Improvement of the current assessment method of multifunctional dikes

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Cover photo: (Rijkswaterstaat, n.d.-a)

Preface

This is the graduation project for the completion of my Master's in Civil Engineering at Delft University of Technology. The graduation project aims to improve the current assessment method of multifunctional dikes. This thesis is conducted in cooperation with Royal HaskoningDHV.

I would like to extend my gratitude to my university supervisors: S.N. Jonkman, M.Z. Voorendt, and W. Broere, and my supervisors from Royal HaskoningDHV: N. Klein Wolterink and P. Van der Scheer. I also want to thank the water boards of Rivierenland and Schieland and Krimpenerwaard for the time they took for the interviews. Furthermore, I am grateful to the many people at Royal HaskoningDHV who were available to answer my questions and who helped me during my research.

Max Romeijn,

Rotterdam, 9 September 2024

Summary

The Netherlands faces major housing shortages. The total housing shortage is 390 thousand homes and this is expected to increase in the near future because fewer building permits have been issued in recent years. By 2030, the Netherlands will need to have almost a million new houses. To solve this problem, it is essential to build more residential buildings in the near future, but limited space is available. Therefore, the focus shifts to traditionally less conventional spots that potentially can be used to construct residential areas.

One of the proposed solutions is to create residential buildings near dikes, thereby using the dikes not only to combat flood risks but also to relieve pressure on the housing crisis in the Netherlands. To check if buildings can be built on or next to a dike, the assessment method of the Legal Assessment Instrumentation is currently used. However, only a basic assessment is prescribed for this, which is a very conservative approach. This conservative approach often leads to the building not being built or to overdesigning of the dike and thus higher expenses than necessary.

The objective of this thesis is to develop a level I reliability assessment method for multifunctional dikes containing a structure, leading to a less conservative approach than the basic assessment of the Legal Assessment Instrumentation (WBI2017).

First, the possibilities of construction near dikes were studied per water board. The possibilities for building near dikes are prescribed in the water board regulations, previously known as the by-law (Keur). Although the water board regulations vary for each water board, the rules regarding building near dikes are consistent, and almost nothing regarding construction can be done in the profile of free space. Interviews were also held with water boards. During these interviews, the regulations were discussed, including the non-technical obstacles with regards to building near dikes and solutions for them were proposed.

The biggest concern is regarding the management of the houses that would be part of the flood defence. One of the proposed solutions is to use people to regularly send photos to ensure the quality of the parts of the house that will function as flood defence or to use sensors which could measure deformations. This could save much time for the dike managers.

Next, it was determined what failure mechanisms can be affected by the presence of a building on or near a dike. The failure probabilities of macro-stability, piping and overtopping differ when a building is placed on or next to a dike and have been considered in the calculation of the failure probability of the dike. It has been argued by means of an event tree that the absence of a house has a 0.1% probability of occurring. As a result, the schematisation in Figure 2 has been proposed.

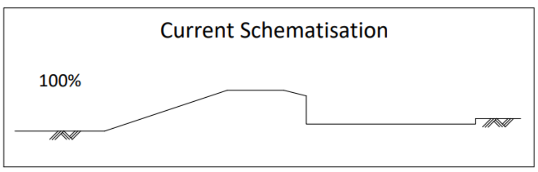


Figure 1: Current schematisation

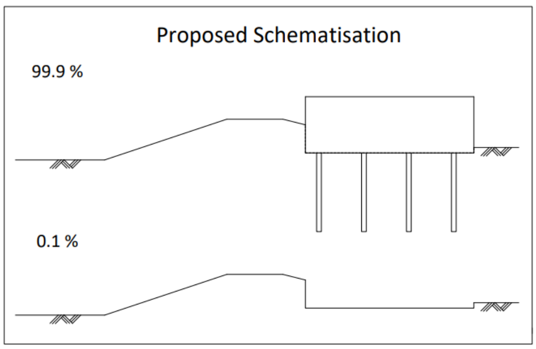


Figure 2: Proposed schematisation

Subsequently, a case was analysed probabilistically using FORM analyses to demonstrate the difference in failure probability between the current and the proposed schematisation. This showed a 75% reduction in failure probability for the assumed cross-section compared to the current schematisation, which can be seen in Figure 1. The effect of new construction on a standard dike profile can both have positive and negative effects on the failure probability of the dike section depending on the situation. Compensatory measures can be taken to reduce the probability of failure.

Since it is time-consuming to perform probabilistic calculations for every situation, it was decided to create a Level I reliability assessment. Based on the probabilistic calculations, partial safety factors were derived that take the probability of the disappearance of a house into account. These partial factors were calculated per stochastic variable. This allows for a Level I reliability calculation to determine whether a dike cross-section with a house meets the required failure probability of the dike section, which can be seen below, but with a partial factor assigned to each stochastic variable.

$$\frac{R_{rep}}{\gamma_R} \geq \gamma_S \cdot S_{rep}$$

It is concluded that incorporating the proposed level I calculation with adapted partial factors has a different impact for each situation but can, in some cases, have a 75 % reduction in failure probability. This is based on the case study, which is elaborated extensively in the report. The developed level I reliability method ensures that existing buildings near houses are assessed more realistically compared to the current WBI assessment, which assumes a gap at the location of the dike. As a result, when this method is used, more dike cross-sections with buildings will meet stability requirements as it is less conservative than the current assessment, which only takes into account the negative aspects of the building. This means that fewer dike sections will be rejected, potentially saving both money and reducing inconveniences. For the design of new structures near a dike, this Level I reliability calculation can provide insight into possible locations for construction in the cross-section of the dike and the potential dimensions of the house. With this method it can quickly be demonstrated whether a multifunctional dike still meets the dike's failure probability requirement, which can also lead to an increase in building possibilities near dikes, as extensive customized assessments are no longer necessary.

For further research, it is recommended to perform the macro stability analysis in PLAXIS, as this allows for a much more accurate determination of the effect of the soil on the structure. In addition, the foundation can be realistically represented, and 3D situations can be considered in PLAXIS. It is also recommended to discover the possibilities for a residual profile for the situations which assume a gap in the dike instead of a vertical slope.

Contents

1 Introduction

The Netherlands faces major housing shortages. In 2023, there were 437 thousand housing applicants and 47 thousand available homes. This brings the total housing shortage to 390 thousand homes, and which is only expected to increase in the near future because fewer building permits have been issued in recent years (Rijksoverheid, 2023b). By the time it will be 2030, the Netherlands will need to have almost a million new houses (Rijksoverheid, 2023a). To solve this problem, it is important to build more residential buildings in the near future, but limited space is available. Therefore, the focus shifts to traditionally less conventional spots that potentially can be used to construct residential areas.

One of the proposed solutions is to create residential buildings near dikes, thereby using the dikes to not only combat flood risks but also to relieve pressure on the housing crisis in the Netherlands. In 2023, the Netherlands had about 17,691 kilometers of dikes (Unie van Waterschappen, 2023a) of which 3,800 kilometers of primary flood defence. Since building on or within the protection zones around dikes is often not allowed, much space is currently not being used. For this reason, the building of (temporary) homes in the profile of free space was discussed in multiple area conferences (Hollandse Delta, 2021).

Building homes on and next to dikes is a challenging task due to increasingly stringent requirements and changing boundary conditions. Building a house should not have a negative impact on the stability of the dike, which is difficult to demonstrate. This report attempts to simplify the demonstration of the reliability of multifunctional dike sections to promote the construction of houses on and in dikes. Additionally, this report discusses the current possibilities and complaints regarding building near dikes.

2
Problem analysis

The problem analysis aims at identifying the problem as accurate as possible. First, an introduction is provided to Non-Water Retaining Objects, to which buildings near dikes belong. Next, the focus is on existing buildings near dikes and why they were possible to be built. Subsequently, the problems with the current construction of NWO's are described, initially addressing the management of flood defences by water boards and the current assessment criteria for the reliability of the flood defences. Following that, the present state of knowledge is described through a study of various conducted research on multifunctional flood defences. Finally, the problem statement and the objective of the report are established.

2.1. Non-Water Retaining Objects (NWOs)

2.1.1. Definition of non-water retaining objects

Sixty percent of the Netherlands is susceptible to flooding (Rijkswaterstaat, n.d.-b). That is why the Netherlands has approximately 17.691 kilometers of flood defence (Unie van waterschappen, 2023). Flood defences have as function to protect the Netherlands against floods and are present in flood prone areas. These flood defences include dams, dikes, locks, weirs and storm surge barriers.

From these flood defences, the dikes form the largest amount of kilometers. The dikes are often combined with other functions, such as traffic and housing, making them multifunctional flood defences. The structures built on or near dikes that can contribute to the water retaining capacity of the dike, are also called Water-Retaining Objects (WOs). If the object does not contribute to the water-retaining function, it is referred to as a Non Water-Retaining Object (NWO) in the Dutch flood risk policy. The non-water retaining objects can be divided into four categories (Hoffmans & Knoeff, 2012):

- Buildings (Figure 2.2)
- Vegetation (Figure 2.1)
- Cables and pipelines
- Other structures

Figure 2.1: NWO vegetation (Seijlhouwer, 2022)

Figure 2.2: NWO buildings (Van Erp, 2020)

For each category the assessment criteria are different. This report focuses on the category buildings.

2.1.2. Examples of existing NWO buildings

Building on or next to dikes has been done much in the past. In the present it is not common anymore due to strict regulations but sometimes with technical adjustments it is still done. In this section two examples are discussed, one project that has taken place in the past and one more recently.

Alblasserdam

Alblasserdam is located in the province of South-Holland and is situated in the Alblasserwaard region. The dike at Alblasserdam serves as a primary flood defence. Just behind the crest, there is a berm which has a road and houses. This situation can be seen in Figure 2.3.

There are currently no specific requirements for dike reinforcement in Alblasserdam. However, this cannot be ruled out for the future. In the event of a potential increase in the design water level there will likely be a need for a higher berm, where currently houses are present. Although efforts will be made to explore alternative solutions it cannot be ruled out that this will be successful and the houses still need to be removed. In 2024 a new evaluation of the dike will take place and it will be analysed if it is still safe regarding the latest safety requirements. Expectations are that the dike does not meet the current safety standards anymore and thus will be rejected (AlblasserdamNieuws, 2020).

Figure 2.3: Alblasserdam dike (Tromp, Van den Berg, Rengers, & Pelders, 2012)

Jackable houses Papendrecht

Technical possibilities that allow for the building of residential buildings without having to demolish the houses in the future exist. Usually this would lead to houses standing deeper in the dike and not being able to perform the needed reinforcements in the future, which is undesirable. The question arose whether it is possible to build flexible around the dike so that, in the case of a dike reinforcement, this can be achieved with relatively simple measures.

A solution is the jacking up of houses. In this process, a concrete slab is placed under the house and steel piles are driven into the ground through the slab. By placing jacks between the piles and the concrete slab, the building can be lifted upward. In the case of necessary dike reinforcement, the house can be raised, allowing for dike reinforcements to be carried out in the future. The houses can be seen in Figure 2.4 and a jack can be seen in Figure 2.5.

Figure 2.4: Jackable houses (Deltares, 2013)

Figure 2.5: Jack (Voorendt, 2013)

Kinderdijk
Another example of houses near a dike is in Kinderdijk. In Kinderdijk, additional soil was added next to the dike on which the house was built. Thus the negative effects of the houses on the failure mechanisms were taken into account and more soil was added to the dike, making it more safe. A sketch of this situation can be seen in Figure 2.7. When a gap is assumed at the location of the house the dike still complies to the failure probability requirements.

Figure 2.6: Kinderdijk (Google Street View, 2023)

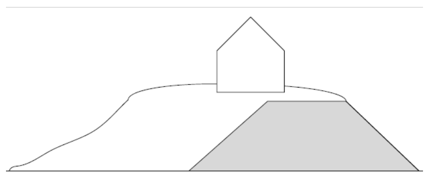


Figure 2.7: Schematisation Kinderdijk

These examples show that building next to dikes is not new. In the past it has been done since the influences of buildings next to dikes were not well known and future dike reinforcements were not taken into account, which can be seen in the case of Alblasserdam. Nowadays it is not that simple anymore to remove residential buildings. Compensatory measures can be taken to strengthen the dike and keep the house in place but these measures are not preferred because they can cost much money. Examples of compensatory measures can be seen in Figures 2.8 and 2.9. The jackable houses can be an alternative, but can also be hard to construct. That is why this report focuses at normal full-fledged homes that will be built on or next to dikes.

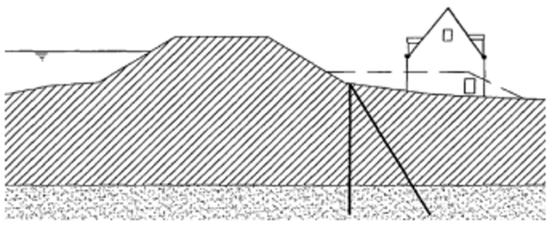


Figure 2.8: Stability screen (STOWA, 2023)

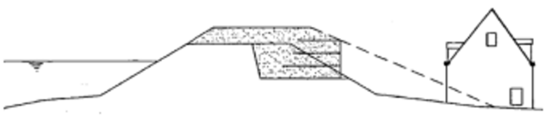


Figure 2.9: Reinforced concrete wall (STOWA, 2023)

2.2. The management of flood defences

The Environmental Act (national level) and the water board regulations (regional level) describe what is allowed regarding construction on and near dikes. On January first 2024, the Water Act (Waterwet) transitioned into the Environmental Act (Omgevingswet), and the by-law (Keur) transitioned into the water board regulation (Waterschapsverordening). The Environmental Act consolidates 26 existing laws into one, with the primary goal of simplifying project realisation.

The water boards manage most of the dikes in the Netherlands. Each water board has established its own Water Board Regulation. The Water Board Regulation prescribes the rules that are used to protect flood defences, waterways, and related engineering structures. These rules prevent dikes and banks from being damaged and maintaining their stability. Each dike has three zones that are established by the water board to protect the dike. These can be seen in Table 2.1 with their corresponding function and in Figure 2.10.

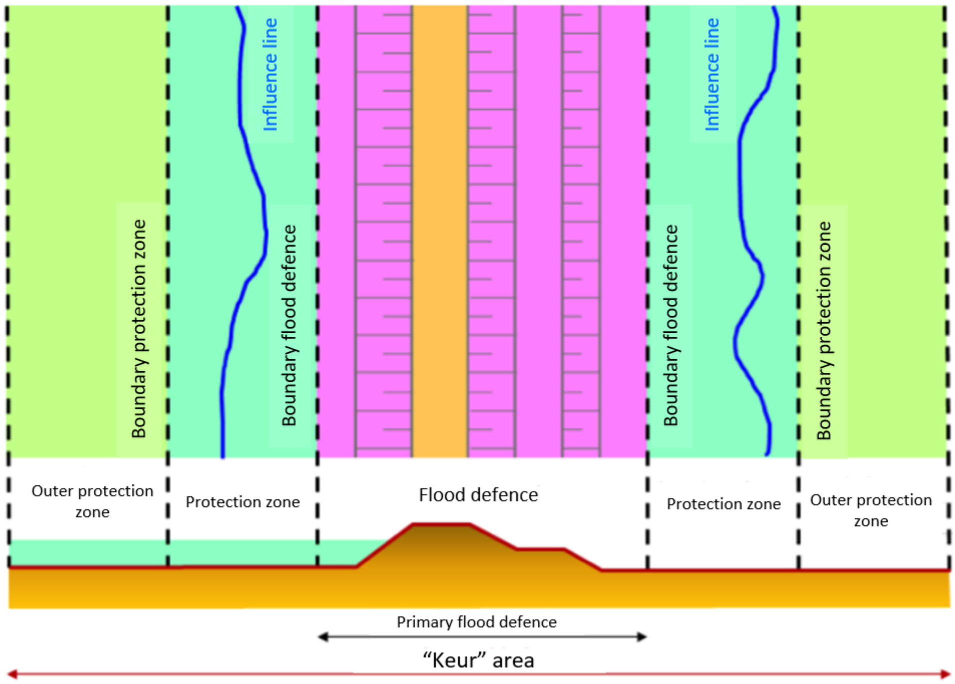


Figure 2.10: Dike zones (STOWA, 2011)

Zone	Type	Function
1st zone	Water Management Work (Structure)	Ensuring the function of the water management work
2nd zone	Protection Zone	Ensuring the stability of the water management work
3rd zone	Free Space Profile	Providing an opportunity to improve the water management work due to future requirements

Table 2.1: Dike zones

The dike's expandability is ensured by applying a free space profile. This allows the water board to indicate the space that could be occupied by a future dike reinforcement within a specified time horizon (for example, 100 or 200 years). This policy considers that future dike reinforcements should be possible without removing or demolishing buildings. The influence lines of the failure mechanisms macro stability and piping determine the boundaries of the protection zone. Structures in the protection zone may danger the stability of the dike (STOWA, 2011).

Each water board has its own perspective and implementation of the policy regarding the free space profile. In most cases, this means that structures may only be placed with the water board's permission. The by-law, and from 2024 the Water Board Regulations, determine what is and isn't allowed in the free space profile. In most cases, this means that no structures can be placed without the water board's permission. Regulations vary slightly in each water board. This results in some water boards not allowing construction in the free space profile and the protection zone, while other water boards may grant a permit if various requirements are met. This often leads to a complex decision for the water board between the interest of the initiator and the water safety concern. In the regulations, no distinction is made between permanent and temporary construction.

With temporary structures, structures that will stay till the next dike elevation are meant. This could open up opportunities to build in the profile of free space. A concern with regard to building in the protection zone is that the safety of the dike may worsen. The safety has to be checked using the Legal Assessment Instrumentation (WBI2017), as seen in Section 2.3.1.

2.3. Assessment of Non-Water Retaining Objects

The official assessment criteria are established in the Legal Assessment Instrumentation (WBI2017). However, it provides limited clarity regarding a more detailed assessment. This is why Deltares and the Province of South-Holland have developed additional follow-up steps to assess the safety of the NWOs, which are elaborated after the WBI2017.

2.3.1. WBI2017

The assessments for these non-water retaining structures can be divided in three assessment levels of detail.

- Basic assessment (assessment level 1). In the basic assessment simple decision rules are used to check whether the likelihood of a failure mechanism occurring is negligibly small.
- Detailed assessment (assessment level 2). The detailed assessment is made based on a fixed probability distribution to determine whether the norm is met. This is achievable through probabilistic and semi-probabilistic calculations.
- Customized assessment (assessment level 3). In the customized assessment, location specific analyses are conducted, ranging from deterministic to probabilistic approaches.

Figure 2.11 shows the basic assessment for non-water retaining objects. For the various objects, a distinction is made. This report will focus on buildings. For buildings on dikes, step 1.2.4 can be further divided into four other steps.

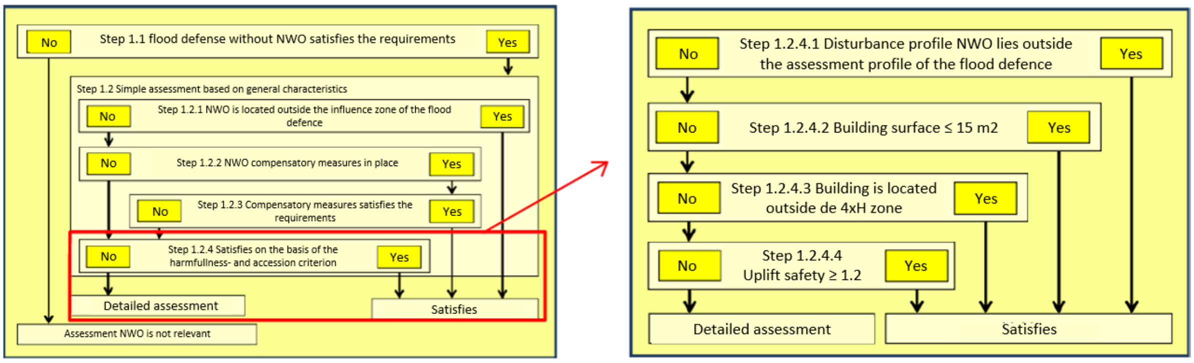


Figure 2.11: Simple test for non water retaining structures for the category buildings (De Bruijn, De Vries, & 't Hart, 2017)

For buildings, no detailed assessment method is available. Therefore, a customized assessment must be carried out if the basic assessment is not sufficient. In this case, the influence of the non water retaining structure must be considered for each failure mechanism in the assessment. A process is described for the customized assessment. It consists of the following steps (De Bruijn et al., 2017).

- Step 1: Assessing possibilities for further analyses.
- Step 2: Evaluating the effectiveness of the analyses (cost-benefit analysis).
- Step 3: Performing a detailed (location-specific) analysis.

2.3.2. Province South-Holland assessment

The province of South Holland has established rules of thumb to make a more detailed assessment (Beijersbergen & Spaargaren, 2009). This is based on three filters, each serving a purpose.

- Filter 0: Applying the legal assessment criterion
- Filter 1: Exclude NWO's that are outside the influence zone
- Filter 2: Characteristics of the non water retaining object
- Filter 3: Assessment profile

For each filter it applies that if it does not result in an outcome the process should proceed to the next filter. If ultimately filter three does not yield a score, the building should be rejected.

Filter 0 assesses whether it complies with the basic assessment of the existing legal assessment instrumentation. If this is not the case, further progression to filter 1 is needed. The influence zone is the area in which a specific failure mechanism could be affected by the NWO. If a house were to be built in the influence zone, it could impact the relevant failure mechanisms. If this is the case, the assessment proceeds to filter 2, where additional steps are outlined based on the location of the structure on the dike and the specific failure mechanisms that must be addressed. A summary of the failure mechanisms that have to be addressed per location can be seen in Figure 2.12.

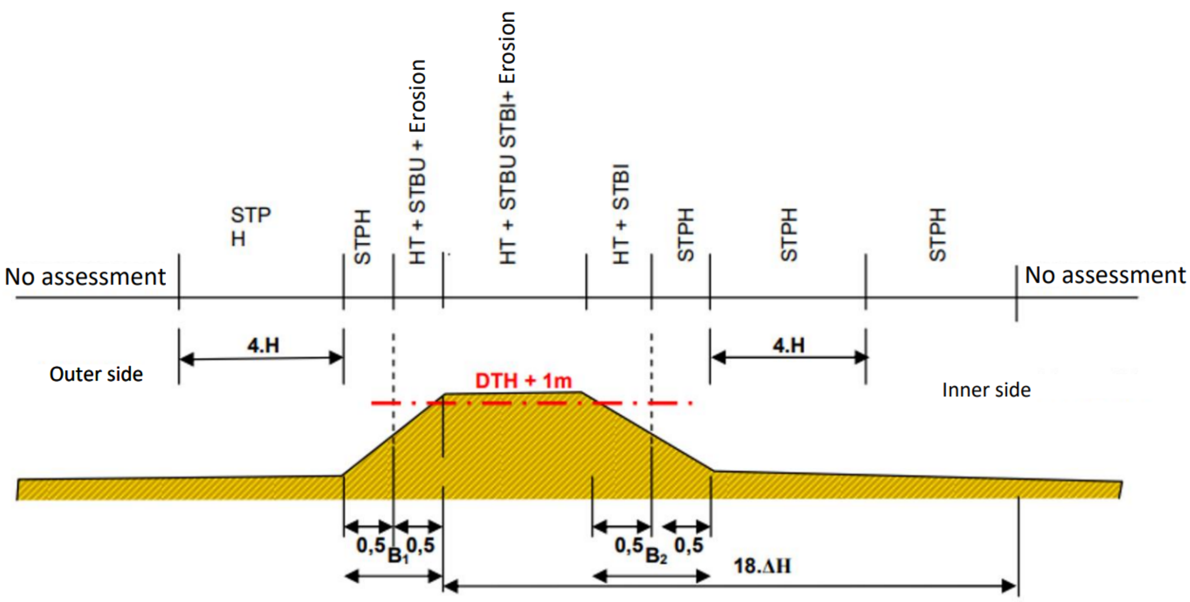


Figure 2.12: Failure mechanisms (Beijersbergen & Spaargaren, 2009)

The steps to follow depend on the surface area of the building, the placement of the building on the dike and the type of foundation. In the box below, the steps of filter 2 can be seen. When these requirements are not met it should be proceeded to filter 3.

The steps to be followed are:

a) Floor area ≤ 15m²?
- Only check for erosion resistance of the outer slope (use available test results of the cladding; if not available, perform a test according to Section 8 Cladding).
- Other mechanisms: NWO management judgment "good":
  a. Such buildings, often sheds, are usually not on piles and generally have no basement → 'piping' is good.
  b. Such structures have limited weight → 'stability' is good.

b) Buildings, > 15 m2, at ground level inside or outside (only 'piping test'):
- Foundation 'on steel': check if there is 1 m of clay underneath (possibly obtainable from the geotechnical profile):
  a. Yes, 'piping' is good.
  b. No, further investigation or follow Filter 3.
- Foundation 'on piles': further investigation or follow Filter 3.

c) Buildings, > 15m2, on the upper half of the slope or crest (test on 'height', 'sliding', and 'piping'):
- Approve if the bottom of the foundation/cellar is above DTH + 1m (height); otherwise, follow Filter 3.
- Foundation 'on piles': no negative impact on sliding (building weight is transferred to deep ground). If this does not result in a shorter horizontal seepage path for piping → approve. If yes, then follow Filter 3.
- Foundation 'on steel': approve if there is healed fore- or hinterland with a soil body of at least 40 m wide above the Assessment Level. Otherwise, follow Filter 3.
- Foundation 'on steel': further investigation (e.g., for a crest width greater than 10 m, there should be sufficient residual profile) or follow Filter 3.

d) Buildings on the upper half of the outer slope ('erosion resistance'):
- For continuous buildings (due to 3D effects), consider only the gable ends of the buildings.
- Core material clay: approve (the residual profile is assumed to be sufficiently erosion-resistant).
- Core material sand: further investigation, for example, approve if the crest width is greater than 10 m or follow Filter 3.

Finally in filter 3 the assessment profile is examined. Based on the various existing failure mechanisms, a critical line can be determined. The critical lines all together are referred to as the assessment profile. This can be seen in Figure 2.13. If a building will be constructed in this assessment profile the construction should be rejected.

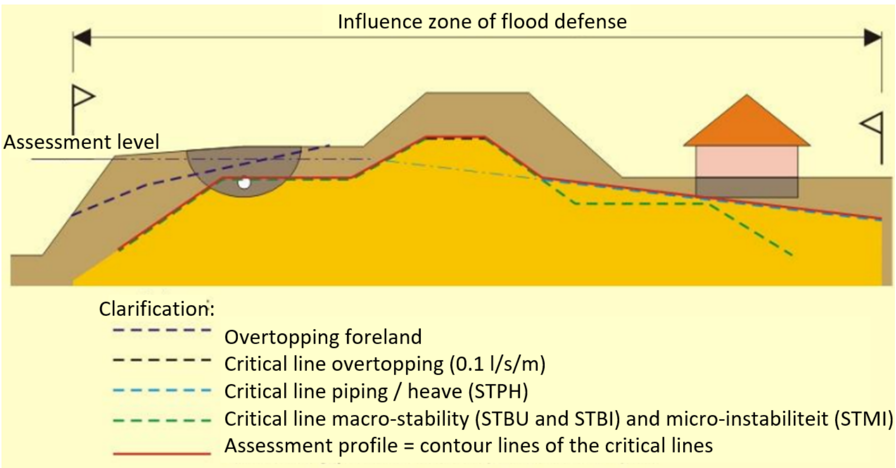


Figure 2.13: Assessment profile (Beijersbergen & Spaargaren, 2009)

2.3.3. Assessment method of Deltares

Further research has been conducted on the customized assessment by Deltares (Hoffmans & Knoeff, 2012). A distinction is made between analyses that do not consider the buildings' strength and those that take the strength into account. For these situations, it is determined what failure mechanisms have to be taken into account depending on the location of the dike. These also take into account a possible basement and the type of foundation. This helps to determine the focus when performing a customized assessment. A summary of what failure mechanisms to take into account depending on the place of the building can be seen in Figure 2.14

Influence of building per failure mechanism

Placement building	Type: (basement, foundation)		Failure mechanisms: STVL	STBU	STPH	HT	STBI	STMI en STBK [2]
Low foreland below assessment level	Basement	Shallow	nvt 1	nvt	Nvt, unless the entry point at the foreland is taken into account when calculating	nvt	nvt	Point of application for erosion, testing for the presence of a clay layer
		Pile						
	No basement	Shallow						
		Pile						
High foreland	Basement	Shallow		nvt [1]	nvt	nvt	nvt	nvt
		Pile						
	No basement	Shallow						
		Pile						
Outside slope	Basement	Shallow		Increase in drive weight	Shortened seepage path	nvt	Increased groundwater level	Application point erosion
		Pile		nvt				
	No basement	Shallow		Increase in drive weight			nvt	
		Pile		nvt				
Outer crest	Basement	Shallow		Increase in drive weight	Shortened seepage path	Floodwalls	Increased groundwater level	Application point erosion
		Pile		nvt				
	No basement	Shallow		Increase in drive weight	nvt		nvt	
		Pile		nvt				
Inner crest	Basement	Shallow	nvt	nvt	Shortened seepage path	Along the inner crest and on the inner slope with concentrated water drainage along the slope	Calculation with basement wall	Application point erosion
		Pile						
	No basement	Shallow			nvt		Usually on adjacent land, calculate a separate profile if necessary	
		Pile						
Inner slope high	Basement	Shallow	nvt	nvt	Shortened seepage path	nvt	Calculation with basement wall	Application point erosion
		Pile						
	No basement	Shallow			nvt		nvt	
		Pile					Usually on adjacent land	
Inner slope low	Basement	Shallow	nvt	nvt	Shortened seepage path	nvt	Calculation with basement wall	Application point erosion
		Pile						
	No basement	Shallow			nvt		Usually on adjacent land, calculate a separate profile if necessary	
		Pile						
Inner bank	Basement	Shallow	nvt	nvt	nvt	nvt	nvt	nvt
		Pile						
	No basement	Shallow						
		Pile						
Inner toe	Basement	Shallow	nvt	nvt	nvt	nvt	nvt	
		Pile						
	No basement	Shallow						
		Pile						
Inner ground level	Basement	Shallow	nvt	nvt	nvt	nvt	nvt	nvt
		Pile						
	No basement	Shallow						
		Pile						

Piping calculation with shortened seepage line
Only soil mechanical stability calculation
The soil mechanical calculation separately, including rigid construction walls and floors

Figure 2.14: Contribution to failure mechanisms
(Hoffmans & Knoeff, 2012)

2.4. Inventory of the present state of knowledge

In the past, research has already been done to determine the impact of buildings on a dike and how this can be assessed. These researches have been examined to assess the existing knowledge regarding the multifunctional use of dikes. By exploring the conducted studies, a solid foundation can be established for this report and prevent redundant research. First, research regarding building in dikes has been mentioned. Next, research that proposed a reliability approach to multifunctional flood defences has been discussed. Finally, the design process of multifunctional flood defences proposed by Voorendt and the current schematisation of buildings in a dike have been discussed.

2.4.1. Building in dikes

Van Mechelen (2013) researched the possibilities of building within dikes, focusing on a case study involving a parking garage in a dike. The case study was assessed for key failure mechanisms. He extensively addressed the technical difficulties associated with building within dikes and assessed the failure mechanisms that the building would influence. In order to analyse the reliability of the stability of the dike and the structural strength, he used FORM analyses. This resulted in an approach to design and assess the dike in the case study in a reliable manner.

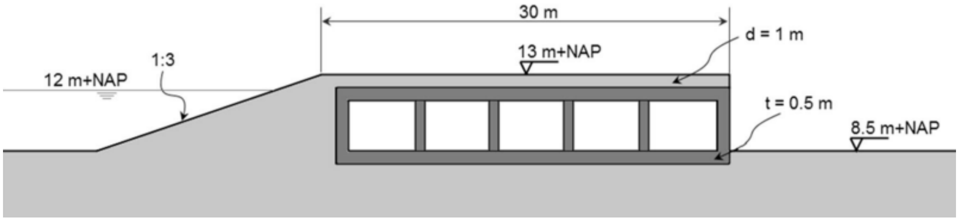


Figure 2.15: Parking garage (Van Mechelen, 2013)

Kentrop (2016) developed an engineering design for a glass dike that satisfies applicable safety standards. The focus was on the strength and stability assessment of the house as it is part of the dike. A probabilistic design of the glass elements was done, and a semi-probabilistic approach was used to assess the failure mechanisms. The results of the case study of the glass dike were used to get general considerations that could play a role for glass flood defences in general.

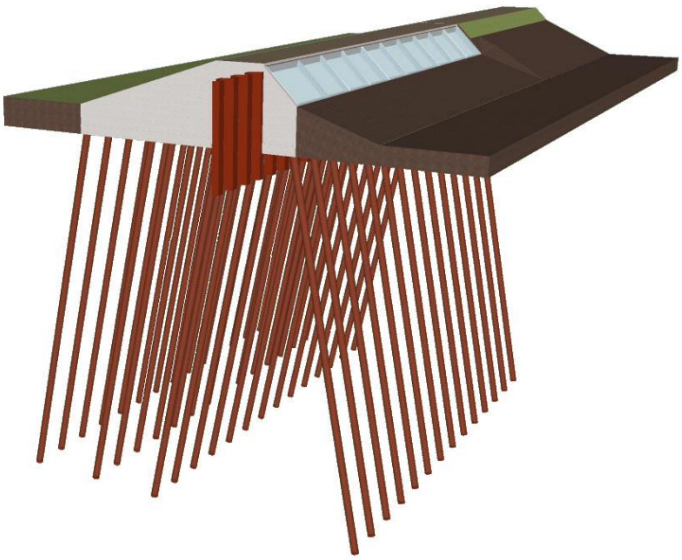


Figure 2.16: Glass house (Kentrop, 2016)

2.4.2. Reliability approach

Research was done by the organisation Natural Hazards and Earth System Sciences in an article called: "Re-evaluating safety risks of multifunctional dikes with a probabilistic risk framework" (Marijnissen, Kok, Kroeze, & Van Loon-Steensma, 2019). The probabilistic procedure they described can be seen in Figure 2.17. They used the First Order Reliability Method (FORM) to determine the failure probabilities of the failure mechanisms.

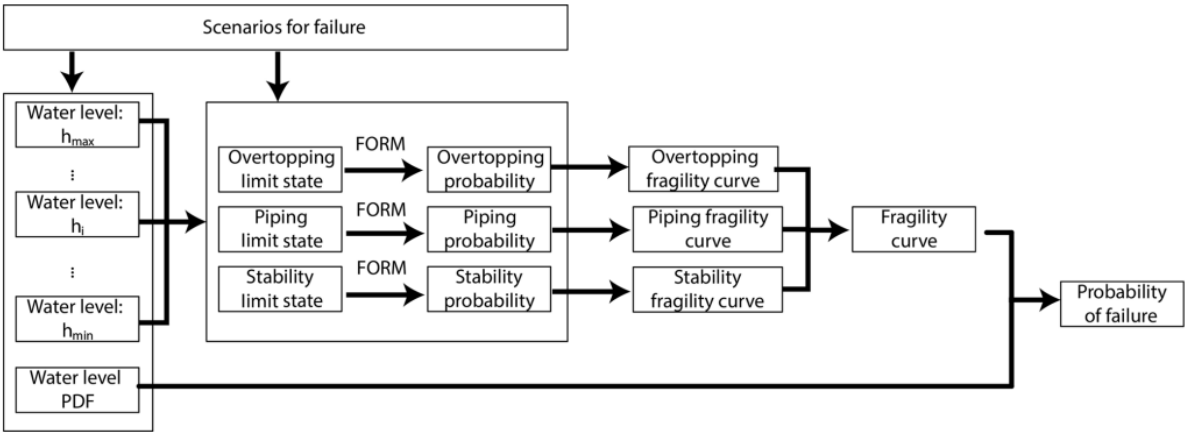


Figure 2.17: Probabilistic procedure (Marijnissen et al., 2019)

The strength of the NWO cannot be taken into account because otherwise, it would become a water-retaining object, which the water boards do not allow. The main reason for this is that it would be harder for the water boards to determine the state of the multifunctional elements and, thus, the safety of the dike. The consequence is that the object needs to be schematised in the worst possible condition for the dike assessment. This means that if the NWO has a negative influence on a failure mechanism, the weight of the house must be taken into account, and if the house has a positive effect, a gap in the dike must be assumed. Therefore, a dike will always be worse with NWO than without it when it is assessed. Marijnissen has investigated what the influence of a NWO is on failure mechanisms when assuming that the object is allowed to retain water, so when also the positive effects are taken into account.

The scenarios that were taken into account can be seen in Figure 2.18. In all scenarios the weight of the house is assumed at 17.5 kN/m and has a width of 15 meters. Furthermore, the house is embedded one meter into the soil.

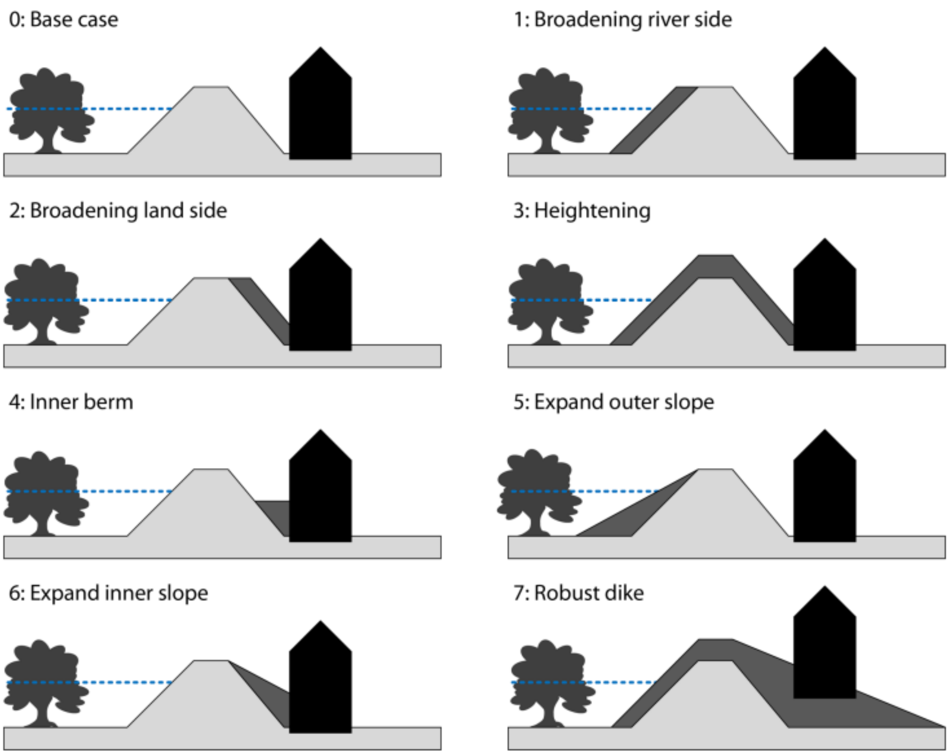


Figure 2.18: Scenarios (Marijnissen et al., 2019)

For each of the scenarios, the probability of failure for the dike is calculated for three situations:

- Structure present; with "structure" the dike profile with the house is meant.
- Unreliable clay cover; the structure in its demolished state leaves a discontinuity in the dike profile and exposes bare clay on the dike slope while leaving the remaining dike intact. This is meant with unreliable clay cover.
- Combination of the two above; combination stands for the combination of the two situations above. It is assumed that the house will be in place 99% of the time and the unreliable clay cover 1% of the time.

For these three situations, the probability of failure is calculated in three manners: without a house, basic assessment with a house and a probabilistic assessment with a house. These results can be seen in the bars in Figure 2.19.

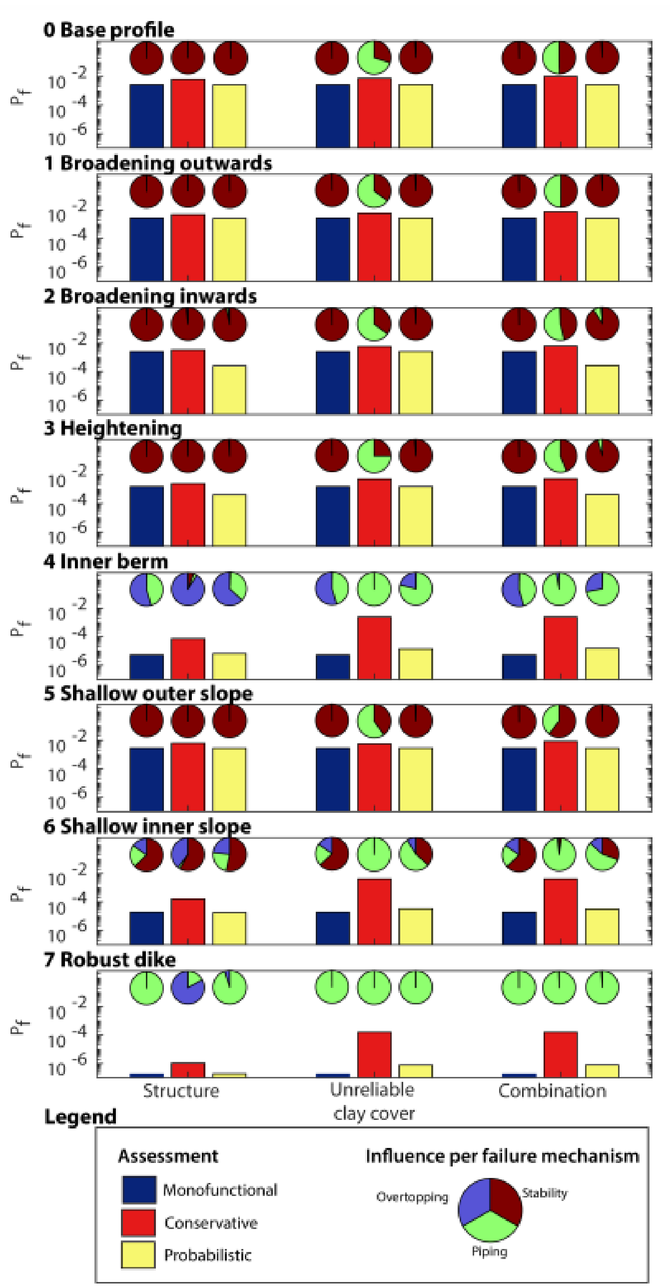


Figure 2.19: Results (Marijnissen et al., 2019)

The bar graphs represent the total failure probability of the assessments. It can be seen that the basic assessment is much more conservative than the probabilistic assessment they suggested. Furthermore, the pie graphs show the contribution of each failure mechanism to the total failure probability.

Jongerius (2016) conducted his master's thesis on the impact of buildings on the slope stability of a dike. His research question was: "What is the influence of a non-water retaining building on the reliability of a dike, and how can this be determined and included in the assessment of flood defences?". This study focuses on the inner slope of the dike and the assessment of houses already built in that area, given their prevalence. In his thesis, Jongerius developed a probabilistic method, which could be seen as a foundation for conducting an advanced assessment of dike stability with a building in the soil profile, where the failure of the buildings could influence stability. The assessment was done using FORM analyses and Monte Carlo simulations. This method combines a structural model and a geotechnical model into an integrated model. After the method was developed it was tested with a case of a house that has been build in the slope of a dike, which can be seen in Figure 2.20. This research showed that the failure probabilities for both the structural and geotechnical model are very low when using the proposed method. However, it is mentioned that the model uncertainties are not included. This makes the method inappropriate to compare with other methods. Further research is needed to address these uncertainties.

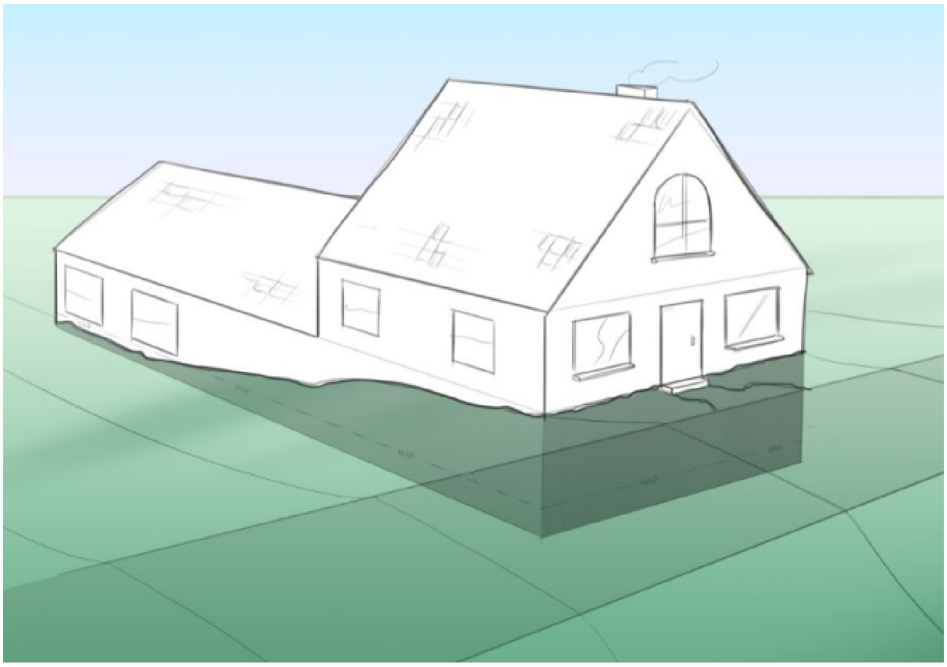


Figure 2.20: Case (Jongerius, 2016)

Additionally, further research was conducted by Van der Zee (2017). He investigated the local influence of a house on the inner slope stability. His research question was: "What is the local influence of a building on the reliability of the inner slope stability of a dike section?". The difference between Jongerius's study and his is that his study considered not only the 2D effects but also the 3D effects. He concluded that the actual influence of an intact structure could be a positive effect, whereas the negative effects are an underestimation of the actual safety,

Research was also done by Aguilar López (2016). His dissertation named, "Probabilistic safety assessment of multi-functional flood defences", was about determining the effects of erosion-based failure mechanisms on multifunctional flood defences. The main outcome was that the incorporation of hard structures in the flood defence has a significant effect on their reliability, and this effect should not be disregarded. Therefore, he recommends including these effects in future safety assessments of multifunctional flood defences.

2.4.3. Design process of multifunctional flood defences

Voorendt proposes a method for the integral and sustainable design of multifunctional flood defences. This is achieved by combining two methods, those of engineering and spatial designers. The proposed method integrates both approaches to complement each other in one method. This method is made to ensure that the design of multifunctional flood defences follow a more efficient, effective and transparent yet creative approach (Voorendt, 2017).

Additionally, the dissertation says something about the influence of buildings on the dike failure mechanisms. Figure 2.21 shows the locations where construction is possible along a dike. Subsequently, Figure 2.22 demonstrates the impact of the buildings on various failure mechanisms. The plus signs indicate a decrease in the failure probability of a failure mechanism, while the minus signs indicate an increase in the failure probability.

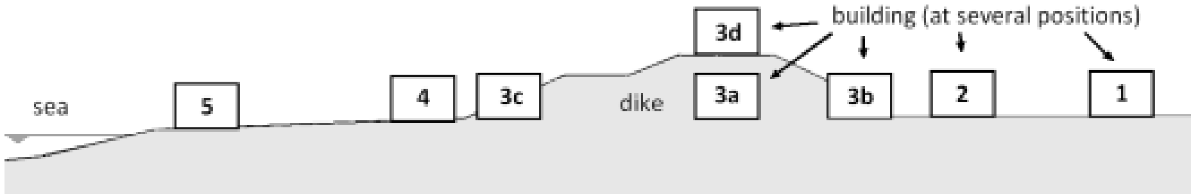


Figure 2.21: Possible house locations (Voorendt, 2017)

	1. overtopping	2. uneven settlement	3. instability foreshore and outer slope	4. macro-instability	5. micro-instability	6. horizontal sliding	7. piping	8. animal actions	9. human actions
location 1	0	0	0	0	0	0	0	0	0
location 2	-	0 / -	0	++	0	0/+	0	0	-
location 3a	0	0 / -	0	+	0	-	--	0	--
location 3b	--	-	0	-	0 / +	0	-	0/+	--
location 3c	+	-	-	-	0	0	0	0/+	--
location 3d	-- / ++ 1)	-	0	--	0	+	0	0/+	--
location 4	++	0 / -	--	++	0	0	0	0	-
location 5	+	0	-	0	0	0	0	0	0

1) negative for the crest, positive for the inner slope

Figure 2.22: Influence on failure mechanisms (Voorendt, 2017)

2.4.4. Schematisation of multifunctional elements

Voorendt (2017) proposes a method to determine the probability of the failure mechanisms by distinguishing types of structural elements in a multifunctional flood defence. This starts with finding the structural parts with a water-retaining function. Subsequently, the erosion-proof and supporting elements are searched for, followed by the sub-soil, closure means, secondary elements, transitions and wave-damping elements. These can be seen in Figure 2.23.

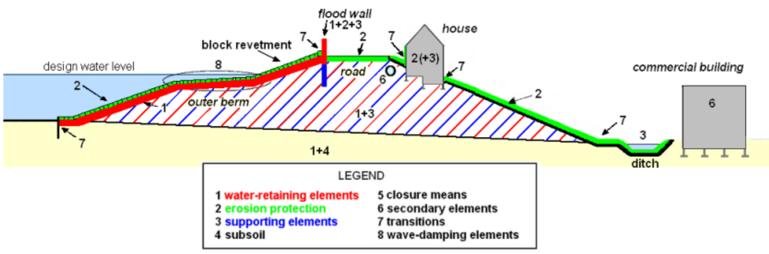


Figure 2.23: Dike with Structural elements (Voorendt, 2013)

The structural elements can be related to failure mechanisms. The failure probability of the failure mechanisms can be compared to the required maximum failure probability.

2.4.5. Concluding remarks and overview

Houses built on or next to dikes are usually schematised in the worst possible scenario when assessed. Reasons for this conservative approach are the inability to guarantee that the house will remain in that location or that it may collapse at some point. If the strength of the house is crucial to the dike, the house serves as a water-retaining structure. This can lead to problems regarding ownership and maintenance because water boards must be able to conduct regular inspections. The question of who is responsible for maintenance also arises. Due to these objections, it is often the simplest to consider a house as a non-water retaining object and use the most unfavourable schematisation for calculations. This means a dike with an NWO is always considered less strong than one with a water-retaining function. This leads to situation 2 of Figure 2.24. In Marijnissen's report, the strength of the house is taken into account and the possibility that the house may not be there is also considered. This results in situations 3 and 4 of Figure 2.24.

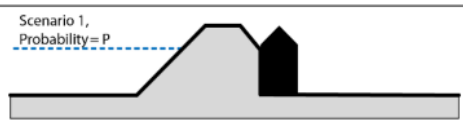
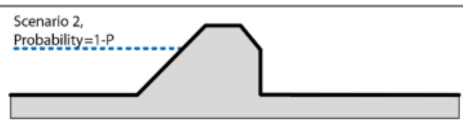
Approach	Assumptions	Example
Monofunctional	No multifunctional elements present.	
Multifunctional Conservative	Functions are always in the critical state for a given failure mechanism. Dike zones affected by the multifunctional elements are omitted from the profile.	
Probabilistic	Uncertainty of multifunctional elements split into scenarios (e.g. present or absent).	
	Each scenario has a probability.	

Figure 2.24: Schematisation of building in dike section (Marijnissen et al., 2019)

An overview of the research described can be seen in the table below.

Category	Area of research
Building in dikes	• Van Mechelen; Extensively addressed the technical difficulties associated with building within dikes and assessed the failure mechanisms that would be influenced by the building • Kentrop; Developed an engineering design for a glass dike that satisfies applicable safety standards
Reliability approach	• Marijnissen; Proposes a probabilistic procedure for determining the failure probabilities of the failure mechanisms • Jongerius; Determined the impact of buildings on the slope stability of a dike • Van der Zee; Investigated the local influence of a house on the inner slope stability, taken also into account the 3D effects • Aguillar Lopez; Determined the effects of erosion based failure mechanisms on multifunctional flood defences
Design process	• Voorendt; Proposes a method for the integral and sustainable design of multifunctional flood defences
Schematisation	• Voorendt; Proposes a method to determine the probability of the failure mechanisms by distinguishing the structural elements in a multifunctional flood defence

All these reports and graduation projects demonstrate that much thought has already been given to building on, next to, and even within dikes. In these reports, the focus often is on probabilistic calculations and trying to include the positive effects of the objects on the total failure probability of the dike. From this, it is clear that objects can contribute to the strength of a dike. In these reports, assumptions were frequently made for the schematisation of the object. Additionally, there is no comprehensive description of what will be done if the structures are no longer present and how to ensure that the schematisation remains valid.

2.5. Problem statement

The assessment method of the Legal Assessment Instrumentation (WBI2017) can be used to check if a building can be built on or next to a dike. However, only a basic assessment is prescribed for this, which is a very conservative approach. This conservative approach assumes a gap at the location of the house, so no strength of the house is taken into account. In practice, this leads to overdimensioning dikes, and, hence unnecessary costs.

Marijnissen (2019) suggested a less conservative probabilistic approach that considers the water-retaining effects of buildings. Marijnissen recommends to delve further into less conservative schematisations for multifunctional structures and determine how probable it is that the multifunctional element will be in place.

2.6. Objective

The objective of this thesis is to develop a level I reliability assessment method for multifunctional dikes containing a structure, leading to a less conservative approach than the basic assessment of the Legal Assessment Instrumentation (WBI2017).

2.7. Scope

The housing shortage is most significant in densely populated areas. That is why this thesis will focus on the situation in the most densely populated water boards. In Table 2.2, the three most densely populated water boards, together with the Hollandse Delta water board, can be seen. These water boards will be considered for finding a suitable case and exploring the legal possibilities regarding construction near dikes. The Hollandse Delta water board is less densely populated, but in multiple years (2021, 2023), discussions about building houses on dikes have arisen during area conferences where multiple representatives of water boards and municipalities were present, so there may be more knowledge and possibilities in this regard. The difference in possibilities with regard to building on and near dikes for these water boards will be established. The number of kilometers of dike has also been indicated for each water board, as this gives an indication of the area which can potentially be used for living areas.

Water board	Residents	Surface area [ha]	kilometers dike	residents per hectare
Amstel, Gooi en Vecht	1,300,000	70,000	1096	18.57
Delfland	1,200,000	40,547	724	29.60
Schieland en Krimpenerwaard	606,000	35,000	202	17.31
Hollandse Delta	870,000	102,400	779	8.50

Table 2.2: Water board statistics (Unie van Waterschappen, 2023b)

Within these water boards, the focus is on primary river dikes as there is a larger area of river dikes than sea dikes in their administrative areas, allowing for more room for living areas. Furthermore, attention is given to primary flood defences, because the assessment methods and regulations for these are more stringent than those for regional flood defences. Furthermore, the emphasis is on the construction of new full-fledged houses on or along the inland area of the dike, and the houses must be able to be built on existing dikes.

2.8. Deepening questions

To gain a better understanding of the subject, deepening questions have been formulated. These deepening questions aim to clarify the current gaps in knowledge. The deepening questions are:

1. What are the legal possibilities regarding construction near dikes?
2. How can the influence of a house on the various failure mechanisms be schematised?
3. How can a dike section with a house be assessed?
4. What is the effect of using the proposed schematisation on the total failure probability of the dike, and how does it compare to the current conservative schematisation?
5. What are the implications of this research on the possibilities of building houses near dikes and on the existing buildings near dikes?

2.9. Methodology & thesis outline

This chapter outlines the thesis's approach. The structure of this chapter resembles the intended organization of the entire thesis. Therefore, this chapter is also considered the outline for the thesis. The first and second chapter of the thesis will include the introduction, problem analysis and methodology. The third chapter describes the first step, and the next chapters will follow these steps.

1. The first step in developing the level I reliability method is to do a literature study regarding the legal perspectives. This begins with investigating what the Water Act and the Water Board Regulations allow regarding construction on and near dikes. Interviews with water boards are also conducted for this purpose because not all considerations of the water boards are expected to be written down (Chapter 3).

   Deepening question 1: "What are the legal possibilities regarding construction near dikes?" will be answered here.
2. Once it is clear what is legally feasible, the relevant failure mechanisms of a dike will be identified. The failure mechanisms that are additionally influenced by a structure will be determined. A hypothetical cross-section of a dike with multiple locations of the house is used for this purpose (Chapter 4).
3. In this step, probabilistic calculations are performed to determine the influence of a house on the total failure probability of the dike. These probabilistic calculations will form the basis of the method. A case is elaborated to show the impact of including the house in the failure probability calculations of the dike. The case is elaborated probabilistically because this makes it easy to compare with the

failure probabilities of the current assessment method, and the influence of the failure mechanisms with respect to the total failure probability can be analysed. It is important that it is a representative case study reflecting the most common aspects of a dike and buildings (Chapter 5).

Deepening questions 2 and 3: "How can the influence of the house on the various failure mechanisms be schematised?" and "What is the effect of incorporating the proposed schematisation method on the total failure probability of the dike, and how does it compare to the current conservative assessment method?" will be answered here.

4. It is not desirable for an assessment method to be probabilistic because it can take much time to implement this for every assessment. In this step, partial safety factors will therefore be derived for a level I reliability assessment based on the probabilistic calculations in step 3 (Chapter 6).

   Deepening question 4: "How can a multifunctional dike section with a structure be assessed?" will be answered here.

5. Next, the case will be generalised to a generic method, making it applicable to multiple situations (Chapter 7).

6. The assessment method can now be validated. This is done by presenting it to an expert and asking for their feedback. Additionally, a discussion is included, which considers the limitations of the method (Chapter 8).

   Deepening question 5: "What are the implications of this research on the possibilities of building houses near dikes and on the existing buildings near dikes?" will be answered here.

7. Finally, the conclusions and recommendations are drafted regarding the method (Chapter 9).

3 Legal perspectives

Step 1 of the main thesis methodology

In this chapter, the legal possibilities regarding building near dikes are discussed. First, the current dike safety standards are addressed. Next, the multifunctional use of dikes is discussed. Subsequently, everything that is allowed regarding building near dikes according to the Environmental Act and the Water Board regulations is discussed. Furthermore, interviews were conducted to determine the objections against the multifunctional use of dikes and solutions to the objections were proposed.

3.1. Dike safety standards

Rising sea levels and more extreme weather increase the risk of flooding in the Netherlands. The Delta Program contains plans to protect the Netherlands from floods in the future. Part of the Delta program includes the safety standards for dikes to ensure that the area behind them is protected against flooding (Rijksoverheid, n.d.). These safety standards are included in the Legal Assessment Instrumentation (WBI2017). New safety standards for dikes have been in place since 2017, which consider a full probabilistic approach. The Legal Assessment Instrumentation contains the following appendices:

- Appendix 1: Procedure for assessing the safety of primary flood defences; this outlines the procedure that must be followed for the assessment and describes the reporting obligations.
- Appendix 2: Hydraulic loads; this section describes the method used to determine the hydraulic loads on the primary flood defences.
- Appendix 3: Strength and safety; this section describes the method by which the primary flood defences must be assessed to arrive at a judgement regarding the safety of the entire dike defence system

Failure probability requirements have been established for the various dike segments to ensure the Netherlands remains well protected. These depend on the possible societal and economic damage in the event of a dike breach. The lower limit failure probability for the various dike segments can be seen in Figure 3.1.

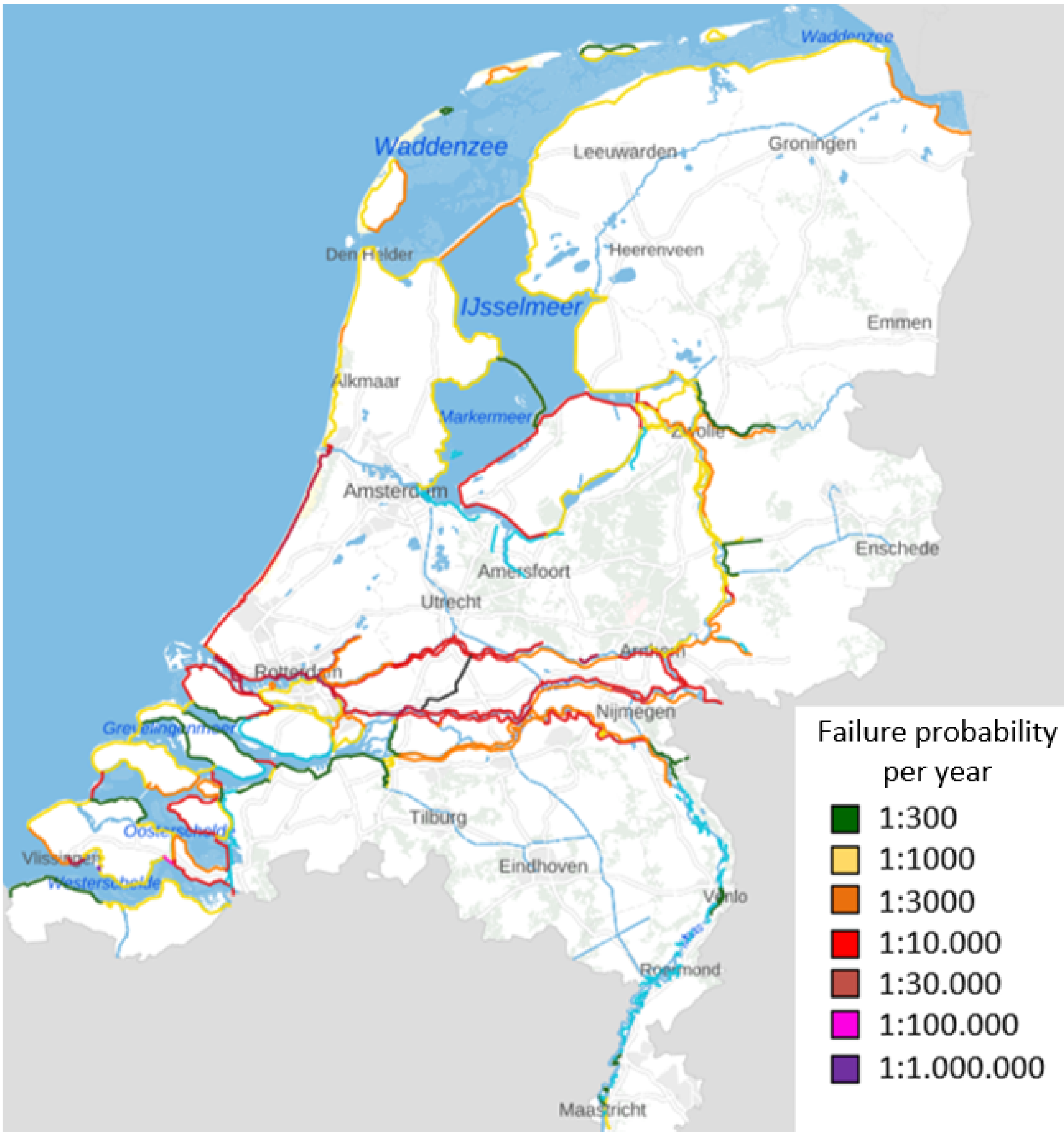


Figure 3.1: Lower limit failure probability dike segments (Waterveiligheidsportaal, 2022)

The permissible flooding probability (de norm) of a dike segment is distributed across the failure mechanisms using a prescribed failure probability distribution (Faalkansbegroting). The available failure probability space of a failure mechanism is indicated by a failure probability contribution factor ω. The safety assessment of the primary flood defences involves various failure mechanisms, which can be seen in Figure 3.2 with their corresponding failure probability contribution. This means that for each failure mechanism individually, the probability must be less than the failure probability of the dike section. An assumption is that all failure mechanisms occur independently, which is not always the case in reality (Diermanse, 2016a).

Failure mechanisms	Dunes	Dikes and dams
Height of structure (HTKW) or grass revetment erosion crest and inner embankment (GEKB)	0	0,24
Piping (STPH)	0	0,24
Macro stability inwards (STBI)	0	0,04
Grass erosion outward slope (GEBU)	0	0,05
Other coverings outer embankment	0	0,05
Reliability closure of flood defence (BSKW)	0	0,04
Piping at flood defence (PKW)	0	0,02
Strength and stability of flood defence (STKWp)	0	0,02
Dune turn-off (DA)	0,70	0
Other failure mechanisms	0,30	0,30

Figure 3.2: Failure mechanisms (Ministerie van Infrastructuur en Milieu, 2017)

Many uncertainties exist when assessing primary flood defences. For this reason, the Dutch standards of flood defences are expressed in terms of failure probabilities. The actual failure probability must be smaller than this standard. Otherwise, the flood defence will be rejected. Probabilistic calculations are carried out to determine this actual failure probability. These calculations can range from fully probabilistic to semi-probabilistic. When performing a probabilistic calculation, the results can be checked against the governing safety standards, where the following has to apply:

$$Failure \quad probability \quad dike \quad \leq \quad safety \quad standard \tag{3.1}$$

The failure probability requirement per failure mechanism for each dike segment is equal to $\omega \cdot P_{eis}$.

With:

P_{eis} The permissible flooding probability of the dike segment [1/year]
ω Failure probability contribution factor

Dike segments consist of multiple dikes sections (dijkvakken). Dike sections are not independent of each other. Each failure mechanism is distributed across the corresponding sections by considering a length-effect. Therefore, a failure probability requirement per section can be derived for each failure mechanism using the length-effect. The length-effect is determined by the variability within a dike section. For failure mechanisms with a large length-effect, the requirement per dike section is much stricter than the requirement per dike segment. For failure mechanisms with a small length-effect, this is smaller (Diermanse, 2016a). The failure probability requirement per dike section is derived as follows:

$$P_{eis;dsn} = \frac{\omega \cdot P_{eis}}{N_{dsn}} \tag{3.2}$$

With:

$P_{eis;dsn}$ Failure probability requirement per dike section
P_{eis} The permissible flooding probability of the dike segment
ω Failure probability contribution factor
N_{dsn} length effect factor of the dike section

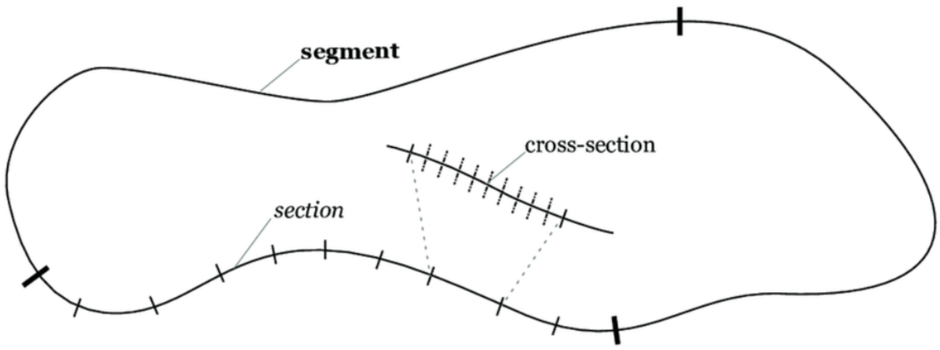


Figure 3.3: Dike segments with its sections (Van der Krogt, 2022)

In Figure 3.4 the probability distribution can be seen for a dike segment with a failure probability of 1/1000 per year.

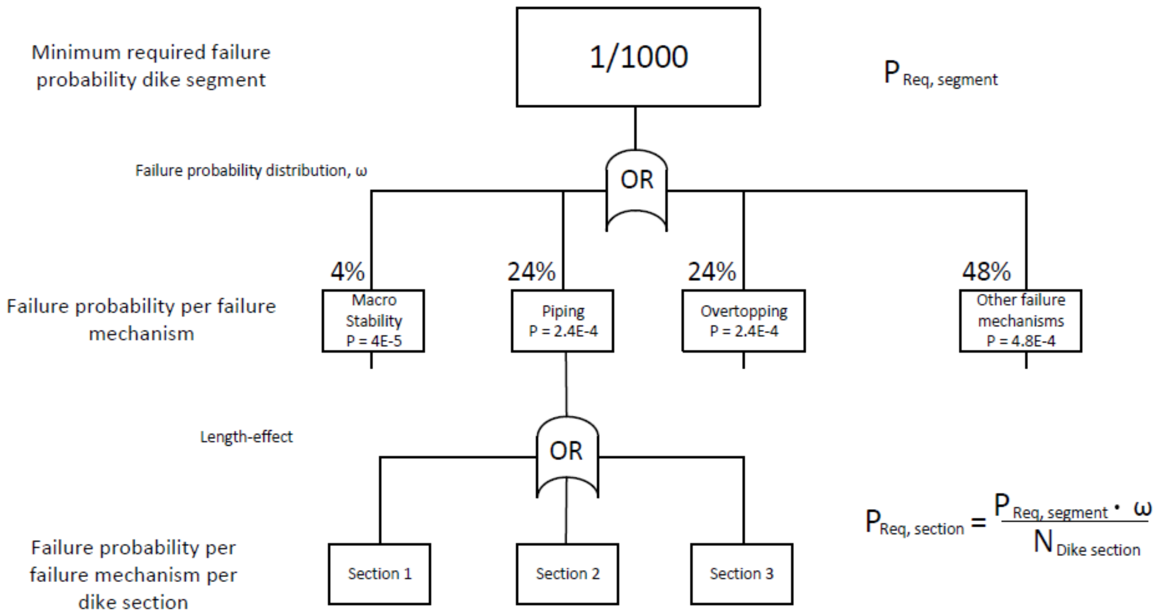


Figure 3.4: Probability distribution for target failure probability of 1/1000 for a dike segment

The length-effect refers to the spatial correlation of various variables. An example of this is the water level, where the spatial correlation is significant. For a water level, it holds that it is approximately the same along a dike section for the entire dike section. The greater the spatial correlation, the smaller the length effect. The length-effect factor can be calculated with the following formula:

$$N = \frac{1 + a \cdot L}{b} \tag{3.3}$$

in which:

N [-]	Length-effect factor of the cross-section
L [m]	Length of the dike section
a [-]	Fraction of the trajectory length that is sensitive to the considered failure mechanism
b [m]	Length measure that indicates the magnitude of the length-effect within the sensitive length of the failure mechanism

For failure mechanisms where the length effect is small, this means that the failure probability requirement at section level will differ relatively little from the failure probability requirement at the dike segment level. For failure mechanisms with a relatively large length effect, this difference will result in a relatively strict failure probability requirement at the dike section level.

3.2. Multifunctional use of dikes

The water boards and Rijkswaterstaat have observed a growing demand for multifunctional use of dikes (Royal HaskoningDHV, 2022). When considering this multifunctional use of the dike, a careful balance must be struck between the different interests and the possible consequences. The multifunctional use of dikes can have various effects on the current and future flood safety situation. These effects can be categorized into three groups (Royal HaskoningDHV, 2022):

- Water retaining capacity: In general, the constructed buildings should not influence the height and stability of the dike. The water-retaining function of the dike must always be ensured.
- Expandability: To ensure flood safety in the future, it is important that sufficient space is available to implement dike reinforcement measures.
- Management and maintenance: This refers to the activities aimed at ensuring the quality of the dike. Dike maintenance should be able to be carried out in an effective and efficient manner.

To ensure that these points can be guaranteed, legislation is in place. The Environmental Act (national level) and the Water Board Regulations (regional level) are important for this purpose.

3.3. Legal possibilities regarding building near dikes

The legal possibilities regarding buildings near dikes can be found in the Environmental Act and the Water board Regulations of the water boards. An overview of the most relevant rules can be seen in this section.

3.3.1. Environmental act

The rules governing the primary flood defences in the management of Rijkswaterstaat are described in the Environmental Act. The Environmental Act is, among other things, aimed at preventing and, where necessary, limiting floods.

In the "Framework for Shared Use of Flood Defenses," various rules are outlined regarding the multifunctional use of a dike. In section 5.2.2, the conditions for granting permits for construction are included. If these conditions are met, there is no objection from a flood safety perspective to granting the permit for the shared use of the flood defence. If any of these conditions are not met, it must be demonstrated through a quantitative approach that the shared use does not affect the dike. These conditions are subdivided into spatial and structural requirements (Royal HaskoningDHV, 2022).

Spatial requirements

1. Buildings (including the lower foundation beam) may not intersect the profile of free space.
2. If the physically present profile exceeds that of the profile of free space, then the construction must be placed above the physically present ground level, except for the foundation. The lower foundation beam may be installed at the usual depth of up to 1.00 m below the physically present ground level.
3. The construction may not be placed in the crest or the (future) slope of the structure. Additionally, the construction must be placed at a minimum distance of 5.00 m from the (toe)line of the inner and/or outer slope
4. No other shared use of the flood defence is allowed within the building's footprint and influence zone.

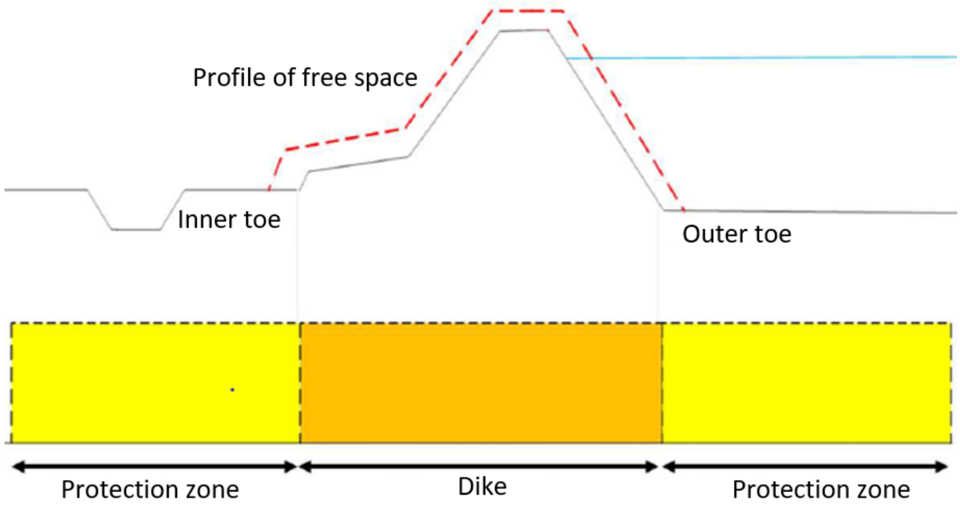


Figure 3.5: profile of free space (Rijkswaterstaat, 2019)

Structural requirements

1. The creation and realization of hollow spaces resulting from the construction (e.g., crawl spaces) and execution (e.g., material and method of installing foundation piles) are not permitted.
2. If settlements of the flood defence are expected or occur as a result of the activities, appropriate measures must be taken.

If it is not possible to meet the conditions mentioned above, then the permit application must demonstrate in an additional approach that buildings will not affect the safety of the dike.

3.3.2. Water board regulations

Most dikes are managed by the water boards. The rules and regulations regarding dikes are described in the Water Board Regulation. The Water Board Regulation contains all the rules about the physical environment that the water board sets within its management area. It also describes the rules that the water boards use to protect flood defences and preventing dikes and banks from being damaged. The Water Board Regulation came into effect on January 1, 2024, replacing the former by-law (Keur). Water boards have until 2026 to complete the Water Board Regulation, so in some water boards, the by-law is still in place. Furthermore, the 'Legger' specifies maintenance obligations and designates who is responsible for those obligations. The 'Legger' also includes information about the location, shape, dimensions, and construction of hydraulic structures (Van der Sommen, 2021). The scope has determined a focus on the following water boards:

- Rivierenland
- Schieland en Krimpenerwaard
- Delfland
- Hollandse Delta

It is described what the various water boards allow according to their Water Board Regulation regarding building near dikes.

Rivierenland
In Section 6.11.1 of the Water Board Regulation of Rivierenland, it is described that the rules are aimed at "preventing and, where necessary, limiting floods, waterlogging, and water scarcity and their consequences." Article 6.11.1 further outlines the following objectives for flood defences when building near it (Waterschap Rivierenland, 2022):

- Ensuring the proper condition and functioning of the flood defence

- Ensuring the possibility of effective inspection of the condition of the flood defence
- Maintaining the flood protection capacity of the flood defence at socially acceptable costs.

To build in water board Rivierenland, an environmental permit is always required unless otherwise indicated in specific cases.

Also, a policy rule regarding building near dikes is present. It concerns policy rule 5.18a, "Structures in and on a primary flood defence and its associated protection zone." This policy rule aims to protect the function of flood defences as part of the overall flood protection system. Water board Rivierenland generally does not permit new permanent structures in a dike. The reason for this is that in the future this space could be crucial for performing possible reinforcements (Waterschap Rivierenland, n.d.).

As mentioned in Chapter 2, Rivierenland uses jackable houses in some places. These houses can be raised when a dike needs reinforcement, and the space that the house occupies is needed. Rivierenland saw much potential at the time, but now they are more cautious. This is because, at that time, mainly from a technical perspective, the possibilities were taken into account. Jacking up a house can have significant costs. It costs around €100,000 to jack up a house (Personal communication, 2024). When multiple houses exist next to a dike, these costs can increase significantly during a dike raising. It is also unclear who should bear the cost of any damage that may occur to a house due to jacking it up. Jacking up houses has never been done before, so the consequences are still unknown.

Existing homes may be expanded within the profile of free space by $100m^3$ in Waterschap Rivierenland (Personal communication, 2024). This is because many dike houses were built in the past and are relatively small, making it difficult to live comfortably in them. They are not allowed to expand too much because their value could increase much. This could cost the water board much money if the house would ever have to be bought out when this space is needed. It is also possible to build small sheds and other works that are not capital-intensive.

Schieland en Krimpenerwaard
Section 6.8 of the Water Board Regulation for Schieland and Krimpenerwaard aims to protect hydraulic structures, including the importance of their future expansion, and ensure their efficient operation for water retention, water storage, and water management.

Article 6.48.1 states: "The construction of a building or the modification of the surface area, basement, foundation, or floor level of a building within the restriction area of a flood defence is prohibited without an environmental permit."

In the policy regulations for primary flood defences of the water board, further details are provided regarding construction near dikes (Hoogheemraadschap van Schieland en Krimpenerwaard, 2019). Policy rule 5.2 mentions that a residence, commercial space, or other construction can increase the risk of flooding in various ways. Furthermore, the policy regulation states that each permit application is assessed individually. The following principles are applied in this assessment.

- We accept the current building intensity as a given
- We do not allow additional construction within the profile of free space
- Rebuilding of structures primarily occurs outside the profile of free space
- Only when not feasible, rebuilding within the profile of free space is possible under certain conditions.

Hollandse Delta
In the water board regulation of Hollandse Delta, Article 2.123.1 states: "It is prohibited to place, modify, replace, remove, or maintain works within the profile of free space of a hydraulic structure without an environmental permit." No substantive changes were made with the transition from the 'Keur' to the water board regulation in this water board (Waterschap Hollandse Delta, 2024).

Delfland
Article 4.1: Designation of Restricted Area Activities states: It is prohibited to carry out the following restricted area activities without an environmental permit:

- Utilizing a hydraulic structure or its associated protection zones for purposes other than their intended function, and performing, holding works on, above, over, under, or within them, leaving fixed substances or objects standing, lying, or altering or maintaining the water level to a different level than established in the water level decree (peilwaterbesluit) (Waterschap Delfland, 2024).

Article 4.4: Assessment rules for flood defences and supporting structures states: in the assessment of an application for an environmental permit for a restricted area activity within, on, above, or below a flood defence, its associated protection zones, or associated profile of free space, or associated supporting structures, the following considerations are taken into account (Waterschap Delfland, 2024):

- The flood protection capacity of the flood defence must not deteriorate
- Compliance with the standards or environmental values applicable to the respective flood defence must not be hindered
- Ensuring future compliance with the standards or environmental values applicable to the respective flood defence must not be hindered if the flood defence does not yet meet the applicable standard or environmental value.
- Maintenance, inspection, and monitoring of the flood defence must remain feasible
- The functioning of other hydraulic structures must not be hindered.

Conclusion
Everything summarized, there aren't many possibilities for building near dikes in all water boards. Additionally, an environmental permit is always required, but it won't be granted if construction takes place within the profile of free space, especially when it is new construction. It is emphasized that the profile of free space exists to enable future dike reinforcements, and anything built there could hinder future reinforcements. This conclusion is the same for every water board according to the water board regulations. To gain more clarity, interviews have been conducted with the water boards Hoogheemraadschap Schieland en Krimpenerwaard and Rivierenland.

3.4. Interviews conducted with the water boards

3.4.1. Objective of the interviews

The purpose of the interviews with the water boards was to discover the possibilities with regard to existing construction and temporary construction near dikes. It has also been asked what the objections are to deriving the strength of the dike from a house. After all objections were properly mapped out, solutions have been suggested. Furthermore, a question was asked about how existing construction near dikes is dealt with. Discussions at Rivierenland were held with individuals with the following positions: Policy advisor, consultant flood defences, specialist flood defences and specialist regional flood defences. Furthermore, a discussion was held with a technical manager at Hoogheemraadschap Schieland en Krimpenerwaard. The following sections contain the results of those interviews.

3.4.2. Results of the interviews

Temporary housing
Permanent new construction is not possible within the profile of free space. This is because this profile must be free for future dike reinforcements. This led to the idea of temporary construction. Temporary construction is defined as construction that only lasts until the next dike reinforcement. So, when the dike needs to be reinforced the house would be demolished. This way, future dike reinforcements will not be hindered, and something can be done about the current housing shortage.

This possibility has been discussed with Water Board Rivierenland. They note that challenging building locations such as near dikes are increasingly being considered for construction due to the high demand for housing. They note some difficulties that could be present, like if a dike needs to be reinforced earlier. Then the people living there unexpectedly have to leave their homes. This can lead to much resistance. Another argument against allowing it is that the housing shortage could remain just as big when the dike needs to be heightened and the temporary construction needs to be removed. Then these people have no place to go and they cannot be put on the street if there is no alternative place for them to go.

Objections to multifunctional use of a dike

The objections among the water boards regarding building near dikes have been identified through interviews with the water boards and the water board regulations. The water board regulations mention the expandability of the dike as the primary objection against building near the dike. Furthermore, there are difficulties concerning responsibility for the management and maintenance of the multifunctional elements. Should the water board or the house owner be responsible? When a basement wall has a water retaining function, it can be difficult to determine when it is damaged and when maintenance is needed. Other difficulties and objections are mentioned below (Voorendt, 2013).

- Different laws and construction codes apply for both the dike and the structure
- Agreements on responsibilities and finance are not standard.
- The design life time can vary per function. As a result, water boards are reluctant to derive strength from buildings because it cannot always be guaranteed that the house will remain in its place in the future.
- The safety level of the flood defence function can change over time. The multifunctional use can complicate the expandability of the dike when this is the case.
- For each situation a customized approach is needed. This takes much time and therefore will cost much money

In conversation with Rivierenland, it has been found that the main objections are the management and maintenance of the multifunctional parts of the house that serve a water-retaining function. In Rivierenland the dike is inspected regularly, and when houses near dikes are multifunctional, the multifunctional parts also need to be checked regularly. In these situations, it is required to come into people's homes to conduct these inspections. This can take very much time. While this is feasible for a few specific cases, it becomes unfeasible when it applies to many houses. To make this possible, more dike managers would be needed, but the water board does not have the funds for it. Ultimately, money is often thus the biggest issue.

Possibilities for building close to a dike

As the various water board regulations have shown, almost nothing is possible regarding permanent construction in the profile of free space. However, this does not necessarily mean that construction must always take place X meters from the toe of the dike. For example, it is possible to build above the profile of free space. This has already been done in some locations in Rivierenland. Examples of how a house can be above the profile of free space can be seen in Figure 3.6 and Figure 3.7.

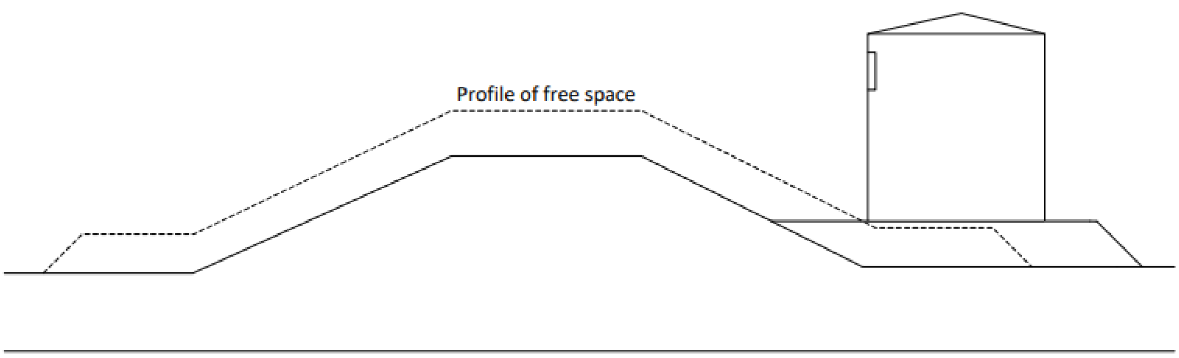


Figure 3.6: House just above the profile of free space

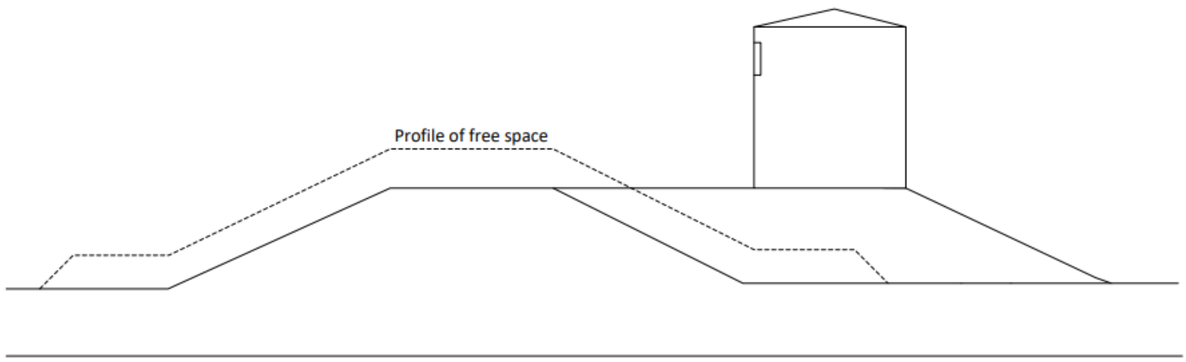


Figure 3.7: House at crest level of the dike

In both situations, no strength of the house would have to be derived to the dike and a gap at the location of the house could still be assumed. As can be seen, the house is still close to the dike but allows for future dike reinforcements, as it is outside the profile of free space. In Figure 3.6, the foundation does cross the profile of free space, which is allowed. It should be examined if the pile foundation itself does not deform, but when considering only the functionality of the dike, there are no objections to these buildings. This method of construction is a good option on sandy soil. In peat areas, this can cause problems for the pile foundations (Personal communication, 2024). For macro stability, the pile foundation would only have a strengthening effect because it could cut through the possible slip circle. For piping, however, it can shorten or extend the piping length depending on the type of foundation. It must be determined for each dike whether this could cause a problem. A solution to piping can be a piping screen placed at the front of the foundation.

3.4.3. Solutions for monitoring of multifunctional flood defenses

To simplify the monitoring of dikes with houses from which strength is derived, various possibilities have been considered. This has been discussed with people from the waterboard of Rivierenland. Solutions were considered that cost little time and money but are still reasonably accurate. The following ideas were conceived:

- **Sensors**: Sensors could measure cracks which could notice when a wall's condition deteriorates or cracks appear.
- **Help of the residents**: Through help from residents, it is possible to ensure that dike managers no longer need to visit the dikes. This can be done by having the residents take a picture of their wall that is part of the flood defence regularly. These pictures only have to be checked after that. This could even be done with Artificial Intelligence, which would eliminate the need for dike managers to check the multifunctional walls. When the water level is high, it could be asked to send an extra picture. This ensures that checks can also be made at critical moments. By implementing this measure, the workload for dike managers is not increased, but it still takes time to implement such a system. Managing this data will also be a huge process. However, Rivierenland sees much potential in this approach (Personal communication, 2024).
- **Geo beats**: Geo beats are beads embedded in the ground. These beads are spaced at specific distances from each other. When this distance changes, it is detected which indicates ground movement. This method allows for the detection of small ground shifts that are associated with the deterioration of the building's condition.

3.5. Conclusion

The main objection of water boards for deriving strength from buildings to the dike is the management aspect. This would require much more inspection by dike managers and means that more dike managers would need to be hired, which would significantly increase costs, and this money is not available. Solutions such as having people send in photos themselves have been proposed to simplify the management. Potential is seen in this approach. The following deepening question summarises what is allowed regarding building near dikes.

Deepening question: "What are the legal possibilities regarding construction near dikes?"

The possibilities for building near dikes are prescribed in the water board regulations, previously known as the by-law (Keur). Although the water board regulations vary for each water board, the rules regarding building near dikes are consistent.

Permanent construction
Dikes maintain the profile of free space to allow for future dike reinforcements. Regarding permanent construction near dikes, there is little to no possibility for building within the profile of free space. In some cases, rebuilding a structure is possible, but only under strict conditions.

However, there are possibilities outside the profile of free space. This does not necessarily mean that buildings have to be far from the dike. Construction is allowed above the profile of free space. This requires adding extra soil to the toe of the dike so that the house itself is above the profile of free space. The dike is essentially being over dimensioned. An example of possible situations can be seen in Figure 3.8 and Figure 3.9. Only the foundation cuts through the profile of free space, which is permissible.

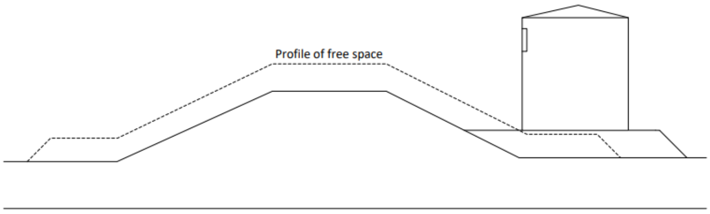


Figure 3.8: House just above the profile of free space

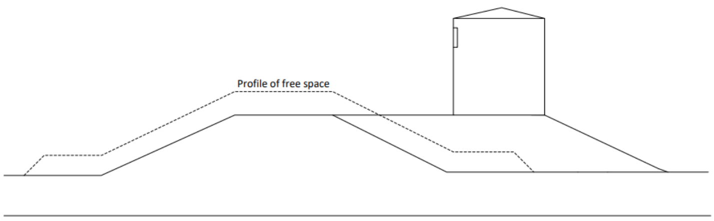


Figure 3.9: House at crest level

Temporary construction
Temporary construction is also not seen as a realistic option. With temporary construction, buildings that exist until the next dike reinforcement are meant. The issue is that temporary construction often becomes permanent, which will cost the water boards much money in the end. One concern is the current housing shortage, which might still be an issue when the dike reinforcement needs to take place. You cannot simply evict these people. The expectation is that there will be significant resistance to this, and to prevent such issues, temporary construction is not allowed.

4

Inventory of the relevant failure mechanisms of multifunctional dikes

Step 2 of the main methodology

In this chapter, the failure mechanisms that a house could additionally influence are determined. First, an overview of all the dike failure mechanisms is given. Subsequently, the influence of an object on the failure mechanisms is discussed.

4.1. Inventory of the failure mechanisms

4.1.1. Dike failure mechanisms without objects

A dike can fail because of multiple failure mechanisms, as shown in Figure 4.1. The total failure probability distribution (faalkansbegroting) in Chapter 3 shows which failure mechanisms are considered the most dominant.

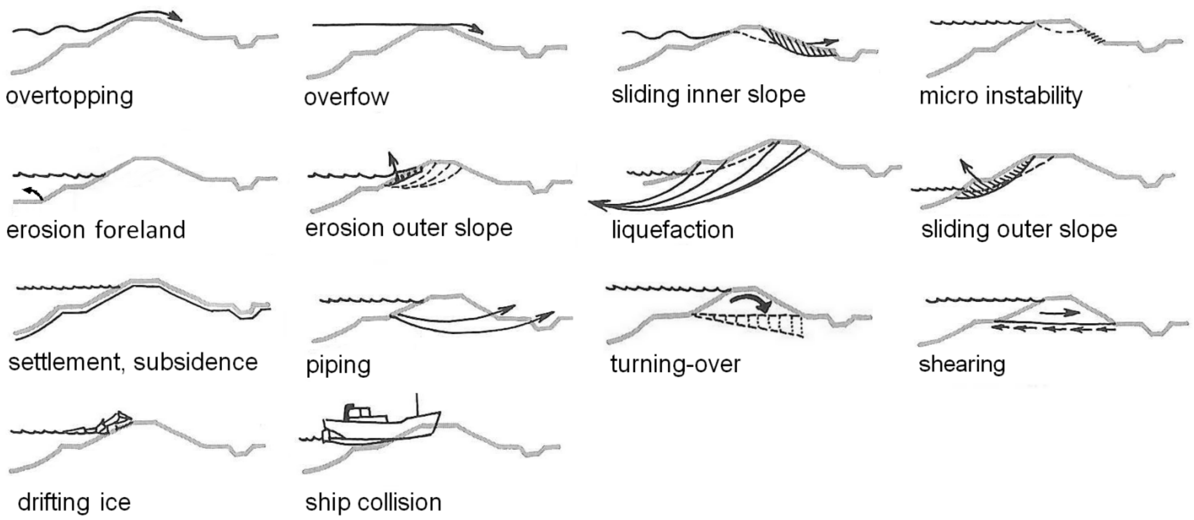


Figure 4.1: Failure mechanisms (Rijkswaterstaat, 1987)

4.1.2. Failure mechanisms including water retaining objects

The failure mechanisms that involve buildings can be seen in Figure 4.2. For the situations that have been considered, the building is on the crest or behind the dike, so when the building fails, it does not immediately mean that the dike has lost its water-retaining capacity. In the next chapter, the situation is taken into account when the structure has lost its stability or is no longer in its place.

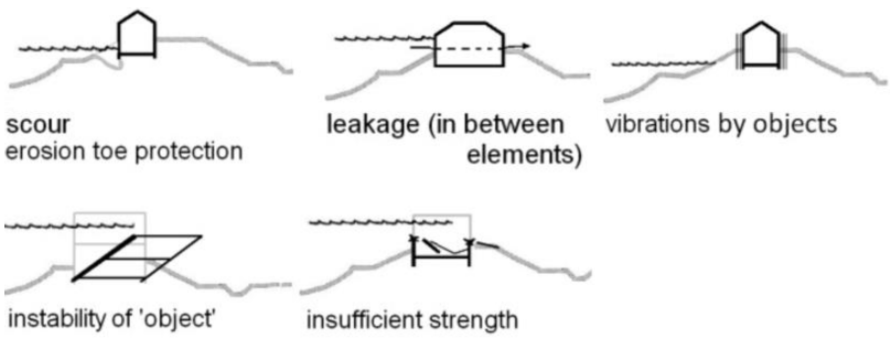


Figure 4.2: Building failure mechanisms (Voorendt, 2013)

4.1.3. Failure mechanisms due to buildings

When a house is built in the cross-section of a dike, this can lead to additional failure mechanisms of the dike. The following situations have been identified for this risk, which could potentially lead to failure of the dike.

- Gas explosion
- Pipeline rupture
- Erosion pit next to the building

When the strength of the dike would be derived from the house, the following failure mechanisms could also cause the dike to collapse:

- Building collapse
- Building demolished

These situations will be further elaborated and quantified in Chapter 5.

4.2. The influence of objects on the failure mechanisms per location

A hypothetical situation is created to determine the influence of buildings on the total failure probability of the dike.

4.2.1. Situation description

For the situation description, rough assumptions were made. Common positions of the house have been selected, and it has been examined whether the location of the construction on a dike correlates with the soil type of the dike. Most dikes consist of clay because it is an impermeable material. Therefore, a clay dike was chosen with a sand soil underneath it. The geometry of the dike can be seen in Figure 4.3.

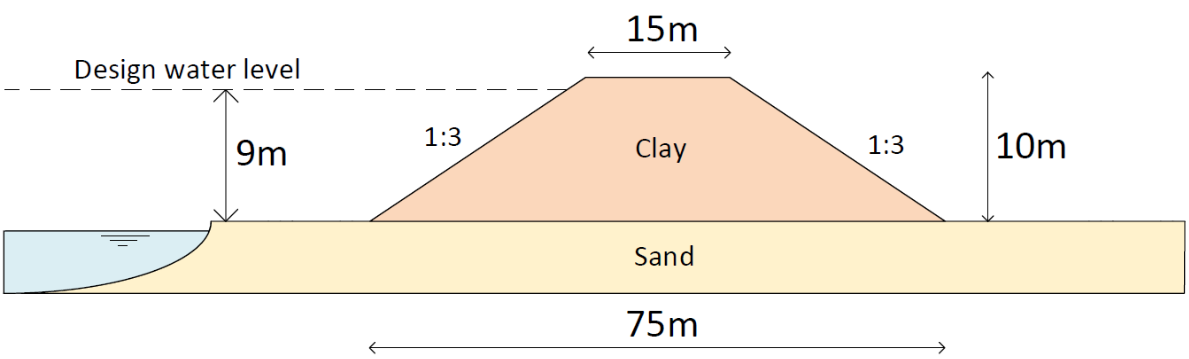


Figure 4.3: Dike geometry (not to scale)

The various locations that were considered are shown in Figure 4.4.

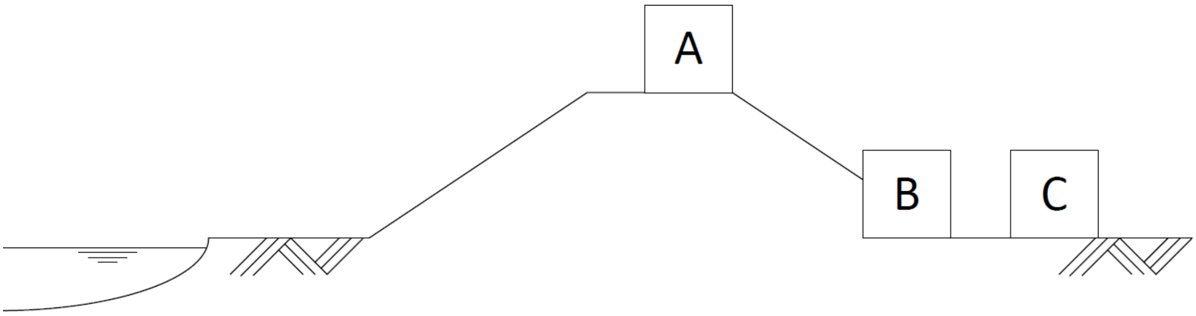


Figure 4.4: Possible house locations

For these three locations, three scenarios were considered: the scenario with no structure (a gap), the scenario with a shallow foundation, and the scenario with a foundation on piles. This results in nine scenarios. These situations can be seen in Figure 4.5.

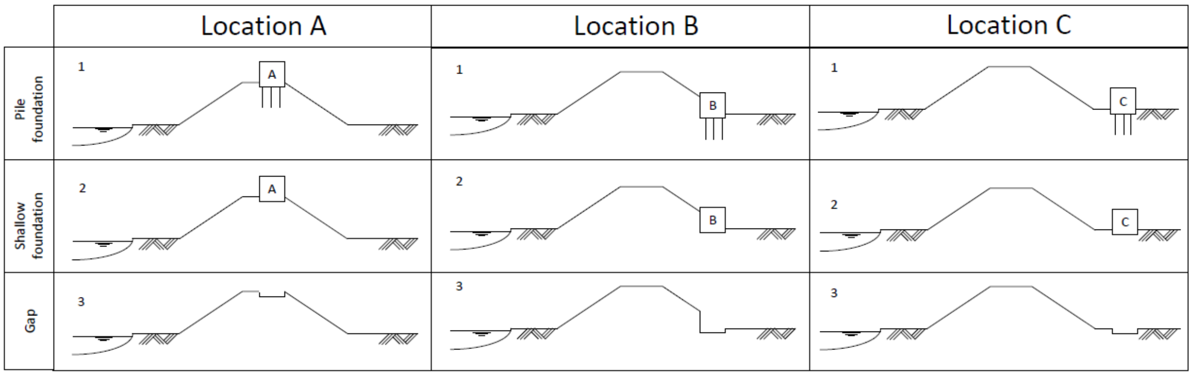


Figure 4.5: Nine scenarios

4.2.2. Analysis of the failure mechanisms that are influenced by the presence of an object

The failure mechanisms to consider for the three situations have been determined per location. The various situations have been compared with the situation where no construction or excavation is present, so just a plain dike, which can be seen in Figure 4.6. If it is stated that the structure has a positive influence on a failure mechanism, the failure probability decreases, and if it is mentioned that construction has a negative effect on the failure probability, the failure probability increases. The influence on the failure mechanisms has been based on the report of Voorendt (2013).

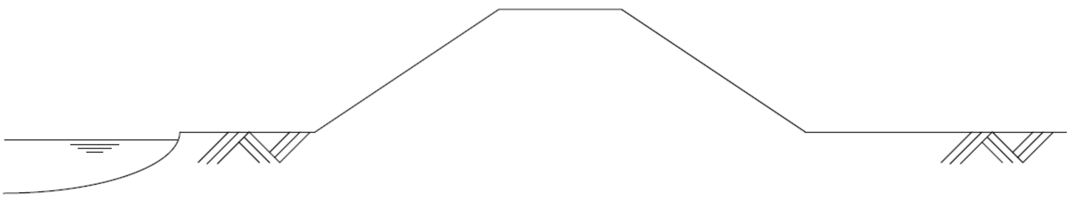


Figure 4.6: Dike without building

Location A

For location A, the following three situations have been distinguished. Figure 4.7 indicates which failure mechanisms are influenced by the object.

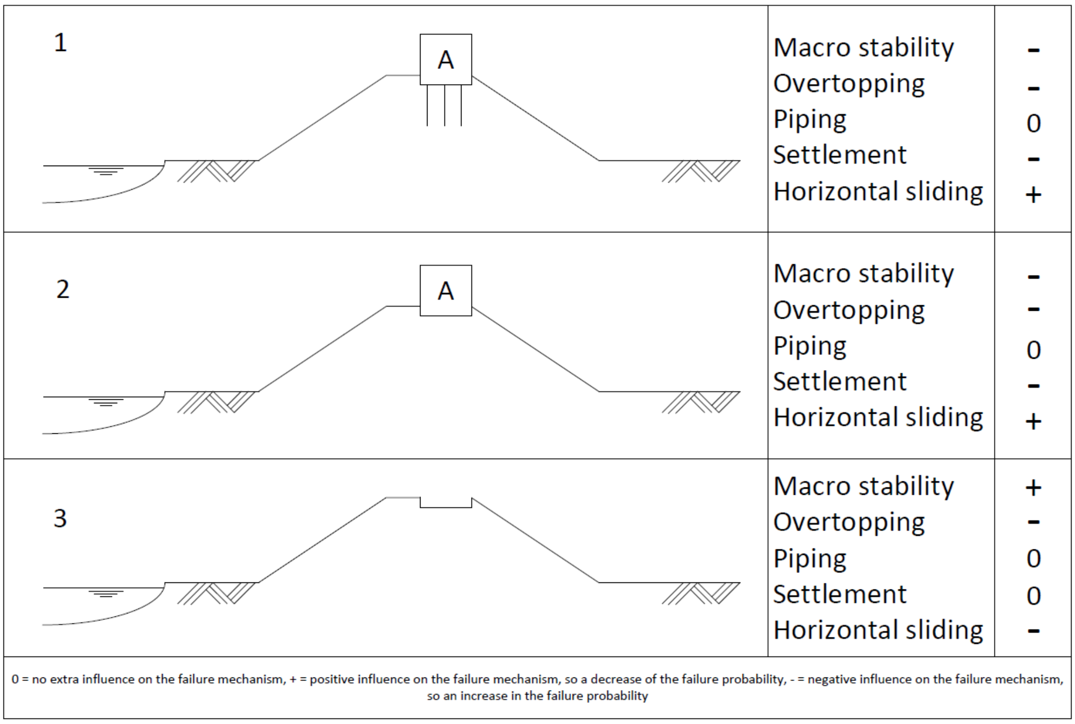


Figure 4.7: Location A

Macro stability inner slope

The failure mechanism macro stability is negatively influenced because the weight of the house negatively affects the moment equilibrium. In the scenario with a pile foundation, the piles cross the sliding surface, which has a positive effect. Furthermore, the scenario without any structure has close to no influence on the failure mechanism.

Overtopping

The situation with a house on the dike could influence the allowable amount of overtopping. The overtopping requirement prescribed for a grass-covered dike is 1-10 l/s/m (Eurotop, 2017). Due to the transitions between the house and the dike, which are more susceptible to erosion, a stricter overtopping requirement of 1 l/s/m is imposed. The third situation where a gap is assumed at the location of a house could also be extra susceptible to erosion and an allowable overtopping requirement of 1 l/s/m is also assumed for this situation.

Settlement

In situations 1 and 2, in which a house is located on the dike, settlements can occur, causing the dike's height to decrease locally, thus negatively affecting the dike. The third situation has a slightly positive influence on the settlement of the dike because weight has been removed from the dike. The impact of this is presumed to be so small that it is neglected.

Horizontal sliding

The weight of the houses adds extra weight to the dike, making it less prone to sliding. The third situation has a slight negative effect, but because only a 1 meter gap is assumed for the excavation, it is expected to not play a significant role.

Location B

For location B, the following three situations can be distinguished. Figure 4.8 indicates which failure mechanisms are influenced by the object.

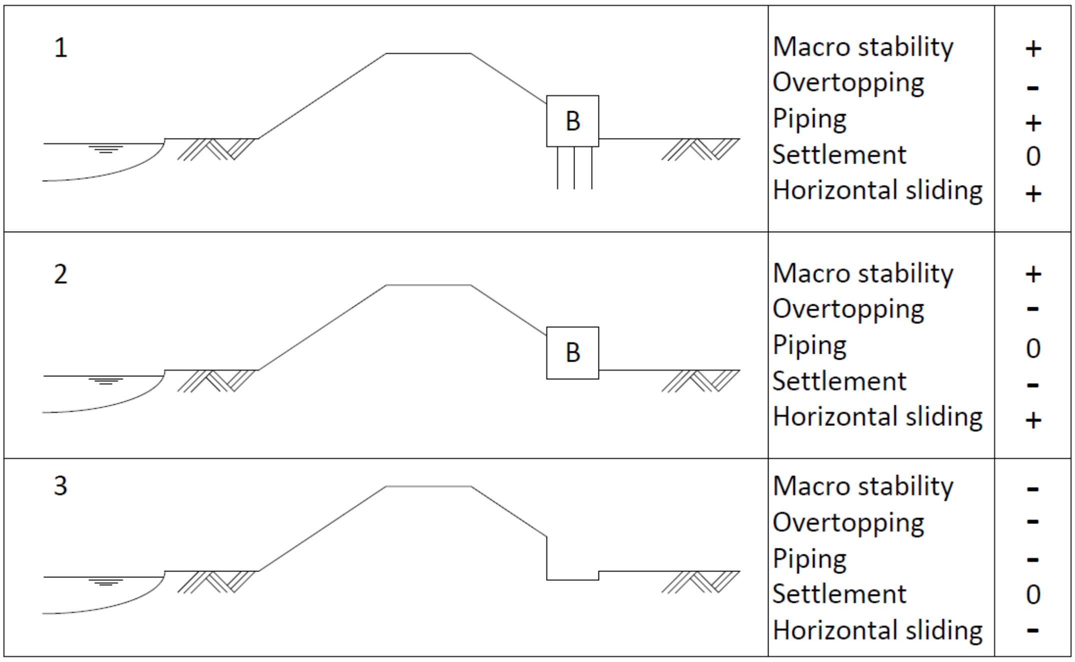


Figure 4.8: Location B

Macro stability inner slope

In this situation, the house is built at the bottom of the slope of the dike. This creates a counteracting moment for the sliding soil layer, thus positively affecting the macro stability failure mechanism. In situation 1, the piles intersect the location of the sliding surface. This also has a positive effect on macro stability. The third situation, where the house is absent, has a negative impact on macro stability because there is a missing section of the dike that previously provided a counteracting moment.

Piping

The construction affects the piping path, making it longer, so the structure positively influences piping. The third situation results in a shorter piping length due to a gap in the dike, which shortens the piping path.

Overtopping

The overtopping requirement is for all situations the same because of the serviceability limit state of 1 l/s/m, which does not damage the dike. In situation 3 this is the case because of the irregularities in the dike profile.

Location C

For location C, the following three situations can be distinguished. Figure 4.9 indicates which failure mechanisms are influenced by the object.

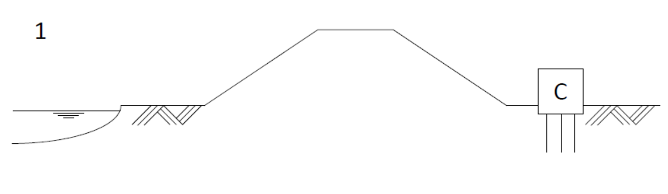
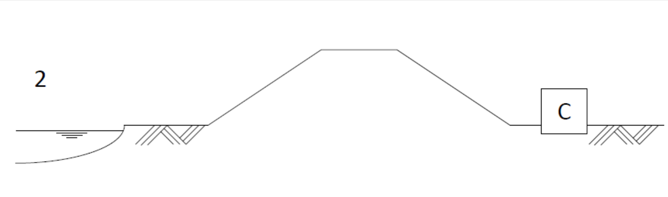
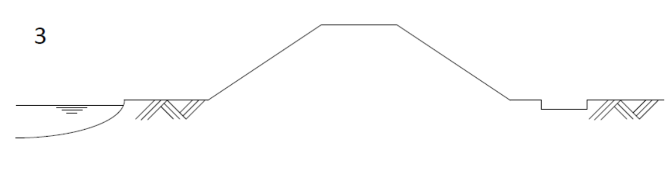
	Macro stability Overtopping Piping Settlement Horizontal sliding	+ - 0 0 0
	Macro stability Overtopping Piping Settlement Horizontal sliding	+ - 0 0 0
	Macro stability Overtopping Piping Settlement Horizontal sliding	- - 0 0 0

Figure 4.9: Location C

Macro stability inner slope

The house counteracts the moment of the ground around the slip circle, thereby positively affecting the inner slope macro stability of the dike. The piles in the ground provide even better resistance against macro stability. The third situation has a negative effect on the macro stability failure mechanism because a portion of the weight is missing.

Overtopping

For overtopping, the same requirement of 1 l/s/m applies as in previous locations. This makes this requirement stricter than when no house would be present.

4.2.3. General description of the failure mechanisms influenced by NWOs

The failure mechanisms that are influenced in one or more of the scenarios by the structure have been described in this section. It is also shown how they influence the failure mechanisms.

Macro Stability inner slope, without object

Macro stability inner slope is the sliding of the inner slope of a dike. It can occur during high water when the dike is saturated and, therefore, lacks sufficient shear resistance. This will create a circular sliding plane on the inner slope of the dike. This happens because gravity and external forces create a moment that the soil can no longer withstand with its own weight and shear resistance. This can be seen in Figure 4.10.

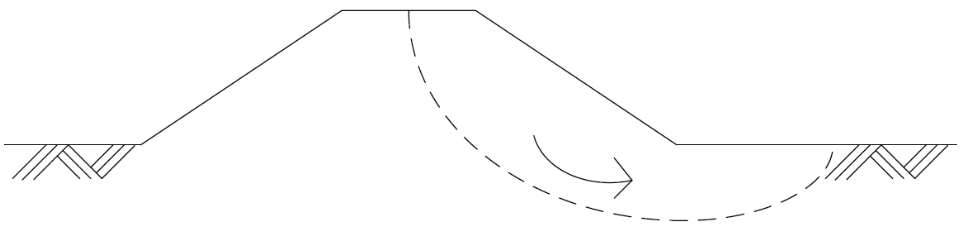


Figure 4.10: Macro stability

Macro stability typically occurs during high water levels. This causes water pressures to increase within the dike body, resulting in a crack in the dike. Consequently, there is increasing subsidence on the landward side of the crack, leading to the loss of stability. This prompts further adjustments to the remaining profile, causing the breach to widen, ultimately resulting in dike failure ('t Hart, 2018). This can be observed in Figure 4.11.

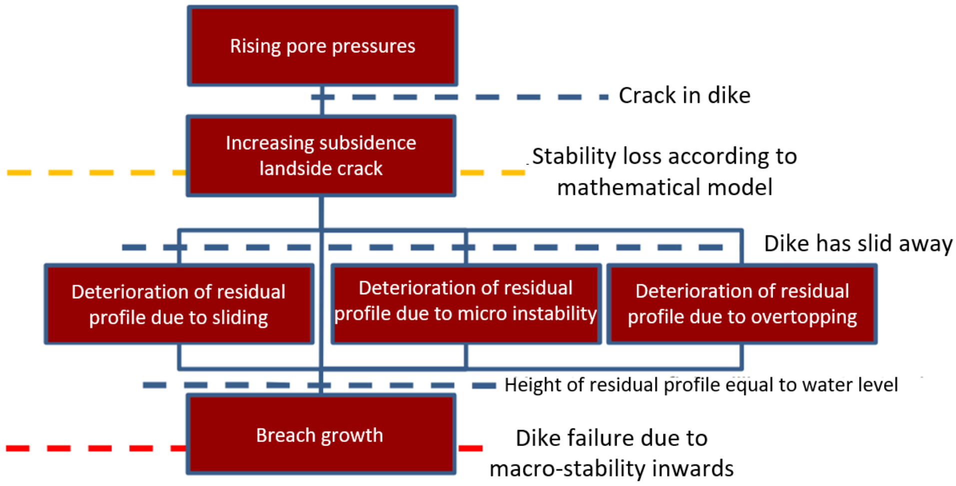


Figure 4.11: Stages of macro stability (?, ?)

Macro stability inner slope, with object

For calculating the factor of safety for macro stability, the sum of the moments of the resisting forces is divided by the sum of the moments of the active forces working around the middle point. When a house is built on the crest, it works favourably for the active moment and thus has a negative influence on the failure mechanisms. If a house is built after the dike, it works as a resisting moment against the soil and thus has a positive influence on macro stability. Damages to the house do not affect the influence that the house provides on macro stability. Even if the entire house were to collapse but remains present at the same location, it still contributes to macro stability because the weight of the house is still present at that location. However, if the house is removed from the location, it can no longer contribute to the stability of the dike.

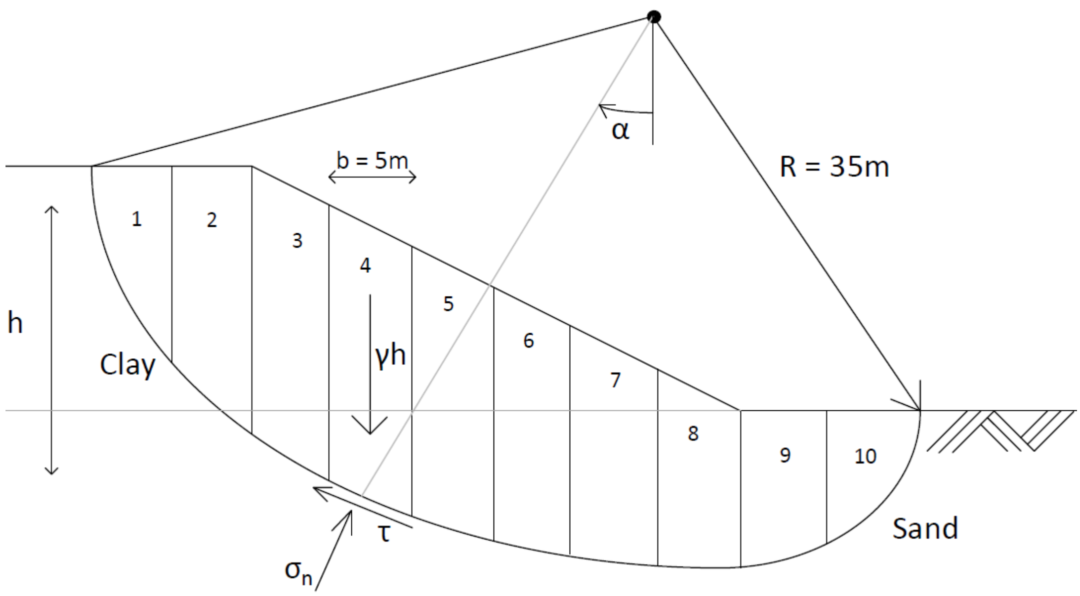


Figure 4.12: Stability calculation using Fellenius

$$F = \frac{\sum M_R}{\sum M_A} \tag{4.1}$$

Piping, without object
Piping is a failure mechanism that can occur to various hydraulic structures. Piping is caused by the difference in water level in front of and behind the dike. This difference in water level creates significant pressure variations in the dike, allowing water to flow under the dike and emerge behind it. The amount of flow depends on the difference in water level on both sides of the dike, the dimensions of the dike, and its permeability. The primary factors for piping are the properties of the sand layer (Förster, Ham, Van der Calle, & Kruse, 2012). Piping consists of several phases. Initially, the soil cracks open on the inside of the dike because the buoyant pressure on the aquifer exceeds the weight of the overlying soil. Subsequently, the backward erosion process begins, transporting sand particles to the surface. This leads to the growth of a piping path under the dike. This process is illustrated in Figure 4.13.

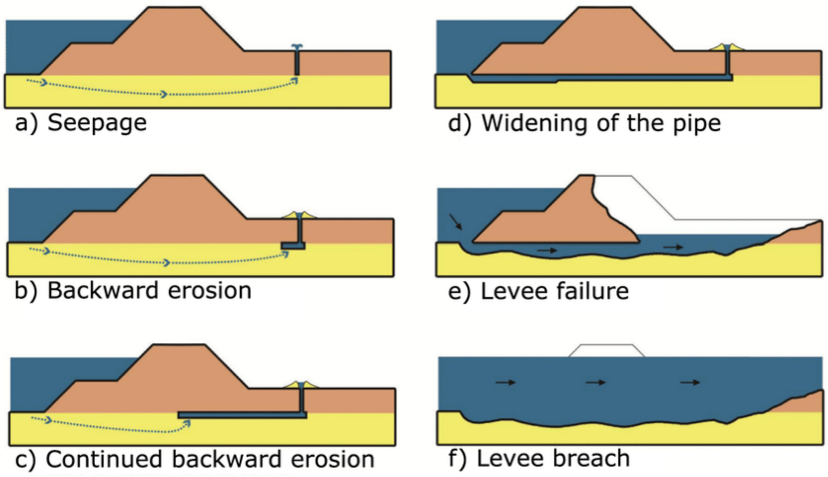


Figure 4.13: Piping (Beek, 2015)

Piping, with object
The location of a house can extend or shorten the piping length, while assuming a gap can shorten the piping path. When the piping path becomes longer, a larger pressure difference can be present between both sides of the dike without piping occurring. This is because the pressure gradient will be smaller when the piping length increases. Similarly, when the piping length decreases, a smaller pressure gradient is permissible. Additional chances of piping are also possible if certain elements of a house fail. In the following ways, a house can influence the piping failure mechanism.

- Leakage, pipeline breaks.
- The building can shorten the piping path.
- A pile foundation can shorten the piping length.

The critical head difference for piping can be computed with the equation of Sellmeijer, which can be seen below. A house with a pile foundation can reduce the piping length. A house with a shallow foundation can extend the piping length.

$$\frac{H_c}{L} = F_R \cdot F_S \cdot F_G \tag{4.2}$$

With:

H_c $[m]$	critical head difference
L $[m]$	(horizontal) seepage length

Overtopping / Overflow, without object

Overflow occurs when the water level in a river rises higher than the dike. Wave overtopping occurs when waves flow over the dike. Both overflow and overtopping can lead to erosion of the inner slope of the dike over time. Wave overtopping plays less of a role in river dikes compared to sea dikes, as the waves are generally smaller, but it is still considered. Dike damage due to overtopping typically begins at the lowest crest level or at a dike discontinuity. The amount of overtopping that is allowed depends on three types of requirements: structural requirements (ULS), Serviceability requirements (SLS) and the storage capacity of the water system behind the dike. The amount of overtopping that is allowed depends on the most strict situation. The maximum required overtopping for the types of dikes and situations can be seen in Table 4.1. The maximum required overtopping for the serviceability limit state of different situations can be seen in Table 4.2.

Hazard type and reason	mean discharge q (l/s/m)
Embankment seawalls / sea dikes	
No damage if crest and rear slope are well protected	50-200
No damage to crest and rear face of grass covered embankment of clay	1-10
No damage to crest and rear face of embankment if not protected	0,1
Promenade or revetment seawalls	
Damage to paved or armoured promenade behind seawall	200
Damage to grassed or lightly protected promenade or reclamation cover	50

Table 4.1: ULS overtopping requirements (Eurotop, 2017)

Hazard type and reason	mean discharge q (ℓ /s/m)	max. volume V_{max} (ℓ/m)
For pedestrians		
Trained staff, well shod and protected, expecting to get wet; overtopping flows at lower levels only, no falling jet, low danger of fall from walkway	1 - 10	500 at low level
Aware pedestrian, clear view of the sea, not easily upset or frightened, able to tolerate getting wet, wider walkway	0,1	20 - 50 at high level or velocity
For vehicles		
Driving at low speed, overtopping by pulsating flows at low flow depths, no falling jets, vehicle not immersed	10 - 50	100 - 1000
Driving at moderate or high speed, impulsive overtopping giving falling or high velocity jets	0,01 - 0,05	5 - 50 at high level or velocity
For property behind the defence		
significant damage or sinking of larger yachts	50	5000 - 50 000
sinking small boats set 5 - 10 m from wall; damage to larger yachts	10	1000 - 10 000
Building structure elements	1	-
Damage to equipment set back 5 - 10 m	0,4	-

Table 4.2: SLS overtopping requirements (Eurotop, 2017)

The amount of overtopping depends on various parameters including wave height, dike height, dike slope, dike covering, and whether buildings are on the dike. To determine the overtopping height, the Van der Meer formula can be used. The overtopping requirement changes for the situations with a house from 10 l/s/m to 1 l/s/m. As can be seen in Equation 4.3, the change in overtopping requirement results in a change in required dike height.

$$R_C = \frac{\epsilon_{m-1,0} \cdot H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}{2.5} \cdot (-ln(\frac{q \cdot \sqrt{\tan(\alpha)}}{\sqrt{g \cdot H_{m0}^3} \cdot 0.026 \cdot \gamma_b \cdot \epsilon_{m-1,0}}))^{\frac{1}{1.3}} \tag{4.3}$$

With:

R_c $[m]$	overtopping height
$\epsilon_{m-1,0}$ $[-]$	breaker parameter
H_{m0} $[m]$	significant wave height
γ_b $[-]$	influence factor of a berm
γ_f $[-]$	influence factor for the permeability and roughness of the slope
γ_β $[-]$	factor for oblique wave attack
γ_v $[-]$	influence factor for a vertical wall on top of the crest
q $[m^3/s/m]$	overtopping discharge
α $[°]$	outer slope of the dike

Overtopping / Overflow, with object

The overtopping requirement for a dike with grass covering is 10 l/s/m (Eurotop, 2017). When a house is present, the transitions between the house and the dike become critical, as these transitions are more susceptible to erosion. For this, a requirement of 1 l/s/m is assumed to be allowed to ensure that the erosion pit at the transitions does not become too large. Because overtopping against a building can only flow to the sides, the areas next to the building experience more overtopping. This can be seen in Figure 4.14. To meet the same failure probability requirement for overtopping, the dike must be raised locally, or a small wall must be installed.

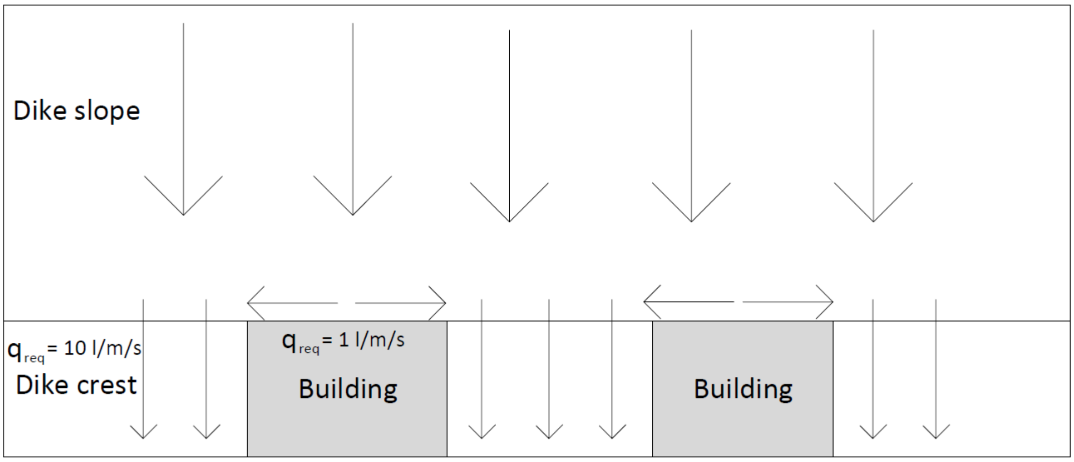


Figure 4.14: Top view 3D erosion

Settlement

A house built on the dike can contribute to settlements of the dike. This will lower the crest level, making the dike more susceptible to overflow and overtopping. The house in this example does not cover the whole crest, so it is expected that settlement does not play a large role.

The settlement of the dike can be calculated with equation 4.4, of which the strain can be calculated with the formula of Koppejan. The equation takes into account both primary settlement and creep (Voorendt & Molenaar, 2021). If a house is being built on the crest of a dike, the change in stress ($\Delta\sigma'_V$) will increase, and therefore, the strain and the total settlement of the soil will increase too.

$$\Delta H = \epsilon \cdot H \tag{4.4}$$

$$\epsilon = (\frac{U}{C'_P} + \frac{1}{C'_S}\log\frac{\Delta t}{t_{ref}}) \cdot \ln(\frac{\sigma'_{v;i} + \Delta\sigma'_V}{\sigma'_{v;i}}) \tag{4.5}$$

With:

ϵ $[-]$	relative compression = $\frac{\Delta H}{H}$
H $[m]$	layer thickness
U $[-]$	degree of consolidation
C'_p $[-]$	primary compression coefficient
C'_s $[-]$	secondary compression coefficient
t $[day]$	duration after the application of the additional loading
t_{ref} $[day]$	reference duration (one day)
$\Delta\sigma'_V$ $[kPa]$	increase of the vertical effective stress in the weak layer
$\sigma'_{V;i}$ $[kPa]$	initial vertical effective pressure

Horizontal sliding
Horizontal sliding is a failure mechanism in which the dike shifts away under the force exerted by the water. Horizontal sliding often occurs during summer periods when relatively little water in the dike is present and it has a relatively low weight. If a high water level occurs, the load exceeds the resistance, causing the dike to slide away. Horizontal sliding usually occurs in canals where the water level is near the crest level, but is less common for river dikes with its typical design and dimensions. Sliding can usually be neglected for river dikes (Jonkman, Jorissen, Schweckendiek, & Van den Bos, 2021). For this reason and because it has a significant small contribution to the total failure probability contribution, it will be neglected in the case study.

4.3. Conclusion
In this chapter, the failure mechanisms to consider when building a house near a dike have been determined. Both the positive and negative influences have been identified, and it has been demonstrated how they impact certain formulas. It has been determined that macro stability, piping and overtopping are the most important failure mechanisms to consider.

Possible influences on the failure mechanisms have been determined but have not been quantified. Comparing the influences on the failure mechanisms with a deterministic approach is not accurate. Additionally, when using a deterministic approach, the different failure mechanism contributions to the total failure probability of the dike cannot be determined. Therefore, to precisely assess the failure probabilities, a probabilistic approach is applied in the real-life case in Chapter 5.

5

Influence of a house on the failure probability of a dike section

Step 3 of the main methodology

In this chapter a schematisation is proposed for taking into account buildings near dikes and this is compared to the current schematisation. First, general theory about FORM analysis has been elaborated. Next, a case study has been suggested to apply the probabilistic calculations to. Subsequently, the probabilistic approach has been explained and a schematisation has been proposed. Finally, the calculation of the failure probability for the proposed schematisation was done, and it was compared to the current conservative schematisation and a green dike without buildings.

5.1. FORM analysis

5.1.1. Reliability approaches

Different approaches can be used for calculating the reliability of a flood defence:

- Level 0: Deterministic approach
- Level 1: Semi-probabilistic approach
- Level 2: Simplified probabilistic approach
- Level 3: Fully probabilistic approach

In the deterministic and semi-probabilistic approach, an expected design load (S) for a design period is compared to the design strength of the structure (R). Safety factors are used to make sure a design is safe. A full-probabilistic approach is more cost-efficient in both the assessment and design (Slomp, 2016). When the load minus the resistance (R-S) is smaller than zero the structure fails. The relation between the load, resistance and failure probability can be seen in Figure 5.1, where the load is represented by Q.

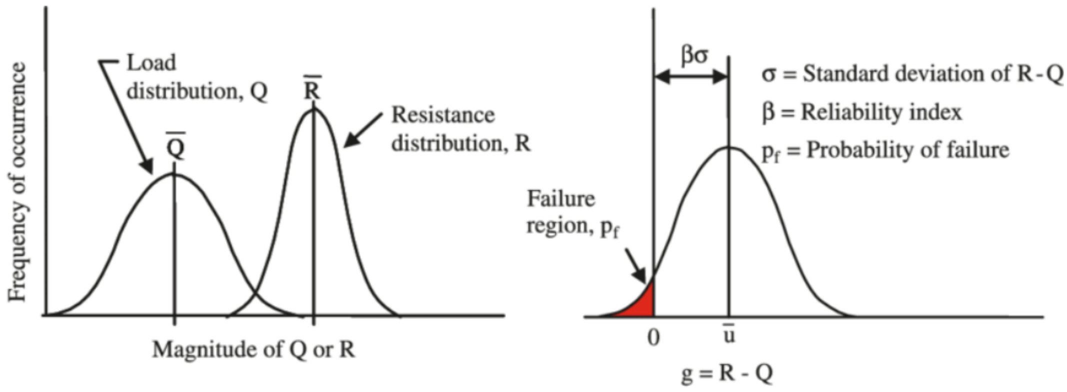


Figure 5.1: Probabilistic approach (Bathurst, 2008)

5.1.2. FORM theory

The First Order Reliability Method is an analytical approach that can be used to investigate the reliability of an engineering problem. It computes the probability of failure P(Z < 0), by approximating the limit state function, Z = 0. The limit state function represents a condition beyond which the relevant design criteria are no longer fulfilled (Baran, 2023). The approximation to the failure probability is:

$$P_f = P[Z \leq 0] \approx \Phi(-\beta) \tag{5.1}$$

With:

Φ Standard normal distribution
β Reliability index

So, with a First Order Reliability Method (FORM), it is possible to calculate the failure probabilities of dike cross-sections. This needs to be done for the various failure mechanisms influenced by a house and the dike sections where a house is located. In the case study, a single house in a dike section is examined. FORM is a Level II design method. Only the mean values and the moments of the first and the second order are used in most cases. Whether the flood defence fails is determined with a limit state function and can be written as follows:

$$Z = R - S \tag{5.2}$$

With:

Z Limit state function
R Resistance
S Load

When Z<0 it means that the flood defence fails. For each of the relevant failure mechanisms, determined in Chapter 4, a limit state function will be formulated.

In the FORM-analysis variables are used which are normally distributed. These values will be connected to stochastic variables in the FORM calculation. The reliability index is calculated by computing the mean and standard deviation of the limit state function and divide them with each other.

$$\beta = \frac{\mu_z}{\sigma_z} \tag{5.3}$$

With:

β Reliability index
μ_z Mean value of the limit state function
σ_z Standard deviation of the limit state function

5.1.3. Physical interpretation

The limit state function Z(x) is standardised into the limit state function Z(u) by normalizing the random variables to a standard normal distribution with a mean of 0 and a standard deviation of 1. This is done as follows:

$$U_i = \frac{X_i - \mu_{X_i}}{\sigma_{X_i}} \tag{5.4}$$

With:

U_i	Normalized random variable
X_i	Random variable
μ_{X_i}	Mean of the random variable
σ_{X_i}	Standard deviation of the random variable

By doing this, the reliability index has the geometrical interpretation as the shortest distance to the limit state function. The limit state line forms the boundary between the safe domain and the domain where failure occurs and can be seen in Figure 5.2.

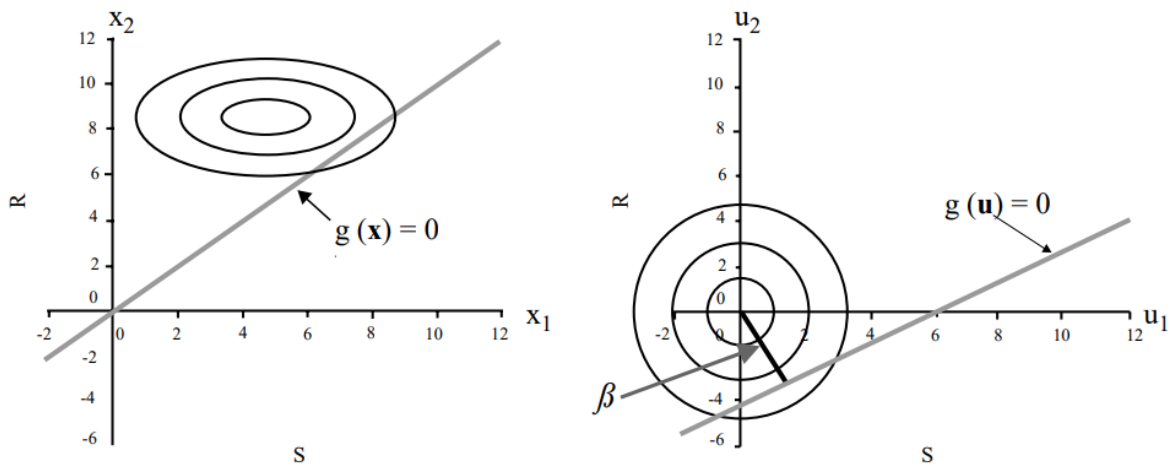


Figure 5.2: Standardised limit state function (Faber, 2019)

If the limit state function is non-linear, to represent the failure domain of the boundary between the safe domain and the failure domain needs to be linearised. Hasofer and Lind proposed a linearisation in the design point of the failure surface represented in normalised space. This situation can be seen in Figure 5.3. In this point the Limit State Function: $Z(X_1,...,X_i)$ is linearised through a Taylor function and can be written as:

$$Z_L = A + B_1 \cdot x_1 + ... + B_i \cdot x_i \tag{5.5}$$

With:

A, B	Values obtained after linearisation
x_i	Standard normally distributed variable i

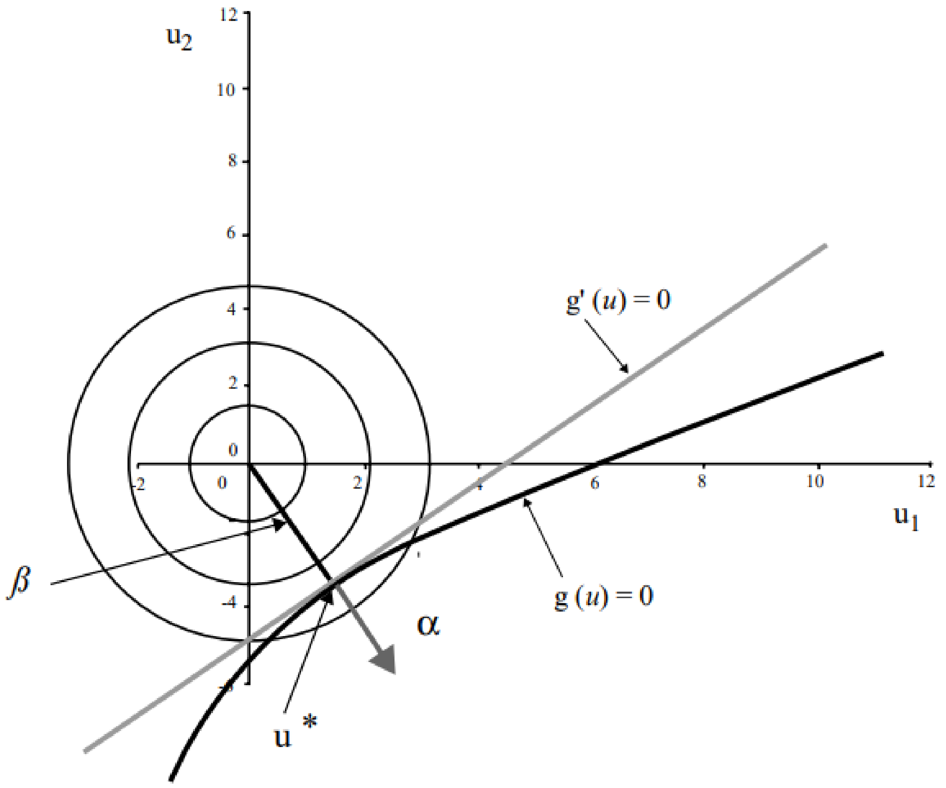


Figure 5.3: Non linear limit state function (Faber, 2019)

The reliability index, β, is related to the failure probability. The reliability index is the shortest distance to the limit state function, so where the failure probability is the biggest. The point where the reliability index touches the limit state function is called the design point, $u*$. The influence factor, α, is the outwards pointing normal vector to the failure surface in the design point $u*$. The failure space is linearised in the design point, which gives $g'(u) = 0$ in Figure 5.3 (Faber, 2019).

The α vector can be interpreted as a sensitivity factor that indicates the relative importance of a single stochastic variable for the reliability index, β. For the influence factors, the sum of the squares of the influence factors must add up to 1:

$$\sum \alpha_i^2 = 1 \tag{5.6}$$

5.2. Description of the basic case for the derivation of partial safety factors

To demonstrate the influence of a house on the total failure probability, a situation near Lith has been chosen. This research aims to investigate the possibility of new structures near dikes. For this reason, a newly built situation has been chosen. A dike where several houses already exist within the inner slope of the dike has been selected for the case. So, this is a representative case even for the assessment of existing buildings, as many houses on the slope may correspond to the case. Therefore, by choosing this location, consideration has been given to both new design and the assessment of existing buildings. An image of the selected location can be seen in Figure 5.4.

Figure 5.4: Lith (Google Street View, 2023)

The specific location that has been assumed for the house can be seen in Figure 5.5. DinoLoket was used to determine the soil composition on-site. The soil composition has been determined based on probing and drilling investigations. The location of both the case and the probing can be seen in Figure 5.5.

Figure 5.5: Case location

The actual and the assumed soil composition can be seen in Figure 5.6. The assumed soil composition is a simplification of the actual soil composition.

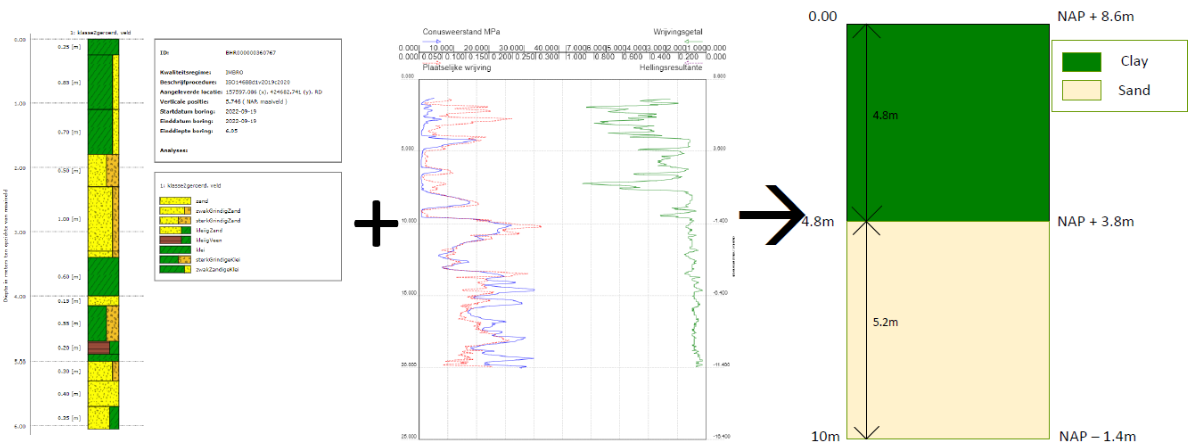


Figure 5.6: Soil composition

To determine the geometry of the dike, AHN (Algemeen Hoogtebestand Nederland) has been used. AHN is a map of the Netherlands from which the altitudes can be derived. From this, the cross-section which can be seen in Figure 5.7 is derived. Furthermore, the ground level outside and inside the dike has been determined. The ground level inside the dike is at NAP + 6.10m (right side). The ground level outside the dike is at NAP + 4.90m (left side). This gives the following slope:

Outer slope: $\frac{dy}{dx} = \frac{3.6}{11} = 0.33 \approx 1:3$

Inner slope: $\frac{dy}{dx} = \frac{2.5}{11} = 0.23 \approx 1:4$

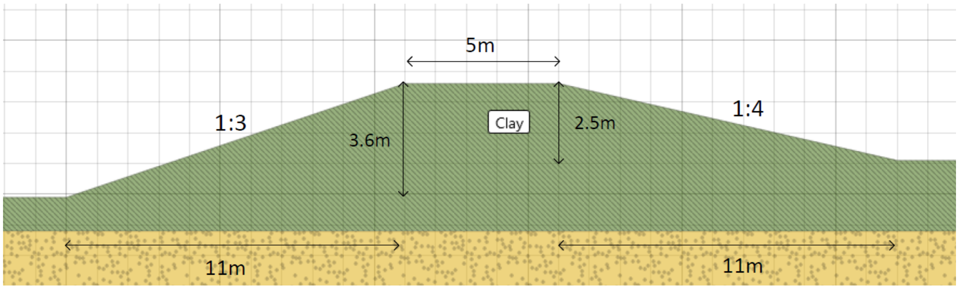


Figure 5.7: Dike cross-section

The purpose of this research is to explore new opportunities for construction, so a new house is assumed at the location. Various assumptions have been made regarding the dimensions, weight, and foundation for the house. These assumptions can be seen below in Table 5.1.

Parameter	Value
Length	15m
Width	10m
Weight	$10 kN/m^2$
Foundation type	Pile foundation
Foundation length	4m
Foundation width	0.5m

Table 5.1: House parameters

The direct surface exists of clay, which does not have a good load bearing capacity. For this reason, a pile foundation is assumed. However, a load-bearing sand layer is only a few meters away so the piles only need to be four meters to ensure the piles are one meter embedded into the load bearing sand layer. A sketch of the situation can be seen in Figure 5.8.

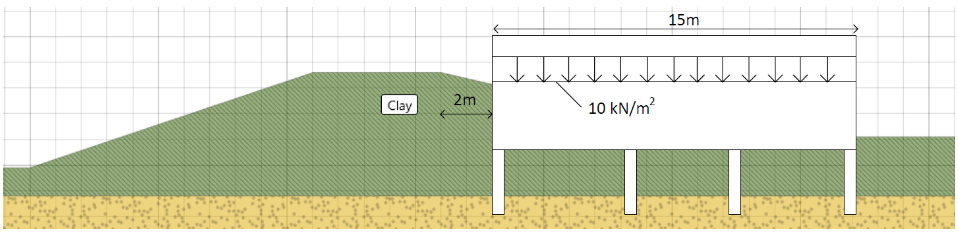


Figure 5.8: Case sketch

The assessment water level near Lith is NAP + 7.4m (Ministerie van Verkeer en Waterstaat, 2007). For the Meuse it is expected that in the future more low discharge periods will occur (Agency, 2021). However, more extreme rainfall is also expected in the future, which could temporarily raise the water level. For this reason, a water level rise of 0.3m is assumed for over a lifetime of 100 years. This gives a design water level of NAP + 7.7m.

This case corresponds to situation B in Chapter 4. As discussed in Chapter 4, the failure mechanisms to be taken into account in this situation are macro stability, piping, overtopping and horizontal sliding. Since horizontal sliding, in general, only occurs with peat dikes, this failure mechanism is not being assessed for this situation.

5.3. Calculation of the failure probability of a multifunctional dike section with a full probabilistic approach

5.3.1. Adapted probabilistic framework

The probabilistic framework for the current dike assessment has been discussed in Chapter 3. When a house is present this probabilistic framework changes. The allowed failure probability for each failure mechanism in each dike section remains the same. However, it cannot be guaranteed that a house will always remain in the same location; it may, for example, be demolished in the future. This increases the failure probability of the dike and can lead to exceeding of the target reliability, which should be avoided. This is a major concern of the water boards regarding relying on the strength derived from houses. That is why both situations, where failure occurs within a given year, with and without a house have been taken into account in the probabilistic framework. The failure probability when the house is present depends on the chance that the house is present and the failure probability of the dike section with a house present. The failure probability when the house is absent depends on the chance that the house is absent and the failure probability of the dike section without a house. This leads to the probabilistic framework in Figure 5.9.

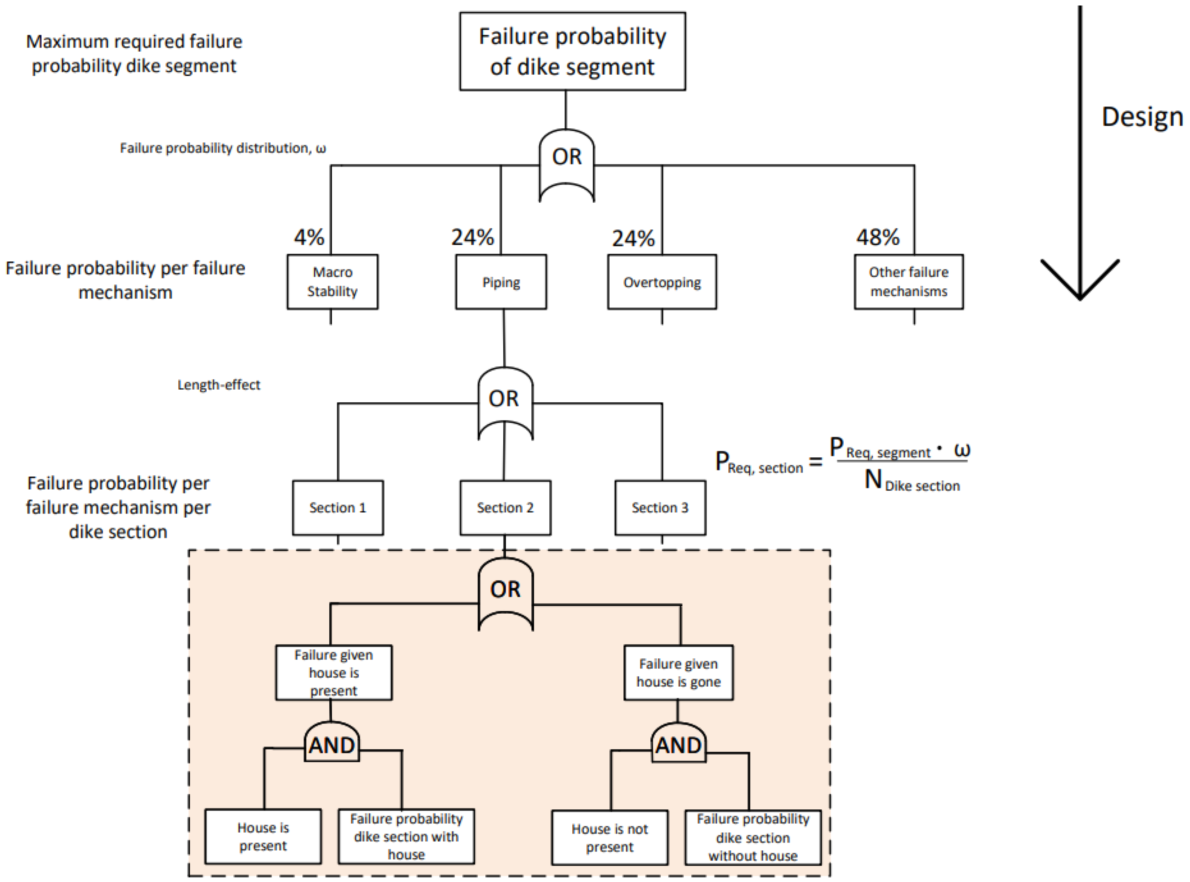


Figure 5.9: Example of probability distribution with a house taken into account

The collapse of a house does not necessarily always have a significant impact on the dike. When a house collapses, its weight remains in the same location, as does the pile foundation. Only if the remnants of the house are removed and this weight is eliminated, it may no longer provide any strength. Depending on the failure mechanism and the location of the house, the absence of the house can positively or negatively influence the probability of failure. It has to be shown that the situation with a house and the situation without a house together do not exceed this required failure probability.

Two situations can be distinguished:

- Designing a new structure near the dike
- Assessing an existing dike section with structures already present

When designing a new structure near a dike, the fault tree can be followed top-down to ensure that the dike section with a house satisfies the required failure probability. To assess if a dike section with an existing building near a dike satisfies the required failure probability, the fault tree needs to be followed from the bottom up. This distinction will be made in this chapter.

The selected case is part of dike segment 36-4. This section has a maximum failure probability of 1/3000 per year. To determine the failure probability per failure mechanism, the fixed failure probability distribution mentioned in Chapter 3 is applied. This is common practice for a semi-probabilistic assessment. The corresponding failure probabilities for the various dike sections have been determined using the different length-effect factors. The parameters for calculating the length-effect can be seen below (Diermanse, 2016b):

Failure mechanism	a	b
Macro stability	1/30	50m
Piping	1	350m

Table 5.2: Length-effect factors (Diermanse, 2016b)

5.3.2. Failure probability distribution for the selected case

These length-effect factors lead to the failure probability distribution which can be seen in Figure 5.10 for this specific case.

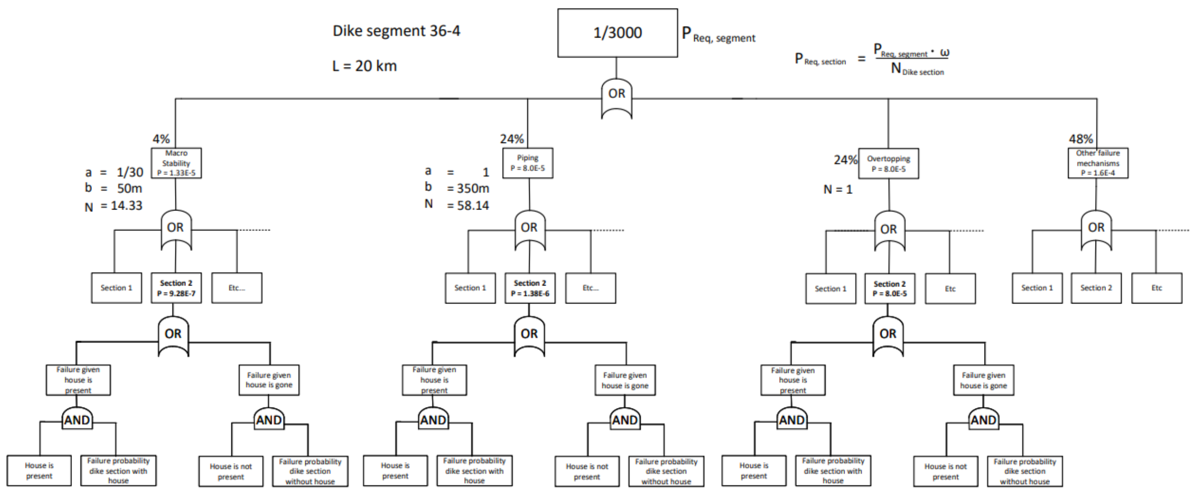


Figure 5.10: Failure probability distribution selected case

For the six scenarios, failure given with house and without house (lowest row of events in Figure 5.10), the failure probabilities need to be determined to assess whether it meets the failure probability requirements. For the situation with and without a house, percentages are estimated for the time they could occur. Various reasons can cause the absence of a house, such as demolition or collapse. For each failure mechanism, a percentage is estimated for when a failure mechanism can be present. The proposed schematisation of the house can be seen in Figure 5.11.

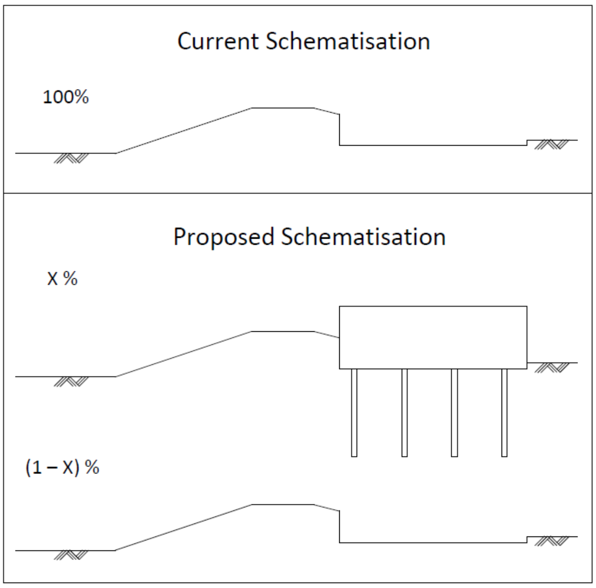


Figure 5.11: Proposed schematisation

5.3.3. Determination of the presence of a house when it has a flood protection function

To determine the probabilities of a house not being present at the given location, the different conditions of the house have been described. These conditions can be seen in Figure 5.12.

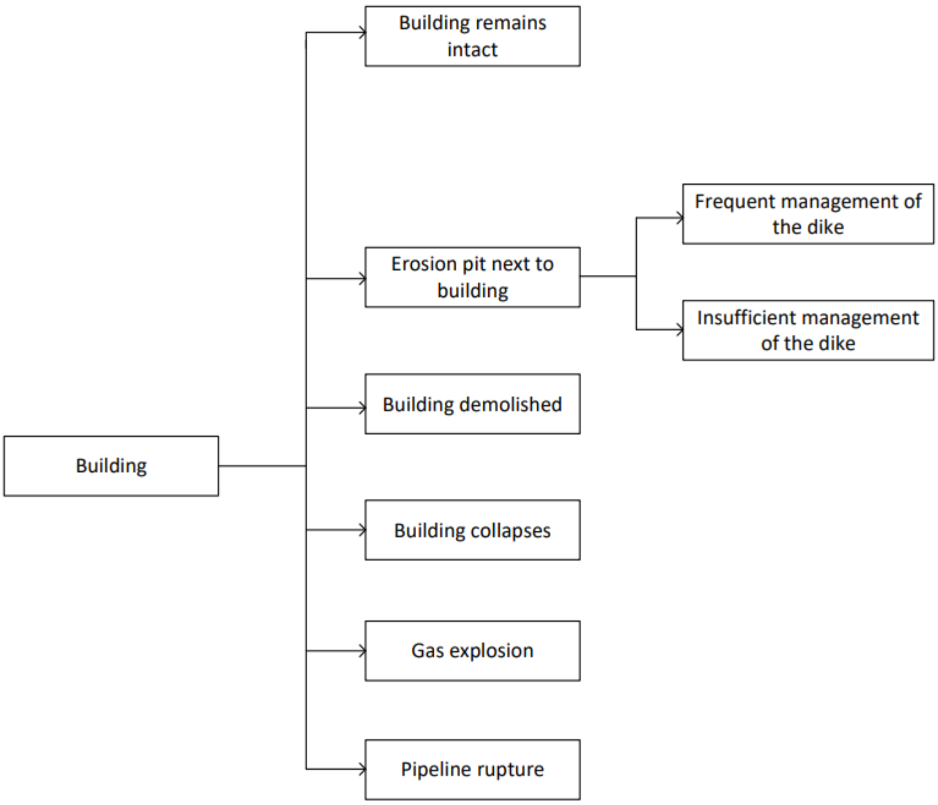


Figure 5.12: Overview of states new buildings

Building present

If the building is present in the slope or at the toe of the dike, the building will not negatively effect the stability of the dike. The weight of the building causes a big additional resisting moment to prevent the sliding of a soil body. The foundation may also contribute positively to stability due to the pile foundation that intersects the slip circle. The house can negatively affect macro stability when it is located on the crest of the dike.

Erosion pit next to building

A house that is located on a dike creates transition locations that are more susceptible to erosion. Transition locations are the places where the dike merges into the house. At these locations, the dike is more prone to erosion compared to the rest of the dike. An erosion pit causes a small increase in the failure probability for macro stability because a relatively small amount of soil is removed. A slip plane for a primary dike is 25-50m long (longitudinally of the dike) (Bisschop & Boxhoorn, 2024). A relatively small reduction in passive resistance due to an erosion pit causes little to no increase in the failure probability. When an erosion pit occurs at the crest of the dike it could have a beneficial effect, but in practice this is never considered (Bisschop & Boxhoorn, 2024). It is assumed that an overtopping requirement of 1 l/s/m will prevent the erosion pit from getting significant.

Insufficient management of the dike

As mentioned earlier, dikes are checked every two weeks in Rivierenland and even more often when high water levels are present. It is expected that the other water boards will have a similar procedure. This means that the dikes are well managed and damage or unexpected work on the dike will be noticed quickly.

Building demolished during or right before high water period

When the building is demolished, the dike is locally weakened because no dike revetment is present at that location at that time. The demolition rate is roughly 0.2 to 0.3 percent of the total Dutch housing stock per year (Van der Flier & Thomsen, 2006). Assuming that the demolition rate is 0.3% per year and assuming that the average change of high water occurring is 1/10. This gives a failure probability of 1/3000 per year.

The probability that a building will be demolished just before a high water period when a water board is aware that the building is part of the dike's strength may be considered to be smaller than this stated 0.3 percent. This is for the following reasons (Bisschop & Boxhoorn, 2024):

- Demolition work within a flood defence must be authorized according to the by-law and Legger by the waterboard. This permit indicates that (in principle) no excavation is allowed in the barrier during the storm season. In addition, other stipulations state that a 'hole' in the barrier may be present for a short period of time and must be filled within a short period of time when it is not storm season.
- A high water period can be predicted some time beforehand.
- Regular inspections of the dikes are done every two weeks (for waterboard Rivierenland), and from a certain high water level, the dike watch (dijkwacht) is deployed. This ensures early detection of constructing and demolition activities.

It may take some time for the dike revetment to be repaired, but because timely measures can be taken and it must take place outside the storm season, it can be assumed that the dike revetment is repaired in time. The same goes for when a house is demolished and the weight is removed. New construction should be quickly provided in the same location because the house is part of the flood defence. Because of all of these reasons, the probability of a building being demolished right before a high water event may be considered negligible.

Building collapses during high water period

The collapse of the building during a high water period will initially not result in the weakening of the dike. If the weight of the house remains at the same location, then it will still have a positive effect on macro stability. Also, the foundation remains present in the ground. Furthermore, buildings must meet the requirements in the Building Code (Bouwbesluit) (Bisschop & Boxhoorn, 2024). This means that each building has a certain reliability and the probability is considered negligible that the building will collapse during a high water period.

Gas explosion

Gas explosions have a very low chance of occurring in the Netherlands. The consequences of a gas explosion can be enormous, so many measures are in place to keep this chance as low as possible. Every year, around 700 gas incidents occur in the Netherlands (Meinders, 2017). There are approximately 8 million homes in the Netherlands. It is assumed that 10% of the gas incidents lead to an explosion and possible structural damage. The annual probability that a house will sustain structural damage due to a gas explosion can be determined as follows:

$$P = \frac{Amount\ gas\ incidents\ per\ year}{Amount\ homes\ in\ Netherlands} \cdot \%\ gas\ explosions\ leading\ to\ structural\ damage \tag{5.7}$$

$$P = \frac{700}{8,000,000} \cdot 0.10 = 8.75 \cdot 10^{-6} \tag{5.8}$$

The probability of a gas explosion, especially during high water, is therefore considered negligible.

Pipeline rupture

Pipeline rupture can sometimes happen. However, the probability of occurring is low, and when it does, immediate action is taken to restore this. Because of this, the probability is considered negligibly small that a pipeline rupture will occur during high water.

Conclusion

The approach above shows that the probability of a house not being present given high water is almost negligible. This is probably an underestimate of the actual probability of the house not being in place. Based on the percentage of houses demolished annually and considering the various other situations, a probability of 0.1% is assumed that the house may not be present at the location. This assumption is considered conservative, but it is better to include some conservatism rather than underestimate the chance of the house being absent. This leads to the following percentages:

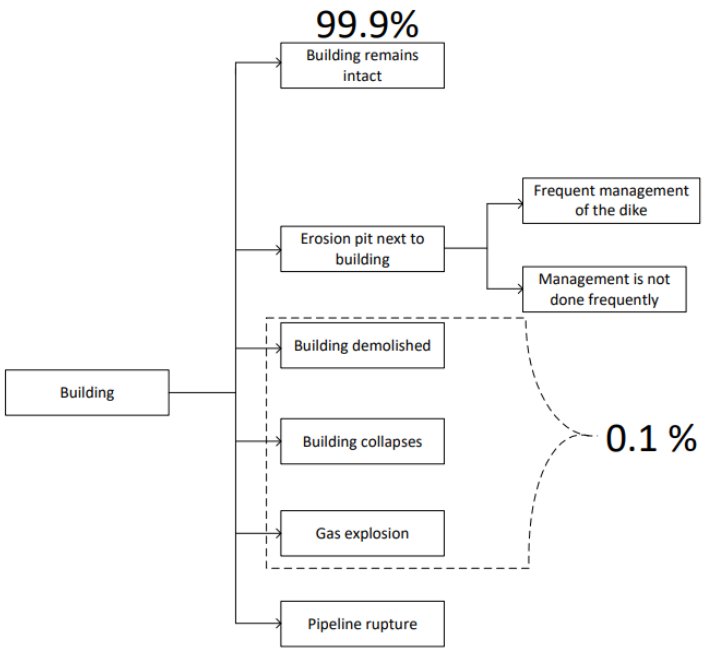


Figure 5.13: Building states

Macro stability
Taking the above situations into account, there is a 99.9% probability that the house is not present and 0.1% probability that the house is not present and a gap is assumed at the location of the house. These two situations are combined to derive the probability of failure for the failure mechanism macro stability.

Overtopping
For overtopping, the Ultimate Limit State of the dike is considered. The situations that can occur are shown in Figure 5.13. The typical overtopping criterion is 10 l/s/m for a grass dike (Eurotop, 2017). Transitions from the dike to the house are particularly susceptible to overtopping. Therefore, an overtopping requirement of 1 l/s/m is determined for when the house is present. Residents themselves can influence the total erosion that occurs at these transitions by, for example, adding protection in the form of gravel at these transitions. However, it is difficult to require everyone to do this and to subsequently monitor it. Therefore, a requirement of 1 l/s/m is assumed.

When a gap is assumed in the dike, it will be more susceptible to erosion due to possible irregularities in the soil profile. For this reason, an overtopping requirement of 1 l/s/m is assumed compared to the typical overtopping criterion of 10 l/s/m for a grass dike. Since the requirements for both situations with and without a house are equivalent, a single calculation can be made for the entire scenario, regardless of the probability of the house being present. This means that the failure probability in the proposed schematisation, due to overtopping, will be the same as the current conservative schematisation.

Piping
For piping, it does matter whether the house is present at the location. When the house is present and has a shallow foundation, it can extend the piping length compared to the situation of a dike without a house, where a gap is assumed. If the house is absent, the piping length would become much shorter and thus much more susceptible to piping. Based on the multiple scenarios above, also a probability of 0.1% is assumed that the house is not present for piping.

Now that the percentages have been determined for the presence and absence of the building, the failure probability for both situations can be calculated. Since the percentages are conservative, a sensitivity check will be performed at the end to determine the contribution of this chosen percentage.

5.4. Calculation of the failure probability for the case

For calculating the failure probability of both the current schematisation and the proposed schematisation a FORM analysis has been performed for each of the relevant failure mechanisms. The steps that will be taken per failure mechanisms are the following:

- Defining the limit state function
- Describing the properties of the relevant parameters
- Schematisation of the situation
- Results FORM analysis
- Reflecting

5.4.1. Macro stability

Limit state function

Macro stability can be calculated using the equation of Bishop. This equation computes the active moment and the resisting moment. When the active moment becomes larger than the resisting moment, the dike will fail. This leads to the following limit state function:

$$Z_{macro-stability} = \sum M_R - \sum M_S \tag{5.9}$$

Using the method of Bishop, slip plane needs to be assumed. However, it is uncertain which critical slip plane is governing. For this, the program D-Stability has been used. To obtain the failure probability from this program, a FORM analysis has been performed in D-stability.

Parameters

In D-stability, it is possible to treat the cohesion and the internal friction angle of the soil as stochastic. All the data used, including the mean, standard deviation, and distribution, can be seen in Table 5.3. The Coefficients of Variation for the various parameters are provided in the document "Legal Assessment Instrumentation Uncertainties". Using Formula 5.10, the standard deviation has been determined from the Coefficient of Variation(V) and the mean(μ) of the values.

$$V = \frac{\sigma}{\mu} \tag{5.10}$$

All soil parameters are derived from Eurocode 6740. For clay, clean solid clay is assumed as this is usually used for clay dikes (Den Boer, 2018). For sand, clean solid sand is assumed.

Parameter	Description	Mean, μ	Standard deviation, σ	Distribution
γ_{clay}	Volumetric weight of clay	19 kN/m^3	-	Deterministic
c_{clay}	cohesion of clay	$15kN/m^2$	4.125	Normal
ϕ_{clay}	internal friction angle of clay	25°	3.75	Normal
γ_{sand}	Volumetric weight of sand	19 kN/m^3	-	Deterministic
ϕ_{sand}	Internal friction angle of sand	35°	5.25	Normal
c_{sand}	Cohesion of sand	0	-	Deterministic
h	Design water level	NAP + 7.70m	-	Deterministic
GWL	Ground water level	NAP + 3.30m	-	Deterministic

Table 5.3: Description of parameters for macro stability

Schematisation

To determine which schematisation of the situation to use and what the effect is of different measures in D-stability, a sensitivity analysis has been performed. Forbidden lines have been used to schematise the house. Forbidden lines ensure that no slip plane can occur through the forbidden lines. No specific option for the foundation is available in D-stability, so soil nails have been used to schematise the foundation. In the last situation, the house is schematised as a rigid body. The schematisations in Table 5.4 have been looked at:

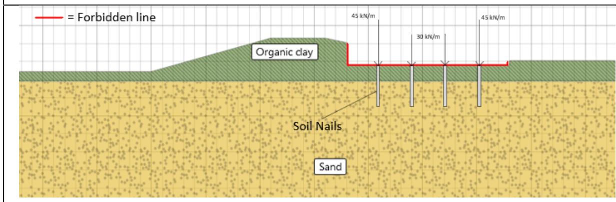
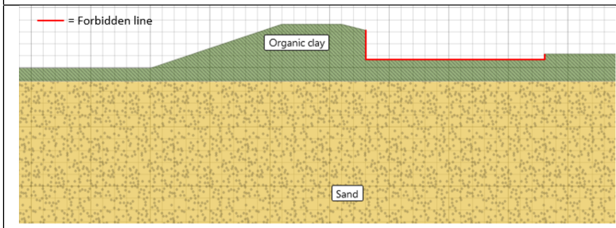
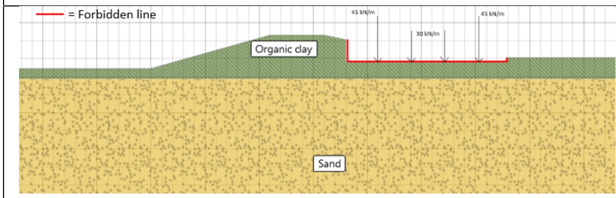
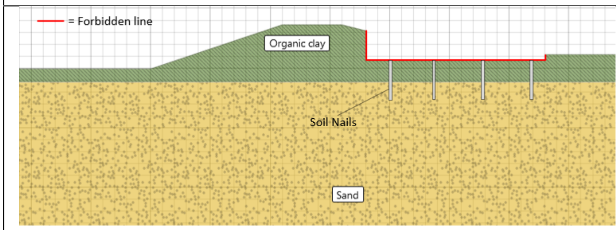
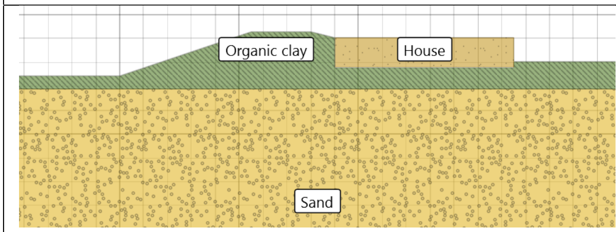
Situation	Description	Safety factor
	Forbidden line + forces + soil nails	3.717
	Forbidden line	3.285
	Forbidden line + forces	3.717
	Forbidden line + soil nails	3.285
	Rigid body	2.967

Table 5.4: Sensitivity analysis

These situations illustrate that soil nails cannot be used to schematise pile foundations because the Safety factor and thus the failure probability does not change. Furthermore, it can be concluded that when a rigid body is assumed as the house with the same weight as the forces together, it has a higher failure probability. The most realistic situation is where the house is schematised with soil nails, forces and a forbidden line and has been used for further calculations. This has been chosen because, for buildings, it is not realistic that a failure plane will occur through the house, especially when new buildings which will be designed for these extra horizontal forces will be present.

In D-stability, the situations with and without a house are schematized. The situation that takes the house on a pile foundation into account can be seen in Figure 5.14. To ensure that the walls and the floor remain in the same place, forbidden lines have been used in D-stability.

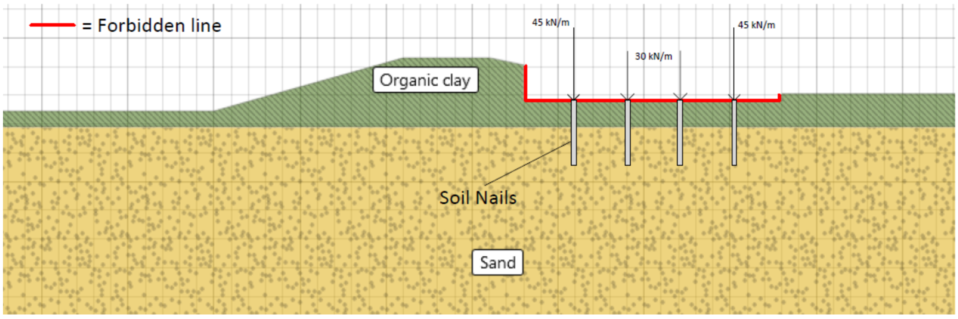


Figure 5.14: Schematisation of the house in D-stability

Results FORM analysis
The situation with a house could not be calculated full probabilistcally in D-stability. For this reason a semi-probabilistic assessment has been done at first. For the semi-probabilistic assessment, design values of the different parameters have been used to calculate the safety factor. In the Legal Assessment Intrumentation a direct relation is given between the Safety Factor and the reliability index, β, for macro stability. This relation can be seen in Figure 5.15. So the failure probability of the situation with a house is calculated at this manner.

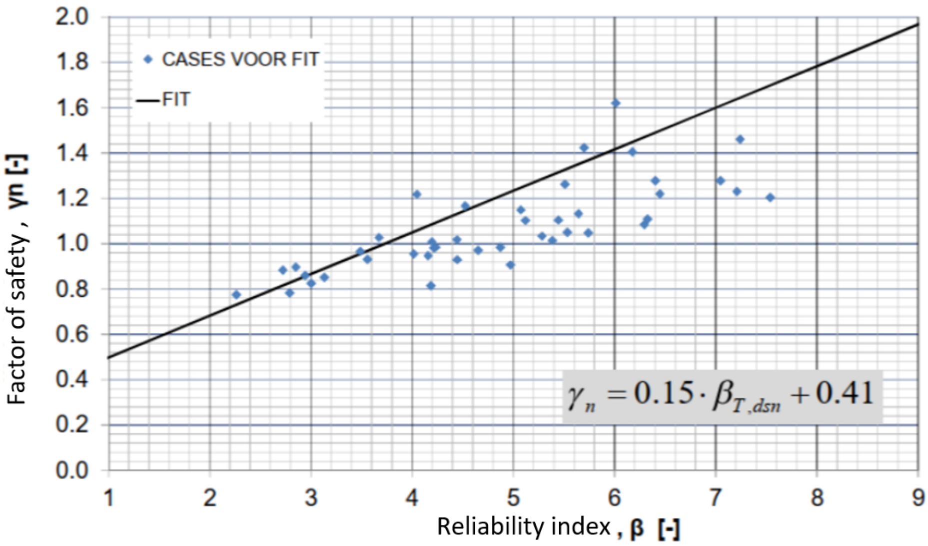


Figure 5.15: Correlation safety factor and beta for macro stability

The different points in the graph are the different cases considered. These are different dike cross sections from different materials. An attempt was made to include as much variation as possible. It is therefore assumed that this graph is also true for the case discussed in this chapter. The graph only shows a correlation up to a safety factor of 2.0. However, the calculated values in Table 5.4 are greater than 2.0. Possibly, the formula no longer holds up, but it can be assumed that when the partial safety factor is bigger, the failure probability becomes smaller. It will be shown later in this section that the precision of this relationship is not very important (Kanning, 2016).

In D-stability the method of Bishop has been chosen for the stability calculations. This has been done because it is assumed that the soil only consists of two layers. This is a relatively simple soil structure, which is usually analyzed using the Bishop method. However, when more soil layers are involved and hydrostatic pressure cannot be assumed everywhere, it is more accurate to use the Uplift Van or Spencer-Van der Meij model (Van der Meij, 2012).

The first step in D-stability is determining the representative slip plane. This is done in by identifying several points that approximately lie in the center of the slip plane. Subsequently, the depth of the slip plane needs to be determined. D-stability searches through the various specified centers and slip plane depths to find the lowest Safety Factor against macro stability. The slip circle that yields the lowest Factor of Safety or highest probability of failure is considered the representative slip circle. The governing slip circle for the situation with a house can be seen in Figure 5.16.

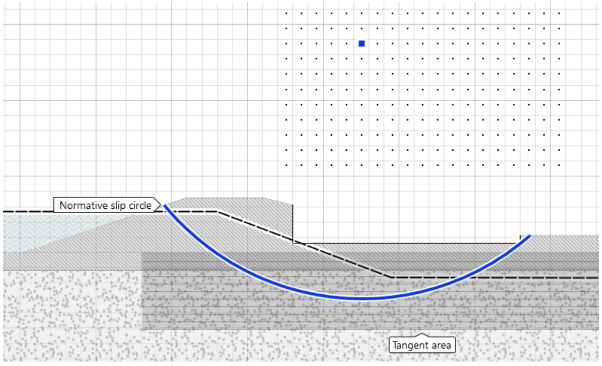


Figure 5.16: Governing slip plane

For the situation with a house this gives a Safety Factor of 3.717 which corresponds to a failure probability of $8.51 \cdot 10^{-60}$.

The situation where no buildings are present is schematized as a gap, without forbidden lines. This can be seen in Figure 5.17. The governing slip circle can be seen in Figure 5.18.

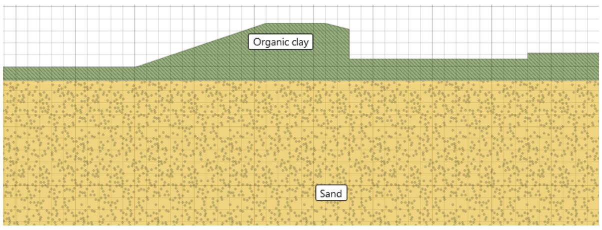


Figure 5.17: Schematisation D-stability

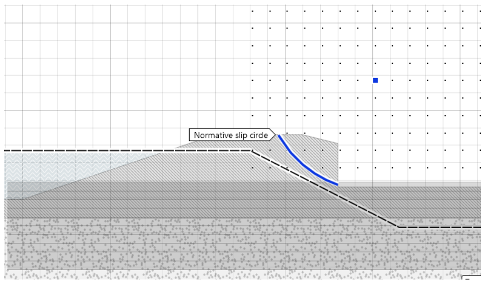


Figure 5.18: Failure plane

The situation without a house gives a Safety Factor of 1.006. This corresponds to a failure probability of $2.00 \cdot 10^{-4}$. The failure probabilities for both situations can be seen below:

$P_{f,situation\ without\ house} = 2.00 \cdot 10^{-4}$
$P_{f,situation\ with\ a\ house} = 8.51 \cdot 10^{-60}$

The failure probability of the situation with a house is much lower than the situation without a house. The total failure probability of the current conservative method is equal to the failure probability of the situation without house. The failure probability of the proposed method takes a 0.1% chance into account that the house will not be present. This gives the following probability of failure:

$$P = P_{house} \cdot P_{f,situation\ with\ a\ house} + P_{no\ house} \cdot P_{f,situation\ without\ house} \tag{5.11}$$

$$P = 0.999 \cdot 8.51 \cdot 10^{-60} + 0.001 \cdot 2.0 \cdot 10^{-4} = 2 \cdot 10^{-7} \tag{5.12}$$

The FORM analysis gave the following influence factors:

α, clay cohesion: -0.856
α, clay friction angle: -0.517

Reflection
As the results turn out, the situation without a house determines the failure probability because it gives a much bigger failure probability, even though it only contributes as 0.1%. The reason for the failure probability with the house being so small can be derived from the sensitivity analysis and is primarily due to the presence of the forbidden lines through which no slip circle can occur. These forbidden lines have been assumed because it is deemed unrealistically for a slip circle to cross the floor or wall of a house. That is why only the situation without a house is taken into account from now on for this case. For this situation, a FORM analysis is performed in D-stability. The FORM analysis could not be performed from the beginning for both situations because the situation with a house could not run the simulation. Now that it has been determined that the situation with a house has a negligible small failure probability it is not taken into account and a FORM analysis for the situation without a house has been performed. First, the slip plane has been determined using design values and subsequently this slip plane was used for performing the FORM analysis. These steps had to be done separately because otherwise it could take too much calculation time.

5.4.2. Piping

Limit state function
For piping, Sellmeijer's equation can be used. With Sellmeijer's equation the critical head difference can be calculated. The driving force behind piping is the pressure difference on both sides of the dike. The driving force is formed by the difference in water level across the dike and the length over which this water level difference is present ('t Hart, 2018). This leads to the following limit state function:

$$Z_{piping} = H_c - H_{actual} \tag{5.13}$$

This is the critical pressure head minus the actual pressure head. The critical pressure head can be determined using Sellmeijer's equation, which can be seen below.

$$H_c = F_R \cdot F_S \cdot F_G \cdot L \tag{5.14}$$

$$F_R = \eta \frac{\gamma_P - \gamma_W}{\gamma_W} \cdot \theta \cdot \tan(\eta) \tag{5.15}$$

$$F_S = \frac{d_{70}}{\sqrt{K \cdot L}^3} \tag{5.16}$$

$$F_G = 0.91 \cdot \frac{D}{L}^{\frac{0.28}{(\frac{D}{L})^{2.8}-1}+0.04} \tag{5.17}$$

Parameters
The actual piping length can be determined from the cross-section of the case. The parameters used in the FORM calculations can be seen below. The stochastic variables and their standard deviations have been based on the "WBI onzekerheden" document.

Parameter	Description	Mean, μ	Standard deviation, σ	Distribution
γ_P	The submerged weight of the particles in the aquifer	$26.5 kN/m^3$	-	Deterministic
γ_W	Volumetric weight of water	$10\ kN/m^3$	-	Deterministic
η	Drag factor	0.25	-	Deterministic
d_{70} (sand)	70th percentile of the grain size distribution	0.0002m	0.000024	Normal
D_{clay}	Thickness of the aquifer	2.30m	0.23	Normal
L	Piping length of the aquifer	33m	3.3	Normal
k_{sand}	Hydraulic conductivity	$4.86 \cdot 10^{-4}$ m/s	$2.43 \cdot 10^{-4}$	Normal
h	Design water level	NAP + 7.70m	-	Deterministic
ν	Kinematic viscosity	$10^{-6} m^2/s$	-	Deterministic

Table 5.5: Description of parameters for piping

The intrinsic permeability, K, can be calculated with the following formula:

$$K = \frac{\nu}{g} \cdot k = 4.95 \cdot 10^{-11} m^2 \tag{5.18}$$

Schematisation

The failure probability for piping is the same for the situations with a house and with a gap, as can be seen in Figure 5.19. The pile foundation crosses the clay layer, making it easy for piping to occur along the pile foundation. Below the structure, gaps could be present between the structure and the soil. Via the bottom of the structure the water can flow to the end of the structure, which does not give resistance. That is why a piping length of 18 meters is assumed for this situation.

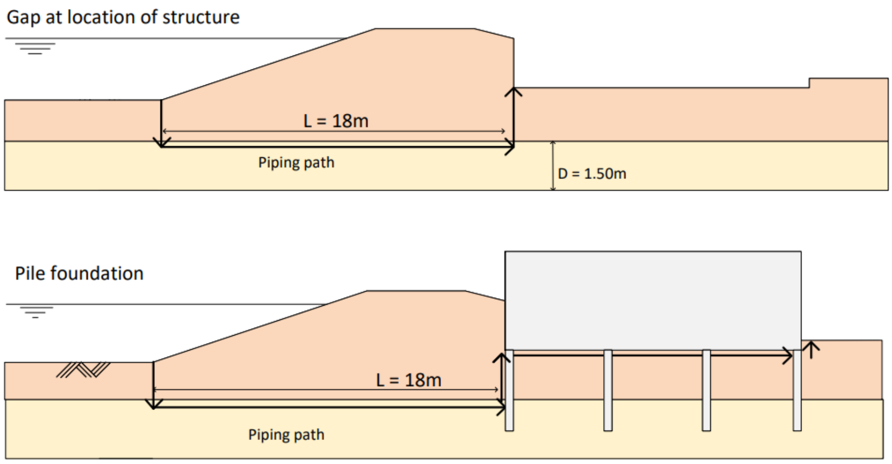


Figure 5.19: Piping length

Results FORM analysis

With the FORM analysis the probabilities of failure have been calculated for the situations without a house and the house with a pile foundation. As can be seen in Figure 5.19, these situations have the same piping length, which results in the same failure probability. The following probabilities of failure have been calculated.

$P_{f,\, without\ house} = 6.67 \cdot 10^{-5}$
$P_{f,\, with\ house} = 6.67 \cdot 10^{-5}$

The Python code corresponding to these calculations can be seen in Appendix A. The corresponding influence factors can be seen below:

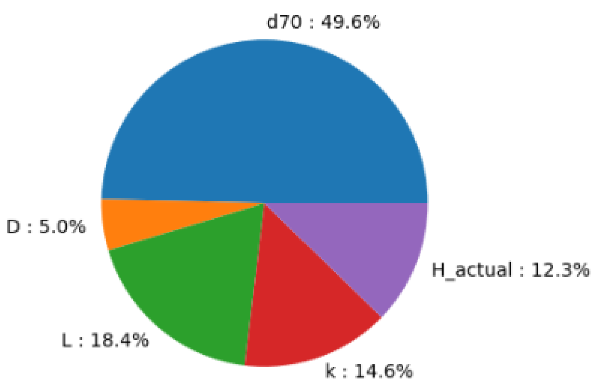


Figure 5.20: Influence factors for piping

Next, with the failure probabilities of both situations, the failure probability for the proposed method can be calculated.

$$P = P_{house} \cdot P_{f,situation\ with\ a\ house} + P_{no\ house} \cdot P_{f,situation\ without\ house} \tag{5.19}$$

$$P = 0.999 \cdot 4.59 \cdot 10^{-9} + 0.001 \cdot 6.67 \cdot 10^{-5} = 7.13 \cdot 10^{-8} \tag{5.20}$$

Reflection
As shown in Figure 5.19, the piping length is the same when a house or a gap is assumed at the location of the house. This will result in the same failure probability for all situations. For a house with a shallow foundation this is different, but this will be discussed in the generalisation. When designing a new house, it is possible to influence the piping length by placing the house further away from the dike crest. Another possibility is to add a seepage screen in front of the pile foundation to increase the piping length.

5.4.3. Overtopping

Limit state function
Failure due to overtopping is determined by the discharge getting over the dike.

$$Z_{overtopping} = q_c - q_{actual} \tag{5.21}$$

The critical discharge has been determined in Chapter 4 and is 1 l/s/m. The actual amount of overtopping can be determined with the Van der Meer equation (Eurotop, 2017).

The amount of wave overtopping has been determined with the Van der Meer formula.

$$q_{overtopping} = \frac{0.067}{\sqrt{\tan(\alpha)} \cdot \gamma_b \cdot \epsilon_{m-1,0}} \cdot e^{\frac{-\frac{4.3}{\epsilon_{m-1,0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_V} \cdot R_c}{H_{m0}}} \cdot \sqrt{g \cdot H_{m0}^3} \tag{5.22}$$

$$\epsilon_{m-1,0} = \frac{\tan(\alpha)}{\sqrt{\frac{H_{m0}}{L_{m-1,0}}}} \tag{5.23}$$

$$L_{m-1,0} = \frac{g \cdot T_{m-1,0}^2}{2 \cdot \pi} \tag{5.24}$$

The significant wave height, H_{m0}, and the wave period, T_m, will be determined with the equation of Brettschneider. This equation takes as input the the fetch of the river, the wind speed at 10 meters above the surface level and the water depth. The maximum fetch can be seen in Figure 5.21 and is 1300 meters.

Figure 5.21: Fetch

The average wind speed is determined based on the wind speed at Schiphol. This is usually done for locations where direct wind data is not available (De Waal, 2017). The average wind speed at Schiphol is 11.3 m/s (Stepek, Schreur, & Wijnant, 2013). The variation coefficient can be assumed to be 0.1 (Rackwitz, 2001). Furthermore, the design water level is considered a stochastic variable. The riverbed is located at NAP + 0.5 meters.

The equation of Bretschneider consists of the following formulas (TAW, 1991):

$$\tilde{H} = 0.283 \cdot \tanh(0.53 \cdot \tilde{d}^{0.75}) \cdot \tanh(\frac{0.0125 \cdot \tilde{F}^{0.42}}{\tanh(0.53 \cdot \tilde{d}^{0.75})}) \tag{5.25}$$

$$\tilde{T} = 2.4 \cdot \pi \cdot \tanh(0.833 \cdot \tilde{d}^{0.375}) \cdot \tanh(\frac{0.077 \cdot \tilde{F}^{0.25}}{\tanh(0.833 \cdot \tilde{d}^{0.375})}) \tag{5.26}$$

$$T_{1/3} = \frac{\tilde{T} \cdot u_{10}}{g} \tag{5.27}$$

$$T_P = 1.08 \cdot T_{1/3} \tag{5.28}$$

$$T_m = \frac{T_P}{1.1} \tag{5.29}$$

$$H_{m0} = \frac{\tilde{H} \cdot u_{10}^2}{g} \tag{5.30}$$

Parameters
As input parameters, the wind speed, river depth and fetch have been used to calculate the significant wave height and the mean wave period. The significant wave height is 0.32 meters. The mean wave period is 1.98 seconds.

The factor for oblique wave attack can be determined from the angle of the fetch and can be seen in Figure 5.21. Since the fetch is much longer in this direction than in other directions, the combination of this fetch with the corresponding factor for oblique wave attack has been assumed as governing. For short-crested waves, the factor for oblique wave attack can be calculated with the following formula:

$$\gamma_\beta = 1 - 0.0022 \cdot \beta = 0.857 \tag{5.31}$$

The input parameters used for the FORM calculation can be seen in the table below. It is also stated whether the parameters have been assumed deterministic or probabilistic and what their corresponding distribution is. H_{m0} and $T_{m-1.0}$ are calculated with the Bretschneider equation.

Parameter	Description	Mean, μ	Standard deviation, σ	Distribution
h	Design water level	NAP + 7.70m	0.1	Normal
z_{crest}	Crest height	NAP + 8.6m	-	Deterministic
α	Outer slope of the dike	1:3	-	Deterministic
γ_b	Influence factor of a berm	1	-	Deterministic
γ_f	Influence factor for permeability and roughness	1	-	Deterministic
γ_β	Factor for oblique wave attack	0.857	-	Deterministic
γ_v	Influence factor for vertical wall	1	-	Deterministic
F	Fetch	1300m	-	Deterministic
u_{10}	Wind speed 10 meter above the surface area	11.3	1.13	Normal
d	Depth	NAP + 0.5m	-	Deterministic

Table 5.6: Description of parameters for overtopping

Results FORM analysis
For overtopping, only one calculation has to be performed, because the overtopping requirements is for both situations, with and without the house, the same. The FORM analysis gives a failure probability of $3.81 \cdot 10^{-7}$. The influence factors can be seen in Figure 5.22.

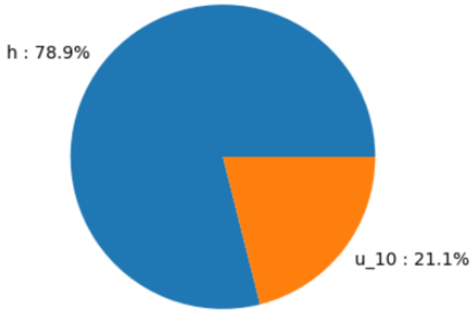


Figure 5.22: Influence factors overtopping

This illustrates that for this situation the design water level has a primary role in the contribution to the failure probability due to overtopping.

Reflection
For overtopping it does not matter if a gap or a house is assumed, because both situations have the same overtopping requirement. Furthermore, the exact position of the house does not matter. This means that when the overtopping requirements are not met two things can be done:

- Decrease the amount of actual overtopping
- Increase the maximum allowable amount of overtopping

5.4.4. Total Failure probability

An overview of the calculated failure probabilities per failure mechanism and the total failure probability of the conservative current schematisation and the proposed schematisation can be seen in Table 5.7.

	Proposed method	**Conservative method**
Macro stability	$0.02 \cdot 10^{-5}$	$20 \cdot 10^{-5}$
Piping	$6.67 \cdot 10^{-5}$	$6.67 \cdot 10^{-5}$
Overtopping	$0.0381 \cdot 10^{-5}$	$0.0381 \cdot 10^{-5}$
Total failure probability	$\mathbf{6.73 \cdot 10^{-5}}$	$\mathbf{26.71 \cdot 10^{-5}}$

Table 5.7: Failure probabilities

In this particular situation the total failure probability is significantly lower. For overtopping the requirements are kept the same, so for overtopping no additional failure probability is present. The piping length is also equal in both situations, leading to the same probability of failure for piping. So, the difference in total failure probability, in this case, is due to the difference in failure probability for macro stability. This can lower the failure probability due to macro stability with 99.9%, and lowers total failure probability by 75%. The influence of this schematisation method is much depended on the situation.

Sensitivity analysis
As discussed earlier in this chapter, the 0.1% that is chosen for the absence of a building is conservative. For this reason the sensitivity of this percentage is checked against the chances of the building being absent of 0.01% and 0.001%. This gives the following results:

	Proposed method (0.1%)	**0.01%**	**0.001%**
Macro stability	$0.02 \cdot 10^{-5}$	$0.002 \cdot 10^{-5}$	$0.0002 \cdot 10^{-5}$
Piping	$6.67 \cdot 10^{-5}$	$6.67 \cdot 10^{-5}$	$6.67 \cdot 10^{-5}$
Overtopping	$0.0381 \cdot 10^{-5}$	$0.0381 \cdot 10^{-5}$	$0.0381 \cdot 10^{-5}$
Total failure probability	$\mathbf{6.73 \cdot 10^{-5}}$	$\mathbf{6.71 \cdot 10^{-5}}$	$\mathbf{6.71 \cdot 10^{-5}}$

Table 5.8: Failure probabilities

When a 0.01% absence of the house is assumed, a total failure probability almost equal to the proposed method is achieved. For an absence of 0.001% of the time the additional failure probability is negligible compared to the situation of 0.01% absence. This shows that when a lower percentage is assumed it does not lower the total failure probability by much. For this reason, the conservative assumption is made for 0.1%.

5.5. Comparison with a standard dike profile

In previous sections the current schematisation which assumes a gap and the proposed schematisation which takes into account the house were compared to each other. To determine the effect of new construction, the dike profile of the case study is compared to the same dike section without a house or a gap, which can be seen in Figure 5.23. This comparison can show whether the house strengthens or weakens the dike.

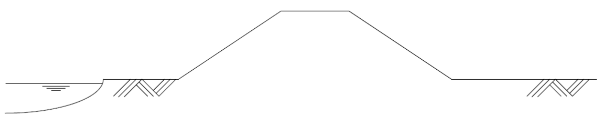


Figure 5.23: Standard dike section

For overtopping, the failure probability requirement changes from 1 l/s/m to 10 l/s/m for a standard dike because there are no longer transitions between the house and the dike that are extra susceptible to erosion. This results in a failure probability of $1.35 \cdot 10^{-16}$.

For piping, the piping length is reduced by the placement of the house. This means that the situation without buildings has a lower failure probability. The piping length of a dike without buildings is 27 meters, corresponding to a failure probability of $1.15 \cdot 10^{-7}$. When a shallow foundation is used, the piping length extends to 33 meters. This increases the piping length compared to the standard dike, thus having a positive impact on the failure probability. For a piping length of 33 meters, the failure probability is $4.59 \cdot 10^{-9}$. Therefore, the type of foundation is crucial for the failure probability due to piping and consequently for the overall failure probability.

For macro stability, the reliability index is 11.696 for the standard dike. This corresponds to a failure probability of $6.68 \cdot 10^{-32}$. An overview of the failure probabilities can be seen in Table 5.9.

	Standard dike	**Case (pile foundation)**	**Shallow foundation**
Macro stability	$6.68 \cdot 10^{-32}$	$0.02 \cdot 10^{-5}$	$0.02 \cdot 10^{-5}$
Piping	$1.15 \cdot 10^{-7}$	$6.67 \cdot 10^{-5}$	$4.59 \cdot 10^{-9}$
Overtopping	$1.35 \cdot 10^{-16}$	$0.0381 \cdot 10^{-5}$	$0.0381 \cdot 10^{-5}$
Total failure probability	$\mathbf{1.15 \cdot 10^{-7}}$	$\mathbf{6.7 \cdot 10^{-5}}$	$\mathbf{5.86 \cdot 10^{-7}}$

Table 5.9: Failure probabilities

As can be seen in Table 5.9, the total failure probability of a standard dike is lower than that of the case study. It has to be said that it is very depended on the specific situation. When a shallow foundation is assumed instead of a pile foundation, the failure probability would already be much lower. So depending on the situation, the building could lower or higher the total failure probability of the dike section.

When the failure probability of the dike increases, bringing the failure probability above the required failure probability of the dike section, the house cannot be build on the dike. The house can only be constructed after the dike has been reinforced by a sufficient amount. If the failure probability of the dike section decreases, the construction only has beneficial effects for the dike and thus could take place.

When the required failure probability is not met, mitigation measures can be taken for the failure mechanisms overtopping and piping. For overtopping, the failure probability increases due to the transitions that are created between the dike and the house, resulting in a stricter failure probability. If these transitions receive proper protection, more overtopping could be allowed, thus reducing the failure probability due to overtopping. To increase the piping length and thus decrease the failure probability due to piping, a piping screen could be added as a mitigation measure.

5.6. Conclusion

Deepening question: "How can the influence of the house on the various failure mechanisms be schematised?"

The current schematisation method is unrealistic and overly conservative. As described in other documents, it is not likely that the house would not be present at the location. It has been argued using an event tree (Figure 5.24) that the probability of the presence of a house is 99.9% and the probability that a house would not be present is 0.1%. As a result, the following schematisation in Figure 5.25 has been proposed.

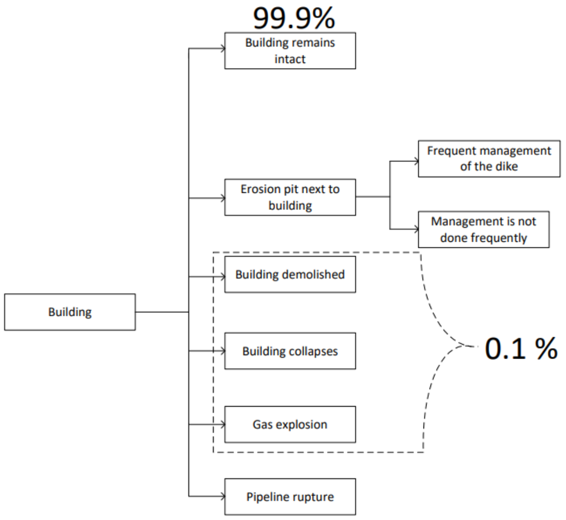


Figure 5.24: Event tree

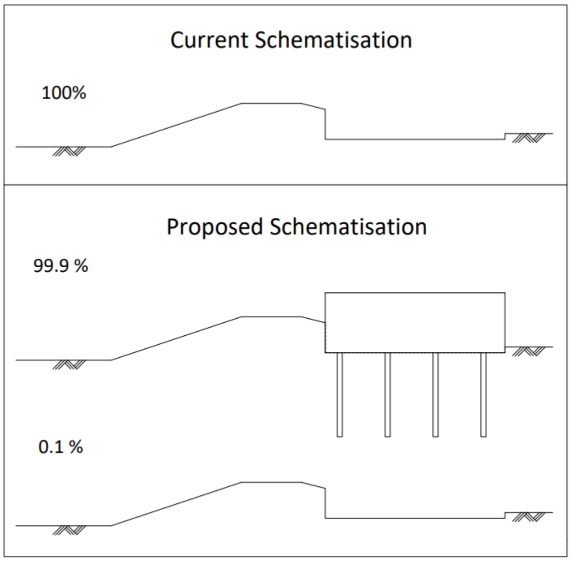


Figure 5.25: Proposed schematisation

Deepening question: "What is the effect of incorporating the proposed schematisation on the total failure probability of the dike, and how does it compare to the current conservative assessment method?"

The reduction in total failure probability for the case is determined at 75%. This result shows that the proposed schematisation, which takes into account the influence of the house, is considerably less conservative than the existing method, resulting in a lower failure probability for the dike. Therefore, the dike can rely significantly on the strength of the house. When this strength is practically attributed, it can lead to more construction near dikes and less rejection of existing construction near dikes.

A probabilistic method for determining the probability of failure has been established. However, this is not desirable for a method because it is not easy to apply and probabilistic calculations can take time to set up. It is therefore desirable to have a Level I reliability assessment, which is easy applicable. By doing this, no probabilistic calculations have to be made and the method will be easy to implement. The partial safety factors, that include the standard deviations of the stochastic variables, will be based on the probabilistic calculations, so it will be a detailed assessment, which is easy to apply. These partial safety factors will be derived in the next chapter.

6

Derivation of the partial safety factors

Step 4 of the main methodology

In chapter 4 the relevant failure mechanisms per location were determined. The contribution of a house to the overall failure probability of a dike section using a probabilistic approach was determined in Chapter 5. In this chapter, the partial safety factors are calculated based on the probabilistic approach in Chapter 5. These partial safety factors are used in the improved simplified assessment method, while still ensuring the required target reliability.

First, general theory about partial factors and how they have been derived is discussed. Subsequently, the partial factors are derived for the selected case and it is explained how they could be used in a Level I reliability assessment. Finally, it is mentioned how the partial safety factors can be used in the design of buildings on and in dikes.

6.1. General theory about partial safety factors

Partial safety factors ensure that the design value of the stochastic variable can be calculated from its mean or characteristic value. The design value of the stochastic variable is the value used for design purposes. The partial safety factor incorporates the standard deviation of the stochastic variable σ, the influence factor α, and the target reliability β. The standard deviations and means of the stochastic variables have been mentioned previously in Chapter 5. The influence factors have been derived from the FORM analysis. The target reliability is the maximum allowable failure probability for a specific failure mechanism per dike segment. This has also been determined in Chapter 5.

When a stochastic variable has a small influence factor and a small standard deviation, this results in a partial safety factor close to 1. However, a stochastic variable with a significant influence factor and a large standard deviation can lead to larger values.

In general, the characteristic values of each stochastic variable are typically chosen as the 95% value for the load and the 5% value for the resistance. From there, a partial factor is usually applied to relate these values to the design value. In this case, however, the decision is made to take the average value as the characteristic value. There are two reasons for this choice in this situation.

- The first reason for this is that when the average values are chosen as the characteristic value, they can be used in the level I calculation. After all, the formula for the level I reliability calculation is:

$$\frac{R_{rep}}{\gamma_R} \geq \gamma_S \cdot S_{rep} \tag{6.1}$$

  When this is done, there is no need to calculate the characteristic value for each parameter, instead the average values can simply be used.

- The second reason is that when using the 95% and 5% values, and the load or resistance factor has a small standard deviation and a small influence factor, it can happen that the load factor is smaller than the characteristic value. For the resistance, this can cause the value to be greater than the characteristic value. This can result in both the load and resistance partial factors being smaller than 1, which might feel intuitively odd. When the average value is chosen as the characteristic value, it is always greater than 1.

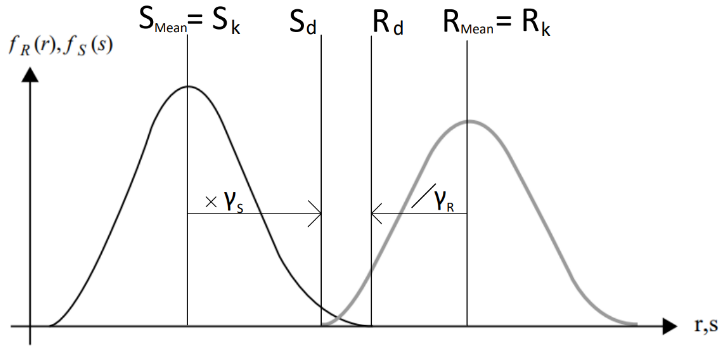


Figure 6.1: Relation between characteristic value and the design value

6.2. Calculation of the partial safety factors for the assessment of multi-functional dikes

First, the formulas that were used to calculate the partial factors are explained in Section 6.2.1. Next, in Section 6.2.2, the stochastic variables and their corresponding properties are given, and ultimately, the partial factors are calculated.

6.2.1. Level I reliability calculation

The assessment with partial safety factors is referred to as a level I assessment. For a level I assessment it is checked if the design value of the required strength is equal to or bigger than the design value of the load. The design values are related to the representative values through partial safety factors. This can be seen below.

$$R_d \geq S_d \tag{6.2}$$

$$\frac{R_{rep}}{\gamma_R} \geq \gamma_S \cdot S_{rep} \tag{6.3}$$

These partial safety factors are derived from the probabilistic calculations in the previous chapter. The design point is the point in the failure space with the highest joint probability density of the load and the strength. Therefore, it is possible that for the calculation of the failure probability, the values of the strength and the load are close to the values of the design point (Jonkman, Steenbergen, Morales Nápoles, Vrouwenvelder, & Vrijling, 2017). These values are:

$$r^* = \mu_R + \alpha_R \cdot \beta \cdot \sigma_R = \mu_R \cdot (1 + \alpha_R \cdot \beta \cdot V_R) \tag{6.4}$$

$$s^* = \mu_S + \alpha_S \cdot \beta \cdot \sigma_S = \mu_R \cdot (1 + \alpha_S \cdot \beta \cdot V_S) \tag{6.5}$$

The characteristic values are calculated using the following formulas:

$$R_k = \mu_R + k_R \cdot \sigma_R \tag{6.6}$$

$$S_k = \mu_S + k_S \cdot \sigma_S \tag{6.7}$$

In this situation it is assumed that the k is 0 and the mean value is the characteristic value. By doing this, the mean values can be used in the deterministic calculations and no additional calculation has to be made to derive the characteristic values.

Next, the partial factors can be computed with the following formulas:

$$\gamma_R = \frac{R_k}{r*} \tag{6.8}$$

$$\gamma_S = \frac{s*}{S_k} \tag{6.9}$$

As can be seen in the formulas above, the partial safety factor will be larger if:

- The reliability index, β, is larger
- The influence coefficient, α, is larger
- The coefficient of variation, V, is larger

6.2.2. Calculation of the partial safety factors

For each stochastic variable, a partial factor is calculated using the formulas above. This is done separately for each failure mechanism. An overview of the stochastic variables per failure mechanism is shown with an indication if the stochastic variable works as a load or resistance. Influence factors, coefficients of variation and mean values are indicated as well. The mean values are derived from Eurocode 7 NEN-EN9997. The coefficients of variation have been derived from the "WBI onzekerheden" document, and together with the mean, the standard deviation of the parameters has been calculated. The influence factors have been determined from the FORM analysis in Chapter 5.

The calculation of the partial safety factor for the internal friction angle for macro stability is included below. The rest of the partial safety factors have been calculated in Appendix B. The results are shown in this section.

$$r^* = \mu_R \cdot (1 + \alpha_R \cdot \beta \cdot V_R) = 17.5 \cdot (1 + 0.517 \cdot 4.769 \cdot 0.15) = 11.03^\circ \tag{6.10}$$

$$R_k = \mu_R + k_R \cdot \sigma_R = 17.5^\circ \tag{6.11}$$

$$\gamma_R = \frac{R_k}{r*} = \frac{17.5}{11.03} = 1.587 \tag{6.12}$$

Macro stability

Parameter	S/R	Mean, μ	Coefficient of variation, V	Influence factor, α	Standard deviation, σ
c_{clay}	R	13	0.257	0.856	3.57
ϕ_{clay}	R	17.5	0.15	0.517	2.625

Table 6.1: Parameters macro stability

The parameters mentioned in Table 6.1 act as resistance. This means when the value of cohesion or the friction angle increases, the probability of failure for the failure mechanism decreases. The target reliability, β_T, for macro stability is 4.769 and is determined based on the maximum required failure probability for the dike section for the failure probability macro stability, as can be seen in Chapter 5. An overview of the partial safety factors can be seen in Table 6.2.

Parameter	partial factor
$\gamma_{c_{clay}}$	2.049
$\gamma_{\phi_{clay}}$	1.587

Table 6.2: Partial factors for macro stability

For macro stability, the calculated partial safety factors can be used directly in D-stability. These must be multiplied by the mean of the parameters, which are assumed stochastic. Next, a deterministic calculation can be done in D-stability from which the safety factor follows. When the safety factor is greater than 1 the dike meets the required failure probability for macro stability.

Piping

Parameter	S/R	Mean, μ	Coefficient of variation, V	Importance factor, α	Standard deviation, σ
$d70_{sand}$	R	0.0002	0.12	-0.705	$2.4 \cdot 10^{-5}$
D_{sand}	S	1.50	0.3	0.224	0.45
L	R	18	0.1	-0.429	1.8
k_{sand}	S	$4.86 \cdot 10^{-4}$	0.5	0.383	$2.43 \cdot 10^{-4}$
H_{actual}	S	1.5	0.1	0.351	0.15

Table 6.3: Parameters for piping

The target reliability β_T for piping is 4.688 and is based on the required failure probability determined in Chapter 5. An overview of the partial factors for piping can be seen below:

Parameter	partial factor
γ_{d70}	1.657
γ_D	1.315
γ_L	1.252
γ_k	1.898
H_{actual}	1.16

Table 6.4: Partial factors for piping

The Level I reliability assessment for piping is done using the formula of Sellmeijer with the partial safety factors included (bold gamma signs). This gives the following formulas:

$$H_c = F_R \cdot F_S \cdot F_G \cdot \frac{L}{\boldsymbol{\gamma}_{\mathbf{L}}} \tag{6.13}$$

$$F_R = \eta(\frac{\gamma_P - \gamma_W}{\gamma_W}) \cdot \theta \cdot \tan(\eta) \tag{6.14}$$

$$F_S = \frac{\frac{d_{70}}{\boldsymbol{\gamma}_{\mathbf{d70}}}}{\sqrt{(\frac{v}{g} \cdot k \cdot \boldsymbol{\gamma}_{\mathbf{k}}) \cdot \frac{L}{\boldsymbol{\gamma}_{\mathbf{L}}}}^{3}} \tag{6.15}$$

$$F_G = 0.91 \cdot \frac{D \cdot \boldsymbol{\gamma}_{\mathbf{D}}}{\frac{L}{\boldsymbol{\gamma}_{\mathbf{L}}}}^{\frac{0.28}{\frac{D \cdot \boldsymbol{\gamma}_{\mathbf{D}}}{(\frac{L}{\boldsymbol{\gamma}_{\mathbf{L}}})^{2.8} - 1}} + 0.04} \tag{6.16}$$

The level I assessment can be performed by checking if the calculated critical head calculated with the partial factors is greater than the actual head multiplied by the corresponding partial factor.

$$H_c \geq H_a \cdot \gamma_{H_a} \tag{6.17}$$

When this requirement is met, the dike with a house meets the required failure probability for piping.

Overtopping

Parameter	S/R	Mean, μ	Coefficient of variation, V	Influence factors, α	Standard deviation, σ
h	S	7.7	0.013	0.888	0.1
u_{10}	S	11.3	0.10	0.459	1.13

Table 6.5: Parameters for overtopping

The target reliability, β_T, for overtopping is 4.798 and is based on the maximum required failure probability determined in Chapter 5. An overview of the partial factors for overtopping can be seen below:

Parameter	partial factor
γ_h	1.055
γ_{u10}	1.220

Table 6.6: Partial factors for overtopping

The level I reliability assessment is done using the Brettschneider equation and the Van der Meer equation, which have been described in Chapter 5. Just like for piping, the stochastic variables in these formulas need to be multiplied by their partial safety factors. Ultimately it can be checked if the calculated amount of overtopping meets the requirements.

$$q_{overtopping} < q_{requirement} \tag{6.18}$$

As argued earlier, it does not matter for overtopping where the location of the house is assumed and whether the house is present for the overtopping requirement.

6.3. Calculation of the partial safety factors for the design of multifunctional dikes

A distinction can be made between designing buildings in dikes and assessing buildings in dikes. In an assessment, an existing design is checked and evaluated to see if it meets the specified requirements. In this process, the loads and resistance are based on what already exists. This results in determining whether the dike does or does not meet the required failure probability (as done in Section 6.2).

In a design process, a new house is being built, which needs to satisfy the requirements. In doing so, the loads cannot be controlled just like most of the soil parameters, but the dimensions and the material properties of the building can be controlled until the design meets the required failure probability. For the different failure mechanisms it is argued which parameters can be influenced in the design process.

Macro stability
For macro stability, the stochastic soil parameters cannot be changed. The dimensions of the house can be adjusted, so the location of the forbidden line in D-stability, through which the slip circle cannot occur, can be changed. As argued earlier in Chapter 5, adopting this forbidden line has the biggest influence on the failure probability of the dike. In D-stability, the calculated partial factors can be used for a deterministic calculation by multiplying the partial factors with the mean of the stochastic variables.

Piping
For Piping, the only parameter that can be influenced in the design is the piping length. The piping length depends on the location of the house near the dike. To calculate the necessary piping length, the Level I reliability assessment can be performed with the length taken as an unknown parameter, and look when the total resistance is greater than the force.

Overtopping
As argued earlier, it does not matter where the location of the house is assumed and whether the house is present for the overtopping requirement. As a result, there is little to do about the house for design purposes

if the required failure probability for overtopping is not met. For overtopping, however, other measures can be taken to reduce the amount of overtopping or to allow more overtopping. Some measures are briefly mentioned but are not discussed in depth because they are beyond the scope.

Measures to reduce the amount of overtopping:

- Placement of a small retaining wall on the dike
- Changes in the dike geometry, like reducing the outer slope angle

Measures to allow more overtopping:

- Protection of the transitions between the house and dike

6.4. Conclusion

Deepening question: "How can a multifunctional dike section with a structure be assessed?"
Based on the probabilistic calculations, partial safety factors have been determined. These partial factors have been calculated per stochastic variable. This allows for a Level I reliability calculation to determine whether a dike cross-section with a house meets the failure probability requirement of the cross-section. This corresponds to the formula below, but with a partial factor added for each resistance parameter (R_{rep}) and load parameter (S_{rep}). Through these partial safety factors, a multifunctional dike containing a house can easily be assessed using a Level I design calculation:

$$\frac{R_{rep}}{\gamma_R} \geq \gamma_S \cdot S_{rep} \tag{6.19}$$

However, these partial safety factors are only applicable to their specific situation. The factors calculated can only be applied if the location, subsoil, foundation and other factors are the same. In the next chapter, the generalisation step will be made, making the method generally applicable.

7

Generalisation of the level I reliability assessment method

Step 5 of the main methodology

The method has been created for one certain case in Chapter 6. In this chapter, the method will be generalised. The goal of the generalisation is deriving partial safety factors for other scenarios, so that a set of partial factors can be chosen depending on the situation.

First, the most common scenarios are identified and partial safety factors have been derived for them. Next, a process description has been given for deriving the partial safety factors for scenarios that have not been discussed.

7.1. Derivation of the partial safety factors for common situations

7.1.1. Determining the most important parameters

In this section, it is determined which aspects are most important in the generalisation. The parameters that can be considered for variation are:

- Dike geometry
- Soil type
- Type of foundation
- Location
- House dimension
- Required failure probability for dike segment
- Existing buildings

For each of the parameters it is described how they influence the failure mechanisms macro stability and piping. For peat dikes, horizontal sliding is also taken into account. Overtopping is not taken into account, as the overtopping requirement will not change. However, using the dike geometry, it is possible to reduce the actual amount of overtopping.

Dike geometry
The geometry of the dike affects the probability of failure of the dike and, thus, the partial safety factors.

- Macro stability: The slope of the dike and the width of the crest affect the stability of the dike. The wider the dike and the less steep the slope, the more stable the dike is.

- Piping: The piping length is influenced by the width of the base of the dike.

Soil types
For the soil parameters in the case study a clay dike on sand was assumed. The type of soil can cause other failure mechanisms to occur. An example of this is horizontal sliding with peat dikes. Most of the dikes in the Netherlands consist of clay because it is a watertight material.

- Macro stability: Other soil types have a different internal friction angle and different cohesion, which can affect macro stability.
- Piping: Changes in the aquifer can also make piping less likely to occur.
- Horizontal sliding: Horizontal sliding can occur in the summer when it has been dry for a long time and the peat dike is relatively light. The dike could literally slide due to the load of water.

Type of foundation
Distinctions have been made between a pile foundation and a shallow foundation. The differences between the various types of pile foundations and shallow foundations have not been addressed.

- Macro stability: For macro stability, the type of foundation can make a difference. A pile foundation can cut through the slip circle and thus provide more stability against shear. For a shallow foundation, this is not the case.
- Piping: It does matter for piping what the type of foundation is for the calculation of the failure probability.

  Pile foundation
  A pile foundation is schematized in Figure 7.1. Water can slip along the piles to the bottom of the structure. Next, spaces can occur between the structure and the soil, allowing the water to flow without resistance. For this reason, a piping length of 18 meters was assumed.

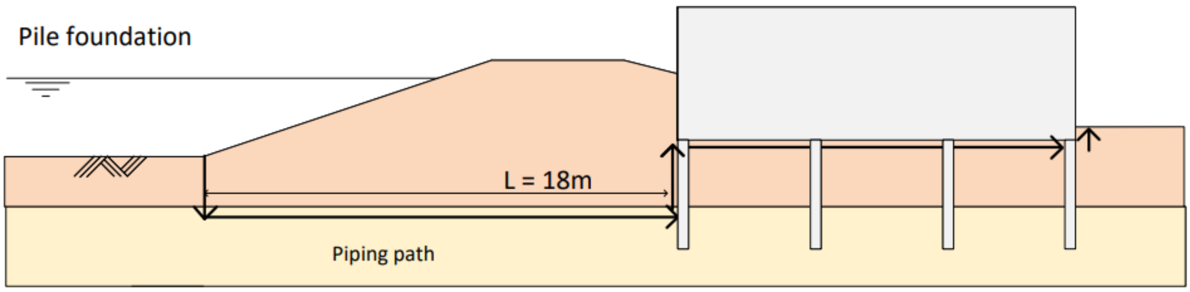


Figure 7.1: Schematisation of a house with a pile foundation

  Shallow foundation
  For piping to occur, uplift has to occur first. There may still be a few spaces below the shallow foundation, but they need to be bigger for uplift to occur. For this reason, the piping occurs right after the structure where uplift can occur.

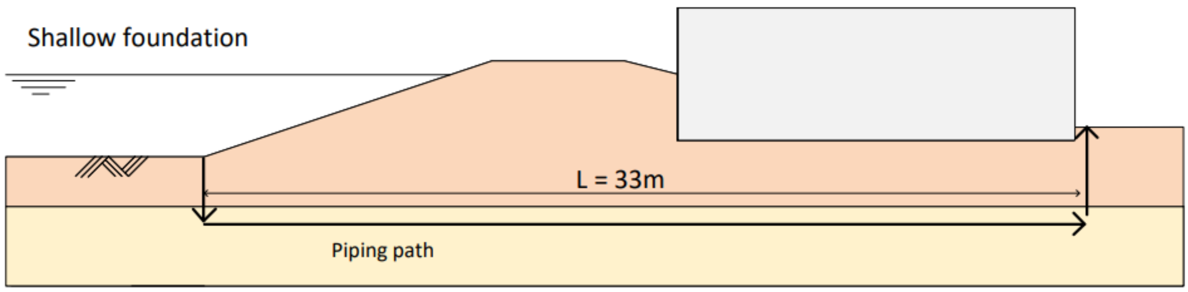


Figure 7.2: Schematisation of a house with a shallow foundation

Location
The location has much influence on the effect of construction per failure mechanism. In Chapter 4 the different effects per location on the failure mechanisms have already been shown.

- Macro stability: The location of a house near a dike can contribute to the strength of a dike when it is located at the toe of the dike but has a negative effect when it is at the crest of the dike. For this reason, it has been decided to derive partial factors for the locations in Figure 7.4.

- Piping: The piping length is also greatly influenced by the placement of the house. When a house is situated in the slope or at the toe of the dike, it could shorten the piping length compared to a plain dike, making it more susceptible to piping.

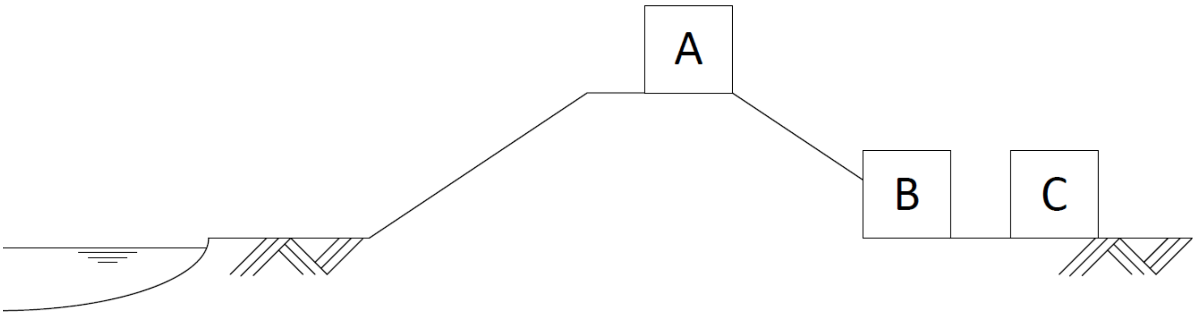


Figure 7.3: Possible house locations

Target reliability
The required failure probabilities of dike sections range from 1/100 per year to 1/100,000 per year. The required failure probability affects the partial factors. After all, a stricter failure probability requirement must lead to a stricter assessment and, thus, more critical partial safety factors. The failure probability of the dike section is linked directly to the reliability index, β. This, in turn, can be translated to the failure probability per dike section using the fixed failure probability distribution and the length-effect factors. Only the reliability index will change when calculating the partial factors for other failure probabilities.

Existing buildings
For new buildings, it is assumed that the state of the multifunctional elements is known and good. For existing buildings, this is often not the case. For this reason, existing buildings will be schematised more conservatively.

- Macro stability: This schematisation will influence macro stability. The schematisation of existing buildings will be taken into account in the next section.

- Piping: For piping there are no extra consequences.

House dimensions
The dimensions of the house can have a large impact on the failure mechanisms of macro stability and piping, and can have both a positive and negative impact depending on the location.

- Macro stability: For macro stability, the slip circle cannot occur through the house, so larger dimensions can provide a lower failure probability for the situation with a house. However, for the situation where a gap is assumed, a larger house can cause a larger failure probability. Because this situation can be normative, it can lead to a larger failure probability overall.

- Piping: For piping, the length of the house can affect the piping length. When a house is built more towards the dike crest, the piping length is reduced, and the failure probability of the dike is increased.

Conclusion
The situations above encompass the different scenarios for which other partial factors can be found. The most diverse and frequently occurring situations have been distinguished from these situations. These are the following five situations:

- Clay dike on sand
- Peat dike
- House located at the crest
- House located at the toe
- Existing buildings

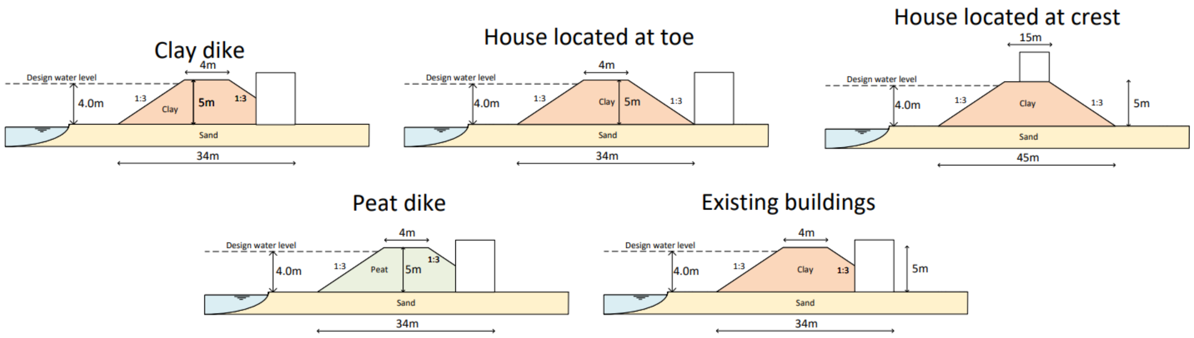


Figure 7.4: Overview of the scenarios

Partial factors have been derived for these five situations.

7.1.2. Derivation of the partial safety factors for the chosen scenarios

The process for deriving the partial factors is the same as has been done in Chapter 5 (probabilistic calculations) and Chapter 6 (derivation of the partial factors). It is first argued for which of the failure mechanisms the failure probability does not change compared to the first situation of a clay dike. Next, it is determined for which failure mechanisms the failure probability does change and how the situation would be schematised. Subsequently, as in Chapter 5, the influence factors are calculated and, as in Chapter 6, the partial factors are derived.

First, the partial factors of the situation with a clay dike have been determined. Subsequently, the partial factors of the other situations have been determined and compared with each other. The steps are not described in great detail, as this has already been done in Chapters 5 and 6. For the different situations, a FORM analysis has been performed to determine the influence factors. The failure probability of the dike section is estimated the same as in the case. From the failure probability of the dike section, the reliability index is determined.

Failure mechanisms	Required failure probability	Reliability index
Macro stability	$9.28 \cdot 10^{-7}$	4.769
Piping	$1.38 \cdot 10^{-6}$	4.688
Overtopping	$8.0 \cdot 10^{-7}$	4.798

Table 7.1: Required failure probabilities per failure mechanism

Each scenario is built up in approximately the same way. First, a short description of the situation is given, followed by the schematisation of the scenario. Subsequently, the influence factors are calculated from the FORM analysis and finally the partial safety factors are determined.

7.1.3. Clay dike

For the generalisation, a standard situation has been determined with a house in the slope. The partial factors for this have been determined first, and variants of this situation have been chosen to see what the effect would be on the partial safety factors.

Schematisation

The clay dike can be seen in Figure 7.5. A slope of 1:3 has been chosen because dike slopes often vary between 1:3 and 1:5. When a slope of 1:5 is adopted, the dike is much more stable and wider, making it more resistant to failure mechanisms such as macro stability and piping. The most critical values are taken, so that when a dike has a flatter slope, it will also meet the requirements when the same partial factors are used.

For the house dimensions, a width of 10 meters has been assumed. This is considered the minimum width that a house would have. This minimum width allows the slip circle to occur more easily than in the case study, which assumed a width of 15 meters for the house.

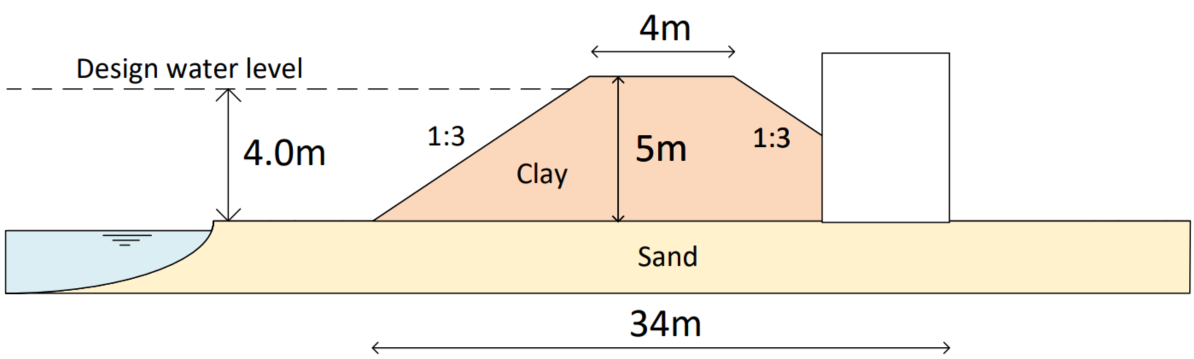


Figure 7.5: Standard situation

Calculation of the partial safety factors

Macro stability

For macro stability, as determined in Chapter 5, the situation without a house is governing. The following partial safety factors have been calculated. The corresponding influence factors derived from the FORM analysis can be seen in Appendix C.

Parameter	**partial factor**
$\gamma_{c_{clay}}$	2.786
$\gamma_{\phi_{clay}}$	1.388

Table 7.2: Partial factors for macro stability

Piping

The piping length is 24 meters. This gives the following partial safety factors.

Parameter	**partial factor**
γ_{d70}	1.424
γ_{D}	1.395
γ_{L}	1.224
γ_{k}	2.334
$\gamma_{H_{actual}}$	1.190

Table 7.3: Partial factors for piping

Overtopping
For overtopping, the same values were used for wind speed and fetch as in Chapter 5. However, the values for the dike geometry are adjusted to the new geometry. This gives the following values for the partial safety factors for overtopping.

Parameter	partial factor
γ_h	1.108
$\gamma_{u_{10}}$	1.208

Table 7.4: Partial factors for overtopping

These partial factors for overtopping apply to each situation for overtopping. For this reason, overtopping is not mentioned again for the remaining scenarios.

7.1.4. Peat dike

Peat dikes occur to a lesser extent in the Netherlands, but for peat dikes, the failure mechanism of horizontal sliding can also play a significant role. This is because peat dikes can have a relatively low weight in summer. When the water level is high, the hydrostatic pressure of the water can cause the dike to literally slide.

Schematisation

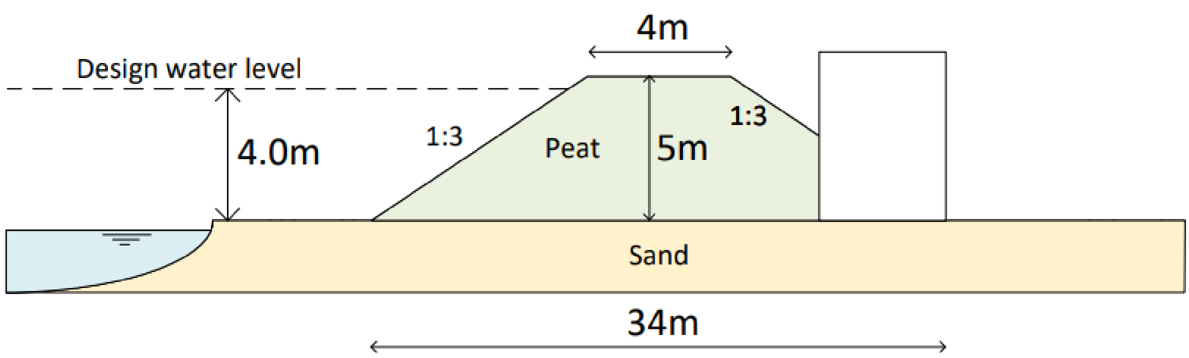


Figure 7.6: Standard situation

Calculation of the partial safety factors

Horizontal sliding
Horizontal sliding depends on the horizontal force acting on the dike and the shear resistance of the dike. This will be taken into account for peat dikes. The limit state function for horizontal sliding can be seen below.

$$Z_{piping} = H_r - H_s \tag{7.1}$$

The resisting force can be determined from the resisting shear stress on the foundation surface. This can be calculated with the following formula:

$$\tau_{max} = f \cdot \sigma'_n \tag{7.2}$$

For the calculation of the resisting force the shear force is multiplied with the surface.

$$H_s = \frac{1}{2} \cdot \rho \cdot g \cdot h^2 \tag{7.3}$$

$$H_r = L_{dike} \cdot \tau_{max} \tag{7.4}$$

in which:

$\tau_{max}[kPa]$	maximum shear stress in the foundation surface
f [-]	coefficient of friction tan(δ)
δ[]	angle of friction between foundation slab and soil
$\sigma'_n[kPa]$	The effective normal stress under the foundation

The main acting force on the dike is the hydrostatic pressure. For calculating the horizontal force on the dike due to the hydrostatic pressure, the design water level is used. The corresponding partial safety factors can be seen in Table 7.5.

Parameter	Value
$\gamma_{\phi_{peat}}$	3.469
γ_h	1.01

Table 7.5: Partial factors for horizontal sliding

Macro stability
The partial safety factors for macro stability can be seen below.

Parameter	partial factor
$\gamma_{c_{peat}}$	2.915
$\gamma_{\phi_{peat}}$	2.524

Table 7.6: Partial factors for macro stability

Piping
The piping length remains the same as that of the clay dike. This ensures that the failure probability with respect to piping will not increase and the partial safety factors will be the same as in the first case.

7.1.5. House located at crest of the dike

As argued earlier in this chapter, the location of the house greatly affects the probability of failure of the dike. If the house is located on the dike crest, it will have a negative effect on macro stability by allowing the house to contribute to the active ground moment.

Schematisation

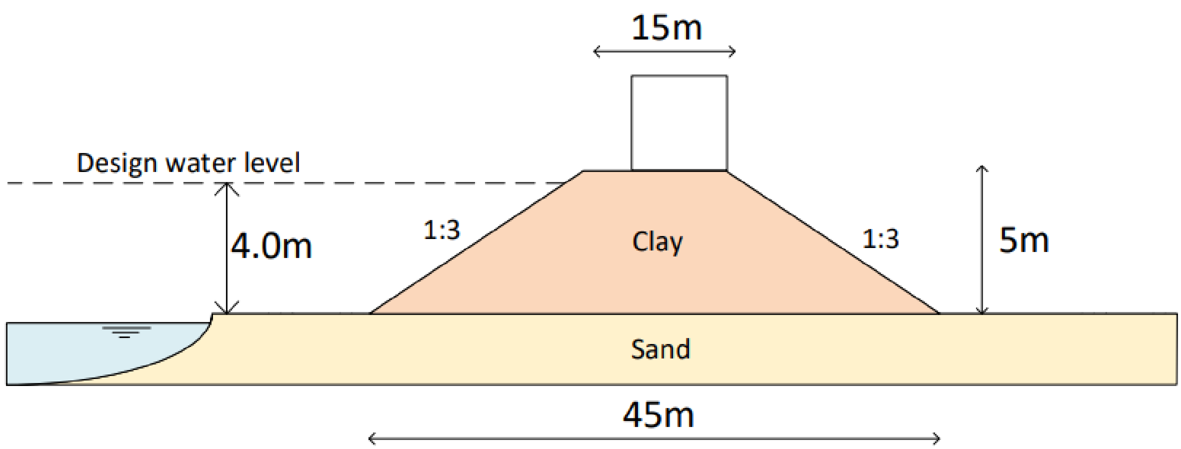


Figure 7.7: Standard situation

Calculation of the partial safety factors

Macro stability
The partial safety factors for macro stability can be seen below.

Parameter	partial factor
$\gamma_{c_{clay}}$	1.376
$\gamma_{\phi_{clay}}$	1.194
$\gamma_{\phi_{sand}}$	3.107

Table 7.7: Partial factors for macro stability

Piping
Because the crest is wider compared to the standard situation, the piping length increases. The piping length is 45 meters. The following partial safety factors have been calculated:

Parameter	partial factor
γ_{d70}	1.599
γ_{D}	1.339
γ_{L}	1.256
γ_{K}	1.970
$\gamma_{H_{actual}}$	1.173

Table 7.8: Partial factors for piping

7.1.6. House located at toe of the dike

The situation with the house at the toe would only make the dike more resistant to macro stability. This ensures that the situation without a house would be governing. However, the situation without a house gives a plain dike because the house is located at the toe of the dike. It can be assumed that the dike meets the required failure probability for macro stability because otherwise, the dike would have had to be reinforced in the first place. For this situation, it is therefore not necessary to consider the macro stability failure mechanism. For existing construction near the toe of the dike that has been rejected for stability, it could be included. This could result in the dike at the location of the house needing less or no reinforcement. For this reason, the influence factors and the partial safety factors have been calculated.

Schematisation

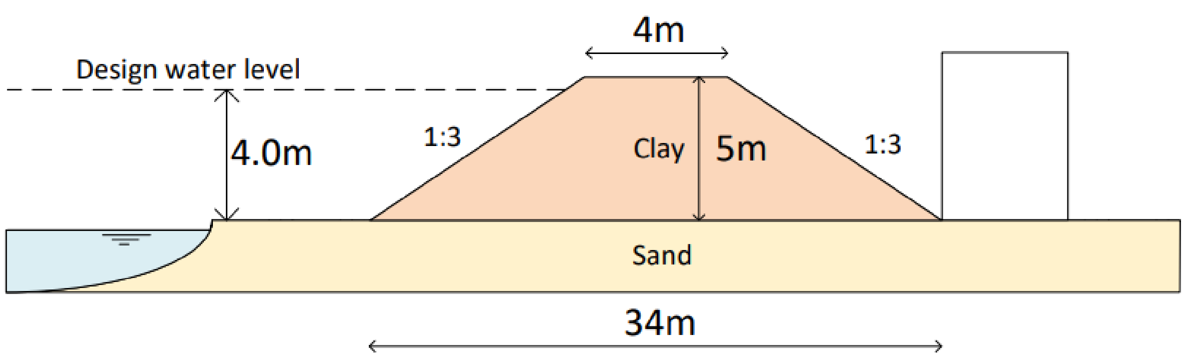


Figure 7.8: Standard situation

Calculation of the partial safety factors

Macro stability
The partial safety factors for macro stability can be seen below.

Parameter	partial factor
$\gamma_{c_{clay}}$	2.496
$\gamma_{\phi_{clay}}$	1.560
$\gamma_{\phi_{sand}}$	2.041

Table 7.9: Partial factors for macro stability

Piping

The piping length is longer compared to the first situation of the clay dike, because the house is not in the dike but at the toe of the dike. This leads to a piping length of 34 meters. The following partial safety factors have been calculated:

Parameter	partial factor
γ_{d70}	1.520
γ_{D}	1.370
γ_{L}	1.250
γ_{K}	2.111
$\gamma_{H_{actual}}$	1.185

Table 7.10: Partial factors for piping

7.1.7. Existing building

The real-life case in Chapter 5 assumes new construction. With new construction, it can be put with some certainty that various parts of the house are in good condition. With existing construction, this strength can no longer be guaranteed and the condition of certain parts of the house cannot be determined exactly. Because of this uncertainty, existing buildings must be schematised more conservatively. The different conditions for existing buildings can be seen in Figure 7.9

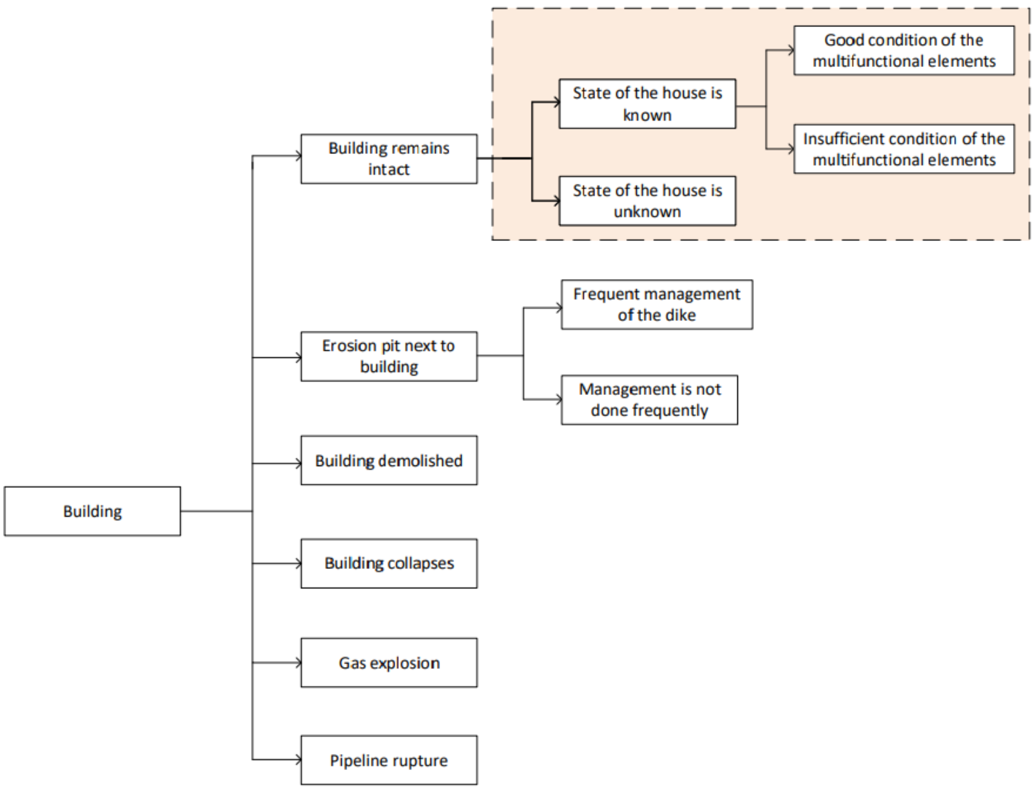


Figure 7.9: States of existing buildings

House has no longer a good condition, or the condition cannot be determined
Knowing the state of the house is important for the schematisation of the house. From existing buildings, the condition of certain walls or floors is difficult to determine, therefore it must be schematised more conservatively. It is usually easier to determine the exact state of buildings that have been built more recent, or are going to be built soon, so they can be schematised in a different, less conservative way. This will only influence the failure mechanism macro stability. Instead of forbidden lines, a rigid block with a density of 5 kN/m^2 and a height of two meters is assumed. This rigid block represents the stiffness of the house, but now it is possible for the critical slip plane to cross the building. This schematisation is much more conservative compared to the use of forbidden lines.

For overtopping, the overtopping requirement and, thus, the failure probability remains the same for both new construction and existing construction. The overtopping requirement is based on the occurrence of erosion at the transitions from the dike to the house. Whether new construction or existing construction is present does not change this requirement. For piping, no distinction is made between new construction and existing construction either.

Schematisation
It has been argued that existing construction requires a different schematisation in D-stability than new construction. This schematisation can be seen in Figure 7.10.

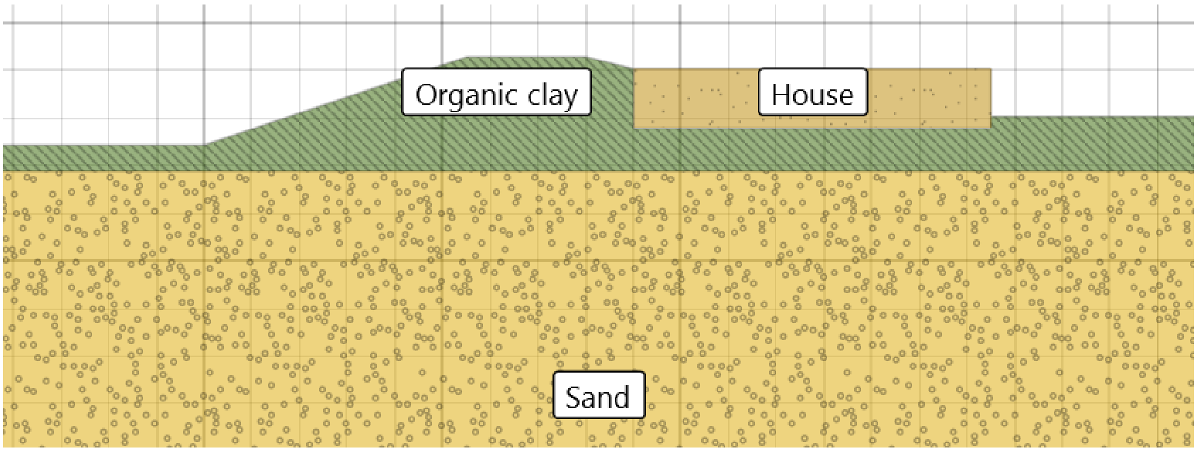


Figure 7.10: Schematisation of existing building

Calculation of the partial safety factors
The partial safety factors for macro stability can be seen below.

Parameter	partial factor
$\gamma_{c_{clay}}$	2.481
$\gamma_{\phi_{clay}}$	1.613
$\gamma_{\phi_{sand}}$	1.983

Table 7.11: Partial factors for macro stability

7.2. Process description for other cases

The process description explains how to proceed for the derivation of the partial safety factors for situations that are different from the situations described above.

The same steps made in Chapter 5 and Chapter 6 should be followed. For piping and overtopping the Python code for deriving the failure probability with a FORM analysis and the derivation of the partial factors can be adjusted easily and can be seen in Appendix A. The code indicates the values used for the parameters. When the parameters that are different are adjusted, the reliability index β and the failure probability follow from the FORM analysis. The influence factors, α, are also calculated following the FORM analysis.

For macro stability, the situation needs to be put in D-stability. The schematisation of the building depends on the building being existent or new, as is described earlier in this chapter. First, the critical slip plane must be determined in D-stability using design parameters. Next, this slip plane needs to be imported in the FORM analysis in D-stability. This will give the failure probability, reliability index and influence factors.

To derive the partial safety factors associated with these probabilistic calculations, the values of the parameters that are different need to be changed just as the reliability index, β. From the prescribed code, the values for the partial safety factors that can be used for a Level I reliability assessment will follow.

7.3. Overview

An overview of the results of the generalisation can be seen in Figure 7.11. The situations are followed by the failure mechanisms that are involved for each situation. The partial safety factors for the respective failure mechanism per situation can be seen in Figure 7.12.

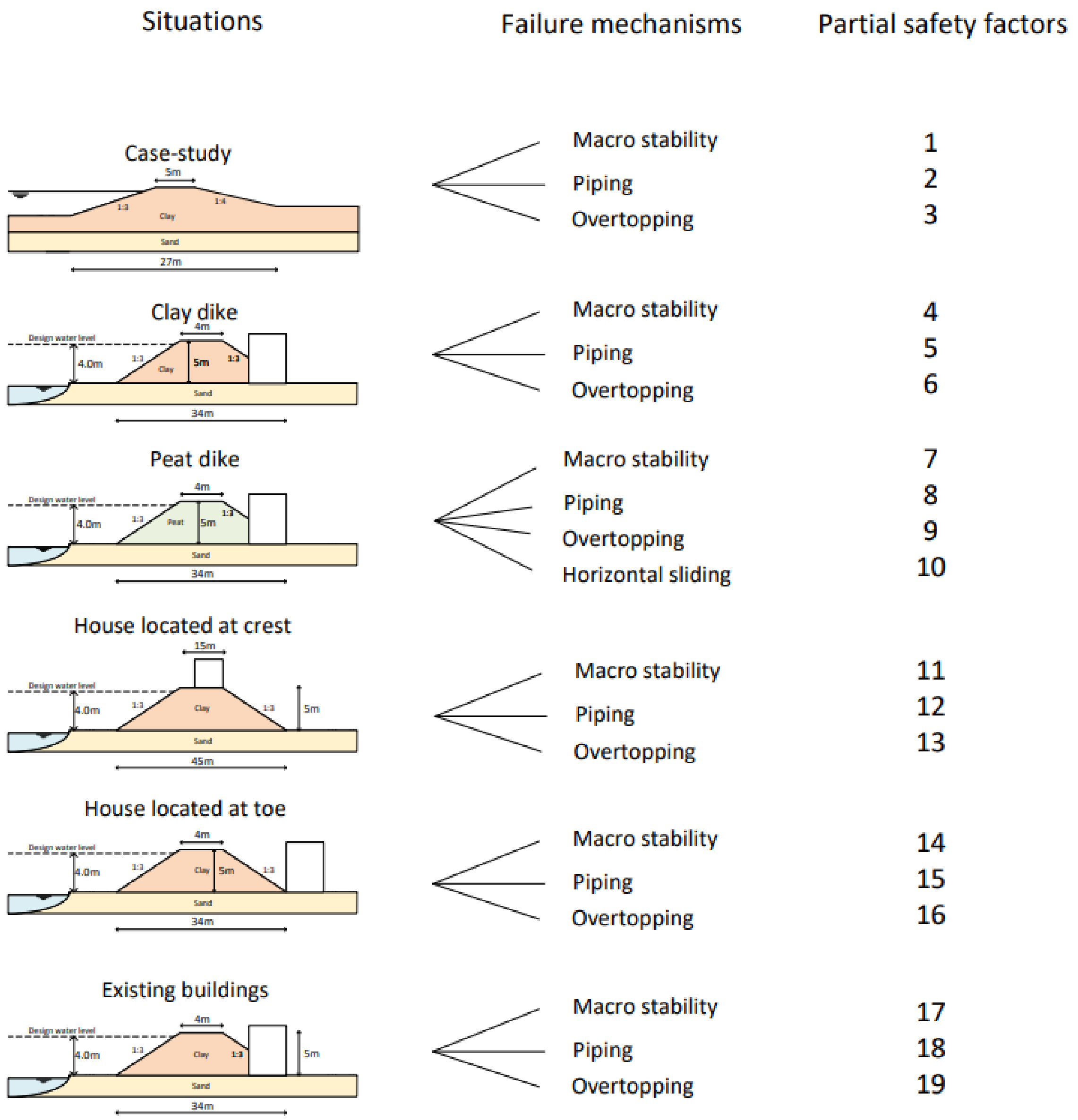


Figure 7.11: Overview of the scenarios

1

Parameter	partial factor
$\gamma_{c_{clay}}$	2.049
$\gamma_{\phi_{clay}}$	1.587

2

Parameter	partial factor
γ_{d70}	1.657
γ_D	1.315
γ_L	1.252
γ_k	1.898
H_{actual}	1.16

3

Parameter	partial factor
γ_h	1.055
γ_{u10}	1.220

4

Parameter	partial factor
$\gamma_{c_{clay}}$	2.786
$\gamma_{\phi_{clay}}$	1.388

5

Parameter	partial factor
γ_{d70}	1.424
γ_D	1.395
γ_L	1.224
γ_k	2.334
$\gamma_{H_{actual}}$	1.190

6

Parameter	partial factor
γ_h	1.108
γ_{u10}	1.208

7

Parameter	partial factor
$\gamma_{c_{peat}}$	2.915
$\gamma_{\phi_{peat}}$	2.524

8

Parameter	partial factor
γ_{d70}	1.424
γ_D	1.395
γ_L	1.224
γ_k	2.334
$\gamma_{H_{actual}}$	1.190

9

Parameter	partial factor
γ_h	1.108
γ_{u10}	1.208

10

Parameter	Value
$\gamma_{\phi_{peat}}$	3.469
γ_h	1.01

11

Parameter	partial factor
$\gamma_{c_{clay}}$	1.376
$\gamma_{\phi_{clay}}$	1.194
$\gamma_{\phi_{sand}}$	3.107

12

Parameter	partial factor
γ_{d70}	1.599
γ_D	1.339
γ_L	1.256
γ_K	1.970
$\gamma_{H_{actual}}$	1.173

13

Parameter	partial factor
γ_h	1.108
γ_{u10}	1.208

14

Parameter	partial factor
$\gamma_{c_{clay}}$	2.496
$\gamma_{\phi_{clay}}$	1.560
$\gamma_{\phi_{sand}}$	2.041

15

Parameter	partial factor
γ_{d70}	1.520
γ_D	1.370
γ_L	1.250
γ_K	2.111
$\gamma_{H_{actual}}$	1.185

16

Parameter	partial factor
γ_h	1.108
γ_{u10}	1.208

17

Parameter	partial factor
$\gamma_{c_{clay}}$	2.481
$\gamma_{\phi_{clay}}$	1.613
$\gamma_{\phi_{sand}}$	1.983

18

Parameter	partial factor
γ_{d70}	1.424
γ_D	1.395
γ_L	1.224
γ_k	2.334
$\gamma_{H_{actual}}$	1.190

19

Parameter	partial factor
γ_h	1.108
γ_{u10}	1.208

Figure 7.12: Overview of partial safety factors

The following can be concluded from the partial safety factors above.

- The partial factors with the biggest coefficient of variation usually have the largest partial safety factor. This can be seen clearly for piping where the hydraulic conductivity, k, has the biggest coefficient of variation.
- For all the situations, the change in the influence factor is the main contributor to the change in the partial safety factor.
- The overtopping requirement is the same for each situation. This leads to the same partial safety factors for each situation.

8

Validation & Discussion

Step 6 of the main methodology

In previous chapters, a Level I reliability assessment for multifunctional dikes has been developed. In this chapter, the developed assessment method is validated. First, Section 8.1.1 describes the purpose of the validation. Next, Section 8.1.2 describes the setup of the validation. Section 8.1.3 discusses the results of the validation. Finally, Section 8.2 consists of the discussion.

8.1. Validation

8.1.1. Purpose of the validation

The purpose of the validation is to assess whether the method works as it should. This is opposed to verification where it is checked if the method meets the requirements. When the method is verified and validated, the method will fulfil its real purpose. Possibly, based on the validation, further improvements can be made to the assessment method to make it a more realistic method.

8.1.2. Setup of the validation

The method is validated by an expert who works at the geotechnical engineering department of Royal HaskoningDHV and has experience in assessing dikes. This is someone who has been independent of the process in which the method has been developed and is therefore not biased. A presentation is given in which the results are presented, and the process by which these results have been obtained is explained. The process begins at Chapter 4 where it is explained which failure mechanisms are important. Next, the probabilistic calculations and the derivation of the partial safety factors are explained. Finally, the generalisation is shown. It has been asked to the expert to take a critical look at the method and the assumptions that have been made. An open discussion will take place during the presentation based on the comments of the expert. Those comments will be included in the discussion.

The goal was to determine if the method has potential for being used in practice. All steps and assumptions that led to the development of the method have been explained. It has been clarified what the method can be used for and how it can be applied. Critical feedback was requested for everything discussed. The expert's comments on the process will be outlined, followed by a conclusion that discusses if there are possibilities for applying this method in practice.

It is explained that this method can be used for both assessing current dikes and designing buildings near dikes. When assessing multifunctional dikes, the deterministic formulas with the partial factors can be applied to determine whether the dike with the house meets the failure probability. For design, the same approach can be used, but a house is being designed. Therefore, the exact location and dimensions are yet to be determined. These values can be treated as unknowns in the formulas and can be calculated to determine when they meet the requirements.

8.1.3. Results of the validation

The method itself is seen as having potential, provided that the points mentioned in the discussion are taken into account. Nevertheless, the method already demonstrates the influence of buildings on various failure mechanisms and shows that the current schematisation is too conservative.

The developed method ensures a more realistic assessment of existing buildings near houses compared to the current WBI assessment, which assumes a gap at the location of the dike. Using this assessment method will result in more dike cross-sections with buildings meeting stability criteria. This implies fewer dike sections being rejected, potentially saving both money and reducing inconvenience.

For the design of new constructions near a dike, this Level I reliability calculation can provide insight into possible locations for construction in the cross-section of the dike and the potential dimensions of the house. With this method, it can also quickly be demonstrated whether a multifunctional dike still meets the dike's failure probability requirement, which can also lead to an increase in building possibilities near dikes, as extensive customized assessments are no longer necessary.

8.2. Discussion

In this section, the limitations of the research are discussed.

- The amount of overtopping has been assumed to be 10 l/s/m for a normal grass dike, with the argument that 1 l/s/m is the requirement for the transitions between the house and the dike. In reality, the maximum allowable overtopping varies per water board and dike segment. This is determined by the water board's board and significantly affects the cost of dike reinforcements. For each dike reinforcement, the allowable amount of overtopping is predetermined. If a house is being built near the dike, this would mean that the overtopping requirement at that location becomes stricter and the dike would need to be raised locally. This is not feasible, and the only solution would be to add a small wall locally to limit the amount of overtopping in front of the house.

- In D-stability, a vertical wall was assumed for the situation without a house. In practice, this is initially assumed as well. However, this can easily lead to a portion of the slope sliding, as shown in Figure 8.1.

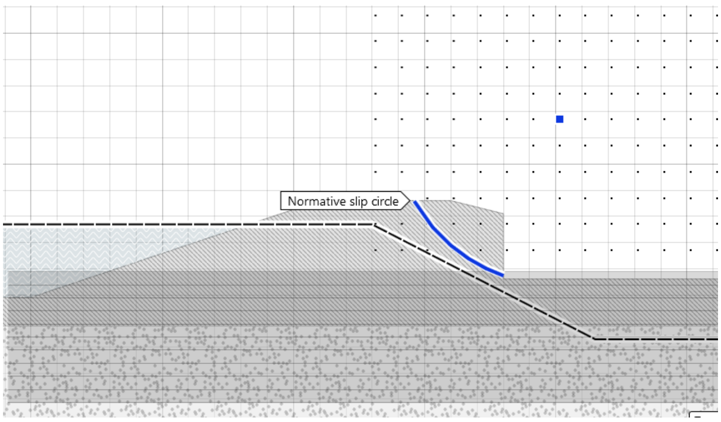


Figure 8.1: Failure plane

In reality, a residual profile is often applied. Therefore, in the calculations, it is assumed that this vertical wall always fails during high water. Subsequently, a residual profile forms and this residual profile is assessed. To determine the residual profile, various methods are used whereby a portion of the soil fails and ends up at the inner toe. For example, one can assume that 2/3 of the dike slips away, leaving 1/3 of the height at the bottom after it has failed. This results in a certain slope depending on the material. If this still does not meet the failure probability requirement, there are other options, such as assuming a natural slope of 1:2. Sometimes, 3D effects are also considered, arguing that macro stability occurs over a length of 50 meters alongside the dike. Therefore, if a single cross-section with a house of 10 meters just fails to meet the requirements, it can be said that the profile next to the house can absorb this additional force. No general procedure is prescribed for the forming of the residual profile, and these decisions are mainly made based on experts' personal judgment. When using a residual profile the failure probability would be lower and thus result in a safer dike.

- In the event tree, it is argued that dikes are well managed and that action is taken promptly when erosion occurs. Under normal circumstances, this is true, but overflow usually occurs during high water levels. When high water levels occur, this often happens along many kilometers of dikes. It is possible that in a critical situation, erosion occurs at multiple locations simultaneously, and there may not be enough manpower to address all these issues. Choices may need to be made in such a situation.
- Clustered buildings have not been considered. Clustered buildings are buildings that are attached to each other and can lead to a larger flow rate over the section of the dike next to the buildings, making these sections more prone to erosion.
- The standard deviations of the parameters can significantly impact the failure probability. The Legal Assessment Instrumentation prescribes a range for the variation coefficients. The failure probability varies considerably depending on whether the lower or upper limit is assumed. In this report, the smallest standard deviation has been assumed for all parameters. If larger standard deviations had been chosen, the partial safety factors would have been bigger.
- For calculating the failure probability due to overtopping, the Bretschneider formula is used at first to determine the wave height and wave period. This has to be done when no measurements are available. When measurements are available, the wave height and wave period can be obtained from these measurements and can be used in the Van der Meer equation.
- The reduction in failure probability due to the proposed schematisation is mainly attributed to the reduction in the macro stability failure probability. This is primarily due to the assumed forbidden lines through which the slip circle cannot occur. These forbidden lines cannot shift positions. In reality, the horizontal forces acting on the building will cause slight deformations in the walls and floors. Since the initial failure probability was extremely small, it is expected that the failure probability will increase slightly but remain negligibly small.
- For the piping situation with a shallow foundation, it is assumed that piping only occurs beyond the house. The reasoning behind this is that, while spaces may form between the foundation and the ground, these spaces are not large enough for uplift to occur. If these spaces become too large, a shorter piping length should be applied in front of the house, just as in the case of a pile foundation. This could influence the failure probability and the influence factors and, thus, the partial safety factors. The thickness of the aquitard also plays a role. When the aquitard is thick, a larger space must be present for piping to occur.

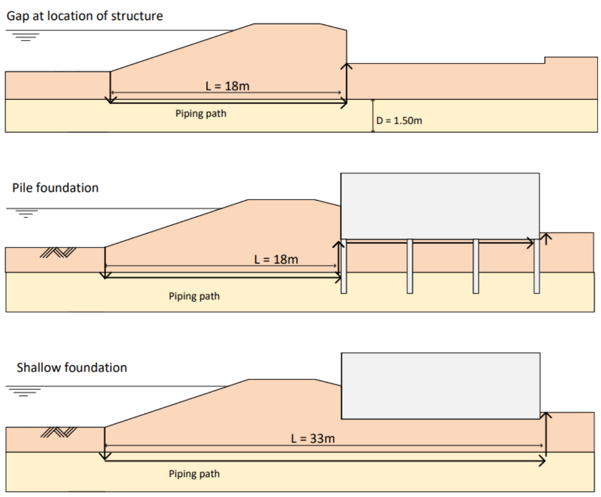


Figure 8.2: Piping length

- When the required failure probability of the dike section is not met, mitigation measures could be taken. This could involve the integration of a piping screen or stability wall to the house. Also, the transitions between the house and the dike could be better protected, allowing for more overtopping. These mitigation measures have not been taken into account in the calculation of the failure probability.
- This research has technically demonstrated that incorporating the strength of the house into the dike assessment can have positive effects. The main objections are no longer related to the technical aspects of building near dikes. The primary concerns now lie with the management aspects of the dike and the possibilities of construction within the profile of free space.

8.3. Conclusion

Deepening question: "What are the implications of this research on the possibilities to build houses near dikes and on the existing buildings near dikes?"

The developed method ensures a more realistic assessment of multifunctional dikes with buildings compared to the current WBI assessment, which assumes a gap at the location of the dike. Using this assessment method will result in more dike cross-sections with buildings meeting stability criteria. This implies fewer dike sections being rejected, potentially saving both money and reducing inconvenience.

For the design of new constructions near a dike, this Level I reliability calculation can provide insight into possible locations for construction in the cross-section of the dike and the potential dimensions of the house. With this method, it can also quickly be demonstrated whether a multifunctional dike still meets its failure probability requirement, which can also lead to an increase in building possibilities near dikes, as extensive customized assessments are no longer necessary.

9

Conclusions & Recommendations

Step 7 of the main methodology

9.1. Conclusions

The objective of this thesis was to develop a level I reliability assessment method for multifunctional dikes containing a structure, leading to a less conservative approach than the basic assessment of the Legal Assessment Instrumentation (WBI2017). This report examines how buildings can be included in the dike assessment calculations and how this affects the failure probability of the dike. It also considers how this can be used in the design of new buildings near dikes. Additionally, concerns regarding building near dikes have been identified. The following conclusions can be drawn from this research:

1. **Legal possibilities regarding building near dikes**

   The possibilities in terms of building near dikes are prescribed in the water board regulations, previously known as the by-law (Keur). Although the water board regulations vary for each water board, the rules regarding building near dikes are consistent. Dikes maintain the profile of free space to allow for future dike reinforcements. Regarding permanent construction near dikes, there is little to no possibility for building within the profile of free space. In some cases, rebuilding a structure is possible, but only under strict conditions.

   However, there are possibilities outside the profile of free space. This does not necessarily mean that buildings have to be built a certain distance horizontally from the dike. Construction is allowed above the profile of free space. This requires adding extra soil to the toe of the dike so that the house itself is above the profile of free space. The dike is essentially being over-dimensioned to allow for future dike reinforcements. Examples of possible situations can be seen in Figure 9.1. Only the foundation cuts through the profile of free space, which is permissible.

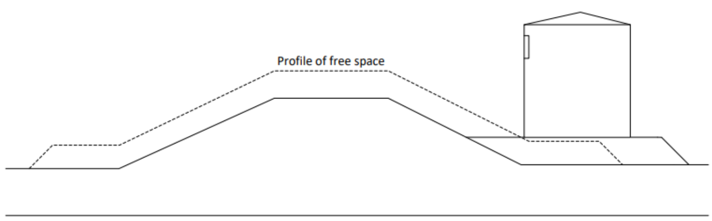


Figure 9.1: House just above the profile of free space

The biggest concern of water boards regarding relying on the strength of houses in dikes is the monitoring of the house. This will be time-consuming. To simplify the monitoring of dikes with houses, the following possibilities have been proposed:

- Help of the residents
- Sensors
- Geobeats

2. **Schematisation of a house on the various failure mechanisms**

The current schematisation is unrealistic and overly conservative. It is not likely that the house would not be present at a specific location. It has been argued by means of an event tree (Figure 9.2) that the probability of the presence of a house is 99.9% and the probability that a house would not be present is 0.1%. As a result, the schematisation in Figure 9.3 has been proposed.

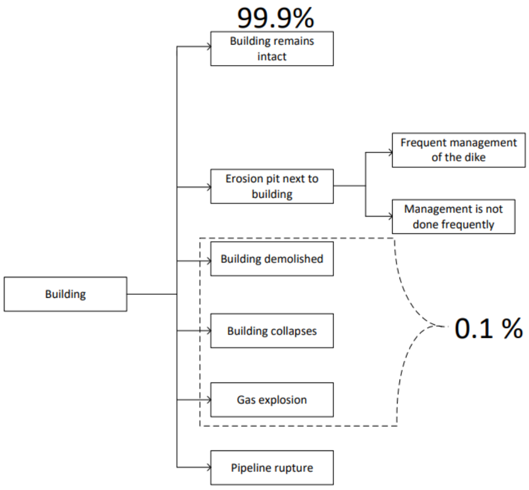


Figure 9.2: Event tree

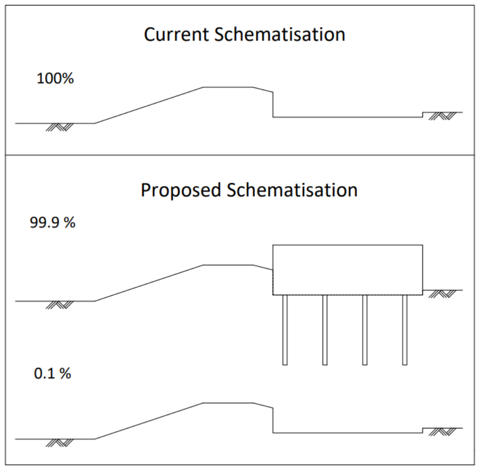


Figure 9.3: Proposed schematisation

3. **Assessment of a dike section with a house**

Based on the probabilistic calculations, partial safety factors have been determined. These partial factors have been calculated per stochastic variable. This allows for a Level I reliability calculation to determine whether a dike cross-section with a house meets the failure probability requirement of the cross-section. This corresponds to the formula below but with a partial factor added for each resistance parameter (R_{rep}) and load parameter (S_{rep}). Through these partial factors, a house near the dike can easily be assessed using a Level I design calculation:

$$\frac{R_{rep}}{\gamma_R} \geq \gamma_S \cdot S_{rep} \tag{9.1}$$

4. **The effect of using the proposed schematisation on the total failure probability of the dike compared to the current conservative schematisation**

The reduction in total failure probability for the case is determined at 75% and this is primary due to the positive effects on macro stability. This result shows that the proposed schematisation which takes into account the influence of the house is considerably less conservative than the existing method, resulting in a lower failure probability for the dike. Therefore, the dike can partially rely on the strength of the house. When this strength is practically attributed, it can lead to less rejection of dike sections that contain buildings.

The effect of new construction on a standard dike profile can have both positive and negative effects on the failure probability of the dike section depending on the location of the building. To reduce the failure probability, compensatory measures can be taken for overtopping and piping. For overtopping, the failure probability increases due to the transitions that are created between the dike and the house, which results in a stricter failure probability. If these transitions receive proper protection, more overtopping could be allowed, thus reducing the failure probability due to overtopping. To increase the piping length, and thus decrease the failure probability due to piping, a piping screen could be added as mitigation measure.

5. **The implications of this research on the possibilities to build houses near dikes and on the existing buildings near dikes**

   The developed method ensures a more realistic assessment of multifunctional dikes containing a structure compared to the current WBI assessment, which assumes a gap at the location of the dike. Using this assessment method can potentially result in more dike cross-sections with buildings meeting stability criteria. This implies fewer dike sections being rejected, potentially saving both money and reducing inconvenience.

   For the design of new constructions near a dike, the Level I reliability calculation can provide insight into possible locations for construction in the cross-section of the dike and the potential dimensions of the house. With this method, it can also quickly be demonstrated whether a dike will still meet the dike's failure probability requirement if a house is built in it, so it can also lead to an increase in building possibilities near dikes, as extensive customized assessments are no longer necessary. Furthermore, this research has shown that the construction of buildings near dikes does not necessarily mean that the dike will be more prone to failure. This report takes the main technical complaint of building near dikes away, which could result in more houses being constructed and eventually contribute to solving the housing crisis.

9.2. Recommendations

Based on the conducted research, several recommendations can be made for further research. The recommendations are listed below.

- When construction is being carried out near a dike, the exact soil parameters must first be determined accurately to understand which values for the parameters can be assumed. On-site soil investigation is required to determine the precise soil composition and variations in the parameters.
- Settlements of the dike that can occur due to construction on the dike have not been considered. These settlements could lead to an increased overtopping failure probability, thereby increasing the failure probability of the dike. Although it is expected that these settlements are small, they need to be investigated further.
- It is recommended to assess the macro stability failure mechanism in PLAXIS. PLAXIS is a finite element program commonly used for dike design. PLAXIS allows for a much more accurate determination of the effect of the soil-structure interaction than D-stability. Additionally, the foundation can be represented more realistically and 3D situations can be considered.
- When the soil consists of multiple layers, as opposed to the assumptions made in this report, the Bishop method, which has been used in D-stability, can no longer be used. Other methods, such as the Uplift Van or Van der Meij method, should be considered in such cases.
- It is also recommended to use a residual profile for the scenarios where a gap in the dike is assumed instead of a vertical slope. This will lead to a reduction in the probability of failure and a more realistic scenario.
- Given that the failure probability can significantly depend on the likelihood of the house being present, a conservative assumption of 0.1% has been made that the house is not present at the location. For a more precise calculation of the probability of failure, the scenarios in which the house is not present need to be further investigated to arrive at a more realistic probability that the house is not present.
- The partial safety factors have been derived for different situations. When a situation does not match one of the prescribed scenarios, the process for deriving the partial factors should be followed. A possibility would be to derive partial factors that apply more generally. The downside of this approach is that it may introduce more conservatism.
- During high water, the dike must remain stable. When high water occurs, there is an increase in horizontal load on the house. It is unknown whether houses can withstand this load. New construction and existing buildings need to be distinguished because of this. In new construction, it can be taken into account that the house becomes part of the dike and will be dimensioned accordingly. Additionally, the condition of certain elements is easier to assess if they have been built more recently. In existing buildings, the condition of a wall is much harder to assess, and it cannot be determined if it is dimensioned to withstand all the horizontal forces. The instability of the building during high water could therefore be a potential problem. Further investigation is needed to determine whether the collapse of existing buildings is a real threat.
- FORM analyses do not always converge to the correct solution. To verify if a FORM analysis has converged to the correct solution, a Monte Carlo simulation should also be performed.
- The ultimate limit state of the dike has only been considered for overtopping. Additionally, a more detailed examination could be conducted regarding the serviceability limit state of a house. According to the Eurotopping Manual, a requirement of 1 l/s/m is prescribed for this purpose (Eurotop, 2017). This leads to the same requirement as currently used for the ultimate limit state, but further investigation is needed to determine if additional measures may be necessary to protect the house.

- In the case of uplift, the ground fails due to the lack of vertical equilibrium in the soil under the influence of water pressures. It is expected that when a concrete floor or a shallow foundation is used, uplift will not be an issue. This ensures that the hydraulic head below the house does not exert more force than the weight of the aquitard layer and the weight of the floor or foundation of the house. Uplift can be a problem when a house has a basement, making the aquitard layer much thinner and less capable of counteracting the hydraulic head. Further investigation is needed regarding uplift in these situations.

- To convince the water board of the benefits of this assessment method, it is recommended to quantify the costs that can potentially be saved so the water boards can clearly see the benefits for them.

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A

Python code

In this appendix, the Python code that has been used for performing the FORM analysis and obtaining the partial safety factors can be seen.

A.1. FORM analysis

First, it is explained how the limit state is defined for each of the failure mechanisms. Subsequently, the general code for deriving the failure probability and the influence factors is given. It is mentioned what part of the code changes for the different failure mechanisms each time.

A.1.1. Piping

Sellmeijer equation

```
def Piping(d70, D, L, k, H_actual):         #Sellmeijer equation for calculation of critical head difference for piping

    #Values that are assumed deterministic
    gamma_P = 26.5
    gamma_W = 10   #kPa
    eta = 0.25
    v = 1.33 * 10**(-6)
    g = 9.81
    theta = 35

    K = (v / g) * k      #Intrinsic permeability

    F_R = eta * ((gamma_P - gamma_W) / gamma_W) * np.tan(theta * (180/np.pi))
    F_S = d70 / (K * L)**(1/3)
    A = 0.28/((D/L)**2.8 - 1) + 0.04
    F_G = 0.91 * (D/L)**A

    H_critical = F_R * F_S * F_G * L

    B = (H_critical / H_actual)

    return B
```

Figure A.1: Sellmeijer equation

FORM analysis

The FORM analysis used for piping applies to all failure mechanisms. The only changes to be made are shown in the figures below:

In [8]:

```python
#Define the Limit State Function

def myLSF1(x):         #The critical piping head minus the actual piping head


    Z = [Piping(x[0], x[1], x[2], x[3], x[4]) - 1]

    return Z

#Indepence between the variables is assumed
R = ot.CorrelationMatrix(5)
multinorm_copula = ot.NormalCopula(R)

inputDistribution = ot.ComposedDistribution((d70, D, L, k, H_actual), multinorm_copula)
inputDistribution.setDescription(["d70", "D", "L", "k", "H_actual"])
inputRandomVector = ot.RandomVector(inputDistribution)

myfunction = ot.PythonFunction(5, 1, myLSF1)

# Vector obtained by applying limit state function to X1 and X2
outputvector = ot.CompositeRandomVector(myfunction, inputRandomVector)

# Define failure event: here when the limit state function takes negative values
failureevent = ot.ThresholdEvent(outputvector, ot.Less(), 0)
failureevent.setName('LSF inferior to 0')

optimAlgo = ot.Cobyla()
optimAlgo.setMaximumEvaluationNumber(10000)
optimAlgo.setMaximumAbsoluteError(1.0e-10)
optimAlgo.setMaximumRelativeError(1.0e-10)
optimAlgo.setMaximumResidualError(1.0e-10)
optimAlgo.setMaximumConstraintError(1.0e-10)

# Starting point for FORM
start_pt = []

algo = ot.FORM(optimAlgo, failureevent, inputDistribution.getMean())  # Maybe change 3rd argument and put start_pt defined a
algo.run()
result = algo.getResult()
x_star = result.getPhysicalSpaceDesignPoint()       # Design point: original space
u_star = result.getStandardSpaceDesignPoint()       # Design point: standard normal space
pf = result.getEventProbability()                   # Failure probability
beta = result.getHasoferReliabilityIndex()          # Reliability index

print(f'Probability of failure = {pf}')
print('FORM result, beta = {:.3f}\n'.format(beta))
```

Figure A.2: FORM analysis piping

In [8]:

```python
#Define the Limit State Function

def myLSF1(x):         #The critical piping head minus the actual piping head


    Z = [Piping(x[0], x[1], x[2], x[3], x[4]) - 1]

    return Z

#Indepence between the variables is assumed
R = ot.CorrelationMatrix(5)
multinorm_copula = ot.NormalCopula(R)

inputDistribution = ot.ComposedDistribution((d70, D, L, k, H_actual), multinorm_copula)
inputDistribution.setDescription(["d70", "D", "L", "k", "H_actual"])
inputRandomVector = ot.RandomVector(inputDistribution)

myfunction = ot.PythonFunction(5, 1, myLSF1)

# Vector obtained by applying limit state function to X1 and X2
outputvector = ot.CompositeRandomVector(myfunction, inputRandomVector)

# Define failure event: here when the limit state function takes negative values
failureevent = ot.ThresholdEvent(outputvector, ot.Less(), 0)
failureevent.setName('LSF inferior to 0')

optimAlgo = ot.Cobyla()
optimAlgo.setMaximumEvaluationNumber(10000)
optimAlgo.setMaximumAbsoluteError(1.0e-10)
optimAlgo.setMaximumRelativeError(1.0e-10)
optimAlgo.setMaximumResidualError(1.0e-10)
optimAlgo.setMaximumConstraintError(1.0e-10)

# Starting point for FORM
start_pt = []

algo = ot.FORM(optimAlgo, failureevent, inputDistribution.getMean())  # Maybe change 3rd argument and put start_pt defined a
algo.run()
result = algo.getResult()
x_star = result.getPhysicalSpaceDesignPoint()       # Design point: original space
u_star = result.getStandardSpaceDesignPoint()       # Design point: standard normal space
pf = result.getEventProbability()                   # Failure probability
beta = result.getHasoferReliabilityIndex()          # Reliability index

print(f'Probability of failure = {pf}')
print('FORM result, beta = {:.3f}\n'.format(beta))
```

Needs to be adjusted to the specific failure mechanism and the amount of stochastic variables

Amount of stochastic variables

Need to be adjusted to the stochastic variables for the specific failure mechanism

Amount of stochastic variables

Figure A.3: General format FORM analysis

Parameters assumed as stochastic

```
In [7]:
#Parameters that are assumed probabilistic

d70 = ot.Normal(0.0002, 0.000024)            #COV = 0.12
D = ot.Normal(1.50, 0.45)                    #COV = 0.3
L = ot.Normal(33, 3.30)                      #COV = 0.1
k = ot.Normal(0.000486, 0.000243)            #COV = 0.50
H_actual = ot.Normal(1.5, 0.15)
```

Figure A.4: Stochastic variables for piping

To derive the influence factors the following code has been used.

```
alpha_ot = result.getImportanceFactors()
print(alpha_ot)
result.drawImportanceFactors()
```

Figure A.5: Influence factors

A.1.2. Macro stability

For macro stability, D-stability has been used. D-stability has a function where a FORM analysis is performed, from which the influence factors are obtained. As a result, this was not programmed in Python. However, the formulas for deriving the partial factors were used to derive the partial factors.

A.1.3. Overtopping

Bretschneider equation

```
def bretschneider(F, u10, g, d):

    Fdak = (F * g) / (u10 ** 2)
    ddak = (d * g) / (u10 ** 2)

    Hdak = 0.283 * np.tanh(0.53 * ddak**0.75) * np.tanh((0.0125 * Fdak**0.42) / np.tanh(0.53 * ddak**0.75))
    Tdak = 2.4 * np.pi * np.tanh(0.833 * ddak**0.375) * np.tanh((0.077 * Fdak**0.25) / np.tanh(0.833 * ddak**0.375))

    T13 = (Tdak * u10) / g
    Tp = 1.08 * T13
    Hm0 = (Hdak * u10**2) / g
    Tm = Tp / 1.1
    return Hm0, Tm
```

Figure A.6: Bretschneider equation

Van der Meer equation

```
def overtopping_discharge(h, u10):

    g = 9.81  # m/s^2
    toe = 4.8# m
    crest = 8.6  # m
    tanalpha = 1/3
    yf = 1
    yb = 1
    yv = 1
    F = 1300  # m
    beta = 65  # degree
    kappa = 3.2e-06
    ms = 3
    WindSetup = 1
    bottom = 0.5

    # Water depth near toe
    d = h - toe

    # Water depth away from toe
    db = h - bottom

    # Calculate the freeboard and water depth at the toe
    Rc = crest - h

    # To get all required wave data
    Hm0, Tm = bretschneider(F,u10,g,db)

    # Incident waves
    if(isinstance(beta, np.ndarray)):
        ybeta = np.ones(len(beta))
        for i in range(len(beta)):
            if(beta <= 80):
                ybeta = 1 - 0.0033 * np.abs(beta);
            elif(beta <= 110):
                ybeta = 1 - 0.0033 * np.abs(80);

    else:
        ybeta = 1
        if(beta <= 80):
            ybeta = 1 - 0.0033 * np.abs(beta)
        elif(beta <= 110):
            ybeta = 1 - 0.0033 * np.abs(80)

    # Calculate the iribarren number
    L0 = (g * Tm**2) / (2 * np.pi)
    ib = tanalpha / np.sqrt(Hm0 / L0)

    # Calculate the overtopping discharge (EurOtop equation 5.10)
    overtopping = (0.023 / np.sqrt(tanalpha)) * yb * ib * np.exp(-((2.7 * Rc) / (yb * yf * ybeta * yv * ib * Hm0))**1.3)
                  * np.sqrt(g * Hm0**3)

    q_total = (overtopping) * 1000  #l/m/s

    return q_total
```

Figure A.7: Van der Meer equation

Parameters assumed as stochastic

```
u10 = ot.Normal(11.3, 1.13)
h = ot.Normal(7.7, 0.1)
```

Figure A.8: Stochastic variables for overtopping

A.1.4. Horizontal Sliding

```
def Sliding(phi, h):

    #Values that are assumed deterministic
    rho = 1000                      #kg / m^3
    g = 9.81                        #m / s^2
    L_dike = 24                     #m
    hoogte_dijk = 5                 #m
    volumetric_weight_peat = 12000  #N / m^2

    effective_normal_stress = hoogte_dijk * volumetric_weight_peat
    delta = 2/3 * phi
    f = math.tan(delta * np.pi/180)         #coefficient of friction

    tau = f * effective_normal_stress


    H_r = L_dike * tau                  #

    H_s = 0.5 * rho * g * h**2           #kN / m

    a = (H_r / H_s)

    return a


```

Figure A.9: Horizontal sliding

Parameters assumed as stochastic

```
phi = ot.Normal(15, 2.25)
h = ot.Normal(4, 0.1)
```

Figure A.10: Stochastic variables horizontal sliding

A.2. Derivation of the partial safety factors

The derivation of the partial factors is done in the same way for all stochastic variables. The formulas used for this purpose are described in Chapter 6. For each stochastic variable, it should be determined whether it serves as a load or a resistance. Furthermore, for all stochastic variables the properties needed for the calculation have already been determined in previous chapters. The Python scripts below have been used to calculate the partial factors. An example is used for horizontal sliding where the internal friction angle (ϕ) acts as resistance and the design water level (h) acts as a load.

```
r_star = angle_p * (1 + alpha_p * beta_sliding * COV_p)
R_k = angle_p + k_r * std_p            Mean
gamma_ifac = R_k / r_star
print(gamma_ifac)
                  Mean
s_star = h * (1 + alpha_h * beta_sliding * COV_h)
S_k = h + k_s * std_h
gamma_h = s_star / S_k
print(gamma_h)
```

Figure A.11: Derivation of the partial safety factors

B

Calculation of the partial safety factors

In this appendix, the partial safety factors that will be used in the level I reliability assessment for the case in Chapter 5 have been derived. These partial safety factors have been derived for each stochastic variable for the failure mechanisms macro stability, piping and overtopping. For each of the failure mechanisms, first, an overview of all the properties of the variables derived in Chapter 5 has been given.

Calculation of the partial safety factors for macro stability

Parameter	S/R	Mean, μ	Coefficient of variation, V	Importance factor, α	Standard deviation, σ
c_{clay}	R	13	0.257	0.856	3.57
ϕ_{clay}	R	17.5	0.15	0.517	2.625

Table B.1: Parameters macro stability

The parameters mentioned in Table B.1 act as resistance. This means when the value of cohesion or the friction angle increases, the probability of failure decreases. The target reliability, β_T, for macro stability is 4.769 and is determined based on the maximum required failure probability for the dike section for the failure probability of macro stability, as can be seen in Chapter 5.

For the cohesion of clay, the following applies:

$$r^* = \mu_R \cdot (1 + \alpha_R \cdot \beta \cdot V_R) = 13 \cdot (1 - 0.856 \cdot 4.769 \cdot 0.257) = 6.34\ kPa \tag{B.1}$$

$$R_k = \mu_R + k_R \cdot \sigma_R = 13\ kPa \tag{B.2}$$

$$\gamma_R = \frac{R_k}{r*} = \frac{13}{6.34} = 2.049 \tag{B.3}$$

For the internal friction angle of clay, the following applies:

$$r^* = \mu_R \cdot (1 - \alpha_R \cdot \beta \cdot V_R) = 17.5 \cdot (1 + 0.517 \cdot 4.769 \cdot 0.15 = 11.03^\circ \tag{B.4}$$

$$R_k = \mu_R + k_R \cdot \sigma_R = 17.5^\circ \tag{B.5}$$

$$\gamma_R = \frac{R_k}{r*} = \frac{17.5}{11.03} = 1.587 \tag{B.6}$$

An overview of the partial factors can be seen in B.2.

Parameter	partial factor
$\gamma_{c_{clay}}$	2.049
$\gamma_{\phi_{clay}}$	1.587

Table B.2: Partial factors for macro stability

For macro stability, the calculated partial safety factors can be used directly in D-stability. These must be multiplied by the parameters which are assumed stochastic. Next, a deterministic calculation can be done in D-stability from which the Safety factor follows. When the safety factor is greater than 1 the dike still meets the required failure probability for macro stability.

Calculation of the partial safety factors for piping

Parameter	S/R	Mean, μ	Coefficient of variation, V	Importance factor, α	Standard deviation, σ
$d70_{sand}$	R	0.0002	0.12	-0.705	$2.4 \cdot 10^{-5}$
D_{sand}	S	1.50	0.3	0.224	0.45
L	R	18	0.1	-0.429	1.8
k_{sand}	S	$4.86 \cdot 10^{-4}$	0.5	0.383	$2.43 \cdot 10^{-4}$
H_{actual}	S	1.5	0.1	0.351	0.15

Table B.3: Parameters for piping

The target reliability β_T for piping is 4.688 and is based on the required failure probability determined in Chapter 6.

For the d70 the following applies:

$$r^* = \mu_S \cdot (1 + \alpha_S \cdot \beta \cdot V_S) = 0.0002 \cdot (1 - 0.705 \cdot 4.688 \cdot 0.12) = 1.21 \cdot 10^{-4}\ m \tag{B.7}$$

$$R_k = \mu_S + k_S \cdot \sigma_S = 0.0002\ m \tag{B.8}$$

$$\gamma_R = \frac{R_k}{r*} = \frac{2 \cdot 10^{-4}}{1.21 \cdot 10^{-4}} = 1.657 \tag{B.9}$$

For the aquifer thickness, D, the following applies:

$$s^* = \mu_R \cdot (1 + \alpha_R \cdot \beta \cdot V_R) = 1.50 \cdot (1 + 0.224 \cdot 4.688 \cdot 0.3) = 1.97\ m \tag{B.10}$$

$$S_k = \mu_R + k_R \cdot \sigma_S = 1.50\ m \tag{B.11}$$

$$\gamma_S = \frac{s*}{S_k} = \frac{1.97}{1.50} = 1.315 \tag{B.12}$$

For the piping length, L, the following applies:

$$r^* = \mu_R \cdot (1 + \alpha_R \cdot \beta \cdot V_R) = 18 \cdot (1 - 0.429 \cdot 4.688 \cdot 0.1) = 14.38\ m \tag{B.13}$$

$$R_k = \mu_R + k_R \cdot \sigma_R = 18\ m \tag{B.14}$$

$$\gamma_R = \frac{R_k}{r*} = \frac{18}{14.38} = 1.252 \tag{B.15}$$

For the hydraulic conductivity, k, the following applies:

$$s^* = \mu_R \cdot (1 + \alpha_R \cdot \beta \cdot V_R) = 4.86 \cdot 10^{-4} \cdot (1 + 0.383 \cdot 4.688 \cdot 0.5) = 9.22 \cdot 10^{-4}\ m/s \tag{B.16}$$

$$S_k = \mu_R + k_R \cdot \sigma_R = 4.86 \cdot 10^{-4}\ m/s \tag{B.17}$$

$$\gamma_S = \frac{s*}{S_k} = \frac{9.22 \cdot 10^{-4}}{4.86 \cdot 10^{-4}} = 1.898 \tag{B.18}$$

For the design water level, H_{actual}, the following applies:

$$s^* = \mu_S \cdot (1 + \alpha_S \cdot \beta \cdot V_S) = 1.5 \cdot (1 + 0.351 \cdot 4.688 \cdot 0.1) = 1.74\ m \tag{B.19}$$

$$S_k = \mu_S + k_S \cdot \sigma_S = 1.5\ m \tag{B.20}$$

$$\gamma_s = \frac{s*}{S_k} = \frac{1.74}{1.5} = 1.165 \tag{B.21}$$

An overview of the partial factors for piping can be seen below:

Parameter	partial factor
d70	1.657
D	1.315
L	1.252
K	1.898
H_{actual}	1.16

Table B.4: Partial factors for piping

Calculation of the partial safety factors for overtopping

Parameter	S/R	Mean, μ	Coefficient of variation, V	Influence factors, α	Standard deviation, σ
h	S	7.7	0.013	0.888	0.1
u_{10}	S	11.3	0.10	0.459	1.13

Table B.5: Parameters for Overtopping

The target reliability, β_T, for overtopping is 4.798 and is based on the maximum required failure probability determined in Chapter 6.

For the design water level the following applies:

$$s^* = \mu_S \cdot (1 + \alpha_S \cdot \beta \cdot V_S) = 7.7 \cdot (1 + 0.888 \cdot 4.798 \cdot 0.013) = 8.13\ m \tag{B.22}$$

$$S_k = \mu_S + k_S \cdot \sigma_S = 7.7\ m \tag{B.23}$$

$$\gamma_S = \frac{s*}{S_k} = \frac{8.13}{7.7} = 1.055 \tag{B.24}$$

For the wind speed the following applies:

$$s^* = \mu_S \cdot (1 + \alpha_S \cdot \beta \cdot V_S) = 11.3 \cdot (1 + 0.459 \cdot 4.798 \cdot 0.1) = 13.79\ m/s \tag{B.25}$$

$$S_k = \mu_S + k_S \cdot \sigma_S = 11.3\ m/s \tag{B.26}$$

$$\gamma_S = \frac{s*}{S_k} = \frac{13.79}{11.3} = 1.220 \tag{B.27}$$

An overview of the partial factors for overtopping can be seen below:

Parameter	**partial factor**
h	1.055
u_{10}	1.220

Table B.6: Partial factors for overtopping

C

Influence factors of the generalisation

In this appendix, the influence factors calculated for the generalisation can be found. For each situation, the influence factors for macro stability and piping are indicated. These influence factors result from the FORM analyses. The corresponding Python code can be found in Appendix A. These influence factors have been used in calculating of the partial safety factors in Chapter 7: Generalisation of the level I reliability assessment method.

Clay dike

Macro stability

Parameter	Value
$\alpha\ c_{clay}$	-0.867
$\alpha\ \phi_{clay}$	-0.498

Table C.1: Partial factors for macro stability

Piping

Parameter	Value
$\alpha\ d_{70}$	-0.529
$\alpha\ D$	0.281
$\alpha\ L$	-0.391
$\alpha\ k_{sand}$	0.569
$\alpha\ H_{actual}$	0.405

Table C.2: Partial factors for piping

Peat dike

Macro stability

Parameter	Value
$\alpha\ c_{peat}$	-0.536
$\alpha\ \phi_{peat}$	-0.844

Table C.3: Partial factors for macro stability

Horizontal sliding

Parameter	Value
$\alpha\ \phi_{peat}$	-0.995
$\alpha\ h$	0.104

Table C.4: Partial factors for macro stability

House located at crest of the dike

Macro stability

Parameter	Value
$\alpha\ c_{clay}$	-0.223
$\alpha\ \phi_{clay}$	-0.227
$\alpha\ \phi_{sand}$	-0.948

Table C.5: Partial factors for macro stability

Piping

Parameter	Value
$\alpha\ d_{70}$	-0.667
$\alpha\ D$	0.241
$\alpha\ L$	-0.435
$\alpha\ k_{sand}$	0.414
$\alpha\ H_{actual}$	0.369

Table C.6: Partial factors for piping

House located at toe of the dike

Macro stability

Parameter	Value
$\alpha\ c_{clay}$	-0.489
$\alpha\ \phi_{clay}$	-0.502
$\alpha\ \phi_{sand}$	-0.713

Table C.7: Partial factors for macro stability

Piping

Parameter	Value
$\alpha\ d_{70}$	-0.608
$\alpha\ D$	0.263
$\alpha\ L$	-0.426
$\alpha\ k_{sand}$	0.474
$\alpha\ H_{actual}$	0.394

Table C.8: Partial factors for piping

Existing buildings

Macro stability

Parameter	Value
$\alpha\ c_{clay}$	-0.487
$\alpha\ \phi_{clay}$	-0.531
$\alpha\ \phi_{sand}$	-0.693

Table C.9: Partial factors for macro stability