter, can be assigned to the fact that both methods rely on the 2 force equilibrium model of Sellmeijer. Therefore, conductivity of the sand is in a similar way included within both methods. Besides, this parameter has also a limited influence on the fictitious foreland within the rule of Sellmeijer for this dike configuration. As consequence the whole or largest part of the foreland length is included within the seepage length for the rule of Sellmeijer. In D-Geo Flow the entire seepage length below the foreland is always included in the calculations. So for this situation there is no or little difference between the seepage length of both methods. Therefore only small differences can be observed between those methods for this parameter.

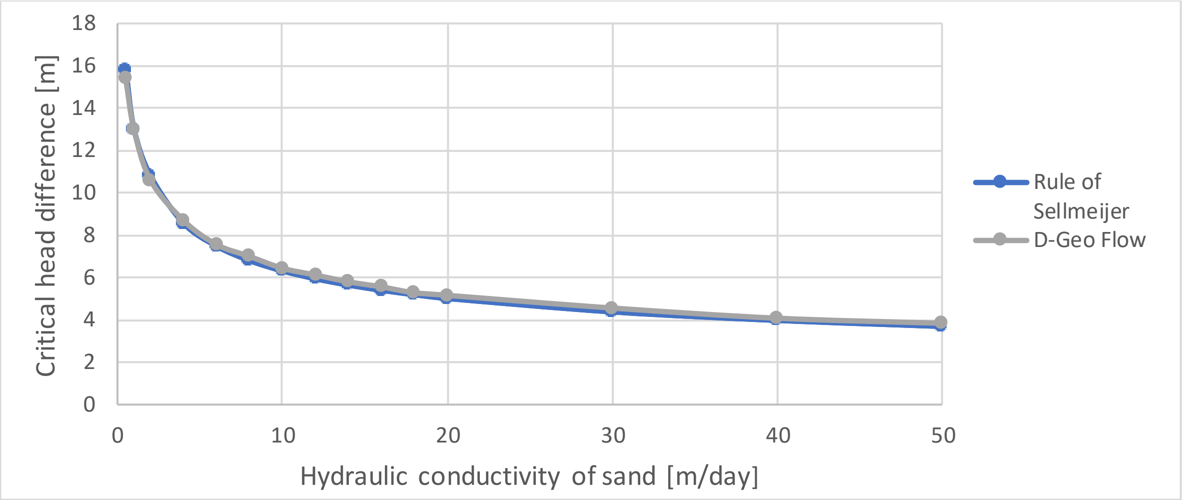

Figure 14 Influence of the sand conductivity in the piping sensitive layer on the critical head difference

5.2 Conductivity of the clay layer

For the conductivity of the clay layer the results are more divergent between both methods see Figure 15. For lower conductivities D-Geo Flow provides higher critical heads than the rule of Sellmeijer. For higher conductivities the results show the opposite. This difference might be caused by the fact that in D-Geo Flow there is always inflow through the top layer towards the pipe. However in the rule of Sellmeijer this inflow is not included in the equations, but is implemented by including less of the foreland length in the calculations.

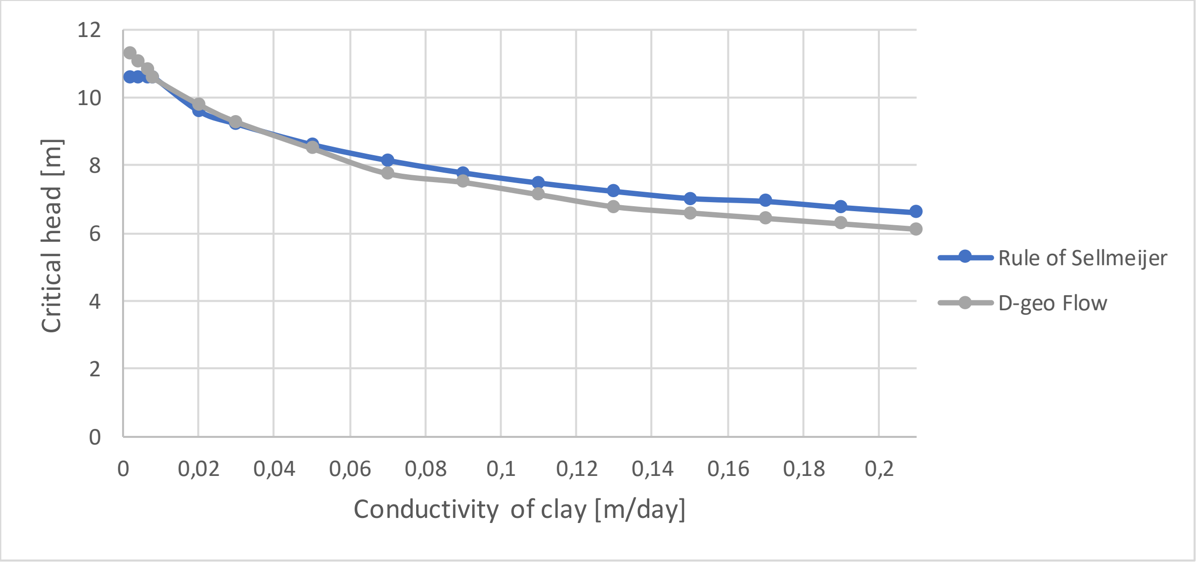

Figure 15 Influence of the clay conductivity on the critical head

5.3 Thickness of the sand layer

The thickness of the sand layer shows a clear trend, when the sand layer becomes thinner the more the critical heads differ. As can be seen in Figure 16 D-Geo Flow provides higher critical heads than the rule of Sellmeijer in case of thin sand layers. The results are remarkable, because the expectation based on all the input values is that difference cannot be that large. All the values are in the range for which the rule of Sellmeijer is calibrated and validated. On top of that the thickness of the piping sensitive layer has also prominent role in the rule of Sellmeijer.

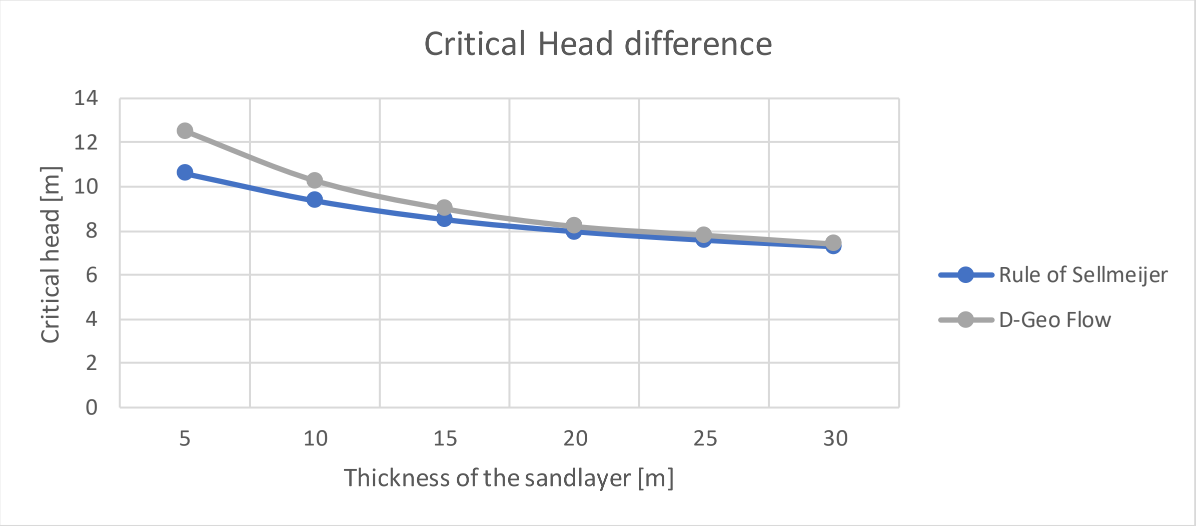

Figure 16 Influence of the piping sensitive sand layer on the critical head

During the verification of the D-Geo Flow model by the rule of Sellmeijer a same size difference was observed between D-Geo Flow and the rule of Sellmeijer. D-Geo Flow calculated a critical head that was a meter higher than the rule of Sellmeijer. After a detailed check of all the input and model, it was concluded that the incision in the river was not representative. The modelling of the incision in the river has a large effect on the inflow in piping sensitive layer. When the incision was adapted the critical heads of both methods coincided. For smaller sand layer probably the same applies, because the inflow into this layer becomes smaller when the thickness decreases in D-Geo Flow.

5.4 Foreland length

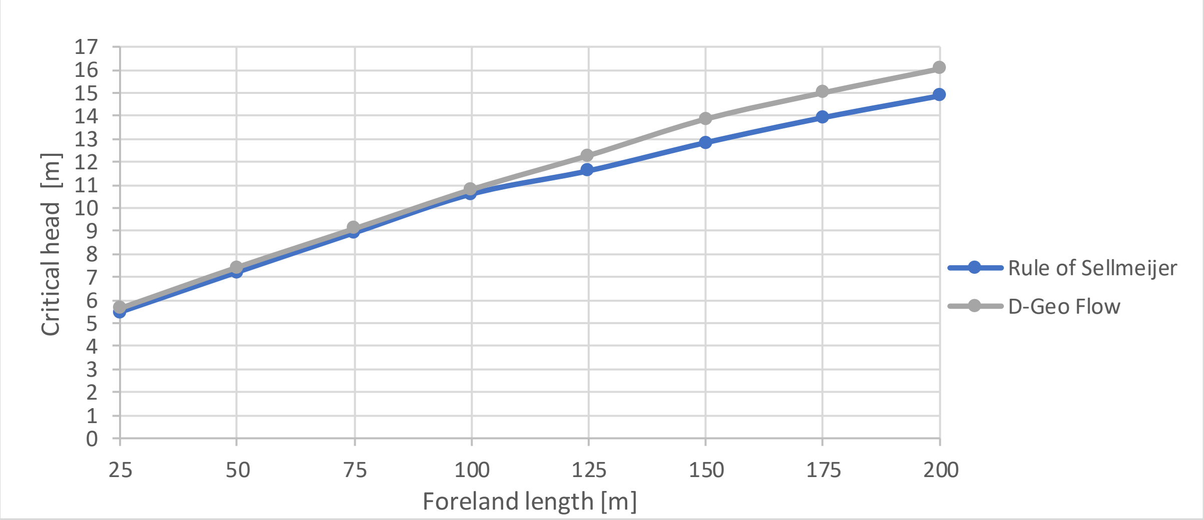

Figure 17 Influence of the foreland length on the critical head

In general it can be observed that for this dike configuration D-Geo Flow provides higher critical heads than Sellmeijer. When the foreland length exceeds the 100 meter in this dike configuration the ratio between the foreland length and the leak length exceeds a boundary for which no longer the whole foreland in the calculation can be included. In Figure 17 this is clearly visible, because after a length of 100 meters the rule of Sellmeijer results in significant lower critical heads.

6. Discussion

This section denotes the side notes by the results. Hereby, the input values and assumptions are reflected. Besides that the validity of the results is criticized.

- First of all it can be argued how representative the standard dike configuration is. The width of the dike base is based on an average value, but if this average is based on a set of large widths and small widths than the average is not that representative. This value however has limited impact on the results. A more important value is length of the foreland. For this is an arbitrary value of 50 meters used, which is chosen as tradeoff between short run lengths and a long foreland. Despite, the differences between the results of both methods, this research has indicated that both methods are not that sensitive towards this length. Longer forelands would have influenced the results more as can be seen in Figure 17
- In the analysis of the conductivity of the piping sensitive layer a constant value of 0,0002 m is used for the d_{70}. This is an appropriate value for the standard situation, but for small conductivities and large conductivities this value might not be appropriate. Therefore the conductivity of the piping sensitive layer results have to interpreted with caution, because this will affect the results. The d_{70} value is an measure for the grain size of the subsoil, which has an influence on the conductivity. Besides this, the d_{70} value is an important parameter for the particle transport in the piping sensitive layer according the two forces model of Sellmeijer. In the rule of Sellmeijer this can be seen within the equation, but also D-Geo Flow is very sensitive for this parameter (van Klaarbergen, 2019). Therefore it is recommended take this value into account in further research.
- The range of the foreland top layer conductivities includes some conductivities that are for a clay soil very high. For these cases it is questionable whether it is safe to include the foreland. The same applies towards thin foreland top layer. The dampening effect on the piping mechanisms is limited in these situations and insecurities can lead to unsafe predictions. For these cases and long foreland lengths(longer than two times the dike base) extra checks and underpinning is necessary (Rijkswaterstaat, Schematiseringshandleiding piping, 2019)
- In the manual of Deltares it is recommended to use a pipe coarseness of 6. In this research the pipe coarseness of 3 is used. This affects the accuracy of the groundwater flow around the pipe. Factor 6 has a higher accuracy than a value of 3, but a factor 6 is considered to be very accurate. The values of other accuracy parameters are more commonly used, but still it can be argued whether these are accurate enough. All the accuracy values remained constant for the entire research, so the observed trends are not depended on this.
- It is also important to realize that in the D-Geo Flow software as well in the rule of Sellmeijer are based on 2D models and do not include 3D flow (van Beek & Hoffmans, 2017). Research in the last decade showed that 3D flow is an important aspect in groundwater flow calculations (van Beek & Hoffmans, 2017). Also both methods consider a straight pipe that growths in a straight the horizontal direction. As a result vertical erosion cannot be included in the assessment. Therefore both methods are only reliable when the pipe progresses in a straight horizontal direction (Stoop, 2017).

7. Conclusion

In this section the summarized answer is given to the sub questions. Afterwards the main research question is answered and an overall conclusion is given.

Question 1. What are the technical differences between the rule of Sellmeijer from the WBI 2017 and the D-Geo Flow model?

Both methods rely on the two force model of Sellmeijer, but have different application of this model. The rule of Sellmeijer is an empirical formula derived from a numerical model that considers this two force model. This force balance can also be found in the different factors of the rule of Sellmeijer equation. D-Geo Flow is graphical user interface for 2D groundwater calculations with a piping module. D-Geo Flow uses the finite element method and subsurface flow equation to solve the groundwater problem. The piping module uses the boundary along the pipe equation based on the two force model of Sellmeijer.

The critical head is in the rule of Sellmeijer calculated by set of input parameters based on the dike configuration and theoretical seepage length in an empirical formula. However in D-Geo Flow this is more complex, because the pipe growth is simulated. The critical head in D-Geo Flow is determined by head difference in the last step for which the pipe did not grow into the river bank.

In the rule of Sellmeijer the foreland is included by a prolongation of the seepage length. This prolongation is determined by several additional equations that kind of asses the flow through the top layer of the foreland. Based on these results it is determined how long the prolongation is. In D-Geo Flow the foreland is incorporated by the created cross section in the model.

Besides these main differences both methods have different assumptions and simplifications.

Question 2. What is an appropriate dike configuration for this research and which parameters are important for a foreland?

The dike configuration for this research can be found section 4.3. The geometry is based on an average geometry of piping sensitive dikes. The other inputs are derived from representative values for which the difference between the rule of Sellmeijer and D-Geo Flow is minimal, such that deviations between both methods easily were detected. Important parameters for the foreland are: the foreland length, the conductivity of the top layer in the foreland, the conductivity of the sublayer and the thickness of the sublayer.

Question 3. Which differences can be observed between the results of the rule of Sellmeijer and D-Geo Flow model?

In general the results from D-Geo Flow show an higher critical head difference than the rule of Sellmeijer, but there is one exemption for high conductivities of the top layer. In that case the rule of Sellmeijer provides higher critical head differences. For small sand sublayers and long forelands D-Geo Flow provides significant higher critical heads, but for the other situations the differences are minimal.

Question 4. How can the differences between the results of the rule of Sellmeijer and D-Geo Flow model be explained?

- For the conductivity of the sand layer the differences are minimal. This can be clarified by that this parameter is very important in piping process and therefore well implemented in both methods.
- The influence of top layer conductivity in the foreland showed to be more complex. The cause of this can be found by the different approaches of both methods towards a foreland. In the rule of Sellmeijer the seepage length is prolonged or shortened. Hereby the inflow through the top layer towards the pipe is not directly included. In D-Geo Flow

the inflow through this top layer has a more dominant role, since it is an ground water flow model.

- The larger differences for large forelands can be explained that in the rule of Sellmeijer for long forelands a smaller part can be added to the seepage length. Because the foreland length leak length ratio determines the size of the seepage prolongation. The larger the this value the smaller the prolongation. D-Geo Flow always incorporates the entire foreland and therefore its dampening effect has more influence than in the rule of Sellmeijer for longer forelands.
- The differences for thin sand sub layers can be explained by the fact that the inflow into the piping sensitive layer decreases more in D-Geo Flow than the rule of Sellmeijer takes into account.

"Too what extent does the critical head from the D-Geo Flow model deviate from the calculated critical head by the rule of Sellmeijer for a dike with a foreland and can this difference be explained by the different approach towards a foreland"

In general the critical head differences are minimal for the researched dike configuration. However for specific less common input values larger differences of 7-18 % can be observed. For more standard values the critical head provided by D-Geo Flow is around 1-3 % higher than the rule of Sellmeijer. Overall it can be concluded that an assessment with D-Geo Flow leads to less conservative outcomes than the rule of Sellmeijer in case of a foreland. However for high top layer conductivities of the foreland the rule Sellmeijer shows to be less conservative.

These differences between both methods can be ascribed to the different approach towards a foreland. However how these different approaches exactly lead to different outcomes is hard to derive. Despite, the fact that both methods rely on the two force model of Sellmeijer, both methods have different application of this model. Besides that, the input for both methods is implemented in a different way.

8. Recommendations

Based on the results of this research, it can be recommended to use D-Geo Flow for a less conservative refinement of the critical head in case of a foreland, for poorly permeable top layers in foreland. This could be further amplified by researching and considering the following subjects:

- In further research it is recommended to research the d70 parameters as well in order to improve the results for the conductivity of the piping sensitive layer. Also the d70 is an important parameter within the two force model and has a large effect on the particle transport in the pipe.
- Besides that it would be useful to research the effect of the different critical heads on the failure probability for practical examples. With this the added value of an assessment with D-Geo Flow could be further confirmed.
- D-Geo Flow is very sensitive to the way the incision with the river is modelled. Hereby the cross section created by the boreholes is important as well as the assigning of the boundary conditions to the model. The inflow in the piping sensitive sublayer can be strongly affected by this, which has major influence on the results. This can be clarified by the fact that D-Geo Flow is a groundwater flow model. To prevent unsafe predictions, it is recommended to verify the model and check the model by an expert.
- The usability of D-Geo Flow could be more improved. As an example if the thickness on sublayer must be changed a whole set of boreholes must be adjusted within the model. Also more automation would be welcome to perform more complex and larger researches. With this version it can be very time consuming

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Appendix A

This appendix shows the tables with the critical heads of both methods and the relative difference of D-Geo Flow towards the rule of Sellmeijer.

Table 14 Results of the piping sensitive layer conductivity

Conductivity of the piping sensitive sand layer [m/day]	**Critical head by the Rule of Sellmeijer [m]**	**Critical head by D-Geo Flow [m]**	**Difference relative to the Rule of Sellmeijer [%]**
0,5	15,81	15,4	-2,59
1	13,02	13	-0,19
2	10,80	10,6	-1,88
4	8,57	8,7	1,46
6	7,49	7,56	0,93
8	6,81	7	2,86
10	6,32	6,44	1,93
12	5,95	6,12	2,94
14	5,65	5,8	2,70
16	5,40	5,56	2,93
18	5,19	5,28	1,66
20	5,01	5,16	2,90
30	4,38	4,56	4,10
40	3,98	4,08	2,51
50	3,69	3,84	3,93

Table 15 Results of the foreland top layer conductivity

Conductivity of the piping sensitive sand layer	**Critical head by the Rule of Sellmeijer [m]**	**Critical head by D-Geo Flow [m]**	**Difference relative to the Rule of Sellmeijer [%]**
0,5	15,81	15,40	-2,59
1	13,02	13,00	-0,19
2	10,80	10,60	-1,88
4	8,57	8,70	1,46
6	7,49	7,56	0,93
8	6,81	7,00	2,86
10	6,32	6,44	1,93
12	5,95	6,12	2,94
14	5,65	5,80	2,70
16	5,40	5,56	2,93
18	5,19	5,28	1,66
20	5,01	5,16	2,90
30	4,38	4,56	4,10
40	3,98	4,08	2,51
50	3,69	3,84	3,93

Table 16 Results of the piping sensitive layer thickness

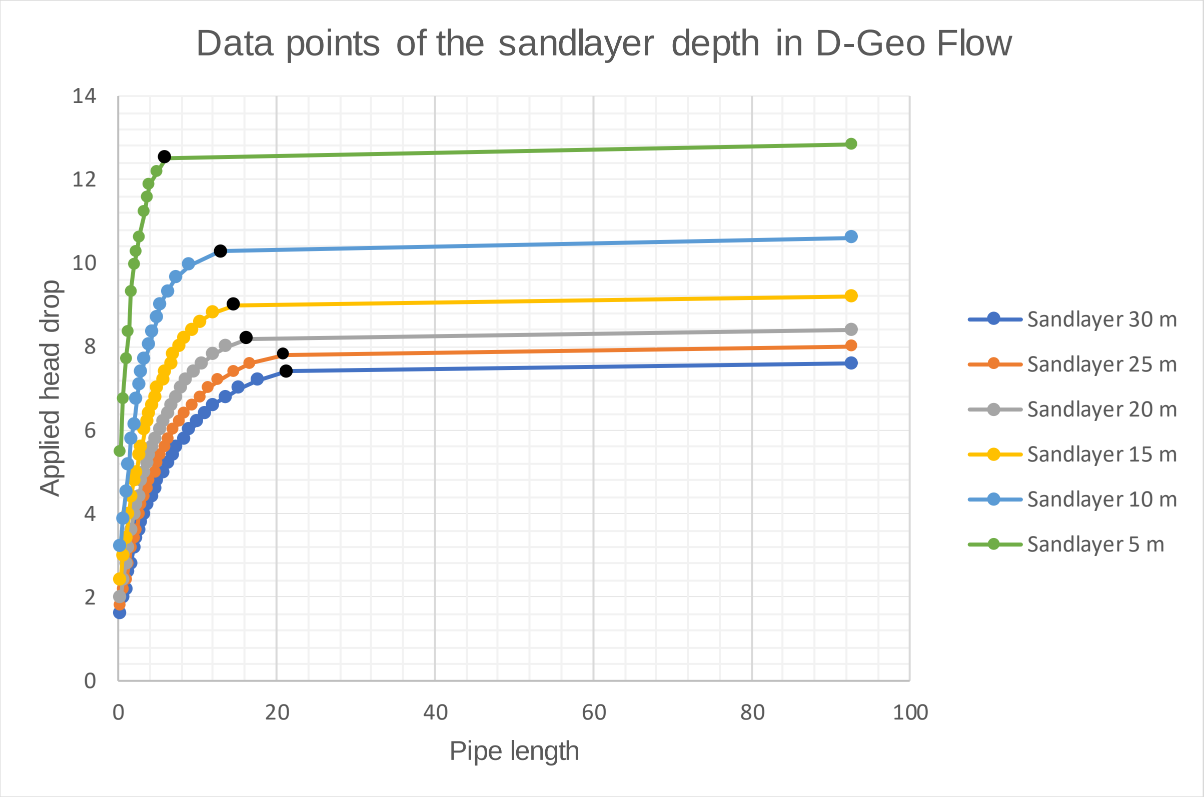
Thickness of the piping sensitive layer [m]	Critical head by the Rule of Sellmeijer [m]	Critical head by D-Geo Flow [m]	Difference relative to the Rule of Sellmeijer [%]
5	10,59	12,52	18,20
10	9,36	10,28	9,78
15	8,51	9,00	5,73
20	7,97	8,20	2,93
25	7,58	7,80	2,92
30	7,29	7,40	1,56

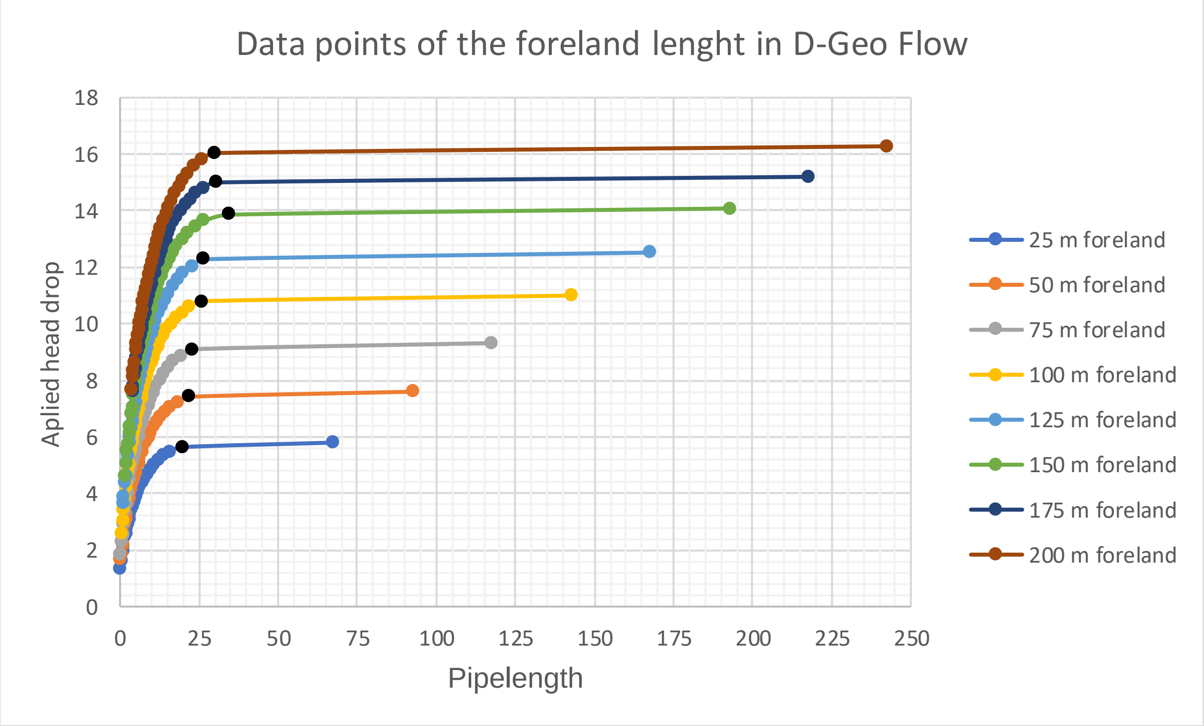
Table 17 Results of the foreland length

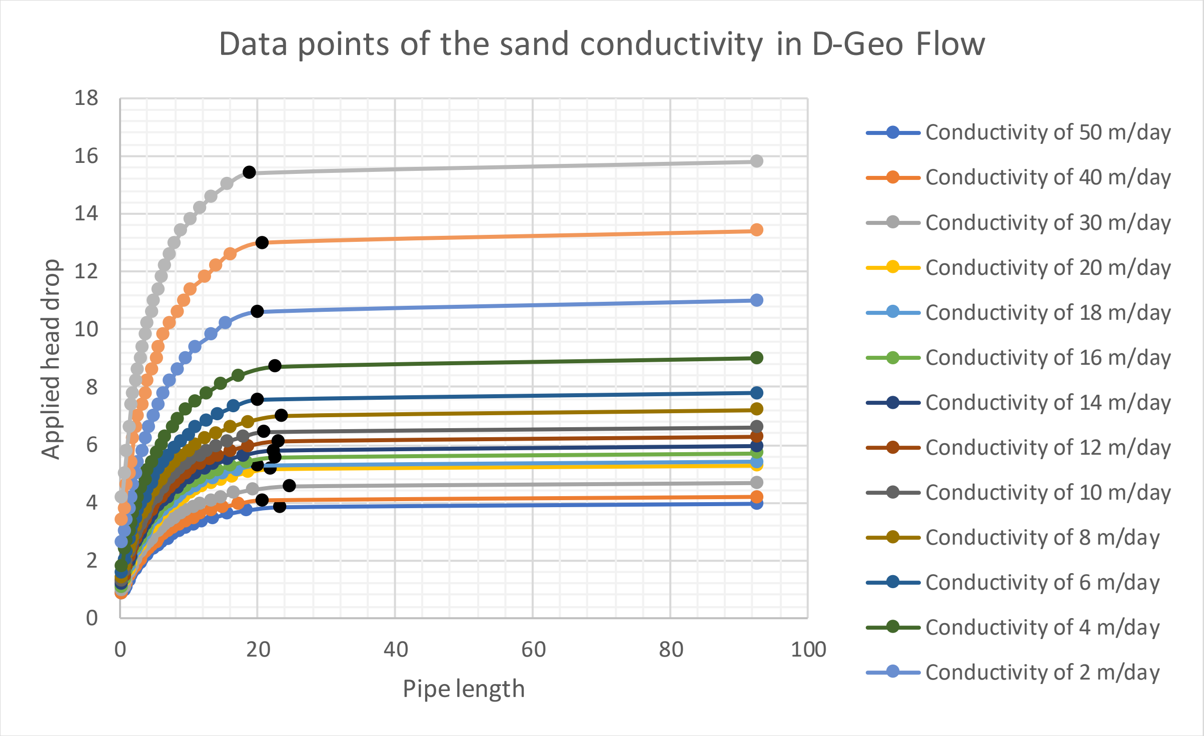
Length of the foreland [m]	Critical head by the Rule of Sellmeijer [m]	Critical head by D-Geo Flow [m]	Difference relative to the Rule of Sellmeijer [%]
25	5,48	5,64	2,91
50	7,22	7,42	2,81
75	8,92	9,10	1,97
100	10,61	10,80	1,83
125	11,62	12,28	5,72
150	12,84	13,86	7,97
175	13,92	15,00	7,75
200	14,87	16,04	7,86

Appendix B

In this appendix the data from the D-Geo Flow model is depicted. These graphs plot the pipe length against applied head drop. The applied head drop is the difference between the head boundary in the hinterland and the river head boundary in D-Geo Flow, or in other words the difference between the river water level and the polder water level. The black dots indicate the critical head by the D-Geo Flow model. After this point no equilibrium is possible and the pipe grows until the entry point.






Data points of the sand conductivity in D-Geo Flow
Applied head drop
Pipe length
0
2
4
6
8
10
12
14
16
18
0
20
40
60
80
100
Conductivity of 50 m/day
Conductivity of 40 m/day
Conductivity of 30 m/day
Conductivity of 20 m/day
Conductivity of 18 m/day
Conductivity of 16 m/day
Conductivity of 14 m/day
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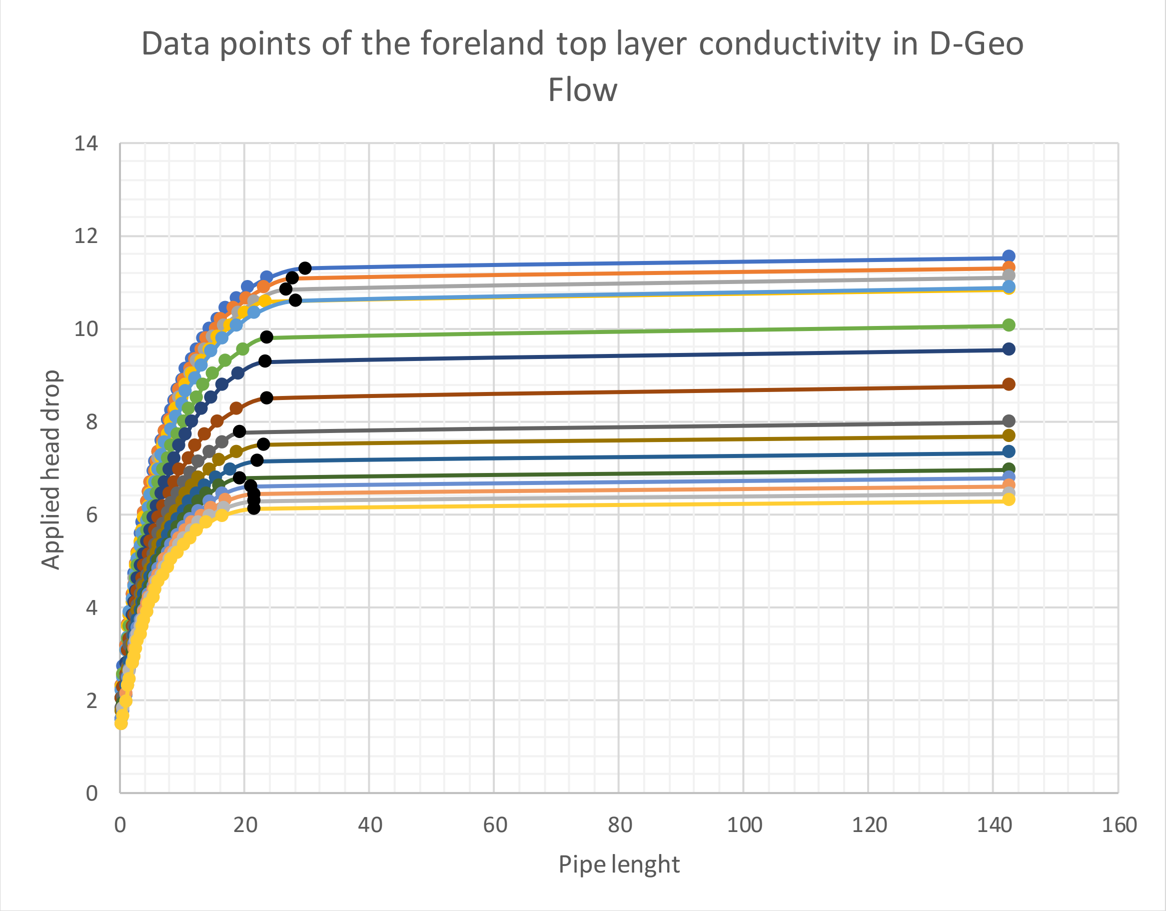
Conductivity of 4 m/day
Conductivity of 2 m/day


Data points of the foreland top layer conductivity in D-Geo Flow
Applied head drop
Pipe lenght
0
2
4
6
8
10
12
14
0
20
40
60
80
100
120
140
160

Appendix C

This appendix indicates the installation set-up version of D-Geo Flow

Version:	1.0.39057
Set-up type:	Typical
Type of license:	Standalone license file