Improved simple test to assess dike safety after failure of pipelines within a clay-covered dike

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Improved simple test to assess dike safety after failure of pipelines within a clay-covered dike

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Title page image: Erosion after failure of a water pipe in a dike of the Hollandse IJssel. (RTV Krimpenerwaard, 2020)

Preface

In front of you lies the final report of my bachelor thesis: 'Improved simple test to assess dike safety after failure of pipelines within a clay-covered dike.' This thesis completes the requirements for my Bachelor's degree in Civil Engineering at the University of Twente.

I would like to thank Witteveen+Bos for giving me the opportunity to work on an interesting and challenging research topic in the field of flood defences. I enjoyed working on the subject in a welcoming and vibrant environment at the office in Deventer.

During the research process, I have received frequent support from my supervisors, for which I am very grateful. To start, I want to thank my supervisors at Witteveen+Bos, Dennis Bottenberg and Hizkia Trul, for their help and feedback. During the weekly feedback sessions, they provided me with valuable suggestions to guide my research in the right direction. The possibility to ask questions at any moment about any content of my research was invaluable. I also want to thank Jos Muller, my supervisor from the University of Twente. He gave me valuable feedback regarding the scientific part of the research and writing process.

Finally, I would like to thank my family and friends for their encouragement during the assignment period.

I am available to answer questions regarding the content of this report via my email address: allmailsteven@gmail.com.

I hope you enjoy reading this thesis.

Steven Akkerman

Deventer, 25 June 2024

Abstract

Failure of gas and water pipelines that lay in or in the close vicinity of dikes forms a potential risk to the safety of the dikes and the people who live behind them. The Legal Assessment Framework provides a simple test that can be used to make a quick distinction between pipes that can and possibly cannot lay safely close to a dike. Assessment of this simple test has resulted in the conclusion that it is not well-substantiated. The probability of pipe failure and the damage effects due to pipe failure are not appropriately integrated, such that concerns are that the simple test cannot fulfil its purpose.

This thesis aims to construct an alternative simple test in which the probability of pipe failure and the damage effects due to pipe failure are integrated together. The research uses failure probability data of pipes together with equations and literature-substantiated assumptions to quantify the damage effects of pipe failure.

The damage effects for pipe failure are calculated for a hypothetical dike cross-section. The failure probability of the damaged dike cross-section was calculated using the D-Stability and D-Geoflow models together with equations from the Legal Assessment Framework.

The increase in failure probability of the damaged dike cross-section has been calculated with respect to the reference situation without pipe failure for gas and water pipes with varying diameter, pressure, and material. For each pipe, the increase in failure probability of the dike was determined and tested against a maximum allowable increase criterion. The findings were generalised for different pipe characteristic groups, and a new simple test was constructed from them.

The new simple test is considerably more conservative than the presently available test, which means that fewer pipes can be considered safe according to the new test. This decreases the chance that the simple test falsely considers a pipe in the vicinity of a dike as safe. However, from a usability point of view, this is undesirable because it increases the time that is needed to assess the safety of many pipe types.

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1. Introduction

1.1 Context

In the Netherlands, dikes play an essential role in protecting the lives and properties of the citizens. Therefore, it is of utmost importance that the dikes are in good condition and stay that way. Being in 'good condition' is for primary flood defences defined as meeting the minimum failure standards as they are stated in the Decree on the Quality of the Living Environment (Dutch: Besluit Kwaliteit Leefomgeving) (Rijksoverheid, 2024). The failure probability standards for each dike section are defined as a value between 1/10 and 1/1,000,000 per year. These values represent the annual allowable failure probability of the dike section. The safety standard of a dike trajectory is assessed by combining the characteristics of the dike itself and external factors that can increase the failure probability of the dike.

The failure of pipes that are present below or in the near vicinity of dikes is one of the external factors that can increase the failure probability of a dike. That is because pipe failure can undermine the safety of the dike via erosion and explosion craters or through soil softening and increased pore water pressure inside the dike. The magnitude of the damage caused by the pipe failure determines, in combination with the dike characteristics, if the dike stays safe enough to act as an adequate flood defence once a pipe has breached.

The increase in the failure probability of a dike due to the presence of a pipe is determined by two factors. The first factor is the probability that a pipe fails. Schweckendiek (2019) calls this the 'occurrence criterion' (Dutch: optredingscriterium). The occurrence criterion checks if the pipe's failure probability is small enough, such that it can be said that the presence of a pipe does not increase the failure probability of the dike significantly.

The second factor is the damage caused to the dike by the pipe failure. Schweckendiek (2019) calls this the 'damage criterion' (Dutch: schadecriterium). The damage criterion checks if the damage that a failed pipe causes to a dike is small enough such that the failure probability of the dike is not significantly affected. Failure of a dike can occur in multiple ways via different failure mechanisms. These failure mechanisms have, among other places, been described in the Legal Assessment Framework (Dutch: Wettelijk Beoordelings Instrumentarium, WBI). According to Schweckendiek (2019, p.2), pipe failure influences the failure mechanisms 'Macro Instability of the Inner Slope (STBI)', 'Piping (STPH)', and 'Grass Erosion of the Crest and Inner Slope (GEKB)' the most. Chapter 2.3 will elaborately explain what the relationship between pipe failure and failure mechanisms is.

Currently, the safety of a situation where a pipe is located close to a dike is assessed by a procedure that is stated in the Arrangement Safety Primary Flood Defences 2017 (Dutch: regeling veiligheid primaire waterkeringen 2017) and NEN3651. An important step in the procedure is the so-called 'simple test' (Dutch: eenvoudige toets). This simple test uses the pipe characteristics material, pressure, and diameter to assess whether the probability of failure of a pipe-dike system is neglectable. If a particular pipe-dike system passes the simple test, the pipe is considered not to pose a threat to the dike. If the situation is not supposed to be safe, further research must be carried out to check if the pipe-dike system is secure. The pipe characteristics that are used in the test are easy to determine, and therefore, the test is quick to use, hence its name, 'simple test'. The simple test is thus a convenient tool that can save a lot of time as it filters pipe-dike systems that are unquestionably safe from systems that need more time-consuming assessment. In Figure 1, the simple test is displayed.

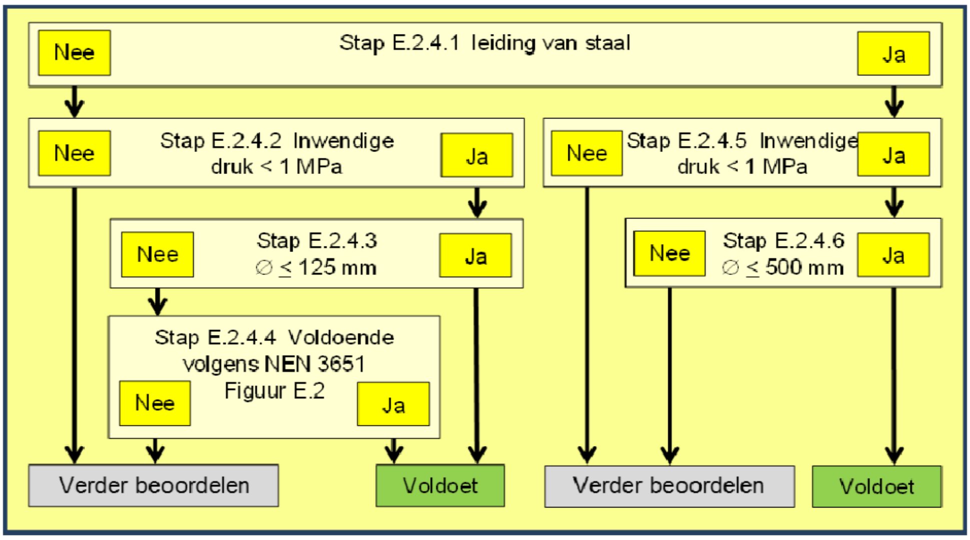

Figure 1: The simple test (Ministerie van Infrastructuur en Milieu, n.d, p.119)

1.2 Problem statement

An essential requirement for the simple test is that it filters only safe pipe-dike systems. When the test is not conservative enough, unsafe pipe-dike systems are unrightfully considered to be secure, which may result in the failure of the dike in the worst case. The Project-Transcending Exploration Cables and Pipes (Dutch: Projectoverstijgende Verkenning Kabels & Leidingen, POV K&L) has shown that the simple test is not always conservative. Schweckendiek (2019, p. 19) states regarding the simple test:

"The simple filters from NEN3651 and the Legal Assessment Framework are not calibrated with respect to the failure requirements that are related to the water safety standards. It is recommended that the existing filters (the simple test) and potential new filters be substantiated, both for the pipeline (occurrence criterion) and the flood defence (damage criterion), to the relevant failure probability requirements."

In other words, the current simple test does not adequately consider the effects of the failure probability of a pipe itself (via the occurrence criterion) and the damage effects due to pipe failure (via the damage criterion) on the failure probability of the dike. Because of this, it is unknown if the safety standard of a dike is met when a pipe is in its vicinity. That is unacceptable because the safety of people and properties behind a dike can then not be guaranteed.

1.3 Research objective

The research objective is to improve the current simple test used to check pipeline safety in the vicinity of a dike. 'Improve' is defined as incorporating the recommendations put forward by Schweckendiek (2019) into the simple test. That means that the goal is to make the probability of pipe failure (the occurrence criterion) and the expected damage of pipe failure to the dike (the damage criterion) an integrated part of the new simple test. Furthermore, the new simple test must be linked to the water safety standard of the dike cross-section. Once the new simple test has been established, the differences with the current test will be assessed.

1.4 Research scope

The scope determines what will be essential parts of the research when pursuing the objective. For this topic, that are factors that influence the occurrence and damage criterion. This section will explain what these factors are and what their importance is.

For the occurrence criterion:

- Properties of the pipes

For the damage criterion:

- Effects of pipe failure on the soil
- Affected failure mechanisms
- Location and orientation of the pipe with respect to the dike
- The properties of the dike cross-section

1.4.1 Properties of the pipes

Relationships exist between the failure probability of the pipe and its properties. The document 'Filters for parallel gas and drinkwater pipelines in and near primary flood defences' from the POV K&L (Ouwendijk et al., 2020) contains information about this topic. Factors such as the transported substance (water or gas), diameter, internal pressure, and pipe material are correlated with its failure probability. More elaborate data about these correlations will be given in Chapter 4.1.

The scope of this research with regard to the pipelines focuses on pressurized water and gas pipes with pressures up to 1 megapascal (10 bars) and a diameter of 0.5 meters. These are the upper limit values of the pipe properties that are used in the current simple test. This decision to include only the pipe characteristics up to the limit values of the current simple test has been made because of safety reasons. It was decided that the new simple test could not be less conservative than the current one because of the lack of experimental substantiation via the methodology. The methodology uses existing equations to quantify the effects of pipe failure instead of an assessment of the actual impacts of pipe failure. The methodology will be elaborated on in Chapter 3.

The pipeline materials that will be considered are asbestos cement (AC), grey cast iron (GC), nodular cast iron (NC), steel, polyethene (PE), and polyvinyl chloride (PVC). These are the most commonly found pipe materials, according to Ouwendijk et al. (2020).

1.4.2 Effects of pipe failure on the soil

A dike can be damaged by pipe failure in a handful of ways. The Royal Netherlands Standardization Institute (NEN, 2020) describes in its regulation NEN3651: 'Additional requirements for pipelines in or nearby important public works' how the failure of gas and water pipes can influence the soil. According to this document, gas pipeline failure can lead to crater formation in two ways. Firstly, the outflow of pressurized gas can displace the soil around the pipe due to its force on the soil particles. The crater that then forms is a so-called 'erosion crater'. Another crater form is the 'explosion crater', which can form when a gas pipeline explodes. An additional effect of the explosion is the phenomenon of soil softening (Dutch: grondverweking), which can lead to a loss of strength between soil particles within the dike. This may result in reduced stability and, subsequently, the dike collapsing under its own weight. Just like for gas pipes, the outflow of water from a broken water pipe can form an erosion crater. This is what happened in the situation that is depicted on the front page. A second way in which water pipe failure can influence the stability of the dike is via a 'creeping leak' (Dutch: sluipend lek). In that case, the outflow rate from the water pipe is not large enough to form an erosion crater, but this can increase the water pressure inside the dike. This will lead to decreased friction between the soil particles and decreased dike stability. A more elaborate description of the effects of pipe failure on the soil around it will be given in Chapter 2.2.

1.4.3 Affected failure mechanisms

The effects of pipe failure on the soil can increase the dike's failure probability when the pipe is located in or near it. Failure of a dike can occur in multiple ways via different failure mechanisms. As stated in section 1.1, pipe failure impacts the mechanisms 'Macro Instability of the Inner Slope (STBI)', 'Piping (STPH)', and 'Grass Erosion of the Crest and Inner Slope (GEKB)' the most (Schweckendiek, 2019, p.2). However, other failure mechanisms also exist, such as 'Macro Instability of the Outer Slope (STBU)' and 'Grass Erosion of the Outer Slope (GEBU)'. The failure mechanisms STBI, STPH, and GEKB are included in the scope, but STBU and GEBU are not. The reason for this requires further explanation about how the failure mechanisms work. That will be given in Chapter 2.3.

1.4.4 Location and orientation of the pipe with respect to the dike

The effect that the location and orientation of a pipe failure will have with respect to the dike is also contained within the scope of this research. In Figure 2, the pipe locations of interest are displayed. Pipe locations A, B, C, and D represent pipes parallel to the dike in the riverside foreland, the crest, the inner slope, and the hinterland. Pipe E represents a pipe that crosses the dike perpendicularly.

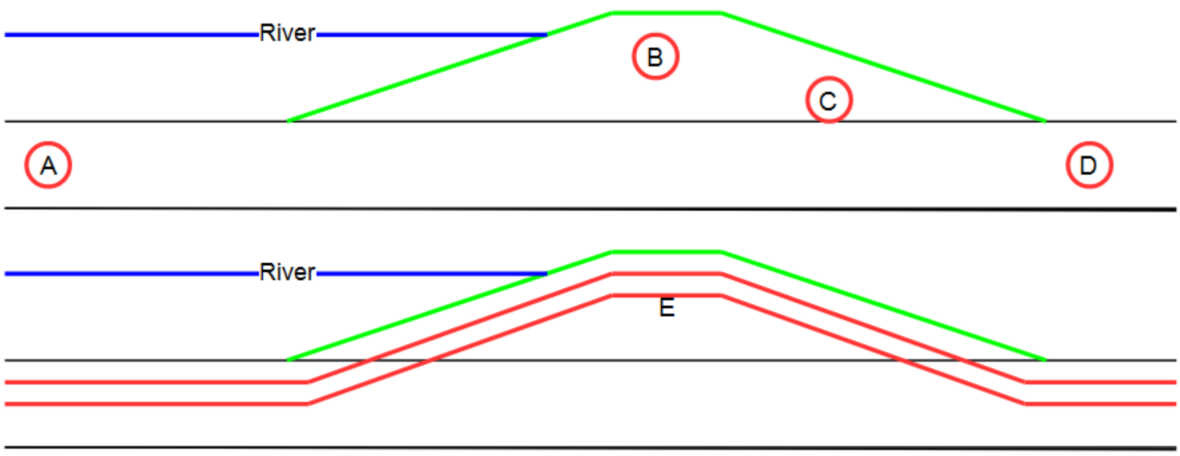

Figure 2: Pipe locations and orientation of interest in the research

The distinction between pipe locations and parallel versus perpendicular pipes is made because it is hypothesized that the location of the pipe failure influences how the safety of the dike is affected. Pipe location A lies in the riverside foreland relatively far from the outer dike toe. Because of this, it is expected that the failure of a pipe will affect the failure mechanism piping the most since this may change the entrance point of the piping and thus shorten the piping distance (Figure 12). Shortening of the piping distance may also be an issue for location D, but in that case, the exit point of the piping may change. For location D, the failure mechanism Macro Instability of the Inner Slope may be affected by pipe failure because an erosion/explosion crater may remove soil from the dike toe. This is also a concern for location C. Finally, the failure mechanism Grass Erosion of the Crest and Inner Slope (GEKB) may be affected for locations B, C, and D since pipe failure could remove a section of the grass cover on top of the dike.

The distinction between parallel and perpendicular pipes is also made because of the occurrence criterion. In principle, parallel pipes are expected to lay closer to a dike over a longer distance than perpendicular pipes. Because of this, the probability that the pipe fails somewhere close to the dike is expected to be larger when the pipe lays parallel.

1.4.5 The properties of the dike cross-section

Dike cross-sections can vary from each other in many aspects. Height, width, and soil characteristics are examples of this. It is expected that those properties can have a significant impact on the damage that pipe failure can inflict on the dike cross-section. For example, a water pipe with a diameter of 0.2 meters and a pressure of 2 bars is expected to cause relatively more damage to a slender dike cross-section than a wide one.

For dike cross-sections, an almost infinite number of combinations between height, width, and soil build-up can be made, and the effects of pipe failure on the stability of the dike can differ for each of them. However, these effects cannot be researched entirely due to time limitations.

Because of the time limitations, the research needs to be applied to a dike cross-section with properties that can commonly be found in the Netherlands to give the most useful results. In the Netherlands, every dike trajectory that is part of a primary flood defence has an annual maximum allowable failure probability. This norm can vary from not very strict (once every ten years) to very strict (once every million years). These values are the extremes that are not very common. For example, the norm of once every million years can only be found near the nuclear powerplant in Borselle. Dikes near the main rivers like the Rhine, Waal, IJssel, and Meusse commonly have a norm between 1/1,000 and 1/10,000 per year (Rijkswaterstaat, 2017). This research is not interested in extreme cases but in the common ones. Therefore, the research will be applied to a hypothetical dike cross-section with a norm of 1/10,000 per year.

The hypothetical dike cross-section that will be subjected to the research is displayed in Figure 3. This cross-section is a hypothetical dike that is considered average and logical for a dike that serves as a primary flood defence near one of the main rivers in the Netherlands.

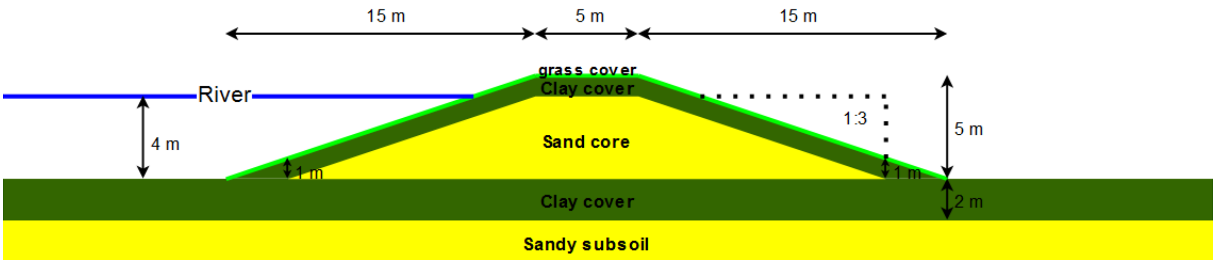

Figure 3: Dike cross-section on which the research will be applied

The soil build-up of the dike consists of a sand core and a 1-meter-thick clay cover layer. This is a logical build-up since a clay cover layer is often applied to a dike because the cohesive forces within the clay protect the dike better against wave impacts than sand can do. The subsoil below the dike body consists of sand with a 2-meter-thick clay cover layer.

The dimensions of the dike are chosen as they are because they can be expected to belong to a dike with a failure norm of 1/10,000 years. The crest has a width of 5 meters and a height of 5 meters above the surface level. The slopes are 1:3. These are similar dimensions to the Waaldijk near Dodewaard or the Nederrijndijk near Arnhem. These cross-sections are displayed in Appendix A (Actueel Hoogtebestand Nederland, n.d.)

1.5 Research questions

The main research question that follows from the research objective is the following:

- **"What are the differences between the characteristics within the groups of pipes that are considered to be (un)safe when they lay in the vicinity of a dike for the current simple test and the to-be-made improved simple test?"**

An improved simple test must be made before this question can be answered. That requires the implementation of the occurrence and damage criterion. The following sub-questions need to be answered in order to be able to do this.

1. **"What is the relation between the probability of failure of a pipe and its diameter, pressure, material, and transported substance?"**
2. **"What is the relation between pipe failure and the failure probability of a dike?"**
   - **2.1 "What is the failure probability for an affected failure mechanism without pipe failure?"**
   - **2.2 "What is the failure probability for an affected failure mechanism with pipe failure?"**
3. **"For which combinations of pipe characteristics, locations and orientation is the change in failure probability (in)significant?"**
   - **3.1 "Which change in failure probability of the dike forms the boundary between an insignificant and significant change?"**

1.6 Reading guide

This report contains the following sections: a theoretical framework, methods, results, discussion, conclusion, and recommendations chapter. References and appendices are also included at the end.

The theoretical framework in Chapter 2 contains information about the properties of gas and water pipes that can be expected near dikes. This section also includes technical details on how pipe failure can affect the soil. Furthermore, it contains information on how failure mechanisms of a dike work and how they can be affected by pipe failure. The purpose of the theoretical framework is to clarify the concepts that need to be understood for the research scope and, thus, the research questions.

The methods Chapter 3 contains the equations and theory about models used to quantify the effects of pipe failure on the failure probability of the dike cross-section. Additionally, the methodology followed to extract an improved simple test from those results will be stated.

Chapter 4 will display the results, which are the quantified effects of pipe failure on the soil and the probability of failure of the dike for the important failure mechanisms. This chapter also contains the newly designed simple test and its differences from the old test.

The findings from the results will be discussed in Chapter 5. Limitations of the used methods and potential shortcomings of the new simple test will be debated.

The most important findings regarding the effects of pipe failure on the soil and the failure probability of the dike will be stated in the conclusion, which is Chapter 6. Most importantly, the implications of the differences between the current and new simple tests will be put forward.

Recommendations that result from the conclusion will be stated in Chapter 7. This section will also put forward suggestions for further research that can be used to make further improvements to the simple test. This relates to difficulties that were encountered during the research process but that could not be entirely resolved due to time limitations.

2. Theoretical framework

2.1 Characteristics of gas and water pipes

The document 'Filters for parallel gas and drinkwater pipelines in and near primary flood defences' from the POV K&L (Ouwendijk et al., 2020) contains data about the length of the water and gas distribution network in the Netherlands. This document distinguishes gas and water pipes based on their diameter, pressure, and material.

For gas pipes, it is stated that the average length of the distribution network was 124,633 kilometres in the period 2009-2018. Regarding pipe material, a distinction is made between asbestos cement (AC), grey cast iron (GC), nodular cast iron (NC), steel, polyethene (PE), and polyvinyl chloride (PVC). Regarding diameter and pressure, a distinction is made between 3 and 4 classes, respectively. Figure 4 displays which portion of the network falls into which categories.

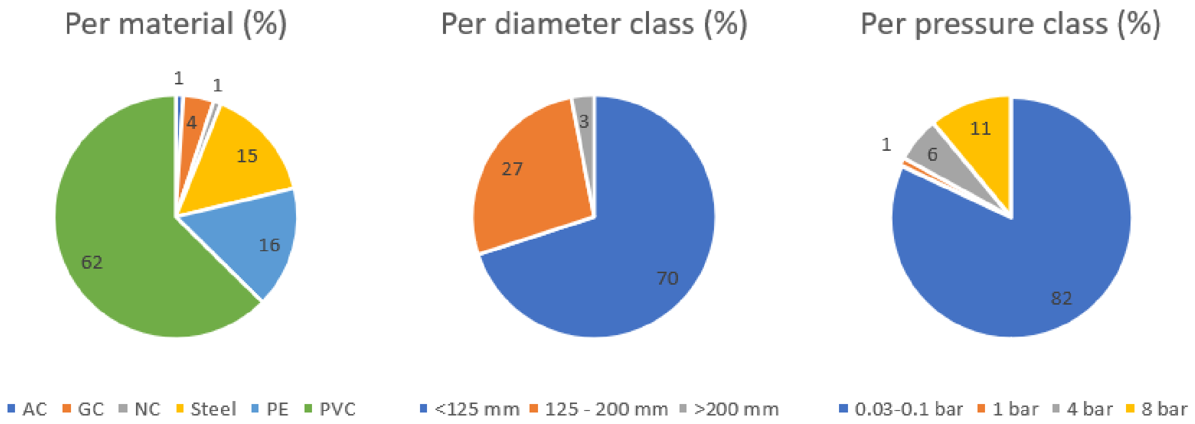

Figure 4: Division of pipe properties in the gas transport network (Data retrieved from Ouwendijk et al. (2020))

What stands out is that PVC pipes are the most common. Furthermore, pipes with a low diameter and pressure make up the most significant part of the network.

For water pipes, Ouwendijk et al. (2020, p. 141) state that the length of the distribution network is 120,061 kilometres. The water pipes can be divided, for the most part, into the same material categories as gas pipes. 98.8% of the water pipes fall into one of the six mentioned material categories. It is stated that water pipes have a wider range of commonly present diameters. Therefore, six diameter classes exist, the largest of which consists of pipes with a diameter larger than 700 millimetres. Ouwendijk et al. (2020, p. 139) states that for water pipes no distinction is made between pressure. In Figure 5, the frequency of the pipe materials is displayed. No data was found for the diameter classes.

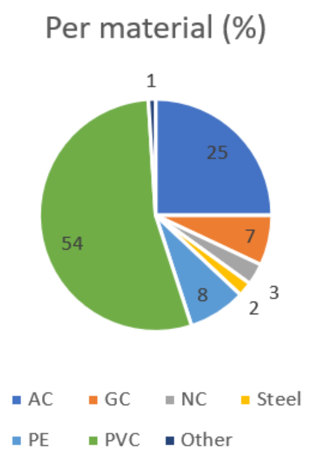

Figure 5: Division of pipe materials in the water transport network (Data retrieved from Ouwendijk et al. (2020))

For water pipes, it stands out that PVC and asbestos cement pipes are the most common.

It should be stated that the statistics mentioned above are for the whole gas and water pipe network and not specifically for gas and water pipes near dikes.

2.2 Implications of pipe failure

The Royal Netherlands Standardization Institute (NEN, 2020) describes in its regulation NEN3651, 'Additional requirements for pipelines in or nearby important public works', how the failure of gas and water pipes can influence the soil. In Figure 6, a schematic overview of these effects is given.

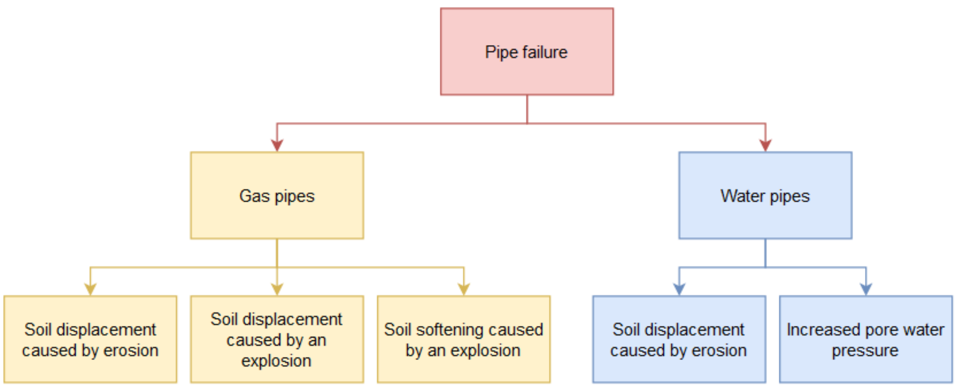

Figure 6: Relation between pipe types and how failure influences the surrounding soil

The following section will give a description of these effects.

2.2.1 Implications of gas pipe failure

2.2.1.1 Soil displacement caused by erosion

When a gas pipe fails, the pressurized gas escapes into the surroundings. The gas then exerts a pushing force on the surrounding soil, which can cause the soil to move away from the pipeline. The formation of this erosion crater continues until the force of the gas outflow can no longer overcome the frictional and cohesive forces between the soil particles and the gravitational force. In Figure 7, the erosion effect of gas pipe failure is depicted.

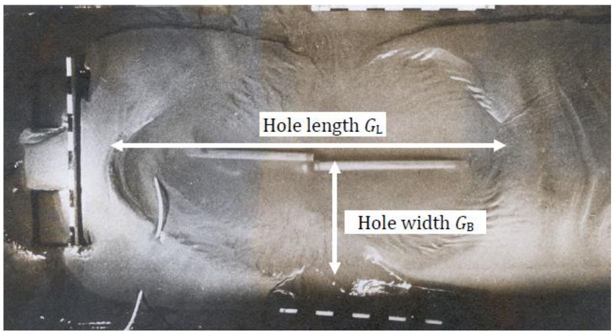

Figure 7: Erosion crater after a full breach of a gas pipe (NEN, 2020, p. 89)

Factors that influence the magnitude of erosion are the force exerted by the gas on the soil and the frictional, cohesive, and gravitational forces on the soil. The force from the gas on the soil depends on the outflow rate through the leak, primarily determined by the diameter and internal pressure of the pipe. The magnitude of the gravitational and cohesive forces depends on the unit weight and soil type.

2.2.1.2 Soil displacement caused by an explosion

Natural gas pipelines under high pressure can explode when subjected to high temperatures (NEN, 2020, p. 92). In such an event, a large amount of energy is released into the surroundings, which can throw away the soil on top of the pipeline. The size of the explosion crater is primarily dependent on the pressure and diameter of the pipeline but independent of the flammability of the gas (NEN, 2020, p. 92).

2.2.1.3 Soil softening caused by an explosion

Soil softening is the effect of shock waves caused by an explosion in which the load-bearing capability of soil is reduced or lost entirely. The load-bearing capability is determined by the friction and cohesive forces between the soil particles, the effective stress. The effective stress in the soil can be calculated with Equation *1*.

$$\sigma' = \sigma - u \qquad \textbf{Eq. 1}$$

In which:

- σ' is the effective stress (N/m^2)
- σ is the total stress (N/m^2)
- u is the pore water pressure (N/m^2)

The shockwaves can temporarily increase the pore water pressure in the soil, decreasing the effective stress given a certain total stress. This may lead to a dike collapsing under its own weight as the lower soil layers in the dike can no longer carry the weight of the soil above it.

According to NEN3651 (2020) and Saathof (1984), soil softening is a phenomenon that is primarily an issue in sandy soils. Saathof (1984) states regarding explosions of gas pipes: ‘Sometimes water overpressures can occur due to sand grains reorienting themselves which primarily occurs in unpacked sands’.

The energy released by the explosion is the factor that influences the magnitude of the soil softening zone. This energy is related to the pipe’s diameter and pressure. Ouwendijk et al. (2020, p. 13) state that soil softening is not an important factor for low-pressure gas pipes. They make this statement based on an analysis performed by the Dutch gas grid management. In this research, the effects of soil softening will be incorporated because the newly designed test needs to anticipate all possible effects.

2.2.2 Implications of water pipe failure

Failure of water pipes can be divided into two categories. The full breach (Dutch: volledige afschuiving) and creeping leak (Dutch: sluipend lek). Both ways of failure influence the soil differently.

2.2.2.1 Soil displacement caused by erosion

Erosion craters due to water pipe failure form similarly to craters formed by gas pipe failure: the pressurized water that flows through the hole in the pipe pushes away the sand in the surroundings. The main difference between erosion caused by gas and water outflow is that water flows down, and gas escapes upward once they are under atmospheric pressure. This may cause additional erosion when the water flows down from a pipe that is located inside the crest or dike toe. Erosion from water flowing down the dike can be viewed on the title page image.

An erosion crater forms only when the force of the water outflow is large enough to overcome the friction forces in the soil. The force of the outflow depends on the diameter and pressure of the pipe as well as the size of the leak. Erosion craters form mostly when the water pipe shears off entirely, such that the complete flow of the pipe ends up in the soil.

2.2.2.2 Increased pore water pressure in the dike

For small leaks, the outflow stream is not powerful enough to cause an erosion crater. In that case, the pipe leaks into the soil and heightens the phreatic line, causing increased pore water pressure. That can happen when a small hole is present in the side of the pipe. Most flow stays inside the pipe, and a small portion flows out. This phenomenon is called a ‘creeping leak’. A creeping leak can remain undetected for a long time since it is not visible. As stated in section 2.2.1.3, increased pore water pressure decreases the soil's load-bearing capacity. Therefore, the effects of leaks that do not cause an erosion crater must also be investigated.

2.3 Affected failure mechanisms

The mentioned effects of pipe failure on the soil can be divided into two categories: crater formation and increased pore water pressure. This section contains information on how this can affect the failure mechanisms of a dike.

2.3.1 Macro instability of the inner or outer slope (STBI or STBU)

The failure mechanism macro-stability of the inner slope (STBI) involves sliding the dike's landward side. In Figure 8, it can be seen that a section of the dike slides down along the path of a circle segment. This happens when the gravity force on the soil becomes larger than the friction force along the slide plane.

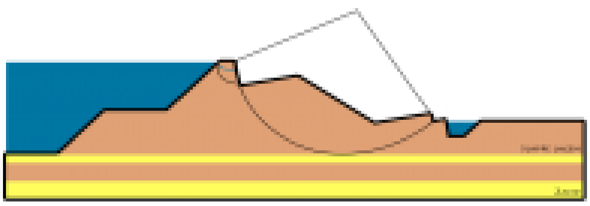

Figure 8: Macro-instability of the inner slope (Macro-instabiliteit Binnenwaarts - Delta Noodmaatregelen, n.d.)

The water pressure inside the dike influences the friction force along the slide plane. The friction force is proportional to the effective stress in the soil. The relationship between effective stress and water pressure is displayed in Equation *1*.

This relation shows that the friction force between the soil particles decreases when the pore water pressure increases, considering that the total stress is constant. The most common factor that increases pore water pressure is a high water level on the riverside. However, the pore water pressure can also be increased due to a water pipeline leak or a gas pipe explosion.

Another way in which the inner slope might fail is due to the presence of an erosion or explosion crater. Especially when soil is removed from the bottom of the slip plane, it can no longer push back the force of gravity acting on the soil at the top. A crater can thus increase the probability of dike failure due to macro instability (Figure 9).

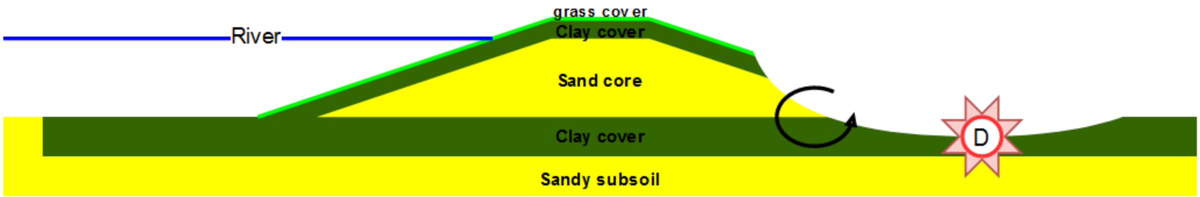

Figure 9: Schematization of how pipe failure can affect the failure mechanism STBI

Macro-stability of the inner slope is a failure mechanism that occurs during high water conditions. This makes STBI a direct failure mechanism, which means that the occurrence of the failure mechanism results in a high probability of flooding of the hinterland. It is also possible that the outer slope of the dike slides down. This failure mechanism is called Macro-stability of the outer slope (STBU) and generally occurs only during low water conditions (Ministerie van Infrastructuur en Waterstaat, 2021, p. 27). Therefore, the occurrence of STBU does not directly lead to flooding of the hinterland. This makes STBU an indirect failure mechanism.

Because STBI is a direct failure mechanism and STBU an indirect one, the probability of occurrence of STBI is normative for the strength of the dike. Therefore, the impact of pipe failure on STBI will be researched and not on STBU.

2.3.2 Piping (STPH)

Piping is a failure mechanism that can occur to a dike when three boundary conditions are present (De Bruijn, 2013):

1. A water level difference exists between the water and land side of the dike, causing a pressure difference.
2. A layer of granular, non-cohesive, porous soil (sand) is present below the dike.
3. The sand layer is covered with a cohesive, poorly permeable soil layer (clay or peat).

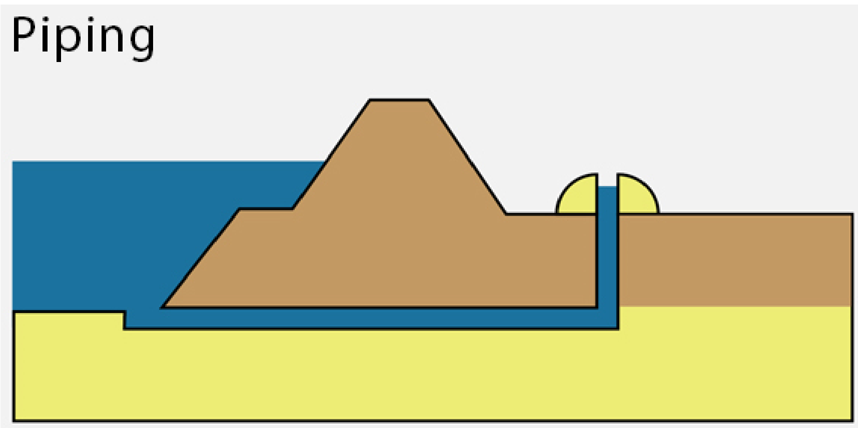

Figure 10: Dike situation for which piping can occur (Projectteam Meanderende Maas, 2017)

When these conditions are present, piping occurs when all three sub-failure mechanisms of piping occur. The three sub-mechanisms are, in chronological order, ‘burst’, ‘heave’, and ‘backward erosion’.

2.3.2.1 Burst

Burst occurs when the pressure difference between the sides of the dike is large enough such that the water can push up and break through the clay cover layer behind the dike (De Bruijn, 2013). This happens when the force from the water on the clay layer is higher than the force of gravity. Once the clay cover layer has breached, a water stream starts to flow below the dike. This stream may or may not transport sand particles depending on the characteristics of the hole in the cover layer and the head difference. The thickness of the cover layer determines if burst will occur. Because the presence of a crater in the cover layer changes the thickness of it, it is vital to investigate the effects of pipe failure on the thickness of the cover layer.

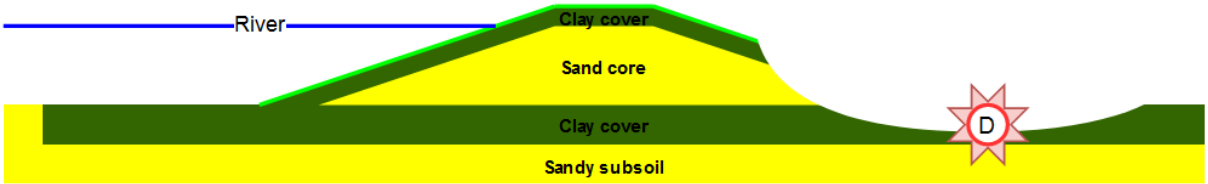

Figure 11: Schematization of how pipe failure influences the sub-mechanism burst and heave (the cover layer thickness is reduced)

2.3.2.2 Heave

Heave is when the flow of water transports sand particles upwards through the hole in the clay layer (De Bruijn, 2013). This happens only when the force from the water flow on the sand is large enough to push the particles through the whole thickness of the clay layer. The thicker the clay layer, the more force is required.

Similarly to burst, the thickness of the cover layer determines if heave will occur. Because the presence of a crater in the cover layer changes its thickness, it is important to investigate the effects of pipe failure on the thickness of the cover layer (Figure 11).

2.3.2.3 Backward erosion

Backwards erosion is the final sub-mechanism that needs to occur before the failure mechanism piping occurs. The backward erosion starts when the horizontal force on the sand grains caused by the water is larger than the friction force (De Bruijn, 2013). That results in horizontal movement from sand from the waterside to the landside of the dike. This movement is possible because the burst sub-mechanism has opened up a void on the landside, the exit point. Once the sand starts to move, the erosion channel moves backwards. After a certain timespan, the piping channel goes underneath the whole width of the dike and reaches the entrance point. The water can now move with low resistance, and because of this, the flow rate increases even further. This again increases the erosion rate of the sand layer. At a certain point, the erosion channel has grown so large that the dike can no longer be supported. Now, the whole dike collapses, and the land is flooded as a result.

Sellmeijer et al. (2011) have derived an empirical equation for the critical head difference for which backward erosion will occur:

$$H_c = F_r F_s F_g L \qquad \textbf{Eq. 2}$$

In which:

- H_c is the critical head difference (m)
- F_r is a resistance term $= \frac{\rho^s - \rho^l}{\rho^l} \eta \tan\theta$
- F_s is a scaling term $= \frac{d_{70}}{\sqrt[3]{\kappa L}}$

- F_g is a geometry term $= 0.91 \left(\frac{D}{L}\right)^{\varsigma}$
- L is the width of the dike at the location of the piping channel (m)

A crater formed by pipe failure can decrease the dike cross-section's width (L) at the piping channel's location. The distance between the backwards erosion's entrance and exit points is lowered, which means that backward erosion will occur at a lower critical head. Figure 12 shows a schematization of this for pipe failure at the riverside. The crater moves the entrance point closer to the exit point.

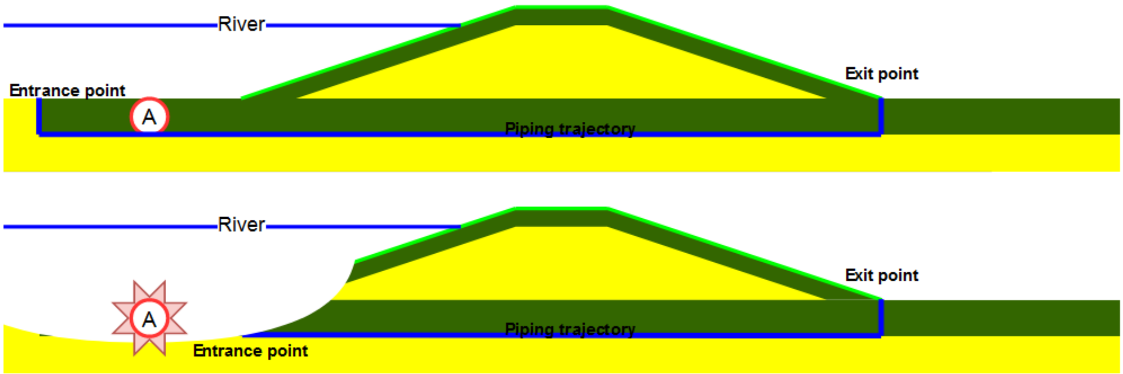

Figure 12: Schematization of how pipe failure can affect the backward erosion sub-mechanism of piping

2.3.3 Erosion of the grass cover (GEKB or GEBU)

The clay and grass covers on a sand dike provide essential protection against dike erosion due to wave impacts and water overflow. The cohesive force between the clay particles and the roots of the grass layer is strong enough to resist the wave impacts and water flow in case of dike overtopping up to a certain flow rate. When a pipeline fails, a hole can be formed in the grass and or clay layer due to an erosion or explosion crater. This hole is a weak point that can create a starting point for dike failure. Water can quickly erode the dike's sand core because there is no cohesion between the sand particles. The dike will likely fail once the overflowing stream comes in open contact with the sand core (Figure 13).

The location of the grass erosion can occur at the inner dike slope, crest, or outer dike slope. These three locations are distinguished by two failure mechanisms. The abbreviation for the failure mechanism of grass erosion on the outer slope is GEBU. Grass erosion of the crest and inner slope is abbreviated as GEKB. A schematic overview of both failure mechanisms can be viewed in Figure 13.

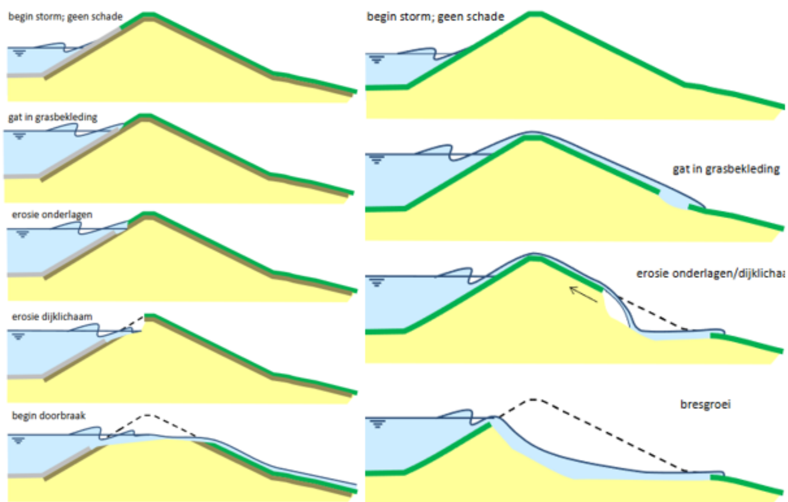

Figure 13: Schematic overview of GEBU (left) and GEKB (right). ('t Hart, 2018)

The impact of pipe failure on the hole in the grass layer will be the same when a pipe fails near the inner or outer dike toe, but GEKB is assessed more strictly than GEBU ('t Hart, 2018). Erosion of the inner slope always occurs during high water conditions due to wave overtopping or overflow. Therefore, failure of the mechanism GEKB will most likely lead to more severe flooding of the hinterland than failure of GEBU.

The fact that GEKB is assessed more strictly than GEBU can be seen in Figure 14. For GEKB, the erosion of the grass layer alone is enough to fail a dike due to insufficient covering. GEBU, on the other hand, requires erosion of both the grass and the clay layers before the covering as a whole is considered unsatisfactory to prevent erosion by wave impacts and overflow.

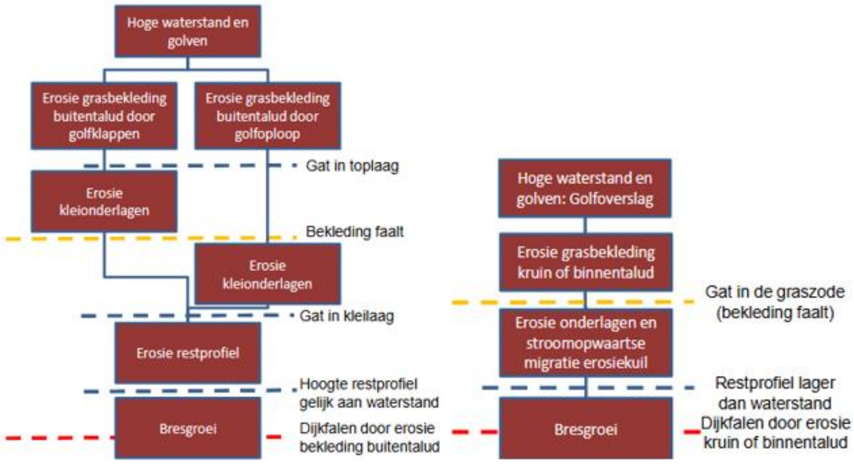

Figure 14: Definition of failure of the dike covering for GEBU (left) and GEKB (right) ('t Hart, 2018)

In conclusion, the definition of failure for grass erosion of the crest and inner slope (GEKB) is stricter than that for grass erosion of the outer slope (GEBU). That means that a pipe failure that results in grass erosion acceptable for the failure mechanism GEKB will also suffice for GEBU. Because of this, only GEKB will be assessed in this research.

2.4 Summary

An overview of the connections between the main topics of this theoretical framework chapter is given in Figure 15. It contains information about how the failure of gas and water pipes affects the soil and subsequent failure mechanisms. The rectangle on the right side clarifies which pipe properties influence the probability of pipe failure (occurrence criterion) and the magnitude of the damage (damage criterion)

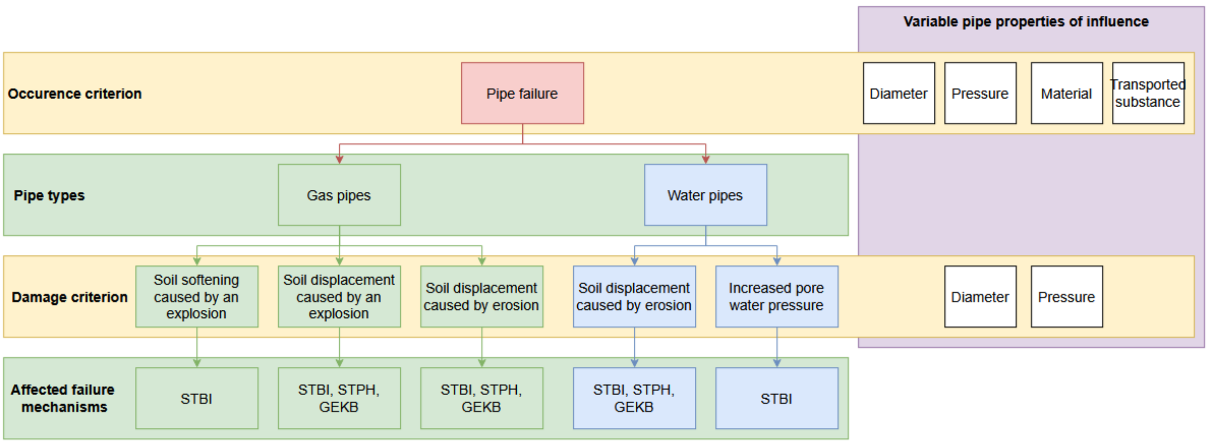

Figure 15: Relationships between elements within the scope of the research

3. Methods

This section contains, per subquestion from Chapter 1.5, the methods that will be used to answer them. Finally, a methodology will be given on how the answers to the subquestion will contribute to fulfilling the research objective and the answer to the main question. Figure 16 contains an overview of the research methodology.

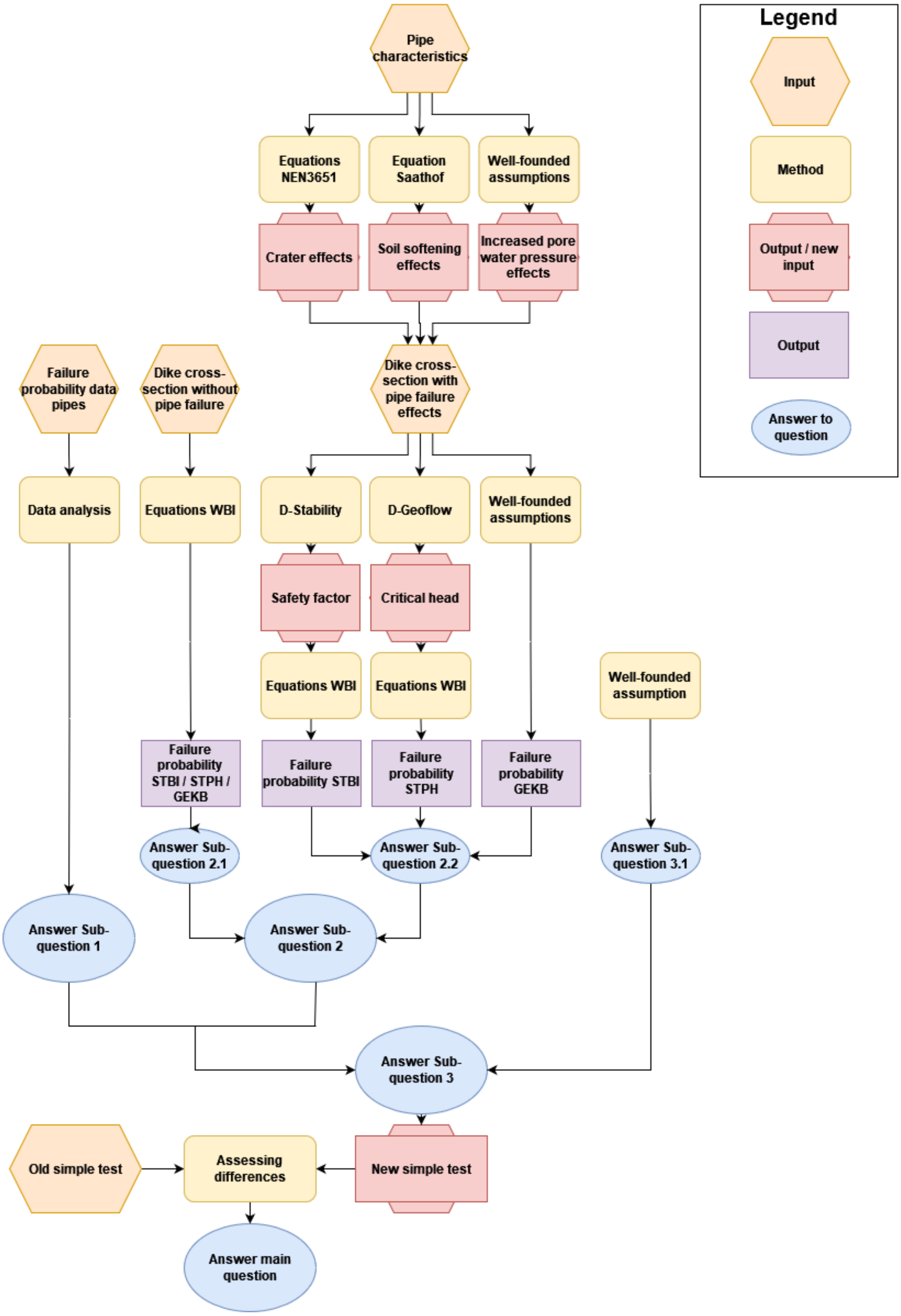

Figure 16: Overview of the research methodology

3.1 Relation between the probability of pipe failure and pipe properties

"What is the relation between the probability of failure of a pipe and its diameter, pressure, material, and transported substance?"

This subquestion will be answered via analysis of data that has been obtained from Ouwendijk et al. (2020). This data relates to the probability of failure of pipes, given their material, diameter, and pressure. The raw data is attached in Appendix B. For this question itself, no calculations will be performed. The data will be displayed differently in graphs such that the relationship between the probability of pipe failure and the properties of the pipe will become more apparent.

3.2 Relation between pipe failure and the failure probability of a dike

"What is the relation between pipe failure and the failure probability of a dike?"

This question requires the calculation of the failure probability of a dike for situations with and without pipe failure. Sections 3.2.1 and 3.2.2 will explain how these probabilities will be calculated.

3.2.1 Failure probability of a dike without pipe failure

"What is the failure probability for an affected failure mechanism without pipe failure?"

As stated in section 1.4.5, the dike that will be the subject of the research is a hypothetical cross-section with a failure norm of 1/10,000 per year (Figure 3). In this research, it is assumed that the failure probability of the dike cross-section is equal to the norm. This is never exactly the case in practice, but since it is a hypothetical dike cross-section and not an actual one, it is unknown what the exact failure probability of the dike is.

The failure norm of 1/10,000 per year is an integrated norm for all failure mechanisms and the whole length of the dike trajectory. Per failure mechanism and on a cross-sectional level, the failure norm is stricter because the dike trajectory consists of many failure mechanisms and cross-sections that all contribute to the failure probability on a trajectory level.

This research is interested in the failure probability on cross-sectional level for each failure mechanism affected by pipe failure (STBI, STPH, and GEKB). The Legal Assessment Framework gives the following equation to convert a failure norm for a dike trajectory to a failure norm for an independent failure mechanism on a cross-sectional level (Ministerie van Infrastructuur en Milieu, n.d., p. 16):

$$P_{norm,cross,mech} = \frac{\omega P_{norm}}{N_{cross}} \qquad \textbf{Eq. 3}$$

In which:

- $P_{norm,cross,mech}$ is the norm for an independent failure mechanism on a cross-sectional level ($year^{-1}$)
- ω is a factor related to the failure norm budget for a failure mechanism (-)
- P_{norm} is the failure norm on a trajectory level ($year^{-1}$)
- N_{cross} is a factor related to the length of the dike trajectory and the failure mechanism (-)

The ω-values are constants given in the Legal Assessment Framework and are displayed in Table 1.

Table 1: Factors related to the failure budget per failure mechanism (Ministerie van Infrastructuur en Milieu, n.d., p. 16))

Failure mechanism	ω –value (-)
Macro instability of the inner slope (STBI)	0.04
Piping (STPH)	0.24
Erosion of the grass cover at the crest and inner slope (GEKB)	0.24

N_{cross} is related to the dike trajectory's length and depends on the failure mechanism. Rijkswaterstaat (2017, p. 13) gives the following formula to calculate the value for macro instability and piping:

$$N_{cross} = 1 + \frac{a \times L_{trajectory}}{b} \quad \textbf{Eq. 4}$$

For the length of the trajectory ($L_{trajectory}$), a value of 20,000 metres will be used. This assumption is needed because the cross-section is a hypothetical one. The chosen value is relatively average for the length of a dike trajectory along one of the major rivers. That can be derived from Rijkswaterstaat (2017, p. 60-62).

The values of constants a and b are displayed in Table 2.

Table 2: Constants to calculate Ncross for piping STBI en STPH (Rijkswaterstaat, 2017, p. 13)

Failure mechanism	a (-)	b (-)
Macro instability of the inner slope (STBI)	0.033	50
Piping (STPH)	0.40	300

For the failure mechanism GEKB, Rijkswaterstaat (2017, p. 14) gives the values 1,2 and 3 as possible values for N_{cross}. In practice, this value is determined for each dike trajectory individually. In this research, a value of 2 will be used because the trajectory is hypothetical.

3.2.2 Failure probability of a dike with pipe failure

"What is the probability of failure for an affected failure mechanism with pipe failure?"

This sub-question requires the effects of pipe failure on the soil, as stated in Figure 6, to be quantified. Firstly, the methods used to do this will be stated. Secondly, the methods used to calculate the failure probability per mechanism will be introduced.

3.2.2.1 Quantifying the effects of pipe failure on the soil

Soil displacement caused by erosion for gas pipe failure

The crater that forms due to the failure of a gas pipe has a certain depth (D_k) and radius (G_B). A schematization of this is given in Figure 17.

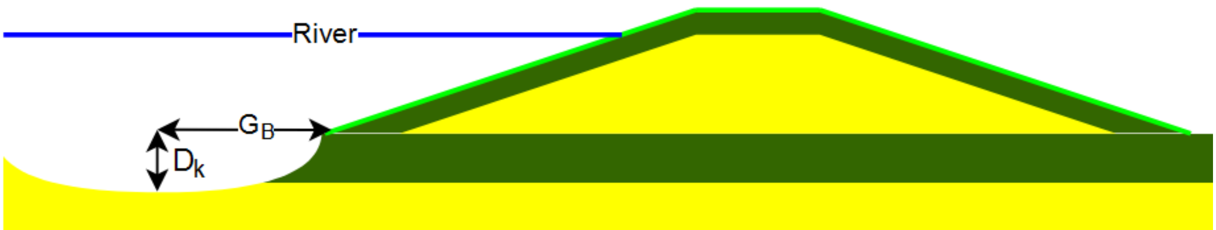

Figure 17: Schematization of crater properties after pipe failure

NEN3651 provides equations to calculate these crater properties (NEN, 2020):

$$G_B = R(w)\left\{\frac{g}{D_k^2} \times \left(\frac{I}{\rho_{omg} \times g}\right)^3 \times t^2\right\}^{0.125} \quad \textbf{Eq. 5}$$

$$D_k = 1.6D_0 + H \quad \textbf{Eq. 6}$$

These equations require the calculation of the following parameters:

$$I = Q^* \times u^* + \left(p^* - p_{omg}\right) \times A \qquad \textbf{Eq. 7}$$

$$Q^* = \rho^* \times u^* \times A \qquad \textbf{Eq. 8}$$

$$u^* = \sqrt{\frac{2k}{k+1} \times \frac{p_0}{\rho_0}} \qquad \textbf{Eq. 9}$$

$$p^* = p_0 \times \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \qquad \textbf{Eq. 10}$$

$$\rho^* = \rho_0 \times \left(\frac{p^*}{p_0}\right)^{\frac{1}{k}} \qquad \textbf{Eq. 11}$$

$$A = \left(\frac{D_0}{2}\right)^2 \times \pi \qquad \textbf{Eq. 12}$$

$$\rho_0 = \frac{p_0}{RT} \qquad \textbf{Eq. 13}$$

In which:

- I is the pulse flow of the radius (N)
- Q^* is the mass flow through the pipe (kg/s)
- u^* is the critical outflow rate of the gas (m/s)
- p^* is the pressure of the gas at the site of the escape opening (Pa)
- ρ^* is the density of the escaping gas in the hole (kg/m^3)
- A is the cross-sectional area of the pipe (m^2)
- ρ_0 is the density of the gas in the pipe (kg/m^3)

The independent variables per pipe are pressure p_0 and diameter D_0. Table 3 contains the value range that will be used for these variables. It has been decided to pick two pressure values and six diameter values. This relatively small spectrum of values has been chosen in preparation for the modelling steps in D-Stability (Section 3.2.2.2). Although the crater sizes can easily be calculated for a larger spectrum of pressures and diameters by filling in Equations 5 and 6, the time required for the follow-up modelling takes longer. Every additional pressure value that would be incorporated into the research would require D-stability to be run 18 times more (6 diameter values multiplied by 3 locations B, C, and D from Figure 2). Due to time limitations, this would not be feasible.

Table 3: Value range of variables per pipe

Variable	Unit	Range
p_0	Pa	200,000 & 1,000,000
D_0	m	0.05, 0.1, 0.2, 0.3, 0.4, 0.5

The other symbols represent constants whose meaning and the justification for the chosen value are given in Table 4.

Table 4: Values of constants used in calculating the erosion crater properties for gas pipes.

Parameter	Value	Unit	Description	Source
$R(w)$	0.025	-	Constant related to the soil type and moisture content. The presented value is valid for wet sand and clay.	(NEN, 2020)
g	9.81	m/s^2	The standard value for gravitational acceleration in the Netherlands.	-
ρ_{omg}	0.833	kg/m^3	Density of gas at ambient pressure.	(NEN, 2020)
t	7,200	S	Duration of the gas outflow that should be assumed (2 hours).	(NEN, 2020)
H	1	m	Assumed soil covering on the gas pipe.	Assumption
p_{omg}	100,000	Pa	Ambient pressure.	-
k	1.33	-	Dimensionless constant for adiabatic isentropic expansion.	(NEN, 2020)
R	518.28	J/kg	Specific gas constant for natural gas.	-
T	288	K	Assumed average temperature during gas pipe failure (15 $°C$).	Assumption

Soil displacement caused by an explosion

Similarly to the erosion crater, the explosion crater has a depth (D_k) and radius (t). For these properties, the NEN also provides equations (NEN, 2020):

$$t = \sqrt{\left\{2.97\left(D_i^3 p_0\right)^{\frac{2}{3}} - 0.83w^2 + 1.40w\left(D_i^3 p_0\right)^{\frac{1}{3}}\right\}} \qquad \textbf{Eq. 14}$$

$$D_k = H + D_0 \qquad \textbf{Eq. 15}$$

These equations require the calculations of the following parameters:

$$w = H + 0.5D_0 \qquad \textbf{Eq. 16}$$

In which:

- w is the depth of the pipeline axis (m)

The independent variables for the explosion crater calculation are the same as in Table 3. In Equation *14*, D_i represents the internal pipe diameter instead of the outer pipe diameter D_0. In the calculation, no distinction will be made between them, so the thickness of the pipe wall is assumed to be 0 millimetres. This is a slightly conservative assumption.

The thickness of the soil covering on top of the pipe, H, is assumed to be 1 meter. This number equals the value in Table 4 used to calculate erosion craters.

Soil softening caused by an explosion

Saathof (1984) provides an equation that relates the magnitude of an explosion to the effects of soil softening:

$$\frac{\Delta u}{\sigma'} = a + b\, ln\left(\frac{w^{\frac{1}{3}}}{R}\right) \quad \textbf{Eq. 17}$$

In which:

- $\frac{\Delta u}{\sigma'}$ is a value that represents the magnitude of the soil softening (-)
- a and b are constants related to the compactness of the sand (1.65 and 0.64, respectively, for average packed sand)
- w is the size of the explosion (TNT-equivalent)
- R is the distance to the location of the explosion (m)

This formula requires an equation that relates the properties of a gas pipe to an explosion size in TNT-equivalent (w). NEN3651 (NEN, 2020) provides this:

$$w = 3.9 D_i^3 \times p_0 \quad \textbf{Eq. 18}$$

The internal diameter D_i is for reasons of simplification, assumed to be equal to the outer diameter D_0. The values that will be used for these independent variables are displayed in Table 3.

The output value of Equation *17* determines the degree of soil softening at a distance R from the pipe. For values below 0.1, softening is assumed to play no role in soil strength (Saathof, 1984). If the value is 0.8 or larger, the soil is completely softened and does not possess any strength. Output values between 0.1 and 0.8 may represent soil that is partially softened. What this means for the soil properties in the dike will be explained in the section 'Modelling soil softening in D-stability'.

Soil displacement caused by erosion for water pipes

Similarly to the erosion and explosion crater that can be formed by gas pipe failure, the erosion crater that forms due to water pipe failure also has a depth (D_k) and radius (R_B). NEN3651 provides equations to relate these crater properties to the properties of the pipe (NEN, 2020):

$$R_B = 7.8 \times d_g \times \left(\frac{P}{\rho \times g^{1.5} \times \mu \times d_g^{3.5}}\right)^{0.243} \quad \textbf{Eq. 19}$$

$$D_k = 1.2(D_0 + H) \quad \textbf{Eq. 20}$$

These equations require the calculations of the following parameters:

$$\mu = 0.0002h^2 - 0.02h + 1 \; or \; \mu = 0.5 \; if \; h > 50 \quad \textbf{Eq. 21}$$

$$P = \rho \times g \times Q \times h \quad \textbf{Eq. 22}$$

$$Q = \left(\frac{D_0}{2}\right)^2 \times \pi \times u \quad \textbf{Eq. 23}$$

In which:

- μ is a discharge coefficient (-)
- P is the hydraulic power of the leak (W)
- Q is the flow rate through the hole (m^3/s)

The independent variables that will be varied per pipeline are the pressure (h) and diameter of the leak (d_g). A description of those variables is given in Table 5.

Table 5: Description of independent variables in the equations for erosion craters caused by water pipe failure

Variable	Unit	Description
h	mWC	The pressure in this equation has the unit of 'meter water column'. One mWC equals 10,000 Pa.
d_g	m	The diameter of the leak can take on any value between 0 and the diameter of the pipe, D_0. In this research, it is assumed that $d_g = D_0$. This is a conservative assumption.

The other symbols represent constant values whose meaning and the justification for the chosen value are given in Table 6.

Table 6: Description of constants in the equations for erosion craters caused by water pipe failure

Parameter	Value	Unit	Description	Source
ρ	1,000	kg/m^3	Density of water	-
g	9.81	m/s^2	The standard value for gravitational acceleration in the Netherlands.	-
H	1	m	Assumed soil covering on the gas pipe.	Assumption
u	2	m/s	Assumed flow velocity in the water pipes	(Waterschap Rijn en IJssel, 2008, p. 11)

Increased pore water pressure in the dike

No equations have been found that relate the properties of a water pipe to the increase in water pressure inside the dike. It is hypothesized that the flow rate through the leak and, thus, the diameter and pressure of the pipe affect the magnitude at which the pore water is increased. It is also likely that the permeability of the soil has an effect.

Because of the lack of equations, conservative assumptions need to be made to quantify how the water table in the dike is affected. Ouwendijk et al. (2020, p. 17) recommend laying the phreatic line at the surface of the dike body if a water pipe fails between the inner and outer toe. Figure 17 shows a schematization of the difference between phreatic lines with and without pipe failure.

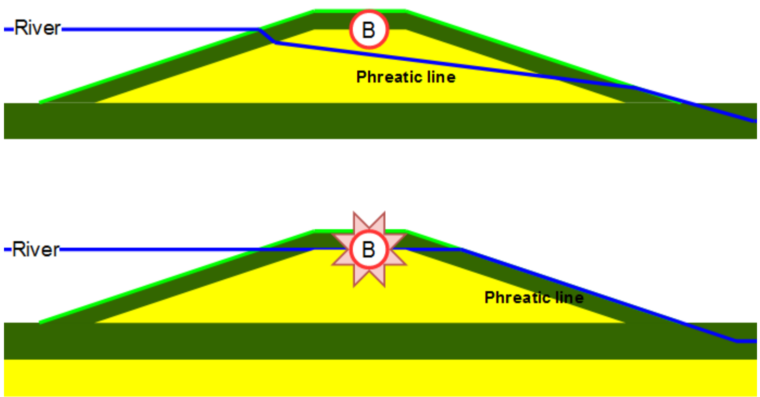

Figure 18: Schematization of the effect of water pipe failure on the phreatic line

3.2.2.2 Effects of the pipe failure implications on the failure mechanisms

Effects on the macro stability of the inner slope (STBI)

In Figure 15, it can be seen that all effects of pipe failure can have an impact on the failure mechanism STBI. These effects will be modelled in the D-Stability model.

D-stability

D-stability is a software developed by Deltares to assess the safety of a dike cross-section regarding the failure mechanism macro-instability (Deltares, 2023b). D-stability aims to find the normative slide circle, which is the one that has the relatively smallest stabilizing moment compared to the destabilizing moment.

The destabilizing moment is the moment that induces sliding of the dike slope. The magnitude of this moment depends predominantly on the force of gravity on the soil mass inside the sliding circle. The unit weight of the soil is important for this.

The stabilizing moment is the moment that counteracts the sliding of the dike slope. The magnitude of this moment depends on the friction force along the boundary of the sliding circle. The friction angle of soil is a parameter that determines this force. Cohesive forces inside clay layers also resist the sliding of soil particles past each other.

D-stability calculates the stabilizing and destabilizing moments of many sliding circles and displays the one with the lowest safety factor. The safety factor is defined as the quotient of the stabilizing and destabilizing moment (Deltares, 2023b):

$$F_s = \frac{M_{stabilizing}}{M_{destabilizing}} \qquad \textbf{Eq. 24}$$

Therefore, a safety factor of 1 or higher means that no sliding will occur.

D-stability calculates the moments on the surface of the sliding circle by splitting the circle into a finite number of slices. The forces on the surface of the sliding surface are calculated for each slice and added together afterwards. In Figure 19, a schematization of the calculation procedure is given.

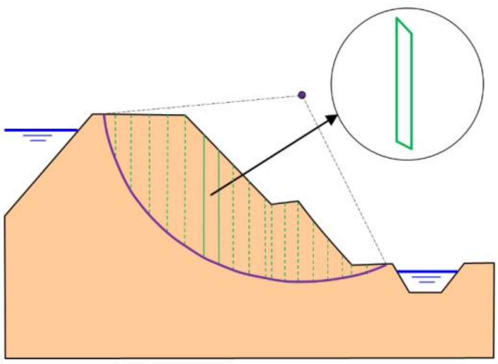

Figure 19: A sliding circle divided into slices to calculate the stability (Deltares, 2023b)

Modelling craters in D-stability

Erosion and explosion craters with sizes calculated with Equations *5*,*6*, and *14*, *15* will be compared. The largest crater will generally undermine the safety of the dike the most and is thus normative. The largest crater is then placed into the dike cross-section from Figure 3. That will be done for locations B, C, and D from Figure 2. Subsequently, the model will be run, and the resulting safety factor for the dike cross-section will be collected. Appendix C contains detailed information about the modelling parameters in D-Stability.

Modelling soil softening in D-stability

An explosion of a gas pipe can leave the sand core of the dike entirely or partially softened, depending on the magnitude of the blast and the distance to it. In D-Stability, the strength parameters of the soil need to be defined for the default situation. The strength parameters are the cohesion and friction angle, and for the default situation, they have been assigned values of 0 kN/m^3 and 30° respectively.

In case of an explosion, it has been assumed that a linear relationship exists between the output of Equation *17* and the friction angle. Sand for which values of 0.8 or higher apply is fully softened and thus gets a friction angle of 0. Values of 0.1 and lower are not softened and get the default friction angle value. Sand for which a value between 0.1 and 0.8 applies gets a friction angle value proportionate to the degree of softening. In Table 7, an example of this methodology is displayed for the softening effects after the explosion of a gas pipeline with a diameter of 0.4 meters and a pressure of 10 bars. Figure 20 shows what this methodology looks like in D-stability.

Table 7: Example of a relationship between the degree of soil softening and the value of the friction angle

Distance to the explosion (m)	Value from softening equation (-)	Degree of softening (%)	Friction angle (°)
1	1.4	100%	0
2	0.9	100%	0
3	0.7	86%	4.3
4	0.5	57%	12.9
5	0.3	29%	21.4
6	0.2	14%	25.7
7	0.1	0%	30

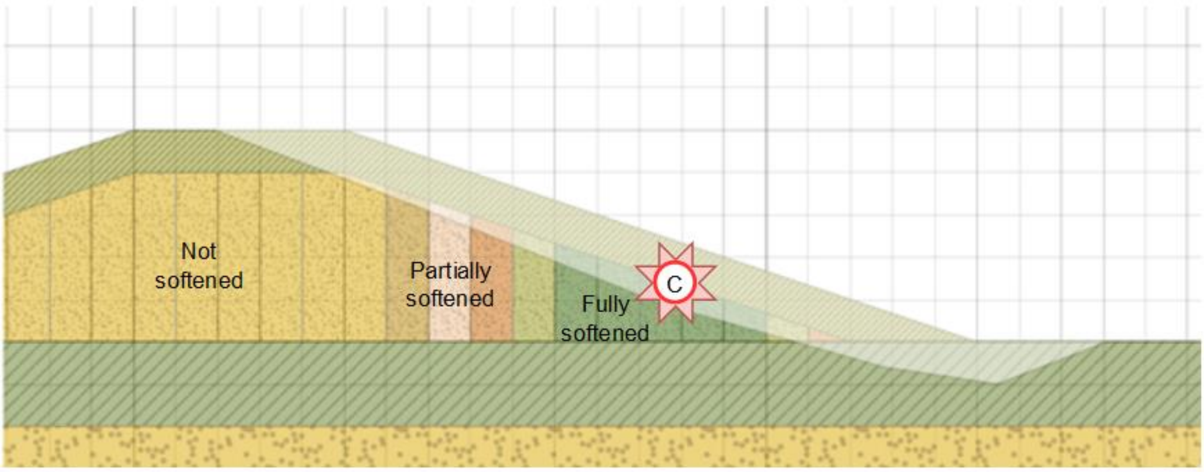

Figure 20: Modelling softening in D-Stability for a gas pipe failure in the inner slope

Modelling increased pore water pressure in D-Stability

In case of a creeping leak in a water pipe between the inner and outer toe of the dike, the phreatic line within the dike is heightened to the surface of the dike profile regardless of the properties of the water pipe. This procedure is also schematized in Figure 18.

Effects on piping (STPH)

In Figure 15, it can be seen that only the formation of craters influences the failure mechanism piping. These effects will be modelled in the D-Geoflow model.

D-Geoflow

D-Geoflow is a software developed by Deltares to assess the occurrence of backward erosion, a sub-mechanism of piping (Deltares, 2023a). The software uses 2D finite element method to calculate forces on soil particles to see when these are in equilibrium or when they tend to move.

The equations behind the model are quite extensive and complicated. In general, it can be said that the D-Geoflow model consists of 4 main parts (Noordam & Van Beek, 2018):

- Groundwater flow model
- Piping module
- Boundary conditions
- Material parameters.

The piping module is based on Sellmeijer's model. Sellmeijer's critical head equation (Equation *2*) has been derived from this model.

The general principle of the model is to find the head difference between the water and land side of the dike for which a pipe forms below the whole width of the dike. When this happens, the dike fails due to piping. The lowest head difference for which this occurs is the critical head difference. The critical head difference exerts a force large enough to overcome the friction forces on all triangular soil elements (Figure 21) in the width of the dike. Whether the force is large enough for a given head difference is determined by varying the water levels and thus the head difference (Deltares, 2023a).

The size of the triangular soil elements can be increased and decreased depending on the trade-off between calculation pace and accuracy. The larger the soil elements, the higher the calculation pace and the lower the accuracy.

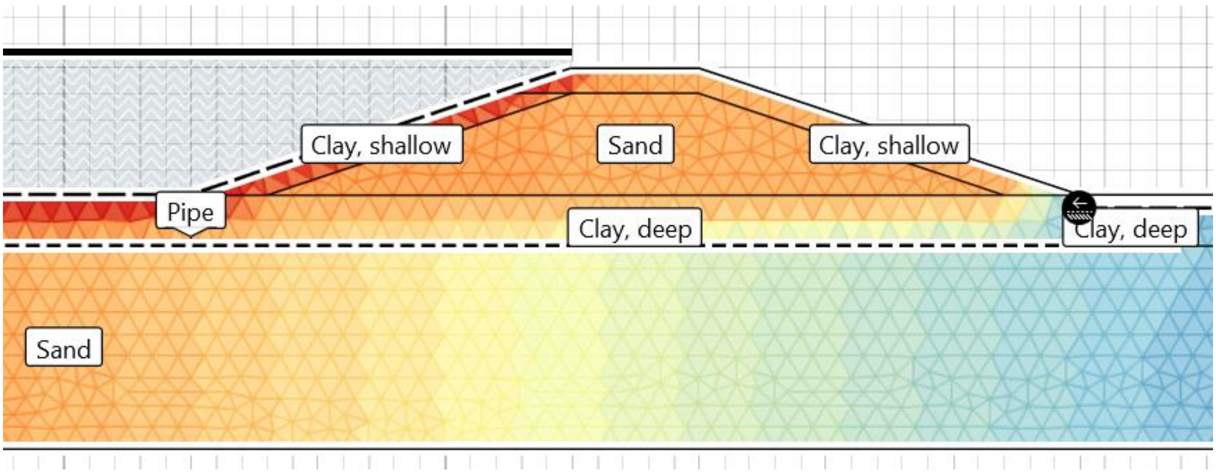

Figure 21: Triangular soil elements in a dike cross-section

Modelling craters in D-Geoflow

The effect of crater formation on backward erosion will be modelled in D-Geoflow for pipes in the fore- and hinterland (locations A and D of Figure 2). This is done because erosion craters at these locations influence the backwards erosion's entrance and exit points, respectively. The new entrance or exit point of the backward erosion has been defined to be at half the distance of the crater radius closest to the dike's crest. Figure 22 contains a schematization of this procedure for both locations.

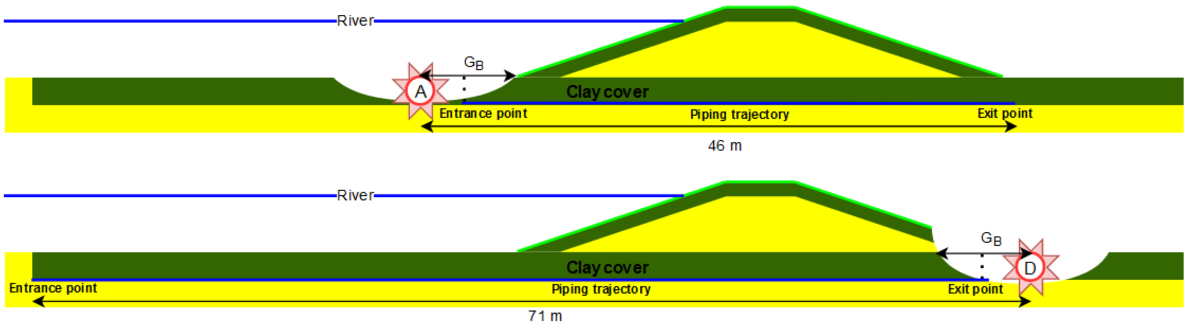

Figure 22: Schematization of the procedure that is followed to model craters in D-Geoflow for pipes in the foreland (A) and hinterland (D)

For pipes in the foreland, the location of the pipe has been defined to be 10 metres from the outer toe. The entrance point is subsequently half the crater width from this location to the dike side. The exit point has been defined to be 1 metre from the inner toe.

For pipes in the hinterland, the entrance point has been defined as the start of the clay cover layer at the riverside. This location is 35 metres from the inner toe, which is the same distance as the width of the dike body. The pipe is located in the hinterland, 1 metre from the outer toe. The exit point of the piping trajectory is subsequently half the crater width from this location to the dike side.

Only the largest crater (formed by erosion or explosion) will be modelled for gas pipe failure.

Effects on erosion of the grass cover at the crest and inner slope (GEKB)

In Figure 15, it can be seen that only the formation of craters influences the failure mechanism GEKB. GEKB will not be assessed via modelling but via analysis of the crater size. If the crater size is larger than 15 by 15 centimetres, the condition of the grass cover will be considered insufficient. A hole this size is considered to be the failure criterion for GEKB according to the Schematization Manual GEKB (Rijkswaterstaat, 2022).

3.2.2.3 Calculation of the probability of failure for an affected failure mechanism

Macro stability of the inner slope (STBI)

The output from the D-Stability model, the safety factor, will be used to calculate the probability of failure of the dike cross-section for the failure mechanism STBI. The Legal Assessment Framework provides a formula that relates these quantities (Ministerie van Infrastructuur en Milieu, n.d., p. 36):

$$P_{f;i} = \phi\left(-\frac{\left(\frac{F_s}{\gamma_d}\right) - 0.41}{0.15}\right) \qquad \textbf{Eq. 25}$$

In which:

- $P_{f;i}$ is the annual probability of failure for the dike cross-section via STBI.
- F_s is the safety factor from D-stability
- γ_d is a model factor (1.11)
- ϕ represents the standard (cumulative) normal distribution.

Regarding the failure mechanism STBI, Wevers (2020) uses a criterion that 3 meters of the crest width should remain after the damage, which is in this case caused by a pipe failure. If the dike ends up with a smaller crest, the dike cannot be considered to have the same height as before the damage.

Because of this, the failure probability of STBI will only be calculated with Equation *25* if the remaining crest width is larger than 3 meters. In other cases, the failure probability of the dike for STBI will be assigned the value of 1. This does not necessarily mean that the annual flooding probability is 1, but instead that the crater formed by pipe failure is so large that the combination of this pipe and its location cannot be considered safe in the simple test. Assigning a failure probability of 1 achieves this goal. In practice, the dike would fail after water flows over the damaged dike cross-section. The chance of occurrence of such a high water event would then be the probability of dike failure for STBI. However, this step is not included in this methodology because the dike cross-section is hypothetical. This means that no data is present about the probabilities of high water events.

In Figure 23, the procedure is clarified about how the failure probability for STBI is determined for the different remainders of the crest width.

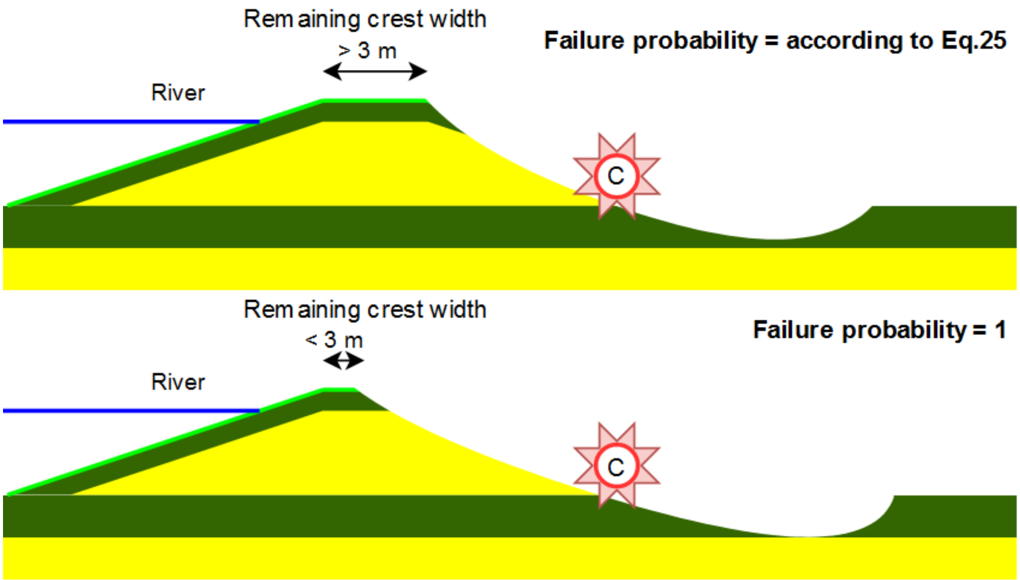

Figure 23: Schematization of the procedure that will be followed in calculating the failure probability for STBI

Piping (STPH)

The WBI provides an equation to calculate the probability of occurrence of each of the three sub-mechanisms of piping (Ministerie van Infrastructuur en Milieu, n.d., p. 43-45)

Burst

The occurrence chance for the sub-mechanism burst can be calculated with:

$$P_{f;u} = \phi\left(-\frac{ln\left(\frac{F_u}{0.48}\right) + 0.27\beta_{norm}}{0.46}\right) \quad \textbf{Eq. 26}$$

In which:

- F_u is a stability factor for the sub-mechanism burst (-)
- β_{norm} is a reliability index of the dike trajectory (-)

Both are calculated with the following formulae:

$$F_u = \frac{\Delta\phi_{c,u}}{\Delta\phi} \quad \textbf{Eq. 27}$$

$$\beta_{norm} = -\phi^{-1}(P_{max}) \quad \textbf{Eq. 28}$$

In which:

- $\Delta\phi_{c,u}$ is the critical piezometric head (m)
- $\Delta\phi$ is the actual piezometric head (m)
- P_{max} is the maximum allowable failure probability on a trajectory level (year^{-1})
- ϕ is the standard (cumulative) normal distribution

The critical and actual piezometric heads are calculated with the following equations:

$$\Delta\phi_{c,u} = \frac{D_{cover}(\gamma_{sat} - \gamma_{water})}{\gamma_{water}} \quad \textbf{Eq. 29}$$

$$\Delta\phi = (h - h_{exit})r_{exit} \quad \textbf{Eq. 30}$$

The meaning and chosen values for the parameters in Equations *29* and *30* are given in Table 8.

Table 8: Parameter value description for the calculation of the piezometric heads

Parameter	Value	Unit	Description
D_{cover}	Variable	m	Thickness of the clay cover layer. The standard value is 2 m, but if the crater affects the thickness, this is less.
γ_{sat}	15.6	kN/m^3	The specific weight of the clay cover layer (Default value in D-Stability)
γ_{water}	9.81	kN/m^3	The specific weight of water
h	4	m +NAP	The water level on the riverside with reference to NAP, with a return period equal to the norm. Because the dike is hypothecal, no data is available on this. Therefore, a water level of 1 meter below the crest has been assumed.
h_{exit}	- 0.5	m +NAP	The water level on the land side with reference to NAP. This has been assumed.
r_{exit}	1	-	The response factor between 0-1 determines how an increase in water level at the riverside increases the water level at the landside. This value is highly variable and situation-dependent. Because of this, the most conservative value of 1 has been chosen.

Heave

The occurrence chance for the sub-mechanism heave can be calculated with:

$$P_{f;h} = \phi\left(-\frac{ln\left(\frac{F_h}{0.37}\right) + 0.3\beta_{norm}}{0.48}\right) \quad \textbf{Eq. 31}$$

In which:

- F_h is a stability factor for the sub-mechanism heave (-)
- β_{norm} is a reliability index of the dike trajectory (-)

The stability factor is defined as:

$$F_h = \frac{i_{c,h}}{i} \quad \textbf{Eq. 32}$$

In which:

- $i_{c,h}$ is the critical heave gradient (0.3)
- i is the actual heave gradient (-)

The actual heave gradient is defined as:

$$i = \frac{(h - h_{exit})r_{exit}}{D_{cover}} \quad \textbf{Eq. 33}$$

The description of the parameters and the chosen values are equal to the sub-mechanism heave and are displayed in Table 8.

Backward erosion

The occurrence chance for the sub-mechanism backward erosion can be calculated with:

$$P_{f;p} = \phi\left(-\frac{ln\left(\frac{F_p}{1.04}\right) + 0.43\beta_{norm}}{0.37}\right) \quad \textbf{Eq. 34}$$

In which:

- F_p is a stability factor for the sub-mechanism heave (-)
- β_{norm} is a reliability index of the dike trajectory (-)

The stability factor is defined as:

$$F_p = \frac{\Delta H_c}{(h - h_{exit} - r_c D_{cover})} \quad \textbf{Eq. 35}$$

In which:

- ΔH_c is the critical head difference (m)
- r_c is a reduction factor for the resistance of the soil against piping at the exit point (0.3)

The meaning and chosen values for the other parameters can be found in Table 8.

The critical head difference, ΔH_c, is the output of the D-Geoflow model. This parameter and the thickness of the cover layer are the independent variables that change depending on the properties of the crater resulting from pipe failure.

Failure probability piping

Piping only occurs when all three sub-mechanisms happen. Therefore, the probability of dike failure due to piping is equal to the smallest occurrence probability from the sub-mechanisms:

$$P_{f;i} = min(P_{f;u}, P_{f;h}, P_{f;p}) \quad \textbf{Eq. 36}$$

Erosion of the grass cover at the crest and inner slope (GEKB)

When the crater size is larger than 15 by 15 centimetres, the grass cover fails (Rijkswaterstaat, 2022). However, this does not directly mean that the dike fails. The dike only fails when the flow rate over the dike is large enough. In other words, the failure probability of GEKB equals the probability that enough water flows over the dike crest. Since the dike cross-section is hypothetical, no data is available for this probability. Therefore, it will be assumed that the probability of overflow is equal to the norm for GEKB. This value can be determined by filling in Equation *3* with the values for GEKB:

$$P_{norm,cross,GEKB} = \frac{\omega P_{norm}}{N_{cross}} = \frac{0.24 \times \frac{1}{10{,}000}}{2} = 1.2 \times 10^{-5} \qquad \textbf{Eq. 37}$$

3.3 Assessing differences in failure probabilities of the dike due to pipe failure

“For which combinations of pipe characteristics, locations and orientation is the change in failure probability (in)significant?”

The change in the failure probability of a dike for a given failure mechanism will be calculated with:

$$\Delta P_{dike,fail,mech} = \frac{P_{pipe,fail,100} \times P_{new,dike,fail,mech}}{P_{default,dike,fail,mech}} \qquad \textbf{Eq. 38}$$

In which:

- $\mathrm{P}_{\mathrm{pipe,fail,100}}$ is the annual probability of pipe failure over a distance of 100 meters.
- $\mathrm{P}_{\mathrm{new,dike,fail,mech}}$ is the new annual failure probability for a dike, given a failure mechanism resulting from pipe failure.
- $P_{default,dike,fail,mech}$ is the default annual failure probability for a dike given a failure mechanism. This is assumed to be equal to the norm $P_{norm,cross,mech}$, which is calculated with Equation 3.

3.3.1 Determining the definition of a significant change

“Which change in failure probability of the dike forms the boundary between an insignificant and significant change?”

No information has been found regarding what can be considered a significant change due to pipe failure. Therefore, a conservative estimate needs to be done. The failure chance budget (Dutch: faalkansbudget) from the Legal Assessment Framework (Ministerie van Infrastructuur en Milieu, n.d., p. 16) reserves 30% of the budget for so-called ‘other assessment tracks’ (Dutch: overige toetssporen). This part of the budget is reserved for factors other than the default failure mechanisms of the dike, such as macro-stability and piping. One of the assessment tracks is the assessment track for objects without a flooding-protection function (Dutch: niet waterkerende objecten). Cables and pipes are considered to be such objects. It has been decided to use one percentage point of the 30% for pipe failure. This means that the failure probability per mechanism cannot increase more than 1%. So a safe pipe-dike system in equation form means:

$$\Delta P_{dike,fail,STBI} \ \wedge \ \Delta P_{dike,fail,STPH} \ \wedge \Delta P_{dike,fail,GEKB} < 1\% \qquad \textbf{Eq. 39}$$

3.4 Answering the main question

“What are the differences between the characteristics within the groups of pipes that are considered to be (un)safe when they lay in the vicinity of a dike for the current simple test and the to-be-made improved simple test?”

The main question will be answered by comparing the current and the newly-developed simple tests. It will be examined whether the new test is more or less conservative and for which pipe types. That means that it will be investigated if there are pipes that are considered unsafe in the new simple test and that were considered safe according to the old simple test or vice versa.

4. Results

4.1 Relation between the probability of pipe failure and pipe properties

The probability that a pipe fails is an important statistic that, together with the damage caused by failure, determines if a pipe can be considered safe in the new simple test. Figure 24 contains the visualized relationship between the probability of failure of a pipe and the transported substance and diameter. The figure is derived from data from Ouwendijk et al. (2020). This data is in table form displayed in Appendix B.

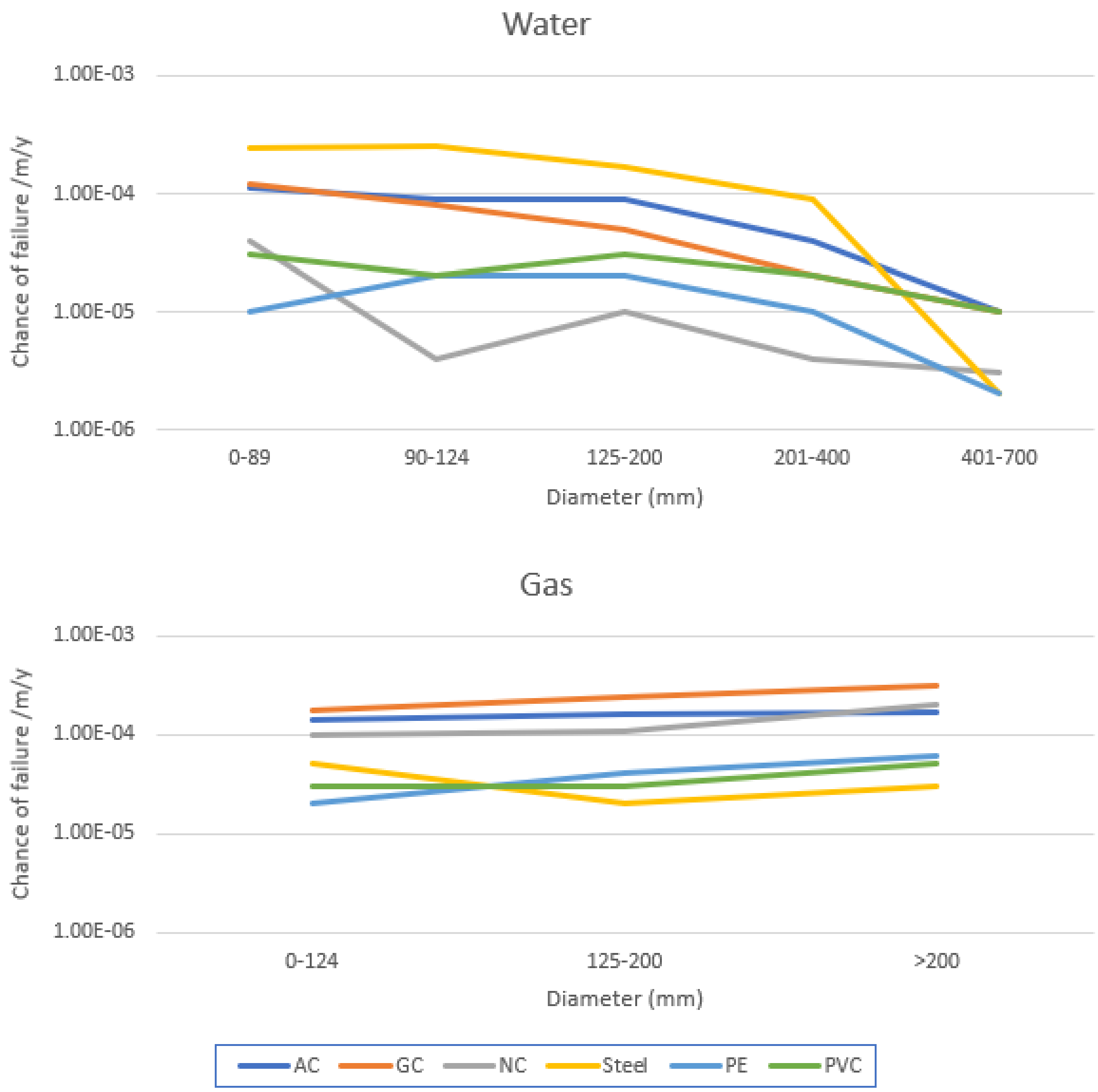

Figure 24: Relation between failure probability and diameters for pipes with different materials

The primary trend that can be noticed for water pipes is that the failure probability decreases with increasing diameter. This is especially the case for steel pipes, which have the largest failure probability in the smallest diameter category but the smallest in the largest category. The probability of failure varies by two orders of magnitude for this material. The reason for the decreasing trend is unknown, but it is hypothesized that the accepted failure probabilities are lower for large-diameter pipes. That may be because the failure of large-diameter pipes leads to larger consequences.

For gas pipes, the probability of failure increases with the increasing diameter of most materials. The increase is not as significant as the decrease for water pipes since all materials' failure probabilities stay within the same order of magnitude. The reason for the upward trend is not known.

Data from Ouwendijk et al. (2020) shows that the probability of failure of gas pipes is also related to internal pressure. These relationships are displayed in Figure 25 for four materials and three diameter categories.

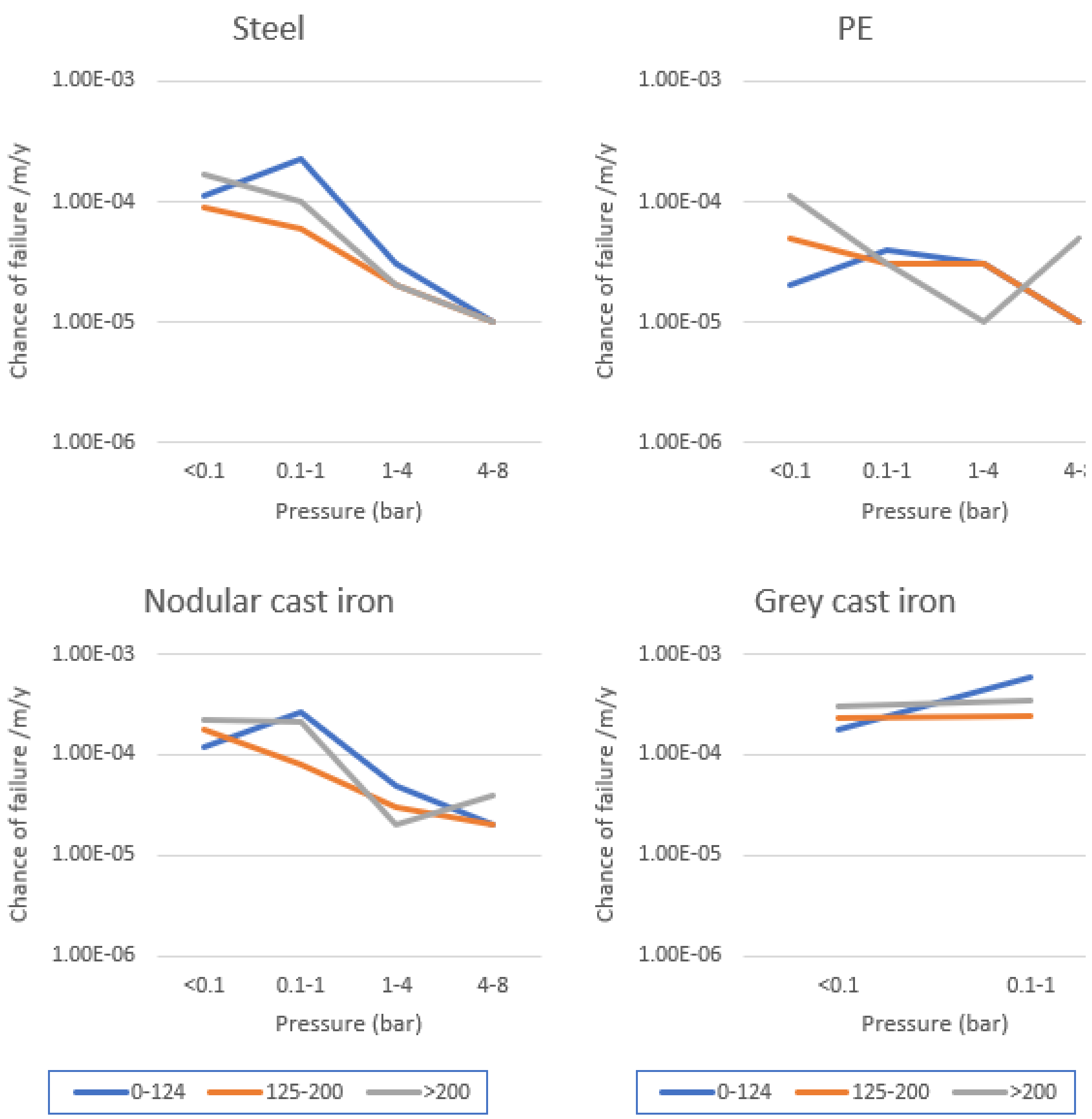

Figure 25: Relation between failure probability and pressure for gas pipes with different materials and diameters

A downward trend can be noticed for steel, nodular cast iron, and, to some extent, PE. Pipes with higher pressure tend to fail less often. The reason for this trend is unknown, but it might be related to the safety standards of the pipe. It is plausible that safety standards for gas pipes are related to the pipes' pressure since NEN3651 (NEN, 2020, p.92) states that the risk of explosion is only present for high-pressure pipelines. Because of this, failure of high-pressure pipes will lead to larger damage consequences, which may be a reason for the demand for higher safety standards.

4.2 Relation between pipe failure and the failure probability of a dike

The relationships between pipe characteristics and their failure probability have now been clarified. This section describes the other relationships that need to be known to assess whether a pipe can lay safely near a dike: the relationships between pipe failure and failure probability of the dike. Section 4.2.1 contains the failure probability of the dike without pipe failure, and 4.2.2 includes the probability of dike failure once a pipe has failed.

4.2.1 Failure probability of a dike without pipe failure

Table 9 contains the failure probability of a dike on a cross-sectional level for the failure mechanisms STBI, STPH, and GEKB in a situation without pipe failure. These have been calculated with Equation 3. A calculation is added in Appendix D.

Table 9: Failure probability of a dike without pipe failure for the failure mechanisms of interest

Failure norm (chance) trajectory level (y^{-1})	Failure probability STBI on cross-sectional level (y^{-1})	Failure probability on cross-sectional level (y^{-1})	Failure probability GEKB on cross-sectional level (y^{-1})
1/10,000	2.81E-07	8.67E-07	1.20E-05

The failure probability per failure mechanism on the cross-sectional level is related to the failure norm on the trajectory level. In this research, a trajectory norm of 1/10,000 has been chosen.

4.2.2 Failure probability of a dike with pipe failure

The relationships that exist between pipe failure and the failure probability for the mechanisms STBI, STPH, and GEKB will be displayed in the following three sections.

4.2.2.1 Failure probability dike for the failure mechanism STBI in case of pipe failure

Figure 26 visualizes the relationships between the effects of pipe failure and the failure probability of the dike for the STBI mechanism. These results follow from the safety factors that were the output of the D-Stability model and Equation 25. The output values from D-Stability are displayed in Appendix E.

In the upper left panel, it can be seen that a full breach of a gas or water pipe located in the hinterland results in a more or less linear relation between the pipe's diameter and the dike's probability of failure. This is as expected since a larger diameter causes more significant failure effects and, thus, an increased probability of failure.

The upper right panel shows that the effects of a full breach within the dike toe do not present a clear relation between the pipe diameter and the probability of failure of the dike. For the water and gas pipe with a pressure of 10 bar, the probability of failure increases quickly and reaches 1 for diameters of 0.3 to 0.5 meters. That is because the craters formed by the failure of these pipes lay partially within the required 3-meter crest width remainder. The considerations for this modelling choice were explained in section 3.2.2.3. The probability of failure of the dike appears to decrease for larger diameters in case the pressure is low (2 bar). This is surprising because larger diameters still cause larger craters for low-pressure pipes. The reason why the dike becomes more stable for pipes of low pressure and large diameter is that a larger crater can also remove more soil from the dike crest. The soil displaced by the pipe failure cannot slide down anymore, which makes the dike more stable. In conclusion, a larger crater may leave a more stable remaining dike cross-section than a smaller one.

The effect of a full breach in the crest is a crater that always lays in the required 3-meter crest width remainder zone. This is the case for all pressures and diameters. As explained in section 3.2.2.3, the failure probability of the dike is determined to be 1. This can be seen in the lower left panel of Figure 26.

The lower right panel shows that the effects of a creeping leak on the probability of failure of the dike for STBI are independent of the diameter and pressure of the pipe but dependent on the location of the failure. This comes down to the knowledge gap between the relationship between the properties of a pipe and the heightening of the phreatic line within the dike body. The phreatic line in the dike body was modelled based on the pipe's location, considering capillary rise.

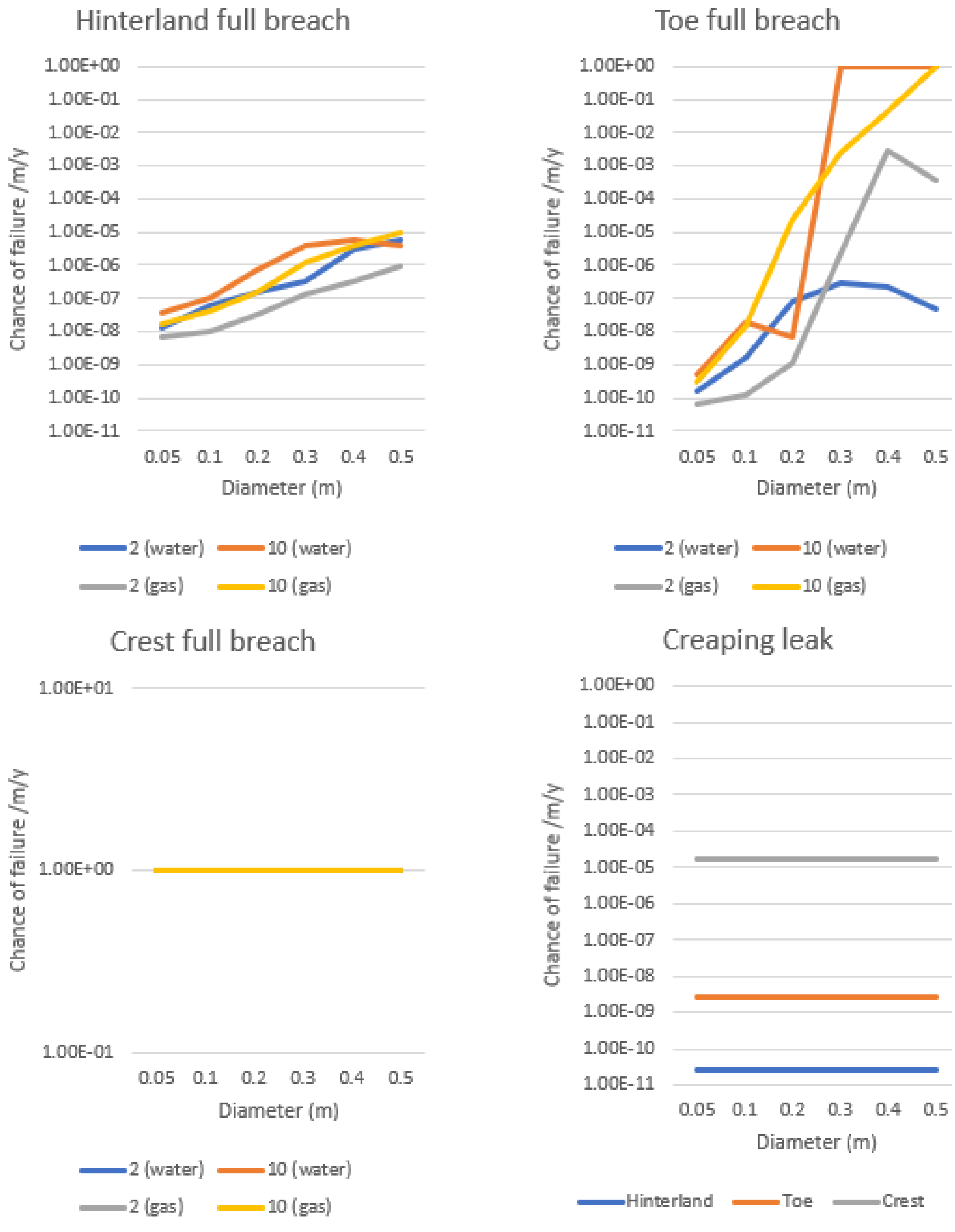

Figure 26: Relationships between the effects of gas and water pipe failure and the failure probability for STBI

4.2.2.2 Failure probability dike for the failure mechanism STPH in case of pipe failure

Figure 27 visualizes the relationships between the effects of pipe failure and the failure probability of the dike for the mechanism piping. These results follow from the critical head output from the D-Geoflow model and Equations 26 to 36. The intermediate outputs of D-Geoflow and the equations are included in Appendix F.

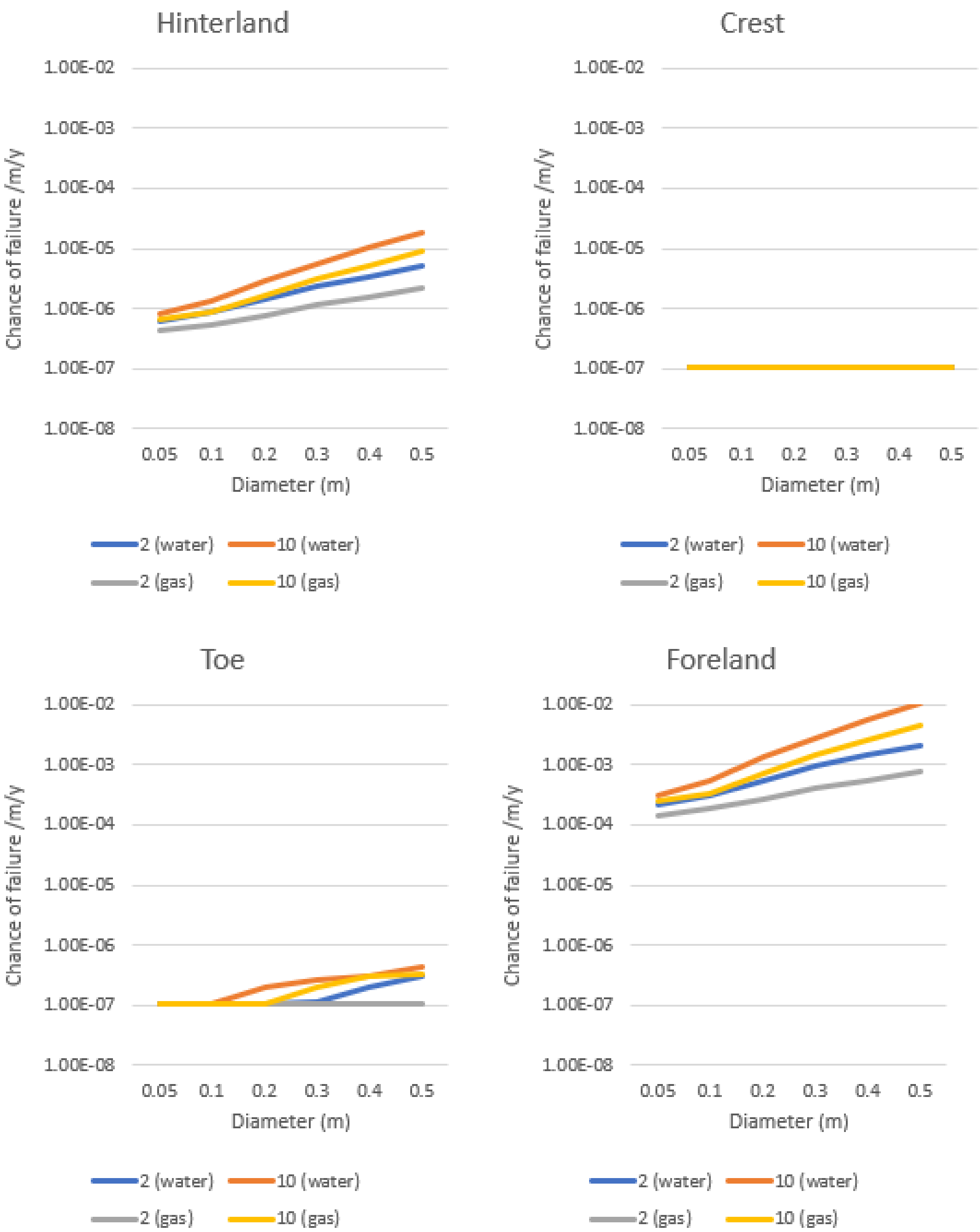

Figure 27: Relationships between the effects of gas and water pipe failure and the failure probability for STPH

The most important result is that the probability of dike failure due to piping is very much dependent on the location of the pipe failure. Pipe failure in the hinterland causes an almost linear increase in the failure probability when plotted against the pipe diameter. Pipe failure in the dike toe affects the probability of failure only after a certain diameter threshold is reached. For the crest, the probability of dike failure is unaffected by the effects of pipe failure. Pipe failure in the foreland leads to a dike failure probability pattern that is similar to the hinterland but with overall higher failure probabilities.

These results can be explained by the crater sizes and how they affect the cover layer and length of the piping trajectory. A pipe in the fore- or hinterland lays in the cover layer; thus, the thickness of the cover layer is directly decreased when the pipe fails. When a pipe is located in the inner toe, the cover layer thickness is only affected when the crater size reaches a certain magnitude. When a pipe lays in the crest, the thickness of the cover layer is never affected.

The differences in failure probabilities for the fore- and hinterland can be explained through the choice for entrance and exit points of the piping trajectory. For the foreland, this trajectory is shorter than for the hinterland, as displayed in Figure 22. This leads to a lower critical head for piping for the foreland, which subsequently results in higher failure probabilities.

4.2.2.3 Failure probability dike for the failure mechanism GEKB in case of pipe failure

Table 10 shows that the crater radius formed by a failure of the smallest researched gas and water pipes is larger than the grass cover failure requirement of 15 by 15 centimetres. This means that the grass cover fails regardless of the diameter and pressure of the pipe. The failure of the grass cover is also independent of the pipe's location since the pipe's depth in the soil is the same.

Table 10: Failure probability and crater sizes for the smallest researched pipes

Transported substance	Diameter (m)	Pressure (bar)	Crater radius (m)	Failure of grass cover?	Chance of overflow
Water	0.05	2	2.2	Yes	1.20E-05
Gas	0.05	2	1.2	Yes	1.20E-05

When the grass cover fails, the failure chance for GEKB equals the chance of overtopping. The chance of overflow is assumed to be equal to the norm for GEKB on the cross-sectional level. This norm is related to the norm on the trajectory level.

4.3 Assessing differences in failure probabilities of the dike due to pipe failure

In this section, the probabilities of pipe failure from section 4.1 and the resulting failure probabilities of dikes from section 4.2 will be combined. Section 4.3.2 will assess whether the combination of these two probabilities leads to a significant change in dike failure. In order to be able to do this, the definition of a significant change needs to be defined. That will be done in section 4.3.1.

4.3.1 Definition of a significant change

Table 11 shows the maximum allowed increase in failure probability per failure mechanism. These are 1% of the values in Table 9, which represent the failure norms and assumed probabilities in the situation without pipe failure.

Table 11: 1% of the failure probability given the failure mechanisms and the norm on the trajectory level

Failure norm on trajectory level	Failure probability STBI	Failure probability STPH	Failure probability GEKB
1/10,000	2.81E-09	8.67E-09	1.20E-07

4.3.2 Assessment of pipes and their induced increase of dike failure probability.

The combination of the failure probability of the pipe (Section 4.1) and the effects that a pipe failure has on the failure probability of the dike for a failure mechanism (Section 4.2) determine if the increase in failure probability is more or less than 1% (Section 4.3.1).

In Figure 28 to Figure 31, the increase in dike failure probability as a result of pipe failure is given. The increase in dike failure probability is plotted in the same graph with the maximum allowable increase given a failure mechanism (Table 11). This maximum allowable increase is displayed with the red dotted line. As long as a line stays below the dotted line, pipes with corresponding properties can be considered safe in the new simple test.

The effects on STBI and STPH are displayed in Figure 28 for gas pipes with varying diameters and materials and given a pressure of 10 bars. The same is depicted in Figure 29 for water pipes. These figures are focused on the hinterland, toe, and crest.

Figure 30 contains the increase in failure probability for piping in case of a pipe failure in the foreland. This is for both gas and water pipes. Figure 31 contains the change in failure probability for GEKB for gas and water pipes independent of their location.

The new simple test that follows from the information in Figure 28 to Figure 31 is displayed in Figure 32. An explanation of this result will be given afterwards.

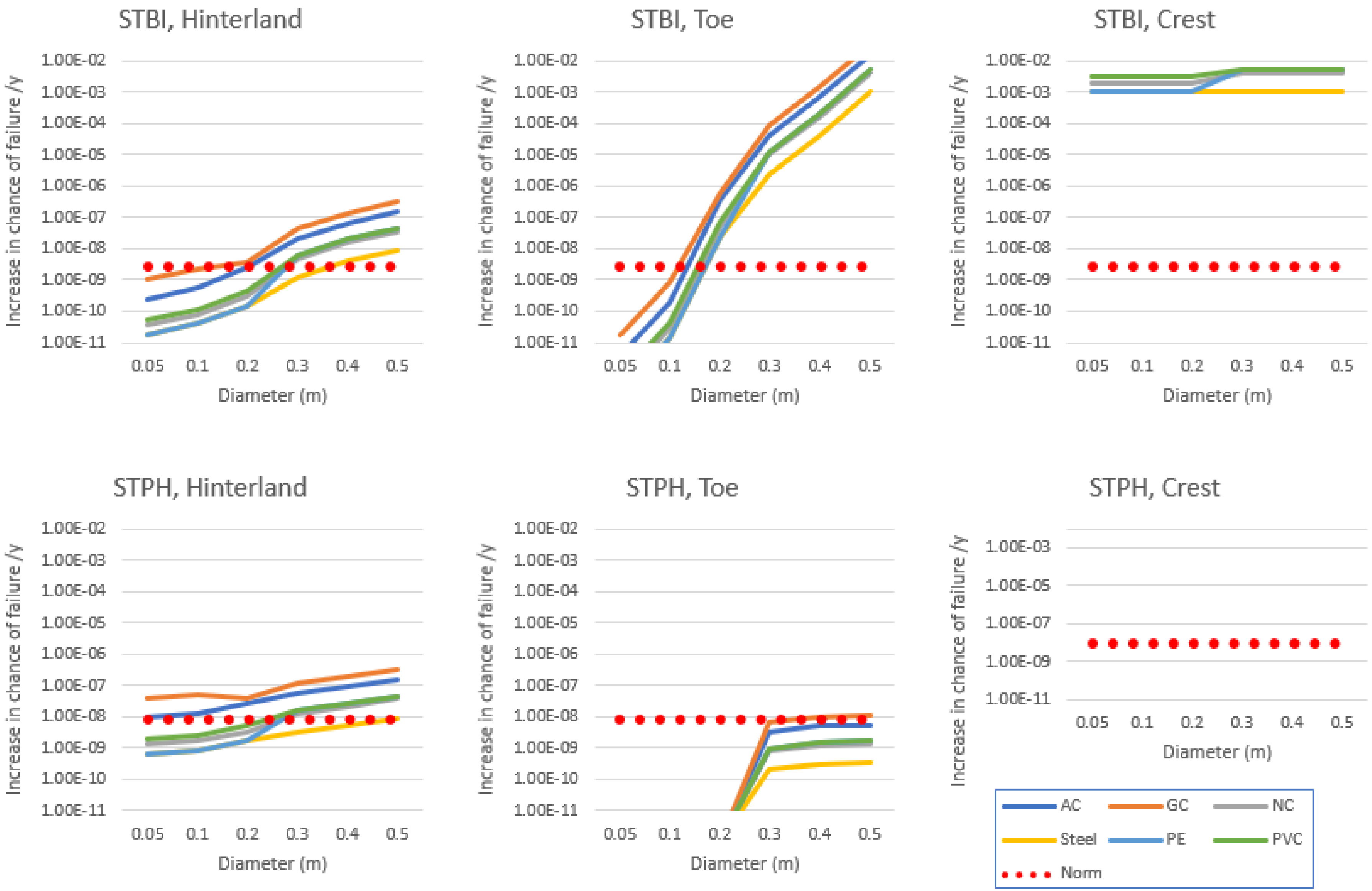

Figure 28: Gas pipes for which the change in probability of failure for STBI and STPH is (in)significant given the combination of location, material, and diameter for pressures of 10 bar.

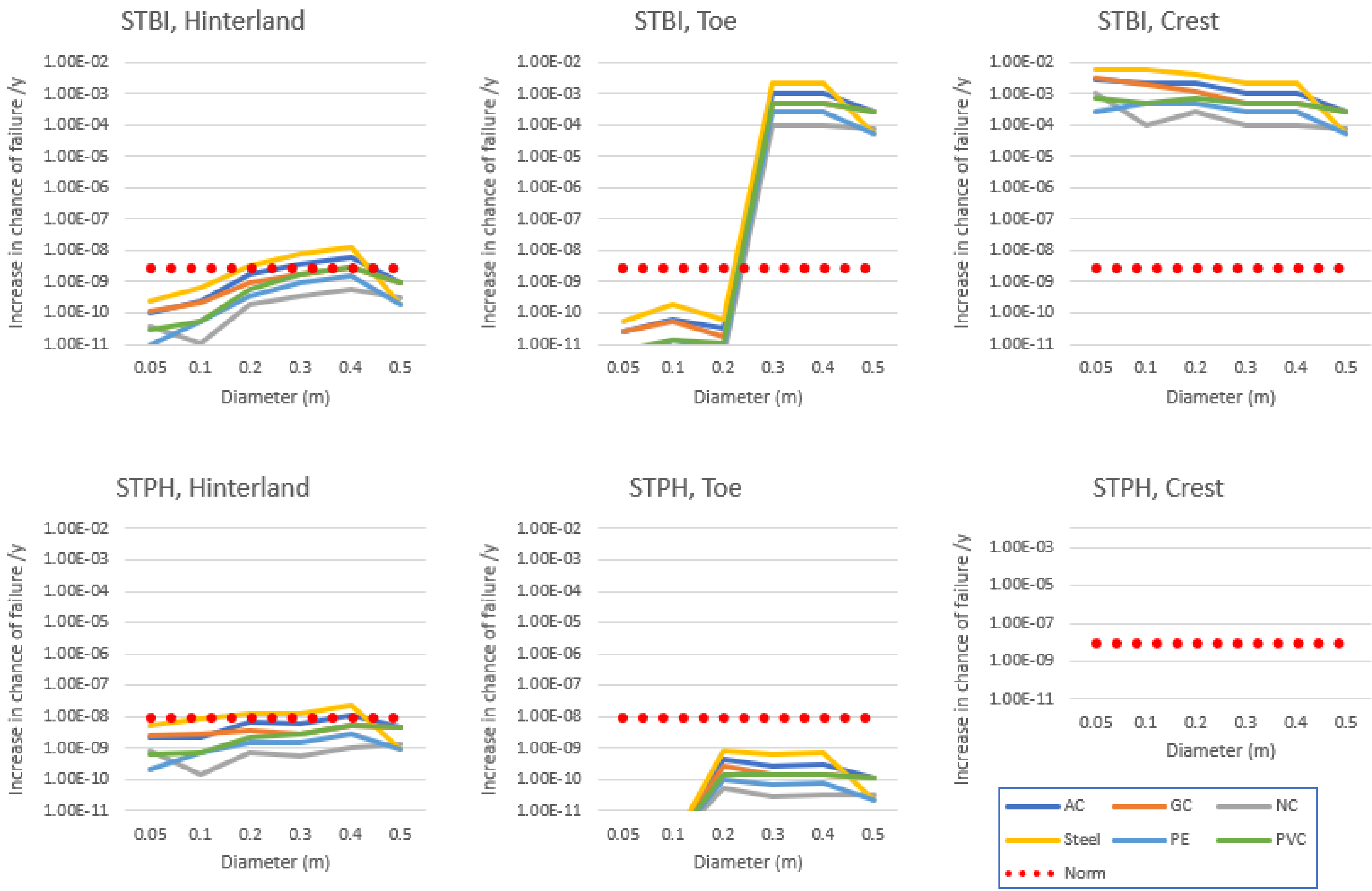

Figure 29: Water pipes for which the change in probability of failure for STBI and STPH is (in)significant given the combination of location, material, and diameter for pressures of 10 bar

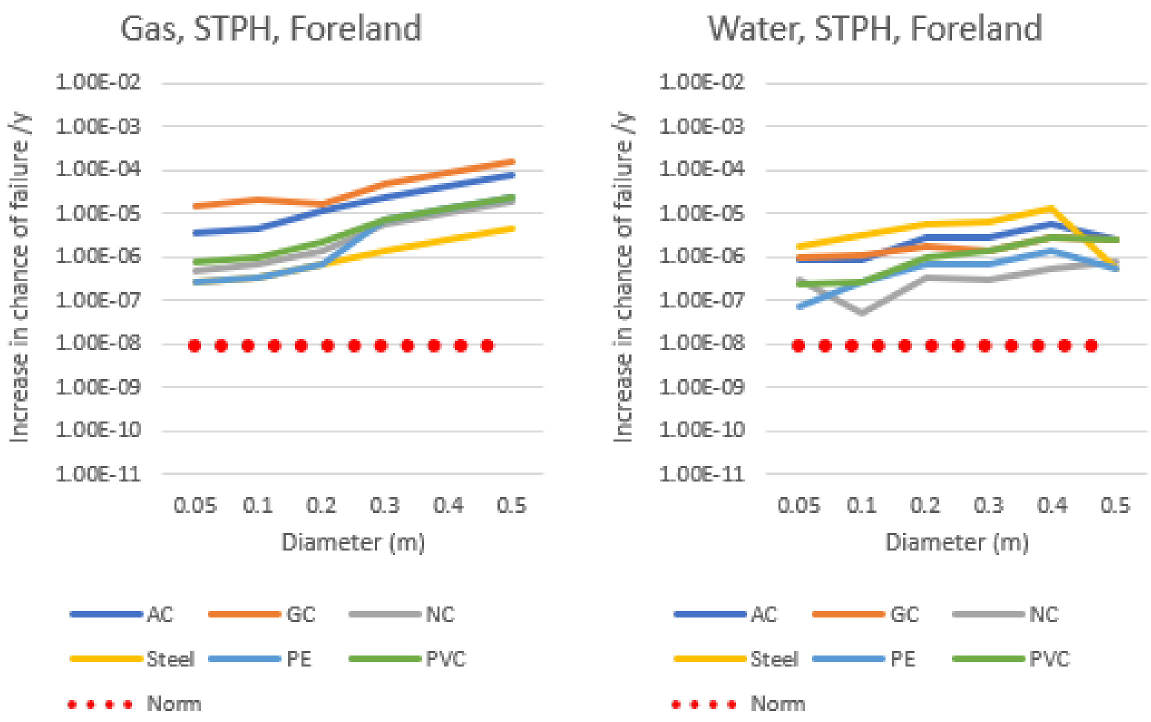

Figure 30: Gas and water pipes located in the foreland for which the change in probability of failure for STPH is (in)significant given the combination of material and diameter for pressures of 10 bar

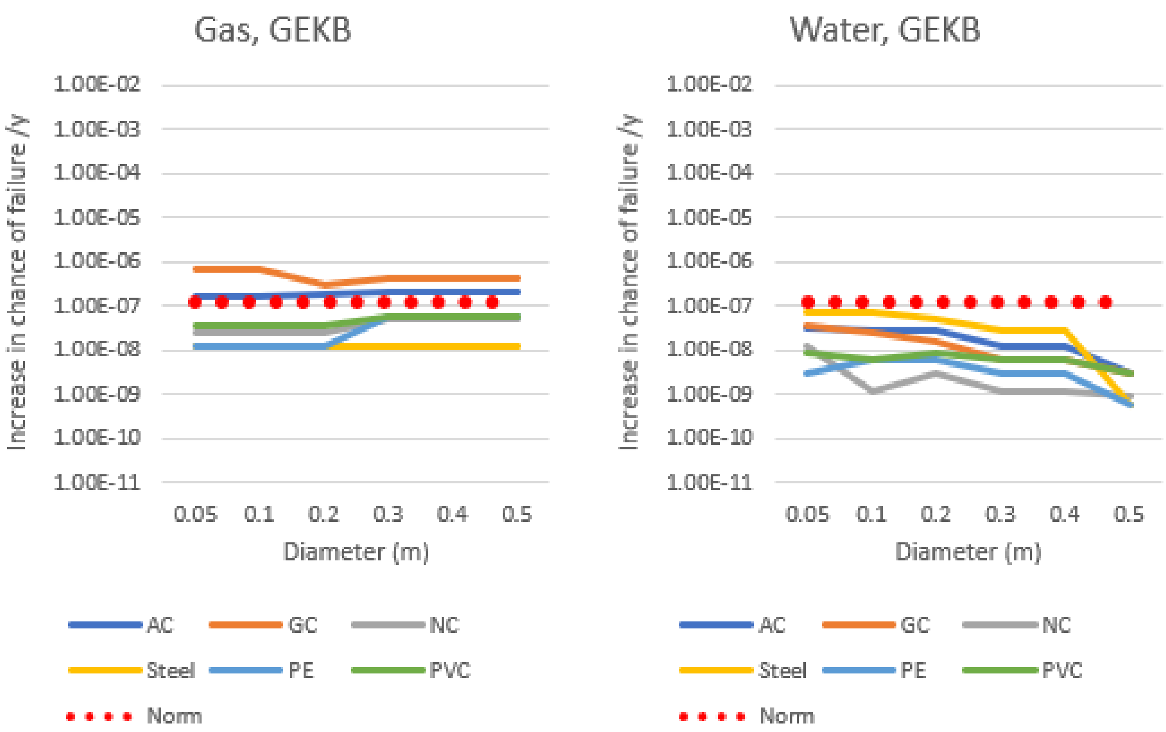

Figure 31: Gas and water pipes for which the change in probability of failure for GEKB is (in)significant given the combination of material and diameter for pressures of 10 bar.

New simple test

Application conditions:

- **Parallel pipelines (maximum 100 meters parallel to the dike)**
- **Dike has a norm on trajectory level <=1/10,000 per year.**

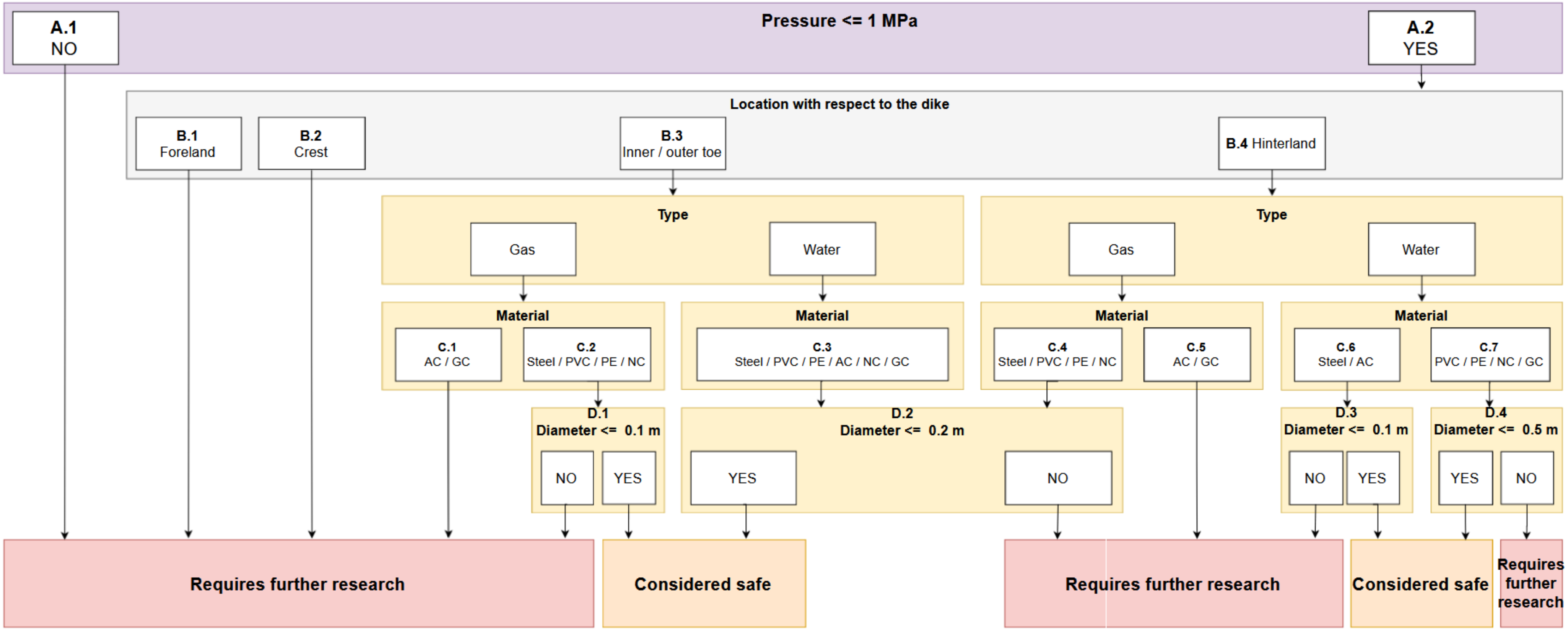

Figure 32: The new simple test

4.3.3 Explanation of the new simple test

In this section, the reasons behind the steps in the new simple test will be explained.

4.3.3.1 Step A: Pressure

The first step in the new simple test is to check for the pressure inside of the pipe. The limit value for this is one megapascal or 10 bars. This step is necessary because two pipe characteristics are independent variables that determine the effects of pipe failure. These are diameter and pressure. These variables all have a continuous range of possible values, which results in an infinite number of possible combinations. It is impossible to display all the combinations in one scheme, which necessitates the choice of a limit value for one of the independent variables. One megapascal was chosen for this, as this was also the limit value in the current simple test.

4.3.3.2 Step B: Location

The next step in the simple test distinguishes between pipe locations with respect to the dike. What stands out is that pipes in the foreland (step B.1) and crest (B.2) can never pass the simple test. The reason for step B.1 can be found in Figure 30. This figure displays that all the pipes fail for the allowable increase requirement for piping. The reason for this is that the entrance point of the piping trajectory is located close to the outer toe of the dike, which makes the piping trajectory short and the probability of failure high.

Pipes in the crest are not allowed because of the required 3-meter crest remainder. Pipe failure always leads to a crater that compromises this zone, which instantly fails the pipes due to the considerations made in this research. This can be viewed in the bottom left panel of Figure 26 and the upper right panels of Figure 28 and Figure 29.

4.3.3.3 Step C: Material

Once a distinction is made between gas and water pipes, the simple test filters pipes based on their material in step C. The differences that are made in this step come down to the differences in the failure probability of the materials (the occurrence criterion) since there is no relationship between the material and the damage caused by failure. For gas pipes made of asbestos cement and grey cast iron that are located in the toe and hinterland (Steps C.1 & C.5), no pipe can pass the test. This is related to the requirement for GEKB, which can be viewed in Figure 31, left panel. In the lower panel of Figure 24, it can be seen that AC and GC pipes indeed have the highest probability of failure.

For the material of water pipes, only a distinction is made for the hinterland (Step C.6 & C.7). The reason for this can be found in the upper panel of Figure 24. That shows that predominantly low-diameter pipes made of steel and asbestos cement have a high probability of failure. This means that the failure probability of these pipes themselves eats up a larger portion of the allowable 1% increase in failure probability. Subsequently, the allowed increase in dike failure probability due to the damage caused by the failure of these pipes is smaller (the damage criterion). This is visualised in the left panels of Figure 29. The magnitude of damage and, thus, the increase in failure probability of the dike varies based on the diameter of the pipe. In the simple test, this is taken into account in Step D.

There is no need to make a distinction based on the material for water pipes located in the toe (Step C.3). As can be seen in the middle lower panel of Figure 29 and the right panel of Figure 31, STPH and GEKB are not of concern. STBI is for all materials equally the limiting factor as can be seen in the middle upper panel of Figure 29. The reason for this is that the failure of pipes with a combination of pressures and diameters equal to or larger than 10 bar and 0.3 metres compromises the required 3-meter crest remainder. This instantly fails all these pipes.

4.3.3.4 Step D: Diameter
The distinction in diameter is made based on how much of the 1% allowable increase in dike failure probability is left for the failure probability of a damaged dike after pipe failure (the damage criterion). In other words, the more of the 1% is eaten up by the probability of pipe failure itself (the occurrence criterion), the higher the allowable pipe diameter. When no distinction needs to be made for the diameter, it can mean two things. Either the differences between the failure probability of a pipe are small, or the differences don't matter because they are small in proportion to the failure probability of the dike due to the damage. The first explanation applies to steps D.3 and D.4, and the last one to D.1 and D.2. For D.1 and D.2, the combinations of pressure (10 bar) and diameter (higher than their respective limit values) lead to a crater that compromises the required 3-meter crest remainder. This fails a pipe immediately regardless of its material and failure probability.

4.3.3.5 Perpendicular pipelines
In the application conditions, it is stated that this new simple test can only be used for perpendicular pipelines. Perpendicular pipelines cannot be assessed due to the methodology that is followed with respect to STBI in the crest. Pipe failure always leads to crater formation, and a crater in the crest can never be allowed due to the required 3-meter crest remainder. A pipe perpendicular to the dike, by definition, goes underneath the crest, which means the new simple test is not applicable to these situations. This is in spite of the small probability that a dike fails exactly below the crest because the crest is (only) 5 metres wide.

4.4 Differences between the old and new simple test
A comparison of the current simple test from Figure 1 with the new simple test in Figure 32 yields that the new test is less simple and more conservative for most pipes.

Step A in the new simple test gives no different results than the current test. For both tests, pipes with a pressure higher than 10 bars cannot be considered safe and thus need further investigation.

Step B in the new simple test distinguishes pipe locations. This is not something that is done in the current test. Pipes in the foreland and under the crest cannot be considered safe and because of this, the new simple test is more conservative in this regard. Only pipes under the inner toe and in the hinterland can be considered safe under conditions specified in further steps.

Step C in the new simple test distinguishes between gas and water pipes, while this is not done in the current test. However, it cannot be said if this step makes the new test more or less conservative than the current test. That is because no pipes are considered unsafe just because they transport water or gas. A combination of transported substance, material, and diameter determines this.

The current simple test considers steel pipes with a diameter smaller than 0.5 meters safe regardless of other characteristics. The new simple test is considerably more conservative because only steel pipes with a diameter smaller than 0.1 or 0.2 meters are considered safe depending on the substance they transport and if they are located in the hinterland or under the inner toe.

The current simple test considers non-steel pipes safe if their diameter is smaller than 0.125 meters, regardless of other properties. The new simple test is partly more and less conservative when assessing these pipes. For example, gas pipes made of asbestos cement or grey cast iron are never considered safe in the new simple test. In contrast, a PVC water pipe in the hinterland is considered safe up to a diameter of 0.5 centimetres.

The current simple test has no application conditions, while the new one has 2. This makes the new simple test also more conservative.

5. Discussion

The product of this research is a new simple test that is mostly more conservative and less versatile than the current test. This means that the new simple test considers a smaller subset of the pipes safe when they are in the vicinity of a dike. From a usability point of view, this is undesirable as many more pipes now need further assessment in order to determine if they are safe. From a safety point of view, this is desirable since a more conservative test, by definition, considers fewer unsafe dike systems as safe. The trade-off between making a versatile or a safe simple test was a consideration that was constantly made during the decision-making process. This issue was most prominent when dealing with knowledge gaps and information deficiencies. A lack of information often requires making conservative assumptions that undermine the versatility of the simple test. This discussion will reflect on decisions that were made based on incomplete knowledge and how this has affected the new simple test.

5.1 Crater formation is not related to the soil covering

The first topic of discussion is the relationship between the pipe characteristics and crater depth, which was quantified with equations *6*, *15*, and *20* from NEN3651. These equations assume that the crater depth is always as deep as the thickness of the soil layer on top of it. This is even the case for pipes with a small diameter. The equations do not recognize that for small-diameter pipes with enough soil covering, craters will probably not form due to pipe failure. Therefore, these equations seem to give rather conservative results for crater formation. This is maybe what was to be expected from a norm like NEN3651, whose purpose is to provide safe guidelines.

5.2 Failure criterion for STBI at the crest

The previous topic had, together with a modelling decision, profound implications on the results and, subsequently, on the new simple test. This forms the main versatility-constraining discussion point.

Pipe failure always leads to the formation of a crater, according to the equations that were used. When a pipe fails below the crest, this then always compromises the 3-meter crest remainder zone. It was decided that this would be undesirable because the dike crest could then not be considered to have the same height as before the pipe failure. Therefore, it was decided to assign a failure probability of 1 to the dike probability of STBI. The consequence of this is that no pipes, parallel and perpendicular, below the crest can be considered safe. Furthermore, a significant portion of pipes below the inner toe also damages the 3-meter zone.

In hindsight, this decision limits the versatility of the simple test too much. It was also too conservative because a dike with a lowered crest still can prevent flooding, albeit up to a lower water level. This means the probability of flooding in a situation in which the 3-meter crest remainder is damaged is equal to the chance of water flowing over the dike and not 1. The question that now arises is: what is the probability of overflow? As a starting point, it could be assumed that this is equal to the norm on a cross-sectional level that results from the norm on a trajectory level. Then, the assumption is that the dike meets the norm, which is questionable because it is unlikely that a dike with a lowered crest due to pipe failure still meets the norm. A better way of dealing with this problem is to look at historical water level data to find the probability of a certain water level occurring. However, for the case used in this research, that is not possible because it is a hypothetical one for which no such data is available. This problem could be resolved by applying this research methodology to specific dike cross-sections out of the real world.

5.3 Variance in the location of the entrance and exit point for STPH

In this research, the location of the entrance and exit points of the piping trajectory has been assumed to be at half the crater radius in the direction of the dike (Figure 22). However, this assumption is not substantiated by research but it has a large consequence for the simple test. The calculated probability of failure is unacceptable for all pipes located in the foreland, which means that the simple test cannot be used to assess pipes in this location quickly. It is thus not entirely certain what the actual consequences of pipe failure in the foreland are. If the entrance point is taken at a different location, it might be possible that piping is no issue.

In general, it is debatable if piping in the foreland should be integrated into a simple test that will be used for all dikes. Piping happens to be a potential issue for the dike cross-section on which this research is applied because there is a clay cover layer located on top of a sandy subsoil below the dike. A clay cover layer is not always present below a dike, which means that piping is not an issue for those dikes to begin with. It might thus be needlessly conservative to consider all the pipes in the foreland as unsafe because of piping. A possibility to counter this concern would be to make the potential risk of piping one of the application conditions.

5.4 Modelling soil softening

Another knowledge gap that might influence the versatility of the new simple test is how soil softening is modelled. This has been done with the help of Equation *17* and the procedure explained in Table 7. Although the equation in itself is substantiated by research, the relationship between the degree of soil softening and the value of the friction angle is not. The chosen approach to relate the degree of softening linearly to the friction angle value is rather pragmatic but not scientifically substantiated. This may result in an overestimation of the effect of soil softening on the stability of the dike, which may leave the new simple test more conservative than necessary. On the other hand, the decision might underestimate the effect of soil softening. In any case, more research on the impact of soil softening on the strength parameters of the dikes' soil is necessary to incorporate these effects better in a new simple test. There appears to be a significant knowledge gap on this topic.

5.5 Modelling a creeping leak

The relationship between the properties of water pipe failure via a creeping leak and the stability of a dike is also uncertain. In this research, the assumption has been made to lay the phreatic line at the surface of the dike, as suggested by Ouwendijk et al. (2020, p. 17). This makes the phreatic line independent of the outflow rate of the pipe and, thus, from the diameter and pressure of the water pipe. Large pipes are therefore assessed equally as strictly as small pipes, which is not desirable for the versatility of the new simple test. In order to quantify the effects of a creeping leak better, further research needs to be done that relates the properties of the pipe to the location of the phreatic line.

5.6 The dependence on the norm

The new simple test is based on a failure norm on trajectory level of 1/10,000 years, as this is a norm that is common for dike trajectories along the major rivers. This makes the test suitable for dike trajectories with this or a less strict norm. For dike trajectories with a less strict norm, for example 1/1,000 per year, it can be argued that the new simple test is too conservative. After all, the new simple test assesses if the increase in failure probability is smaller than 1%, and this 'budget' grows larger when the norm becomes less strict. Therefore, the new simple test can approve more pipes for dikes with a safety standard lower than 1/10,000 per year. It can be argued that one cannot simply decrease the safety standard for this because this would skew the calculations related to the damage to the dike. The stability calculations were conducted on a dike cross-section, for which it was assumed that a norm of 1/10,000 per year applies. A less strict norm will likely not correspond with this cross-section but with one with smaller dimensions (height and crest width). It is likely that the effects of pipe failure with given characteristics are relatively more significant for a smaller cross-section. For example, relatively more soil is eroded off a small dike cross-section by a crater with a 2-meter radius. Additional research needs to determine if the relative effects of pipe failure are more significant given a smaller dike. This research has not been included due to limited time.

6. Conclusions

The main objective of this study was to substantiate the simple test with the probability of pipe failure (the occurrence criterion) and the change in failure probability of the dike due to the damage of pipe failure (the damage criterion). Three sub-questions were formulated in order to answer one main question. This chapter will answer these questions.

1. **"What is the relation between the probability of failure of a pipe and its diameter, pressure, material, and transported substance?"**

The relationship between the failure probability of a pipe and one of its characteristics seems often to depend on other characteristics. For water pipes, it appears that the failure probability decreases for increasing diameters. For gas pipes, this seems to be the other way around, although not as significantly.

For water pipes, no relationships were found relating the failure probability and the pressure inside the pipe. For gas pipes, the failure probability generally decreases with increasing pressure.

The material of a pipe is also correlated with its failure probability. For water pipes, especially low-diameter ones made of steel and asbestos cement, it was found that they fail more often compared to the other materials. This can vary up to two orders of magnitude. For gas pipes, asbestos cement and grey cast iron pipes fail more often than other materials. For gas pipes, the failure probability can vary up to one order of magnitude depending on the material.

2. **"What is the relation between pipe failure and the failure probability of a dike?"**

For STBI, it was found that the failure probability increases for pipe failure in the hinterland, inner toe, and crest. This is especially the case for pipe failure in the crest and large-diameter pipe failure in the inner toe. In those cases, the required 3-meter crest remainder is damaged. Due to a modelling decision, it was decided to assign a failure probability of 1 to the dike. This is too conservative, as a lower crest still requires an overflow of water over the dike before flooding occurs. The probability that this occurs is always smaller than 1, but what this exactly is requires further research.

For STPH, it was found that the failure probability of the dike increases when pipe failure occurs in the foreland, hinterland, and below the inner toe for large-diameter pipes. The most noticeable effects could be seen for the hinterland because the entrance point of the piping trajectory is moved significantly to the dike due to crater formation in the cover layer. It should be noted that the position of the entrance and exit points of the piping trajectory requires further research as they are now not scientifically substantiated. Furthermore, it can be argued that piping is not a concern for all dikes in the default situation without pipe failure effects.

For GEKB, it was found that pipe failure always leads to the formation of a crater that is larger than 15 by 15 centimetres. The grass cover will thus always fail in case of a pipe breach. The probability that a dike fails due to GEKB after pipe failure is equal to the chance of overflow, which in this research has been assumed to be equal to the required norm. This probability is independent of the location of the pipe failure.

3. **"For which combinations of pipe characteristics, locations and orientation is the change in failure probability (in)significant?"**

In this research, a 1% increase in dike failure probability was used per failure mechanism as the boundary between an insignificant and significant change. This criterion resulted in all pipes in the foreland and under the crest causing a significant change in dike failure probability. Due to the decision that the failure probability of STBI was considered to be 1 when the 3-meter crest remainder zone was compromised, all pipes perpendicularly crossing the dike are also considered to cause a significant change.

Due to the fact that gas pipes made of asbestos cement and grey cast iron have a relatively high failure probability, they always cause a significant increase in the failure probability of the dike when they are located in the vicinity of it. The same reason applies to steel and asbestos cement water pipes located in the hinterland. However, these pipes can still be allowed up to a small diameter.

For the not aforementioned pipes, it can be said that they do not cause a significant increase in the failure probability of the dike up to a diameter that varies between 0.1 metres and 0.5 metres depending on the location and material of the pipe.

6.1 Answering the main question

The answers to the sub-questions have led to a new simple test which can be compared with the old simple test. This comparison can answer the main question:

- **“What are the differences between the characteristics within the groups of pipes that are considered to be (un)safe when they lay in the vicinity of a dike for the current simple test and the to-be-made improved simple test?”**

The current simple test considers all non-steel pipes safe up to a diameter of 125 millimetres and steel pipes up to a diameter of 500 millimetres. That is, regardless of the location and orientation of the pipe.

The new simple test can only consider pipes safe when they lay in the hinterland or below the inner slope. Furthermore, the pipe diameter range approved by the new test is smaller except for non-steel water pipes in the hinterland. The new simple test does not consider any perpendicular pipes safe.

In conclusion, it can be said that the newly developed simple test is, in most aspects, more conservative than the test that is currently used. This makes the new simple test less versatile because fewer pipe types can be assessed via the quick route that the simple test provides. There is also a positive side to a better substantiated and more conservative simple test, which is the safety aspect. A more conservative test, by definition, considers fewer unsafe dike systems as safe.

All in all, it is thought that the disadvantage of the new simple test is large compared to the advantage. The usability of the new simple test is very much compromised by the methodology followed in this research. However, it is possible to use the provided methodology together with additional research to improve the usability of the new simple test further. Recommendations for this will be provided in the next chapter.

7. Recommendations

The usability of the new simple test is limited by knowledge gaps and a lack of substantiation of certain model choices. Further research on those topics can make the new simple test more versatile because fewer conservative model assumptions need then to be made.

7.1 Including the probability of dike overtopping into the assessment of STBI

The main recommendation is to include the probability of water overtopping the dike in the failure probability for STBI when the required 3-meter crest remainder is damaged by pipe failure. A dike retains a part of its flood protection function, even when this zone is compromised. The probability of dike failure for a dike with a lower crest is equal to the likelihood of a water level reaching the height of the crest. This probability is always smaller than the very conservative failure probability of 1 that was used in this research. The probability of a water level occurring is situation-dependent and thus not available for the hypothetical dike cross-section on which this research was applied. Therefore, it is recommended that this research methodology be applied to several real-world case studies so that data on water level probabilities are available. Execution of this recommendation can lead to more pipes in the crest being considered safe, as well as pipes that cross the dike perpendicularly.

7.2 The effect of the location of the entrance and exit points for piping

Regarding piping, it is recommended that a sensitivity analysis be performed to determine the influence of the location of the entrance and exit points of the piping trajectory. The current assumption of the entrance point is not well-founded, and this results in all pipes in the foreland not passing the new test. If the outcome of the sensitivity analysis is that pipes can be considered safe if the entrance point is taken on a different location, the choice of the new point needs to be substantiated by research in order to know for sure that this is a safe choice.

7.3 Making the simple test dependent on the risk of piping

Piping is a failure mechanism of concern in this research because a cohesive clay cover layer is present on a sandy subsoil below the chosen dike cross-section. This situation is not universally present below all dike cross-sections, which means that piping is not always a concern. The new simple test rejects all the pipes in the foreland because of the risk of piping. This is unnecessary for certain dikes when no risk of piping exists in the first place. Therefore, it is recommended that the possibility of making the new simple test risk-dependent for the failure mechanism of piping be investigated.

7.4 Sensitivity analysis on the effects of the norm on the simple test

The difference between an acceptable insignificant increase in failure probability of the dike and a significant unacceptable growth was made by using 1% of the norm per failure mechanisms as a boundary. This 1% is dependent on the norm of a dike trajectory, which in this research was chosen to be 1/10,000 per year. When this norm is less strict, the 1% increase limit becomes bigger in an absolute sense. This means that more damage can be allowed for dikes that are assessed less strictly. Therefore, there is a possibility that the new simple test is too conservative for dikes with a safety standard lower than 1/10,000 per year. It is recommended that a sensitivity analysis be performed on the effects of the norm on the pipes that pass the 1% limit. For this, it is advisable also to implement the damage effects of pipe failure on dike cross-sections that are representative of the respective failure norm. That is because dikes with a failure lower norm can have smaller dimensions due to the lower strength that is expected from them. The effects of a crater can then be larger for a small dike because the crater eats away more of the dike's body.

7.5 Further research into the effects of soil softening

Regarding the modelling of soil softening, it was chosen to relate the output of Equation 17 to the strength parameters of the soil. This was a pragmatic choice that is not substantiated by research because no relationships were found regarding this in the literature. It is recommended that further investigation be conducted into the relationship between soil softening and the strength parameters of the soil, such that these effects can be modelled to assess the stability of a dike in D-Stability.

8. References

Actueel Hoogtebestand Nederland. (n.d.). https://ahn.arcgisonline.nl/ahnviewer/

De Bruijn, H. T. J. (2013). *Het pipingproces in stripvorm*. Deltares. https://kennis.hunzeenaas.nl/images/hunzeenaas/e/e5/Het_pipingproces_in_stripvorm.pdf

Deltares. (2022). *D-GEO Gebruikersdag 2022 - softwaredagen*. https://softwaredagen.deltares.nl/-/d-geo-gebruikersdag-2022

Deltares. (2023a). *D-Geo Flow user manual*. https://www.deltares.nl/en/software-and-data/products/d-geo-flow

Deltares. (2023b). *D-Stability user manual*. https://www.google.nl/url?sa=t&source=web&rct=j&opi=89978449&url=https://iplo.nl/publish/pages/169760/d-stability-user-manual-2023-01.pdf&ved=2ahUKEwjE47Ls5rmFAxVw4AIHHUcACMwQFnoECBMQAQ&usg=AOvVaw2pKzTTy-m3nuqQ7iSQBdRZ

Macro-instabiliteit binnenwaarts - Delta Noodmaatregelen. (n.d.). https://v-web002.deltares.nl/sterktenoodmaatregelen/index.php/Macro-instabiliteit_binnenwaarts

Ministerie van Infrastructuur en Milieu. (n.d.). *Regeling Veiligheid Primaire Waterkeringen 2017*.

Ministerie van Infrastructuur en Waterstaat. (2021). *Schematiseringshandleiding macrostabiliteit*. Retrieved April 6, 2024, from https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/primaire/beoordelen/@205756/schematiseringshandleiding-macrostabiliteit/

NEN. (2020). *EN 3651:2020 (nl) Aanvullende eisen voor buisleidingen in of nabij belangrijke waterstaatswerken*.

Noordam, A., & Van Beek, V. (2018). *Cursus programma - D-Geo Flow - Deltares Public Wiki*. https://publicwiki.deltares.nl/display/DGeoFlow/Cursus+programma

Ouwendijk, P., Teeuwen, J., Van Maurik - De Graaff, M., Roorda, H., Bom-Lemstra, A., Doedel, R., Slootweg, H., & Erik Wagener. (2020). *Filters voor parallelle gasen drinkwaterleidingen in en bij primaire waterkeringen*. https://www.hwbp.nl/documenten/rapporten/2020/12/14/filters-voor-parallelle-gas--en-waterleidingen-in-en-bij-primaire-waterkeringen

Projectteam Meanderende Maas. (2017, April). *Wat is: Piping?* Meanderende Maas. https://www.meanderendemaas.nl/wat-zegt-u-piping/

Rijksoverheid. (2024). *Besluit Kwaliteit leefomgeving*. Retrieved April 3, 2024, from https://wetten.overheid.nl/BWBR0041313/2024-01-01#BijlageII

Rijkswaterstaat. (2017, February). *Handreiking ontwerpen met overstromingskansen : veiligheidsfactoren en belastingen bij nieuwe overstromingskansnormen*. Rijkswaterstaat Publicatie Platform. https://open.rijkswaterstaat.nl/open-overheid/@178516/handreiking-ontwerpen/

Rijkswaterstaat. (2022). *Schematiseringshandleiding grasbekleding*. https://www.helpdeskwater.nl/publish/pages/157023/sh-grasbekleding-6-0_223003_def3-2c.pdf

RTV Krimpenerwaard. (2020, August 25). *Waterleiding gesprongen aan IJsseldijk - RTV Krimpenerwaard*. https://www.rtvkrimpenerwaard.nl/site/waterleiding-gesprongen-aan-ijsseldijk/

Saathof, L. E. B. (1984). *Leidraad bij Bodemonderzoek in en nabij waterkeringen*. Retrieved June 3, 2024, from https://edepot.wur.nl/441288

Schweckendiek, T. (2019). *WBI Veiligheidsraamwerk Kabels en Leidingen: Generieke uitgangspunten als vertrekpunt voor nadere uitwerking in (pilot) projecten*. Deltares. https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/primaire/beoordelen/@214110/wbi/

Sellmeijer, H., De La Cruz, J. L., Van Beek, V., & Knoeff, H. (2011). Fine-tuning of the backward erosion piping model through small-scale, medium-scale and IJkdijk experiments. *European Journal of Environmental and Civil Engineering*, *15*(8), 1139–1154. https://doi.org/10.1080/19648189.2011.9714845

’t Hart, R. (2018). *Fenomenologische beschrijving Faalmechanismen WBI*. https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/primaire/beoordelen/@205760/fenomenologische/

Waterschap Rijn en IJssel. (2008). *Derde toetsronde waterkeringen: Verstoringszones lage druk leidingen*. https://edepot.wur.nl/453851

Wevers, H. (2020). *Stabiliteitsbeoordeling van de IJsseldijk ter plaatse van dijkwoningen* [Bachelor thesis]. University of Twente.

9. Appendices

A. Dike cross-sections with similar geometry to the hypothetical dike

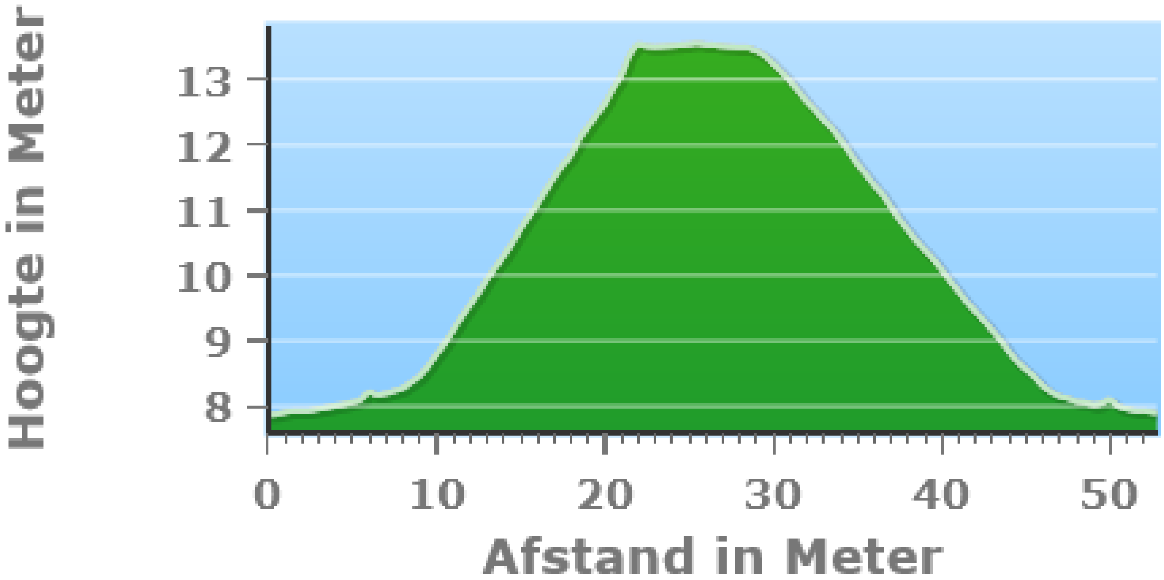

Figure 33: Cross-section of the Waal dike near Dodewaard (Dike trajectory 43-5, norm 1/10,000)

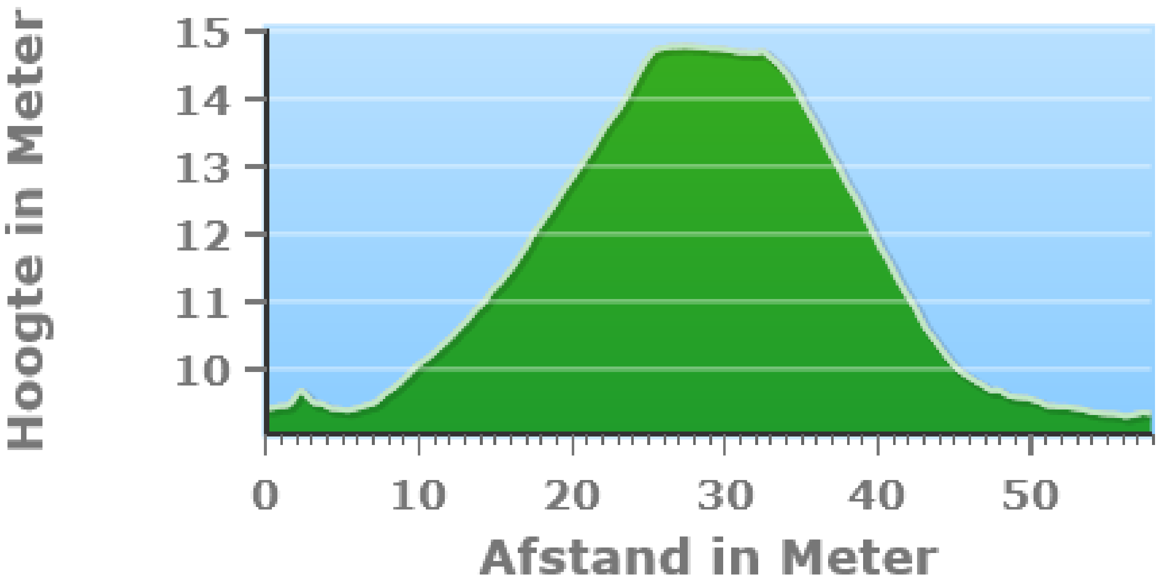

Figure 34: Cross-section of the Nederrijn dike near Arnhem (Dike trajectory 43-3, norm 1/10,000)

(Actueel Hoogtebestand Nederland, n.d.)

B. Annual failure probabilities of pipes per meter

Table 12: Annual failure probabilities for drinkwater pipes per meter length (Ouwendijk et al., 2020, p. 19)

Material	Diameter ranges (mm)			
	0-89	90-124	125-200	401-700
AC	1.10 E-04	9.00 E-05	4.00 E-05	1.00 E-05
GC	1.20 E-04	8.00 E-05	2.00 E-05	1.00 E-05
NC	4.00 E-05	4.00 E-05	4.00 E-06	3.00 E-06
Steel	2.40 E-04	2.50 E-04	9.00 E-05	2.00 E-06
PE	1.00 E-05	2.00 E-05	1.00 E-05	2.00 E-06
PVC	3.00 E-05	2.00 E-05	2.00 E-05	1.00 E-05

Table 13: Annual failure probabilities for gas pipes per meter length (Ouwendijk et al., 2020, p. 19)

Material	Diameter ranges (mm)	Pressure (bar)			
		< 0.1	0.1 - 1	1 – 4	4 – 8
AC	**0 – 124**	1.40 E-04			
	125 – 200	1.60 E-04			
	201 -315	1.70 E-04			
GC	**0 – 124**	1.80 E-04	5.90 E-04		
	125 – 200	2.30 E-04	2.40 E-04		
	201 -315	3.00 E-04	3.50 E-04		
NC	**0 – 124**	1.20 E-04	2.60 E-04	5.00 E-05	2.00 E-05
	125 – 200	1.80 E-04	8.00 E-05	3.00 E-05	2.00 E-05
	201 -315	2.20 E-04	2.10 E-04	2.00 E-05	4.00 E-05
Steel	**0 – 124**	1.10 E-04	2.30 E-04	3.00 E-05	1.00 E-05
	125 – 200	9.00 E-05	6.00 E-05	2.00 E-05	1.00 E-05
	201 -315	1.70 E-04	1.00 E-04	2.00 E-05	1.00 E-05
PE	**0 – 124**	2.00 E-05	4.00 E-05	3.00 E-05	1.00 E-05
	125 – 200	5.00 E-05	3.00 E-05	3.00 E-05	1.00 E-05
	201 -315	1.10 E-04	3.00 E-05	1.00 E-05	5.00 E-05
PVC	**0 – 124**	3.00 E-05			
	125 – 200	3.00 E-05			
	201 -315	5.00 E-05			

C. D-Stability modelling details

Figure 35 contains a schematization of the soil layers in the standard situation. Table 14 contains the parameter values given to these layers.

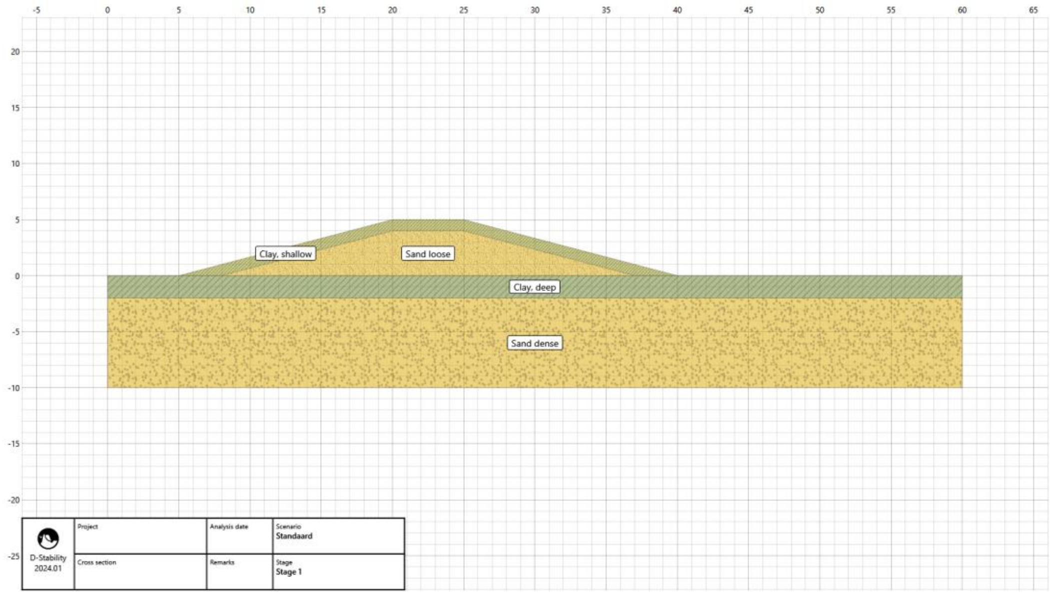

Figure 35: Soil build-up of the standard dike cross-section

Table 14: Parameter values of the soil

Soil type	Unit weight above phreatic line (kN/m^3)	Unit weight below phreatic line (kN/m^3)	Cohesion (kN/m^2)	Friction angle (deg)
Clay, shallow	14.8	14.8	8	20
Sand loose	18	20.5	0	30
Clay, deep	15.6	15.6	8	20
Sand, dense	21	22.5	0	30

For all soil layers, the Mohr-Coulomb Classic (drained) shear strength model was used both above and below the phreatic line.

Figure 36 contains the schematization of the phreatic line in the standard situation.

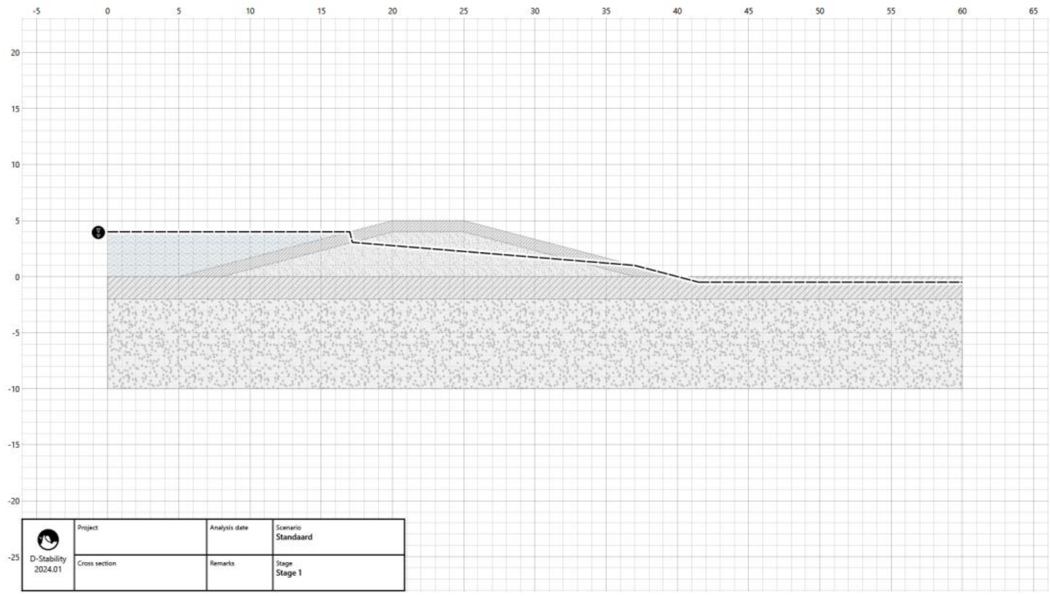

Figure 36: Schematization of the phreatic line

The water level on the riverside is + 4 meters NAP. The landside water level is – 0.5 meters NAP.

No loads or reinforcements were applied to the model.

D. Calculation of the failure probability of a dike without pipe failure per mechanism

$$P_{norm,cross,mech} = \frac{\omega P_{norm}}{N_{cross}}$$

- P_{norm} = 1/10,000 year^{-1}

Failure mechanism	ω –value (-)
Macro instability of the inner slope (STBI)	0.04
Piping (STPH)	0.24
Erosion of the grass cover at the crest and inner slope (GEKB)	0.24

$$N_{cross} = 1 + \frac{a \times L_{trajectory}}{b}$$

- $L_{trajectory}$ = 20,000 m

Failure mechanism	a (-)	b (-)
Macro instability of the inner slope (STBI)	0.033	50
Piping (STPH)	0.40	300

For GEKB N_{cross} = 2

$$P_{norm,cross,STBI} = \frac{0.04 \times \frac{1}{10,000}}{1 + \frac{0.033 \times 20,000}{50}} = 2.81 \times 10^{-7}\ \text{year}^{-1}$$

$$P_{norm,cross,STPH} = \frac{0.24 \times \frac{1}{10,000}}{1 + \frac{0.40 \times 20,000}{300}} = 8.67 \times 10^{-7}\ \text{year}^{-1}$$

$$P_{norm,cross,GEKB} = \frac{0.24 \times \frac{1}{10,000}}{2} = 1.2 \times 10^{-5}\ \text{year}^{-1}$$

E. Intermediate results STBI

			Water		Gas
Diameter (m)	Pressure (bar)	Location	Safety factor full breach (-)	Safety factor creeping leak (-)	Safety factor full breach (-)
0.05	2	HIN	1.382	1.547	1.399
0.05	2	TOE	1.502	1.426	1.524
0.05	2	CRE	1.801	1.146	1.547
0.05	10	HIN	1.35	1.547	1.373
0.05	10	TOE	1.471	1.426	1.487
0.05	10	CRE	1.801	1.146	1.547
0.1	2	HIN	1.337	1.547	1.389
0.1	2	TOE	1.442	1.426	1.509
0.1	2	CRE	1.679	1.146	1.552
0.1	10	HIN	1.32	1.547	1.349
0.1	10	TOE	1.369	1.426	1.38
0.1	10	CRE	1.723	1.146	1.514
0.2	2	HIN	1.307	1.547	1.357
0.2	2	TOE	1.329	1.426	1.45
0.2	2	CRE	1.801	1.146	-
0.2	10	HIN	1.257	1.547	1.308
0.2	10	TOE	1.401	1.426	1.132
0.2	10	CRE	1.801	1.146	1.366
0.3	2	HIN	1.282	1.547	1.31
0.3	2	TOE	1.288	1.426	1.216
0.3	2	CRE	1.801	1.146	-
0.3	10	HIN	1.202	1.547	1.239
0.3	10	TOE	1.434	1.426	0.923
0.3	10	CRE	1.801	1.146	1.263
0.4	2	HIN	1.208	1.547	1.285
0.4	2	TOE	1.294	1.426	0.917
0.4	2	CRE	1.801	1.146	1.21
0.4	10	HIN	1.185	1.547	1.199
0.4	10	TOE	1.435	1.426	0.742
0.4	10	CRE	1.801	1.146	1.187
0.5	2	HIN	1.184	1.547	1.251
0.5	2	TOE	1.344	1.426	1.017
0.5	2	CRE	1.801	1.146	-
0.5	10	HIN	1.199	1.547	1.169
0.5	10	TOE	1.431	1.426	0.568
0.5	10	CRE	1.801	1.146	1.143

Figure 37: Intermediate results STBI for gas and water pipes

F. Intermediate results STPH

			Burst				Heave			Backward erosion		
Diameter (m)	**Pressure (bar)**	**Location**	$\boldsymbol{\phi_{c,u}}$ **(m)**	$\boldsymbol{\Delta\phi}$ **(m)**	$\boldsymbol{F_u}$ **(-)**	$\boldsymbol{P_{f;u}}$ **(y^{-1})**	$\boldsymbol{i}$ **(-)**	$\boldsymbol{F_h}$ **(-)**	$\boldsymbol{P_{f;h}}$ **(y^{-1})**	$\boldsymbol{\Delta H_c}$ **(m)**	$\boldsymbol{F_p}$ **(-)**	$\boldsymbol{P_{f;p}}$ **(y^{-1})**
0.05	2	HIN	0.531	4.5	0.118	0.807	5.000	0.060	0.929	5.498	1.300	4.22E-07
0.05	2	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.05	2	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.05	10	HIN	0.531	4.5	0.118	0.807	5.000	0.060	0.929	5.320	1.258	6.64E-07
0.05	10	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.05	10	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.1	2	HIN	0.472	4.5	0.105	0.869	5.625	0.053	0.956	5.439	1.277	5.41E-07
0.1	2	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.1	2	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.1	10	HIN	0.472	4.5	0.105	0.869	5.625	0.053	0.956	5.252	1.233	8.69E-07
0.1	10	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.1	10	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.2	2	HIN	0.413	4.5	0.092	0.921	6.429	0.047	0.977	5.337	1.244	7.70E-07
0.2	2	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.2	2	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.2	10	HIN	0.413	4.5	0.092	0.921	6.429	0.047	0.977	5.031	1.173	1.69E-06
0.2	10	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.2	10	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.3	2	HIN	0.295	4.5	0.066	0.984	9.000	0.033	0.996	5.252	1.207	1.15E-06
0.3	2	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.3	2	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.3	10	HIN	0.295	4.5	0.066	0.984	9.000	0.033	0.996	4.852	1.115	3.22E-06
0.3	10	TOE	0.826	4.5	0.184	0.463	3.214	0.093	0.707	5.600	1.373	1.97E-07
0.3	10	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.4	2	HIN	0.236	4.5	0.052	0.996	11.250	0.027	0.999	5.175	1.182	1.53E-06
0.4	2	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.4	2	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.4	10	HIN	0.236	4.5	0.052	0.996	11.250	0.027	0.999	4.699	1.073	5.26E-06

0.4	10	TOE	0.590	4.5	0.131	0.738	4.500	0.067	0.894	5.600	1.333	2.96E-07
0.4	10	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.5	2	HIN	0.118	4.5	0.026	1.000	22.500	0.013	1.000	5.116	1.152	2.12E-06
0.5	2	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.5	2	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.5	10	HIN	0.118	4.5	0.026	1.000	22.500	0.013	1.000	4.555	1.026	9.14E-06
0.5	10	TOE	0.531	4.5	0.118	0.807	5.000	0.060	0.929	5.600	1.324	3.27E-07
0.5	10	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07

Figure 38: Intermediate results STPH for gas pipes

			Burst				**Heave**			**Backward erosion**		
Diameter (m)	**Pressure (bar)**	**Location**	$\phi_{c,u}$ (m)	$\Delta\phi$ (m)	F_u (-)	$P_{f;u}$ (y^{-1})	i (-)	F_h (-)	$P_{f;h}$ (y^{-1})	ΔH_c (m)	F_p (-)	$P_{f;p}$ (y^{-1})
0.05	2	HIN	0.437	4.5	0.097	0.902	6.081	0.049	0.969	5.413	1.265	6.11E-07
0.05	2	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.05	2	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.05	10	HIN	0.437	4.5	0.097	0.902	6.081	0.049	0.969	5.294	1.237	8.26E-07
0.05	10	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.05	10	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.1	2	HIN	0.401	4.5	0.089	0.930	6.618	0.045	0.980	5.303	1.234	8.55E-07
0.1	2	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.1	2	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.1	10	HIN	0.401	4.5	0.089	0.930	6.618	0.045	0.980	5.133	1.195	1.32E-06
0.1	10	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.1	10	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.2	2	HIN	0.331	4.5	0.073	0.971	8.036	0.037	0.993	5.141	1.187	1.44E-06
0.2	2	TOE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.2	2	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.2	10	HIN	0.331	4.5	0.073	0.971	8.036	0.037	0.993	4.869	1.124	2.92E-06
0.2	10	TOE	0.826	4.5	0.184	0.463	3.214	0.093	0.707	5.600	1.373	1.97E-07
0.2	10	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.3	2	HIN	0.260	4.5	0.058	0.992	10.227	0.029	0.998	5.005	1.146	2.28E-06

0.3	2	TOE	1.121	4.5	0.249	0.224	2.368	0.127	0.464	5.600	1.425	1.15E-07
0.3	2	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.3	10	HIN	0.260	4.5	0.058	0.992	10.227	0.029	0.998	4.657	1.066	5.69E-06
0.3	10	TOE	0.649	4.5	0.144	0.667	4.091	0.073	0.853	5.600	1.343	2.68E-07
0.3	10	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.4	2	HIN	0.189	4.5	0.042	0.999	14.063	0.021	1.000	4.886	1.109	3.45E-06
0.4	2	TOE	0.826	4.5	0.184	0.463	3.214	0.093	0.707	5.600	1.373	1.97E-07
0.4	2	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.4	10	HIN	0.189	4.5	0.042	0.999	14.063	0.021	1.000	4.470	1.015	1.04E-05
0.4	10	TOE	0.590	4.5	0.131	0.738	4.500	0.067	0.894	5.600	1.333	2.96E-07
0.4	10	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.5	2	HIN	0.118	4.5	0.026	1.000	22.500	0.013	1.000	4.784	1.077	4.99E-06
0.5	2	TOE	0.590	4.5	0.131	0.738	4.500	0.067	0.894	5.600	1.333	2.96E-07
0.5	2	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07
0.5	10	HIN	0.118	4.5	0.026	1.000	22.500	0.013	1.000	4.300	0.968	1.82E-05
0.5	10	TOE	0.354	4.5	0.079	0.960	7.500	0.040	0.990	5.600	1.296	4.38E-07
0.5	10	CRE	1.180	4.5	0.262	0.192	2.250	0.133	0.422	5.600	1.436	1.03E-07

Figure 39: Intermediate results STPH for water pipes