Spatial integration of dike reinforcements

Development of a method that compares the spatial influence of design alternatives

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Development of a method that compares the spatial influence of design alternatives

By

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in partial fulfilment of the requirements for the degree of

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Preface

The report in front of you presents my master thesis research "Spatial integration of dike reinforcements". This report is written to complete my education program at the Delft University of Technology. The study introduced me in the interesting challenges that we are facing when we try to integrate technical designs into spatial planning.

Special thanks to Witteveen + Bos, for giving me the opportunity to conduct my master thesis in their company. I want to thank all colleagues for sharing knowledge on designing dike reinforcements.

I would like to warmly acknowledge the help of the members of my graduation committee; Mark Voorendt, Marinus Aalberts, Wim Kanning, Erik-Jan Houwing and Bas Jonkman. Their feedback and insights throughout the last ten months, are much appreciated. Finally, I would like to thank my fellow students that helped me in achieving this result.

N. van den Berg
Delft, November 2018

Abstract

In the Netherlands, a new assessment method for the required safety level of primary flood defences is introduced in the Water Act. It is estimated that currently roughly 1900 kilometres of flood protection does not meet the safety requirements for the future (Jonkman, Jorissen, Schweckendieck & Van den Bos, 2017). Past flood defence projects show that integrating reinforcement measures is a difficult assignment.

It is specifically focused on dike reinforcement projects in this thesis. A deficiency in the design process is identified in the role that the influence on the existing situation has on the evaluation and selection of design alternatives that are input for the Environmental Impact Assessment. The difficulty for improving the importance of the existing situation in the surroundings, in the design process is that the subject experts on these themes are typically assessing the consequences of proposed interventions (Aalberts, 2018).

The research objective is set to develop a method that allows to include the influence on the existing situation within the evaluation and selection of design alternatives in dike reinforcement projects. This method aims for providing information to compare the spatial integration of reinforcement designs in early stages of reinforcement projects. Subject experts should assess the provided information, and determine whether a reinforcement design provides a satisfying influence on the project area. It is focused on dike reinforcement projects in rural area.

A research through design study is used to develop the method to compare design alternatives. The study included the identification of technical design measures to increase the strength of dikes in rural area, and the decomposition of rural areas in functional characteristics that can be valued. A conceptual evaluation model is developed to express the relation between functional characteristics and design alternatives for dike reinforcements. It is studied how a method can be provided to compare the outcome of the conceptual evaluation model for a large variety of design alternatives. The value of the developed method is assessed in a case study, which is the dike reinforcement project “Wolferen-Sprok”.

The resulting method is able to compare design alternatives on the influence on the existing situation by following seven steps. It is providing design measures for the identified safety problem of the dike in a certain project area. Simultaneously, the characteristics of the project area should be identified and visualized on maps. This provides the required information to apply the conceptual evaluation model that identifies effects of design alternatives on the existing situation. The retrieved data is visualized to compare design alternatives.

It is concluded that the developed method focusses mainly on natural, cultural, and social economic functions in rural project areas. This means that influence of design alternatives on costs, maintainability, and landscape values should be addressed separately, in the evaluation and selection of design alternatives. It is recommended to study how the influence on these topics can evaluated in a similar method.

The developed method can be applied to include the existing situation in the project area in the evaluation and selection of design alternatives in dike reinforcement projects in rural areas. It is expected that application of the method in design teams provides new input for further improvement of the method.

Contents

1. Introduction

In the Netherlands, a new assessment method for the required safety level of primary flood defences has been introduced in the Water Act. This assessment method provides guidelines to determine a minimal required safety level of primary flood defences, based on the determined impact (group impact, casualties, and economic damage) that a flood causes when a dike segment is breached (ENW, 2017). According to the government (Ministerie van Infrastructuur en Milieu, 2013), the Dutch primary flood protection system consists of 3750 kilometres of dikes and dunes. Due to the new standards on flood protection, this complete primary flood defence system should be reassessed and it should be determined whether reinforcement projects are required. The government aims to have assessed all primary flood defences by 2023 (Unie van Waterschappen, 2015).

The next step is to reinforce flood protection systems at locations that do not meet the required safety standards. The goal has been set to have the complete primary flood defence system adapted to the new standards in 2050. It is estimated that currently roughly 1900 kilometres do not meet the new safety standards, meaning that on average about fifty kilometres per year need to be reinforced for the next thirty years (Jonkman, Jorissen, Schweckendieck & Van den Bos, 2017).

Governmental organizations, such as the Water Boards, provinces and the High Water Protection Program (HWBP) are responsible for the realization of the flood protection reinforcement projects. Their ambition is summarized in three words: smarter, cheaper and faster. Faster focusses on achieving the goal of reinforcing fifty kilometres of dike per year. Cheaper, relates to the price of dike reinforcement projects; it is the goal to reduce this to five million euros per kilometre on average. The ambition smarter should help in achieving the previous mentioned goals, by designing innovative solutions that reduce the costs and lead time of a reinforcement project (H+N+S, 2016).

To achieve the set goals, dike reinforcement projects should be improved. This can be achieved in two ways; by developing new technical design options or by improving the design process. This study focusses on improving the design process of dike reinforcements by providing information on effects of different design alternatives in early stages of the project.

This chapter identifies problems of the design process of dike reinforcement projects, and explains the conducted research. First, in Section 1.1, the topic is introduced by providing background information on the design process of dike reinforcements. Subsequently, the conducted research is explained from Section 1.2 to Section 1.6.

1.1. Problem motivation

In this section, the topic of this research is introduced by explaining past process related problems in dike reinforcement projects (Section 1.1.1). Subsequently, a theoretical approach on project success in dike reinforcements projects is discussed (Section 1.1.2). This is input for Section 1.2, in which a problem statement is provided.

1.1.1. Historical cases of resistance against flood defence reinforcements

In the period between 1850 and 1965, economic progress was seen as the most important value in the flood defence strategy of the Netherlands. In these years, every intervention to the river system was widely supported by civilians, when it was beneficial for the economy (Van

Heezik, 2007). This mind-set changed after the 1965, when the impact of reinforcement projects on its surroundings gained importance. In the next paragraphs, based on three cases, it is explained what caused stakeholder resistance in specific flood defence reinforcement projects.

Oosterschelde storm surge barrier

As part of the Delta Plan (initiated in 1953) a dam had to be constructed to close off the Oosterschelde from the North Sea (Brugsma & Van Houten, 2013). Just before the construction started, in 1969, resistance against the implementation of the dam increased and public protests started, because of the large impact of a dam on the natural values of the Oosterschelde region (Van Heezik, 2007). In 1974, when the construction works were already started, the stakeholder's protests forced the Dutch government to reconsider their decision (Brugsma & Van Houten, 2013). The reconsideration lead to the construction of the Oosterschelde storm surge barrier, because in that case the unique flora and fauna of the Oosterschelde region could be mostly preserved. Implementing this plan meant that the constructed part of Oosterschelde dam was demolished and a storm surge barrier was developed. In the meantime, construction works were stopped for two years. The revision of the plan in such a late stage of the project resulted in a delay of several years and construction costs that were six times higher than initially expected.

It is too easy to conclude that stakeholder involvement in the design process of the Oosterschelde dam would have prevented the delay and costs exceedance of the Oosterschelde project, because initially the proposed measure of the government to close of the Oosterschelde by a dam was widely supported by national and local politicians (De Lijser, 2016). The public opinion on the Oosterschelde dam changed in the sixties, when the influence on the surroundings got a more dominant role in society (Brugsma & Van Houten, 2013). When, besides the safety objectives, also environmental aspects were included in the decision making process, it was found that a storm surge barrier was a more appropriate solution to solve the safety issue of the Oosterschelde region.

Dike reinforcements in "Rivierengebied"

The Oosterschelde-case made clear that including environmental impact (on flora and fauna) in the decision making process did lead to a completely different outcome of the design process of the flood defence reinforcement. Large scale dike reinforcements in the "Rivierengebied" showed the importance of including landscape-, natural, and cultural values (LNC-values) in the design process of dike reinforcements.

In 1956 the normative discharge of the Rhine at Lobith was changed from 13.000 m^3/s to 18.000 m^3/s, with the effect that 550 kilometres of river dikes in the Netherlands did not meet the required safety standards. It was expected that, due to the Zeeland disaster in 1953, local residents saw the urgency for the dike reinforcements and therefore the projects would not be objected by the residents. The specialists, that were responsible for the preservations of LNC-values in the projects saw the urgency of the reinforcements and considered the LNC-values as less important. It was a surprise for the province that the dike reinforcement projects faced a lot of resistance. The resistance was caused by the fact that from the beginning of the projects, dike reinforcements were considered as the only feasible solution, without seriously accounting for the LNC-values. It was found that the large scale protests resulted in that only 20 km of dike was reinforced in the period from 1974 to 1978 (Van Heezik, 2007).

To investigate how the lead time of the dike reinforcements could be reduced, the committee Becht was formed. This committee concluded that stakeholder resistance could be reduced by better integrating the LNC-values in the design process of dike reinforcements. Despite the findings of comity Becht, the strong opposition against the traditional dike reinforcements hold on until 1993, as residents had the opinion that LNC-values were still not seriously considered by the design teams. Therefore, the committee Boertien (in 1993) emphasized the findings on ‘sophisticated design’ and prescribed a big role for an obligatory environmental impact study to reduce the stakeholder resistance in dike reinforcement projects (Jonkman et al., 2017). This resulted in a change of strategy in which LNC-specialists seriously participated in reinforcement projects. Eventually, the resistance against the project had mostly disappeared, but it should be noted that this was also caused by the high waters in 1993 and 1995. The residents of the hinterland saw the urgency for the reinforcement projects, as they were threatened twice by the high river discharge. Also, the national government introduced an emergency law that allowed dike reinforcements without any public consultation procedures. This speeded up the design process of the required dike reinforcements (Van Heezik, 2007).

Markermeerdijken
That stakeholder resistance is not completely solved by following the recommendations of the committee Becht and Boertien is showed in the case of 33 kilometres of dike reinforcement along the Markermeer. The dike section between Hoorn and Amsterdam was already rejected on safety in 2006, while the planned start of the construction works is Medio 2019. The local residents along the dike trace are angry, as they think that the spatial quality of the area will be affected on a large scale. A possible reason for this, is that the dike itself is a monument. Also, questions are asked whether the dike sections are as weak as proposed by the Water Board. According to the residents the unique soil composition provides a higher safety than follows from general assessment methods used in the Netherlands. In addition, the M.E.R. Committee concluded that the necessity of the reinforcement was insufficiently proven and that culture historical- and landscape values were not addressed sufficiently (De Leeuw, 2017).

The Markermeer-case shows that doing an environmental impact assessment does not necessarily lead to a satisfying result for stakeholders. This is caused by the insufficient recognition on the necessity for the safety measures (although there have been more than a hundred meetings) and the attention that is given to environmental criteria that are important to the residents. The role of context managers is essential to resolve the friction between the project team and stakeholders. According to one of the managers, transparency is the key to reduce the resistance against reinforcement projects (Lammers, 2015). In that way, conflicting interests can be identified in early stages. It is then searched for satisfying solutions for both. By resolving issues before they become a bottleneck in the process, the lead time and costs of a project can be reduced. This is something that did not succeed in the Markermeer-case.

1.1.2. Project success of dike reinforcement projects

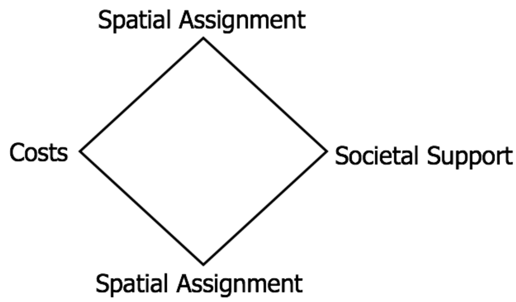


Figure 1: Keystones of a dike reinforcement projects

The example of the Markermeerdijken in Section 1.1.1, shows the importance of a design process and the role of the design team in dike reinforcement projects. In this section a theoretical approach to such a project is given to determine what is required to make such a project successful. Bos, Den Nederlanden & Lagendijk (2007) note that a successful dike reinforcement design can be developed by accounting for four keystones: the safety assignment, the spatial assignment, the project costs and the societal support for the project (see Figure 1). In the remainder of this section each keystone will be elaborated on individually.

Safety assignment
Dike reinforcement projects, in the Netherlands, are initiated when it is found that a certain dike segment does not meet the safety requirements as set in the Water Act. The safety assignment can be easily formulated, since the goal (and obligation) is to deliver a flood protection system which is able to withstand a storm with a certain probability of occurrence. It is dependent on the situation, which failure mechanisms have to be considered in the design calculations on the cross-section of the dike. There are many technical options to reduce the probability of occurrence of different failure mechanisms. Due to the large variety in design options, the safety assignment can be fulfilled in many different ways.

Spatial assignment
The variety of the technical options provides manoeuvring space to fulfil the spatial assignment. Hooimeijer, Kroon & Luttik (2001) defined the spatial assignment as follows: *'the improvement of spatial and ecological conditions so that the essential aspirations of individuals and groups in the society are included as much as possible. Also, it should be focussed on preservation of diversity, cohesion, and sustainability of the physical environment'*.

The inclusion of spatial quality in dike reinforcement projects has evolved over the last few years. Before 1960, the role of spatial quality in dike reinforcement projects was small, as during this time almost everybody focussed on economic progress (Van Heezik, 2007). The findings of committees Boertien and Becht improved the role of spatial quality in the design process of dike reinforcements, by giving a more dominant role to LNC-values in the design process (1960-1995). According to Bos et al. (2007), over the last years the traditional approach of including LNC-aspects in the design has evolved to a spatial quality approach.

Spatial quality is not unambiguously defined in the literature. Janssen-Jansen, Klijn & Opdam (2009) conclude that there are roughly three possibilities to interpret spatial quality of an area:

- Visual experience, which is the experience that people have when they visit or live in an area.
- The quality of the living environment, which is the visual experience and the user value of the area, excluding economic activities.
- Sustainable development, which is the visual experience and the quality of the living environment, including economic activities.

In the last years in the Netherlands, emphasis is put on the sustainable development of the project area. The definition of spatial quality which is commonly used in the Netherlands is as follows: spatial quality is the sum of the user value (the possibilities of the area in relation to the usage wishes of people), perceived value (the way people experience an area), and future value (the adaptability to the future situation) of an area (Janssen-Jansen, Klijn & Opdam, 2009).

Dependent on the size of a project, dike reinforcements can affect the spatial quality largely in a negative or positive manner. The spatial assignment in dike reinforcement projects is dual. One part of the assignment is focused on integrating the dike reinforcement into its environment, which is evaluated in the Environmental Impact Assessment and restricted by several laws (Bos et al., 2007). Appendix B elaborates on this Environmental Impact Assessment. The second part is focused on exploiting chances to increase the spatial quality in the project area. Dauvellier, Puyleart & De Jonge (2008) makes the important remark that spatial quality cannot be uniformly described among the users of an area, because the spatial quality is dependent on personal preferences. The complexity of that, is that often different aspects of spatial quality do interfere in a negative way, meaning that some people can experience a positive development, while others interpret it as negative (Janssen-Jansen et al., 2009).

Costs
The third keystone in the design process of dike reinforcement projects is costs. Costs in these kind of projects mainly consist of construction costs and management costs. In a broader sense the costs of a project can be determined over the life cycle of a project. Coorens (2001) describes what is included in life cycle costs: *'LCC includes the costs associated with acquiring, using, caring for and disposing of physical assets, including the feasibility studies, research, design, development, production, maintenance, replacement and disposal, as well as support, training and operating costs generated by the acquisition, use, maintenance and replacement of physical assets.'*

Societal Support
Societal support is the last keystone, to create a successful dike reinforcement project. The importance of support in dike reinforcement projects is caused by its link to the lead time and costs of a project. Lijklema & Koelen (1999) state that the commonly used "Decide-Announce-Defend"-Model in water management projects often results in problems with societal support. In this model, the governmental decision on a project is announced to the public, subsequently the government defends the retrieved comments on the project. Acceptance problems are the main causes for the inconvenience of such projects. This acceptance is not only focussing on the suitability of the provided measures. Societal support for a project is dependent on the acceptance on the following subjects (Lijklema & Koelen, 1999):

- Necessity of the project
- Intervention of the government
- Policies
- Effectiveness of the provided measures
- Suitability of the provided measures within an area

Communication is essential to achieve support from local stakeholders. Lijklema & Koelen (1999) explains that societal support is optimally created when the public has the impression that their opinion is seriously considered in the ideation of system adaptations and realization of the plans. The government and public should not aim to convince the other of their point, but to create mutual understanding in a project. This mutual understanding can be achieved in a transparent process in which strives for agreement between the public and the project team (Bos et al., 2007).

1.2. Problem statement

The historical flood defence projects at the Oosterschelde and in the "Rivierengebied" emphasize that integrating spatial quality is important to develop dike reinforcement projects that are widely accepted by the stakeholders in that area. The case of the Markermeerdijken showed that the current design process of dike reinforcement does not necessarily achieve the desired result. All three cases are examples of extreme stakeholder interference in flood defence reinforcement projects, leading to exceedance in costs and lead time of the project. In current projects, delays can be caused by stakeholders appealing the Environmental Impact Assessment or Project Proposal at the Council of State. To avoid these procedures, stakeholders wishes and requirements are collected and evaluated in the design process of reinforcement projects. This process ideally results in a dike reinforcement design that satisfies the stakeholders and improves the safety of the hinterland, while project delays and unnecessary expenses are avoided.

However, the dike reinforcement project at the Markermeer shows that current design- and process management tools do not necessarily result in a satisfying dike reinforcement for local stakeholders. It is reflected on the design process by evaluating project success based on the four keystones (safety assignment, spatial assignment, costs and societal support) provided by Bos et al. (2007). Project success is created when every keystone is seriously considered in the design process and the developed reinforcement design. Problems with societal support arise when the public participation process does not result in mutual understanding on the safety problem and qualities of the project area (Lijklema & Koelen, 1999). The problems addressed in this research focus on the spatial assignment. The complexity for fulfilling the spatial assignment is found in the different viewpoints of the desired influence of a dike reinforcement design on the spatial quality in the project area (Janssen-Jansen et al. 2009).

H+N+S (2010) states that a vision on the design of a dike reinforcement, in general, follows from a landscape vision on the project area, combined with a technical vision on increasing the strength of the dike. The spatial assignment (included by the landscape vision) in this process focusses on exploiting the landscape values in a project area (Van Reijn, 2016). A large amount of reinforcement solutions is, in the initial vision on the reinforcement assignment filtered into a small amount of design alternatives (generally three). Design calculations are made to verify the safety of the designs. For these design , it is assessed what the influence on the existing situation is. This is done in an Environmental Impact Assessment, resulting in a political choice for a preferred alternative (Aalberts, 2018). In this design process (visually presented in Figure 2a), the role of the subject experts (e.g. ecologist, archaeologist) is limited to assessing the effect of the proposed design alternatives on the existing situation in the project area. TAW (1994a) concludes that after the EIA, the least bad alternative (in relation to the effect on the existing situation) is chosen as preferred design alternative. It is explained that during execution of the EIA, almost no possibilities are provided to adapt these design alternatives as it affects the project procedures largely. This can induce unnecessary losses to ecological-, historical-, or social economic values within a project area.

The difficulty for improving the role of the existing situation in the surroundings (such as ecological-, historical-, or social economic value in the project area), in the design process is that the subject experts on these themes are typically assessing the consequences of proposed interventions (Aalberts, 2018). In reinforcement projects, these consequences are retrieved in an environmental impact study to verify design alternatives. However, due to limitations in time and budget, it is not possible to manually create a large amount of verified design alternatives (verified on safety) for subject experts, which can be assessed on the influence on the existing situation. This makes it difficult, for the subject experts, to identify wishes and requirements on influencing the existing situation in early stages of the project (development of design alternatives).

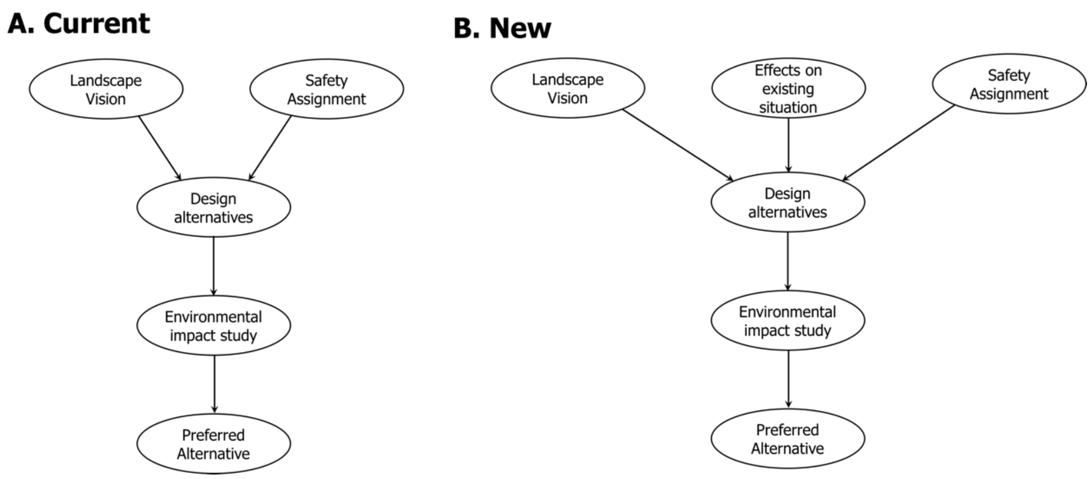


Figure 2: Development of design alternatives

1.3.Research objective

The observation that it is difficult to integrate the effects on the (ecological-, historical- or social economic values of the) existing situation in the development of design alternatives, has resulted in the objective of this research. The objective of this study is to develop a method which provides information, that can be used by subject experts, to compare effects that various design alternatives induce on the existing situation in a project area. This method is used to include the effects on the existing situation in the evaluation and selection of design alternatives in early stages of dike reinforcement projects (creating the situation that is provided Figure 2b).

1.4. Scope definition

This study is focussed on dike reinforcements among the primary rivers in rural areas in the Netherlands. This means that sea dikes and river dikes will not be considered in this research. Also, the dike reinforcement will be constructed following the trace of the existing dike in the project area. Rural area, in this research, is defined as an area which is sparsely populated, in which the use functions are set to be living, working (agriculture), and recreation. Also, the topics nature, transportation, and culture are considered as applicable qualities of the considered project area in this study. It should be remarked, that the dike in the existing situation, is not considered to be a mono-functional element. Functions include living, recreation, transportation, or agriculture is considered. The typical cross-sectional profile of a river dike in rural area is set as a dike with a grass-cover layer on the slopes, that can be occupied by a road located on the crest, and houses built on and near the slopes of the dike (Figure 3). In this study, the scope is set to rural areas to reduce the complexity of spatial planning in the project area. This makes the schematization manageable for a first study to integrate the effects on the existing situation in the development of design alternatives. The influence on the existing situation focusses on long term effects of reinforcement designs. Effects in the construction phase of the dike reinforcement projects are not considered.

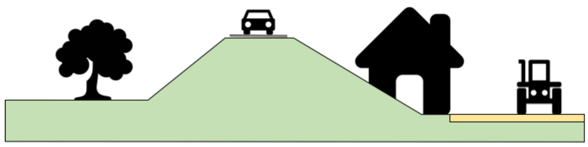


Figure 3: Typical cross-section for a dike in rural areas

The safety assignment against governing storm conditions, in this study, is assumed to consist of the direct failure mechanisms ‘inner slope stability’, ‘inner slope erosion’ (includes the height of the dike), and ‘piping’. By setting the scope to rural areas it is assumed that design measures against erosion of the inner slope, and stability of the inner slope are completely constructed from soil bodies. For piping, also structural solutions are reviewed, since mitigating piping might results in such large berm dimensions, that it is unrealistic to implement these in the existing spatial situation. It is stated that only design measures are considered that fit within the ambition of the HWBP (smarter, cheaper, and faster). The requirement set for fulfilling the safety assignment is stated as follows; the dike reinforcement design is related to the minimum required safety standards, ‘safer’ solutions are not considered. Design rules, to actually fulfil the safety assignment applicable are based on the Dutch design guidelines (OI2014-V4, Rijkswaterstaat, 2017b), retrieved from the WBI (Wettelijk Beoordelings Instrumentarium, Ministerie van Infrastructuur en Milieu, 2016).

In the study is assumed that the existing situation near dikes consists of random composition of functional characteristics of an area. The definition of a functional characteristic is set as a characteristic that an individual can value while being in or using an area, in the present, and in the future (such as social economic-, ecological-, and cultural elements). Aesthetic qualities of a project area are excluded in this definition. The used definition for functional characteristics is based on evaluating the widest definition of spatial quality; sustainable development. In Section 1.1.2, is explained that sustainable development of the project area consists of a visual experience of the project area, and the quality of using the project area now or in the future. Aesthetic qualities of the project area (visual experience) are not considered in this study, because methods have already been developed to express the changes on the visual experience of the project area. An example of such a method is VR-Dijken (Witteveen+Bos, n.d.), which allows the user of the tool to experience the visual changes in the project area, caused by a certain dike reinforcement design. An illustration of VR-Dijken is provided in Figure 4.

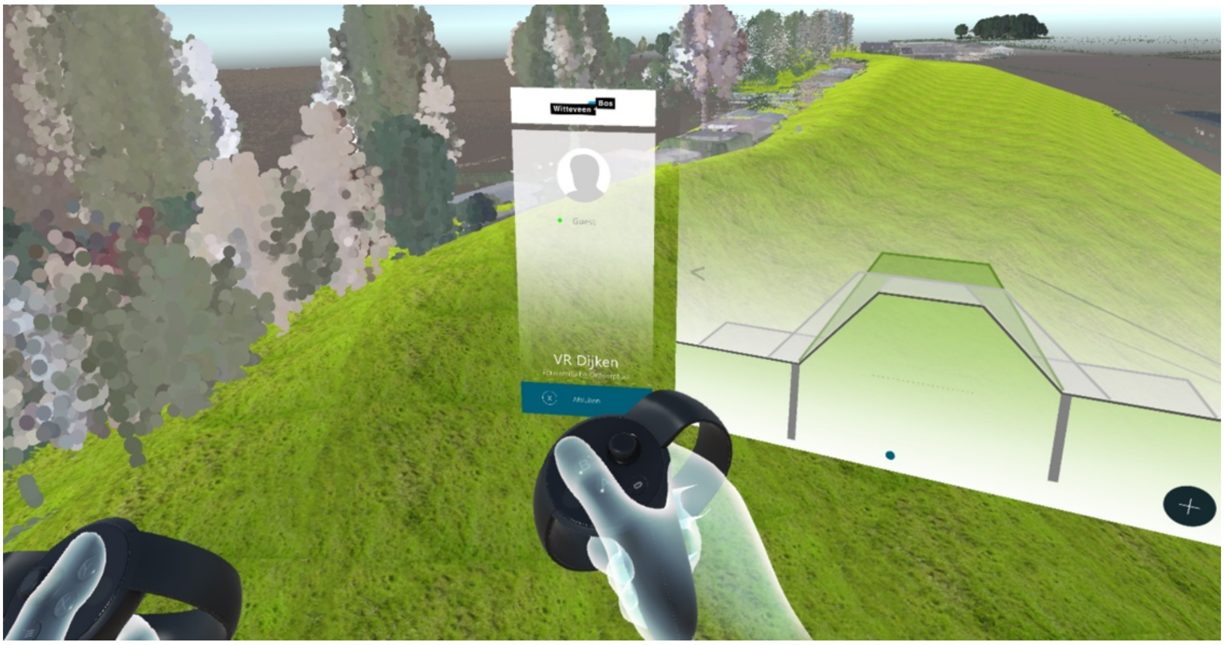


Figure 4: Illustration of VR Dijken (Witteveen + Bos, n.d.)

1.5. Research questions

To achieve the research objective presented in Section 1.3, five research questions are provided. In this section is, for each research question is discussed how an answer to the research question contributes to the development of a method that illustrates the effects of design alternatives on the (functional characteristics of the) existing situation in the project area, within the scope of this research (Section 1.4).

1. How can safety, against the failure mechanisms "inner slope erosion", "inner slope stability", and "piping", be provided in design alternatives of dikes in rural areas?

The answer to the first research question gives insight in design measures that increase the strength of dikes in rural areas. An answer to this question serves two purposes; it sets requirements on the technical capabilities for the development of a method, and it is used to identify the interference of the dike reinforcement on the functional characteristics of a project area.

2. What are the functional characteristics of a project area, that can be interfered with, in dike reinforcement projects in rural areas?

It is determined which functional characteristics can be interfered with in dike reinforcement designs in rural area, in the second research question. In a method that compares the influence of design alternatives on the existing, it is required to know which characteristics of a project area can be interfered with.

3. How can functional characteristics of rural areas be influenced by design alternatives of dike reinforcements in rural areas?

The third research question, identifies the exact relation between the functional characteristics, identified in the second research question, and the design characteristics of the design alternatives. Based on these relations, information can be provided to assess the influence of a reinforcement design on the functional characteristics of a project area.

4. What is a method that compares the effects of various design alternatives on the functional characteristics of rural areas?

Based on the answers to the first three research questions, a method is developed that makes comparing design alternatives possible for dike reinforcement project in rural areas. The answer to this research question is a method that step-by-step explains how effects of design alternatives can be retrieved and compared.

5. What is the value of the method that compares the effects of design alternatives for designing dike reinforcements in rural areas?

Answering the last research question illustrates the added value of applying the method to include the influence on the existing situation within the development of design alternatives. Analysing the method's outcomes determines whether the designed method has value in the design process of dike reinforcement projects.

1.6. Research method

In this section a research method is provided to achieve the objective of this research. As explained in Section 1.5, the research objective will be achieved by providing an answer to the five sub-research questions. The research strategy applied is Research through Design (RtD). *"Research through design (RtD) is an approach to scientific inquiry that takes advantage of the unique insights gained through design practice to provide a better understanding of complex and future-oriented issues in the design field"* (Godin & Zahedi, n.d.). A visualization of the applied research strategy is provided in Figure 5. It is shown that iterations between research questions two, three, four and five are obtained to provide an answer to every research question. These iterations were used to increase the level of detail of the relations expressing the influence of a reinforcement design on the functional indicators of the project area. In the remainder of this section, for each research question is described how an answer to research question is provided.

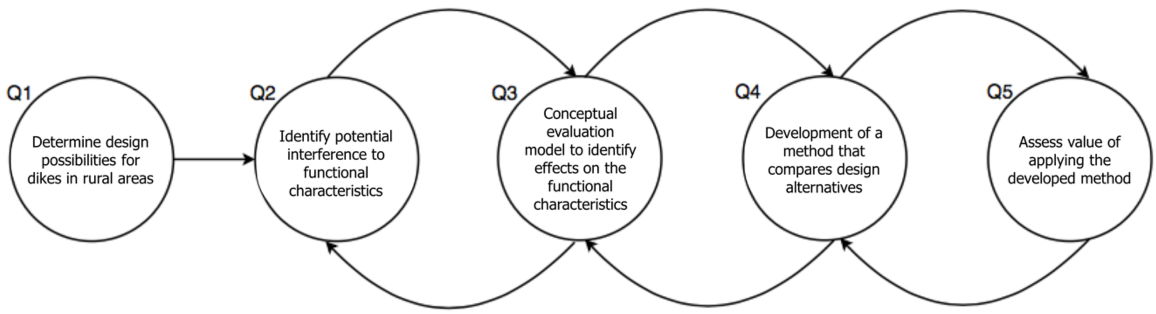


Figure 5: Research strategy

1. How can safety, against the failure mechanisms "inner slope erosion", "inner slope stability", and "piping", be provided in design alternatives of dikes in rural areas?

To answer the first research question a literature study is obtained on the physical process causing failure of a dike due to a specific failure mechanism. Based on the retrieved physical processes, it is reasoned how resistance against the applicable failure mechanism can be increased. The extensive knowledge on this topic, sufficiently provides insight in applicable design measures to fulfil a required safety assignment of a dike reinforcement in rural area (which is required for the further development of the model).

2. What are the functional characteristics of a project area, that can be interfered with, in dike reinforcement projects in rural areas?

The second research question is answered by making an inventory of characteristics of the existing situation that can be interfered with by dike reinforcement projects. For identifying these functional characteristics, the Workbench Method (Hooimeijer et al., 2001) is used. The strength of the Workbench Method is found in the provided decomposition of the complex term spatial quality in construction projects. To decompose spatial quality, from economic, social, ecological, and cultural perspective is reasoned how an individual might experience changes on the user value, perceived value, and future value of a project area. The emphasis in this method is put on the opinion that every individual experiences the spatial quality differently. Topics considered in this method are aesthetic qualities, design process qualities, and functional qualities. Therefore, the outcomes of the Workbench Method are filtered towards the functional characteristics of the project area that might be interfered with (which is the scope of this study). Appendix B further elaborates on the characteristics of the Workbench Method.

The created inventory is a list of functional characteristics, that might be exposed to changes in dike reinforcement projects. For the identified characteristics, it is studied how the geometry of the dike can be related to the functional indicators. Iterations are made, to define the functional characteristics that are actually interfered within dike reinforcement projects in rural areas.

In this study, it is chosen to apply a theoretical method (the Workbench Method) to identify the functional characteristics that are interfered with in dike reinforcement projects. Also other methods, such as interviews with subject experts, could be applied to retrieve the functional characteristics of the project area. The advantage of using the theoretical model, with respect to the interviews, is found in the top-down approach, which provides the possibility to get insight in the effect that an individual, with a random interest, experiences, while constructing a dike reinforcement.

3. How can functional characteristics of rural areas be influenced by design alternatives of dike reinforcements in rural areas?

To answer the third research question, a conceptual evaluation model is developed that can be used to identify changes to the functional characteristics of the project area induced by a dike reinforcement design. A literature study is obtained to identify how the functional characteristics of the project area can be influenced (in general). Afterwards, it is determined whether a dike reinforcement can induce such changes to functional characteristics. The result is a complete decomposition of effects (potentially) induced by a dike reinforcement design. This decomposition is integrated in a conceptual evaluation model. The model provides a framework to retrieve information introduced by a dike reinforcement design.

4. What is a method that compares the effects of various design alternatives on the functional characteristics of rural areas?

This research question is answered by developing a method that makes it possible to apply the conceptual evaluation model (of the third research question) for a large variety of designs. Proving an answer to this research question is obtained by going through three steps. First, a method is developed to create a large variety of design alternatives that are verified on the safety assignment for “Inner slope erosion”, “Inner slope stability”, and “Piping”. Design rules, to actually fulfil the safety assignment are based on the Dutch design guidelines (OI2014-V4, Rijkswaterstaat, 2017b), retrieved from the WBI (Wettelijk Beoordelings Instrumentarium, Ministerie van Infrastructuur en Milieu, 2016).

Secondly, a system is developed that makes it possible to provide a measure on the magnitude of the identified effects on the existing situation. Therefore, a Python-model is created that assesses the shape of the design alternative within a project area. It is studied what data is required to assess the effects of a design alternative automatically. Lastly, a visualization method is developed to express the differences of design alternatives in the influence on the existing situation.

5. What is the value of the method that compares the effects of design alternatives for designing dike reinforcements in rural areas?

For answering the last research question, the developed method is applied on a case study. This case study is a part of the dike reinforcement between the villages Wolferen and Sprok, located in the eastern part of the Netherlands (among the river Waal). The developed method is applied on three dike sections to assess the value of the method. In the case study, first the method is applied to retrieve an illustration that can compare the effects of design alternatives on the existing situation in the project area. Afterwards, simulations are executed to retrieve the insights provided by using the method for the development of design alternatives in dike reinforcement projects in rural areas.

1.7. Graduation thesis outline

The results of the proposed research are provided in this report. In Chapter 2 is explained which design measures increase the safety against failure of the dike, this answers research question 1. Research question 2 is answered by providing functional characteristics of the project area in Chapter 3. Chapter 4 answers research question 3 by explaining the conceptual evaluation model. The created method to compare design alternatives on the influence on the existing situation is provided in Chapter 5, and thereby answers research question 4. Chapter 6 provides the information retrieved from the case study (research question 5). The report will be finished with providing the conclusions and recommendations retrieved in this research (in Chapter 7).

2. Dike improvement possibilities in rural areas

The safety assignment against failure of the dike during normative water conditions is set (in the scope) to consist of three direct failure mechanisms; inner slope erosion, inner slope stability and piping. In this chapter for each failure mechanism is shortly described what physical processes cause failure. Subsequently, it is explained which design measures can be provided to fulfil the safety assignment at a rural location in the Netherlands. This provides an answer to the first research question. An extensive explanation on the occurring processes is provided in Appendix C.

2.1. Erosion of the inner slope

The resistance against erosion on the inner slope and crest is an important boundary condition in the determination of the crest height of the dike. Erosion on the inner slope or crest can be caused by overtopping waves or overflow of the dike. Overflow is the phenomenon that occurs when the water level in the river is higher than the crest height of the dike. This phenomenon is only governing when there are no waves under design storm condition of the dike. Otherwise, wave overtopping is the phenomenon that causes erosion on the inner slope (Jonkman et al., 2017). Wave overtopping occurs when the run-up of the waves exceeds the crest level of dike. The overtopping amount of water will flow over the crest and inner slope into the hinterland, which can initiate erosion of the cover layer. When, at one location, the cover layer is completely eroded, the core of the dike is exposed to overtopping discharge and erosion of the core will be initiated. Erosion of the core is initiated, and a gap on the inner slope will be growing. This can eventually lead to instability and breaching of the dike section.

In Appendix C, it is explained that resistance against this failure mechanism can be created by means of the design parameters as illustrated in Figure 6. In this study, berms on the outer slope will not be considered, because it is expected that waves in rivers (in the Netherlands) are not large enough to make outer berm an effective measure to reduce the crest height of the dike. This results in the finding that different combinations of outer slope angles, crest heights, and cover layer characteristics can provide resistance against erosion of the inner slope.

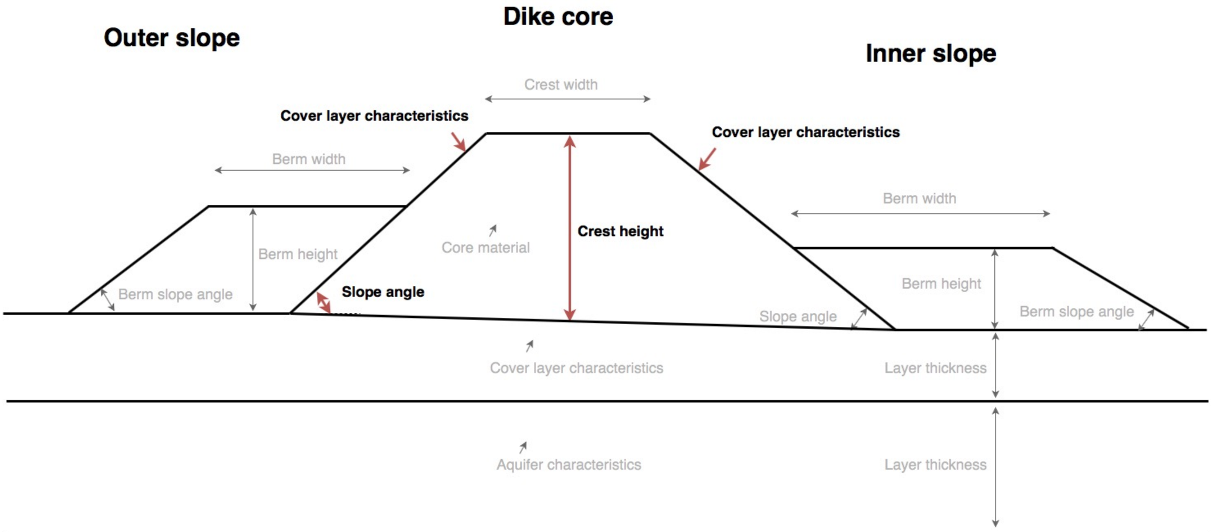


Figure 6: Parameters providing resistance against erosion of the inner slope

2.2. Inner slope stability

The instability of the inner slope is the failure mechanism in which a large part of the inner slope collapses due to the loss in effective stresses in the soil (dike and sub-layers). This failure mechanism focusses specifically on deep sliding planes that cause breaching of the cross-section. Instability of the inner slope often occurs when the water level in the river rises during a long period. Due to high water levels, water will start infiltrating the dike core and sub-soil under the dike. This infiltration causes an increasing pore water pressure in and under the dike, resulting in a decreasing effective stress in the soil in the core and sublayers. Whether the soil will be sliding is dependent on the momentum equation between three forces; the active soil pressure, the passive soil pressure, and the shear stress. When the driving moment (soil weight in the active zone), exceeds the resisting moment (soil weight in the passive zone plus the shear strength), a sliding plane will be developed and the stability of the inner slope is lost. The sliding will be formed at the location of minimum resistance; this is not a fixed location in the cross-section of the dike (‘t Hart et al., 2016).

To provide resistance against sliding of the inner slope, a large variety of design options is available (this is elaborated on in Appendix C). Within the scope of this study, structural solutions are not considered. The geometrical parameters increasing the resistance against sliding of the inner slope are presented in Figure 7 (in colour). The main goal for these design measures is to increase the passive soil weight in the normative sliding planes. This can be achieved by changing the geometrical design of the dike, such as constructing a stability berm, reducing the inner slope angle, or widening the complete dike body. The variety of design measures is large.

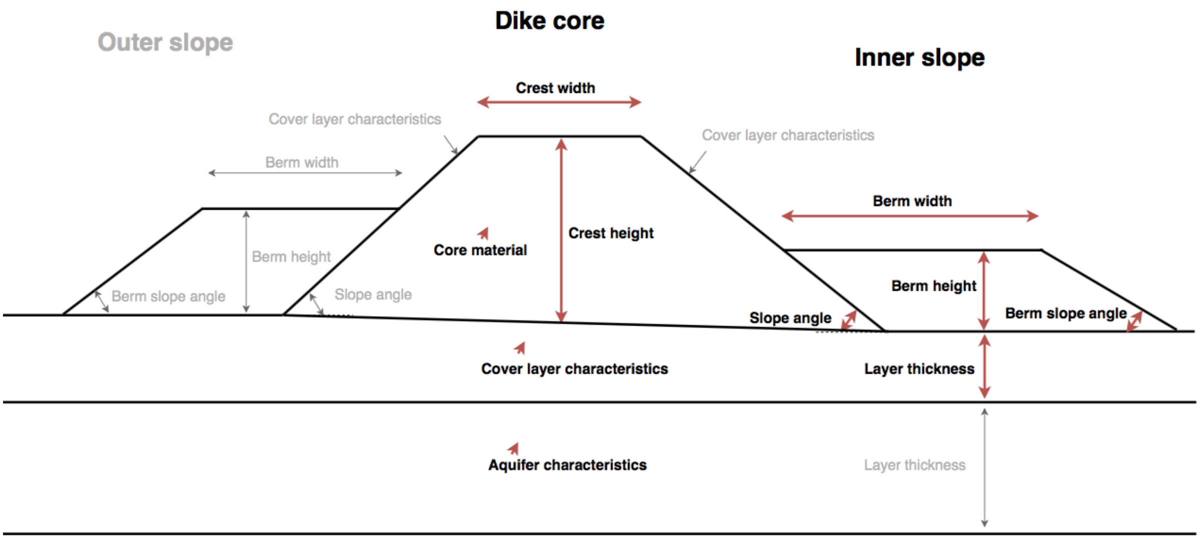


Figure 7: Parameters providing resistance against inner slope stability

2.3. Piping

Piping is the mechanism in which sediment (sand) is washed away from under the dike into the hinterland. Breaching of the dike section occurs when a continuous “Pipe”, under a cohesive layer, is formed between the river side and the hinterland, leading to a structural collapse of the dike due to erosion of the subsoil. The mechanism piping can be described based on the occurrence of six consecutive processes. Due to a large water level difference between the water level in the river and the water level in the hinterland, water pressure is built up in the aquifer under the dike and in the hinterland. When this water pressure is larger than the weight of the cover layer, the cover layer can crack (uplift). This can initiate a concentrated water flow (seepage flow) between the subsoil and the ground level in the hinterland. When the hole gets large, and the water flow is strong enough, grains from the aquifer can be transported through the cover layer towards the ground level (heave). As water flows towards the point of the least resistance, the flow will be concentrated on the place where erosion occurred and more material starts eroding from that location. A “pipe” will be formed on the transition between the cohesive cover layer and the aquifer. The erosion in this pipe will be accelerated, due to the resistance loss when material is washed away from the aquifer. When, eventually, the dike is completely undermined, this hollow pipe will be broadened by the concentrated flow from the river towards the hinterland, eventually resulting in breaching of the dike section (‘t Hart et al., 2016).

Table 1 illustrates potential design measures to increase resistance against piping. Increasing the horizontal seepage length by means of a piping berm, can result in unrealistic large berm dimensions when the subsoil has a piping sensitive composition, therefore it is wise to also consider other design options (TAW, 1999).

Table 1: Piping measures (source: TAW, 1999)

Measure	Example	Uplift	Heave	Piping
Increasing horizontal seepage length	Piping berm width in hinterland Increasing dike width Add clay cover to foreland	Decreases water pressure in aquifer, decreasing upward pressure under cover layer.	Decreases water pressure in aquifer, increasing effective stresses in the cover layer.	The seepage length is longer when the berm is constructed, decreasing the hydraulic gradient in the subsoil. Decreasing the forces on grains, just below the cover layer.
Increasing vertical seepage length	Seepage screen	Due to the extra seepage length, the water pressure on the hinterland side will decrease.	Due to the extra seepage length, the water pressure on the hinterland side will decrease.	Increases the seepage length, creating a lower hydraulic gradient. This decreasing the forces on grains, behind the screen (in the hinterland).
Preventing uplift in critical seepage length	Piping berm height in hinterland	Due to extra downward force, the resistance against the water pressure in the aquifer increases	The effective stress in the cover layer increases due to the berm. Resistance against fluidization of sand increased.	No effect.
Reducing head difference between river and hinterland	Decrease river water level Increase hinterland water level	Increasing hinterland water level, increases weight of the cover layer due to saturation of the cover layer. Chance on uplift decreases	Effective stress in the cover layer decreases, decreasing the resistance against fluidization of the grains flowing through the cover layer.	When the head difference decreases, the mobilization forces on the grains in the pipe decrease. Reducing the probability of occurrence of piping.
Prevent transportation of sand to ground level	Filter construction	No effect.	An extra resistance is created to prevent soil from flowing towards the ground level.	No effect.
Prevent pipe formation	Vertical geotextile Vertical gravel column	No effect.	No effect.	An obstacle blocks the formation of a pipe in the direction of the river side. Undermining of the dike will therefore not occur.

2.4. Concluding remarks

Evaluating the safety requirements results in two important findings that are used in the remainder of this study. It is found that there is a large variety of design measures that can be implemented to fulfil the safety assignment in a particular project area. Having noticed these design options, it is required to develop a model that represents the influence on the functional characteristics of the project area based on specific characteristics of a particular design. Functional impact should therefore be coupled to specific design parameters of the reinforcement design, not to the design as a whole. The large variety of design options, also requires a model that has the ability to automatically generate the influence on the existing functional characteristics of the project area. This provides the possibility to present the influence on the existing situation real time, and it is therefore possible to compare a large variety of design alternatives on the functional characteristics of the project area.

3.

Functional characteristics of rural areas near rivers

This chapter focusses on finding the functional characteristics of rural project areas near rivers that are potentially interfered with in dike reinforcement projects. In Section 3.1, it is explained which method is used to identify the functional characteristics of a random project area. Subsequently, in Section 3.2, the identified functional characteristics of project areas are explained. Lastly, in Section 3.3, it is reflected on the identified functional characteristics. The identified functional characteristics are in Chapter 4 analysed on the interference by specific design characteristics of dike reinforcement designs.

3.1. Methods to identify functional characteristics

The objective of this research is to develop a method that directly expresses the influence of a design alternative on the functional characteristics (elements in the spatial planning from which an individual can value changes in its properties) of the project area. Bos, Den Nederlanden & Lagendijk (2007) created an approach that focussed on including spatial quality in the plan process for water related construction project (note: the functional characteristics of the project area is part of the total spatial quality in the project area). It argues that spatial quality in designs is something that grows throughout the plan process, by making several design iterations. To integrate spatial quality in plan process (and designs), it should be determined what is valued in a project area. This is done by bringing in knowledge of the project location, for example by creating advisory groups or quality teams. It is their task to "protect" importance of spatial quality in such projects. Two methods are explained to conceptualize the influence on spatial quality in construction projects; design studios and the Workbench Method (Bos, Den Nederlanden & Lagendijk, 2007):

- *Design studios:* the characteristic of a design studio is that it retrieves the important spatial qualities of the project area by creating sketch designs in collaboration with people that have location specific knowledge.
- *Workbench method:* the Workbench Method focusses on decomposing the spatial quality in easily interpretable elements that describes qualities in project areas that a random individual can experience. The single elements are presented in a matrix that represents the total spatial quality of a project area (Shown in Table 24, of Appendix B)

For design studios and the Workbench Method, it is important to retrieve location specific data. The strength of the Workbench Method is the top down approach, that is used to identify the spatial quality in the project area. In the beginning of a project, it is directly possible to provide a rough indication of the spatial quality of an area. After iterations, by means of additional research in project areas or stakeholders' interviews, add level of detail to the identified characteristics of the project area (Hooimeijer et al., 2001). In design studios, it is directly focussed on specific characteristics of an area (Bos, Den Nederlanden & Lagendijk, 2007). As the objective is to create a generic method for illustrating the effects of dike reinforcements design in rural areas, it is preferred to apply the Workbench Method, because the spatial quality matrix (in Table 24, of Appendix B) gives guidance on naming characteristics of rural areas.

It should be mentioned that the Workbench Method identifies the complete spatial quality of rural areas (Hooimeijer et al., 2001). As explained in the Scope Definition (Section 1.4), aesthetic and process related values are not included in this study. Therefore, after the first identification of the spatial quality in rural areas results are filtered to the functional characteristics of project areas only. Iterations, in this study, helped refining the functional characteristic of rural areas near rivers, in elements that can be interfered with in dike reinforcement projects. The identified elements (the "functional characteristics" of rural areas) are explained in Section 3.2.

3.2. Identified functional characteristics of rural areas near dikes

Application of the Workbench Method resulted in twenty-two functional characteristics of project areas, that could be interfered with during dike reinforcement projects in rural area near rivers. The functional characteristics are explained in Table 2, by providing a short explanation and a photograph of the characteristic. Also, it is indicated to which Workbench term the identified characteristic is related. To retrieve the characteristics (as provided in Table 2), first a decomposition of spatial quality is provided based on the Workbench matrix (Appendix B). Afterwards iterations were obtained by studying the relation between the dike reinforcement design and the functional characteristics of the project area. This eventually resulted in the decomposition of the project area as provided in Table 2.

Table 2: Functional characteristics of rural areas influenced in dike reinforcement projects

Identified characteristic	Relation to Workbench Method	Number	Explanation	Photograph
Transportation function on the dike	▪ Accessibility	**D1**	A dike often has a transportation function located in the cross-section, by means of a road on the crest of the dike (Figure 8). This road can have two purposes; providing accessibility towards houses located near the dike, and providing a connection between two cities/villages. Changing spatial plans can result in changing requirements to the traffic function on the dike, which influences the cross-sectional shape of the dike reinforcement.	 *Figure 8: Road on the dike (Otten, 2018)*
Living function on the dike	▪ Access ▪ Safety feeling	**D2**	There is a possibility to combine the living function, and the water protection function in the design of a dike reinforcement. Figure 9, shows such an example, in which a house constructed on the stability berm of a dike. It is dependent on the design of a dike, whether there is space available to construct these houses.	 *Figure 9: House on dike (Google, n.d.-a)*
Agriculture on the dike	▪ Access	**D3**	A typical example of combining agriculture and high water protection is provided in Figure 10. This figure shows sheep maintaining the grass cover of the dike. Maintaining the defence structure with sheep is choice that the administrator of the dike can make (AT Osborne, & Deltares, 2013).	 *Figure 10: Agriculture on dike (Jonkman et al., 2017)*
Recreation on the dike	▪ Access	**D4**	Figure 11 shows people using the dike for recreation. Jonkman et al. (2017), explains that winding dikes are attractive for recreational activities such as cycling. It is dependent on multiple factors (accessibility, attractiveness of the area, pollution), whether the dike indeed has a recreational function within the project area (Decisio, 2017).	 *Figure 11: Cycling on dike (Ter Mull, 2007)*

Vegetation on the dike	▪ Ecological structures ▪ Ecological stocks ▪ Healthy ecosystems	**D5**	It is possible to account for nature development within the cross-sectional design of a dike reinforcement in rural area. A typical example is provided in Figure 12, that shows a vegetation rich cover of the dike's slopes.	 *Figure 12: Flowers on dike (Waterschap Rivierenland, 2018)*
Effective space use on the dike	▪ Multi-purpose	**D6**	The "Effective space use on the dike" focusses on combining the flood protection function, with secondary functions, such as agriculture, living, recreation, and nature. Typical examples of these function combinations are presented from Figure 8 to Figure 12. Combining these function increases the efficiency of the project area.	
Historical cross-sectional shape of the dike	▪ Cultural variety ▪ Integration	**D7**	The cultural variety of an area, tells the story of the area from the past to the future. According to the LoLa landscape architects (2014) the existing dike tells a part of this story. Changing the geometry can influence the historical character of the dike. Figure 13, shows an example of an historical dike. Which is, according to TAW (1994a), multifunctional element, with a small gravel path located on the crest.	 *Figure 13: Historical dike (Rijksdient voor het Cultureel Erfgoed, 2013)*
Archaeological values in dike	▪ Cultural variety	**D8**	It is also identified, that the core of the dike can contain valuable archaeological information, which can be lost in dike reinforcement projects. Figure 14 shows a dike in Zeeland, in this dike, a clay box was located, that preserved archaeological attributes. TAW (1994a), explains that old dikes often have a layered soil structure that has been developed due to past dike reinforcement projects.	 *Figure 14: Layered soil composition (Van Dierendonck, 2016)*
Transportation function on the river	▪ Accessibility	**S1**	The importance of waterway transport in the Netherlands is shown by its market share (eighteen percent) for distributing goods within the Netherlands (CBS, 2016). This makes the Dutch rivers important transportation corridors. The corridor can be influenced by the construction of a dike reinforcement, when it results in limitations for waterway transport. This is for example the case when a dike is constructed within the navigation channel of the river.	 *Figure 15: Waterway transport (Van Lokven, 2011)*
Living function in surrounding area	▪ Access ▪ Safety feeling	**S2**	In the Netherlands, houses are often located close to the dikes. An example is given in Figure 16. In dike reinforcement projects, it may be interfered with these houses when the houses are located within the footprint of the cross-sectional design of the dike.	 *Figure 16: Living near dike (Google, n.d.-b)*

Agriculture in surrounding area	▪ Access	**S3**	Agricultural land can also be located near rivers (Figure 17). Wesseling (1978) explains that the water content in the subsoil provides an important condition to growth properties of crops. This makes locations near rivers interesting for agriculture. This agricultural land can be interfered with in dike reinforcement projects, for example when the footprint of the design is located on agricultural land.	 *Figure 17: Agriculture near dike (Google, n.d.-c)*
Recreation in surrounding area	▪ Access	**S4**	Recreational areas can also be located within rural areas in the Netherland. Figure 18, shows a campsite that is directly bordering the flood defence structure. A dike reinforcement project can induce changes to the existing situation in the project area.	 *Figure 18: Campsite near dike (Google, n.d.-d)*
Nature in surrounding area	▪ Ecological structures ▪ Ecological stocks ▪ Healthy ecosystems	**S5**	The future "ecological" value of an area is partly dependent on the ecological stocks that are available in the area. Implementing the dike reinforcement could influence the amount vegetation in the project area. Figure 19, provides a typical example of ecological stocks located in the areas near rivers. A dike reinforcement design might result in interference with these nature areas.	 *Figure 19: Natura 2000-area Rijntakken (Beunen & Jansen, 2017)*
Effective space use in surrounding area	▪ Multi-purpose	**S6**	The influence of the dike design on the existing spatial planning is important indicator of the efficiency of the project area. To exploit land optimally, sufficient space, logical shapes, and appropriate subsoil characteristic are required. Providing good conditions facilitates logical combinations of the functions 'living', 'agriculture, 'recreation', and 'nature' in the project area.	
Ground water balance in surrounding area	▪ Water in balance	**S7**	A dike reinforcement project is initiated to reduce the probability of flooding; this is the 'Safety assignment'. Besides flooding, also desiccation or rewetting in bordering areas can be the result of certain design measures. The effect of (too) high ground water levels has been presented in Figure 20	 *Figure 20: High ground water level (Van der Hoek, 2017)*
Pollution in surrounding area (air-, noise pollution)	▪ Clean environment	**S8**	A clean environment from spatial quality point of view refers to functional limitations of an area caused by pollution due to human activity. Two potential causes are noise-, and air pollution. Dike reinforcement can contribute positively and negatively on reducing these pollution sources due to the implementation of use functions on the dike. A typical example is provided in Figure 21, in which a large traffic function is located on the crest of the dike (producing large nuisance).	 *Figure 21: Pollution caused by traffic on dike (Wunderink, 2018)*
Soil pollution in surrounding area	▪ Clean environment	**S9**	In the Netherlands, it is set by law that further degradation of the soils/water quality is not allowed during construction projects (Kattenberg & Van der Gun, 2012). Nevertheless, it is possible	

			to increase the soil quality when soil is cleaned during such projects.	
Historical flood relics in surrounding area	▪ Cultural variety	**S10**	LoLa landscape architects (2014), explains that historical flood relics near dikes are important elements for the identity of areas. An example of such a historical flood relic is a pond *('wiel' in Dutch*). A pond located close to a dike has been presented in Figure 22. Dike reinforcements can interfere with this typical character, when it is decided to construct at the exact location of the pond.	 *Figure 22: Pond ("wiel" in Dutch) located near dike (Jonkman et. al., 2017)*
Historical military expressions in surrounding area	▪ Cultural variety	**S11**	Besides the flood relics, LoLa landscape architects (2014) also identified military defines lines among Dutch rivers as important cultural values within areas located near dike. An example of such a military element is provided in Figure 23. Dike reinforcement projects can induce mayor changes to the expression of these elements, when they are located within the reinforced dike's cross-section.	 *Figure 23: Military defense element (Jonkman et. al., 2017)*
Heritage structures in surrounding area	▪ Heritage	**S12**	Cultural heritage is an important value in living environments. An example of such a cultural element is the church, presented in Figure 24. It can be observed that the church is located close to the existing dike. Therefore, this value can potentially be lost when the dike is reinforced at that location.	 *Figure 24: Church located near dike (Google Maps, n.d.-e)*
Heritage sites in surrounding area	▪ Heritage	**S13**	Heritage does not only consist of structural elements such as farms or churches. There are also locations where the complete sites are important cultural expressions. An example is provided in Figure 25, that is a castle with large gardens. A dike reinforcement does not necessarily influence the castle, but it may result in an effect on the gardens of the property.	 *Figure 25: Protected castle property (Google Maps, n.d.-f)*
Archaeological values in surrounding area	▪ Heritage	**S14**	The last element that is identified is the archaeological value that could be located in the project area. Figure 26, shows archaeological findings during a dike reinforcement project in Krimpen. The historical well was found during the construction phase of the dike reinforcement project.	 *Figure 26: Old well near dike (Hoogheemraadscap van Schieland en de Krimpenerwaard, 2015)*

Every identified characteristic (presented in Table 2) is labelled with a number. These numbers are used in Chapter 2, to structurally retrieve relations between the design characteristics of a dike and functional characteristics of a project area in a structured manner. Elements indicated with a "D" in front of the number, are characteristics of a dike that can be valued by an individual using the project area. While "S"-numbers are characteristics located within in surroundings of the dike.

3.3. Concluding remarks

In practice, the effect on the functional characteristics of a dike reinforcement project are considered in a plan study and documented in a project plan and Environmental Impact Assessment (ENW, 2017). The impact of developed design alternatives in these plan studies described in the Environmental Impact Assessment. After the large inconvenience on dike reinforcement project in the eighties and nineties, TAW (1994b), researched the topics that should be evaluated to represent the interests of the stakeholders in such projects. It was recommended to research the effect on the following six topics in the Environmental Impact Assessment (more information in Appendix A):

- Landscape values
- Nature values
- Culture historical values
- Social-economic functions
- Maintenance
- Costs

When the defined functional characteristics by the Workbench Method are compared to the environmental values provided by TAW (1994b), it can be concluded that the provided functional indicators are a further breakdown of the rough topics as provided by TAW. The provided terms by TAW (1994b) contain a lot of information and leave interpretation to the subject experts, while the outcome of the Workbench Method breaks these down into small terms that leave small space for interpretation. For example, it is difficult to exactly explain what nature values are, and how they can be valued while using the terms as provided in TAW (1994b). In Table 2, the nature consists of several elements (e.g. pollution, nature in the surrounding area, vegetation on the dike).

Observing the above described six topics, shows that the identified functional indicators mainly focus on the topics nature values, culture historical values, and social-economic functions. In the scope of this study is explained that landscape values (aesthetic values) are not considered in this study. Also, the Workbench Method does not address the effects of a design on maintenance, and costs of the design alternatives. This is caused by the chosen perspective in the Workbench Method, that focuses on the user of the project area, and not on the administrator of the dike. It should be kept in mind that the provided functional characteristics do not cover the interests of the administrator.

4.

Development of a conceptual evaluation model

This chapter explains the development of a conceptual evaluation model, that identifies changes on the existing (functional) situation induced by a dike reinforcement design. The conceptual evaluation model relates the, in Chapter 2, retrieved design characteristics for dike reinforcements, to the, in Chapter 3, identified functional characteristics of a project area. Expressing the relations between the design alternatives for dike reinforcements and functional characteristics answers the third research question of this study.

Section 4.1 explains the conceptual evaluation for dike reinforcement projects in rural areas in the Netherlands. Subsequently, the identified relations in the conceptual evaluation model have been substantiated in Section 4.2. An example of applying the model to identify changes in a project area is provided in Section 4.3. The chapter ends, with final remarks on the conceptual evaluation model (Section 4.4).

4.1. Evaluation model expressing changes on the functional characteristics of a project area induced by the design of a dike reinforcement

In Chapter 2 was concluded that there is a large variety of design options to resolve potential safety problems of a dike in rural areas. These solutions mainly consist of geometrical changes of the design of the dike to increase the strength against applicable failure mechanisms. As a “soil” solution may result in unrealistic large berm dimensions for the failure mechanism “piping”, also structural solutions are considered in this study. For this large variety of design options, it should be considered what the influence on the functional characteristics of the project area (identified in Chapter 3) is. In total, twenty-two functional characteristics are identified that can be interfered with due to the implementation of a dike reinforcement in rural area. This section relates the functional characteristics of a project area to a specific design characteristic of a dike reinforcement.

Two separate models are created to relate the functional characteristics of a project area to the design characteristics of a dike reinforcement (as presented in Figure 29). A separation is made between the influence on the functional characteristics of the dike (indicated with D-numbers in Chapter 3) and functional characteristics of the surroundings (indicated with S-numbers in Chapter 3) to provide a structured overview on the interference in the existing situation caused by a dike reinforcement project. The resulting conceptual evaluation models, based on a literature study on the functional characteristics of rural areas, are illustrated in Figure 27 and Figure 28.

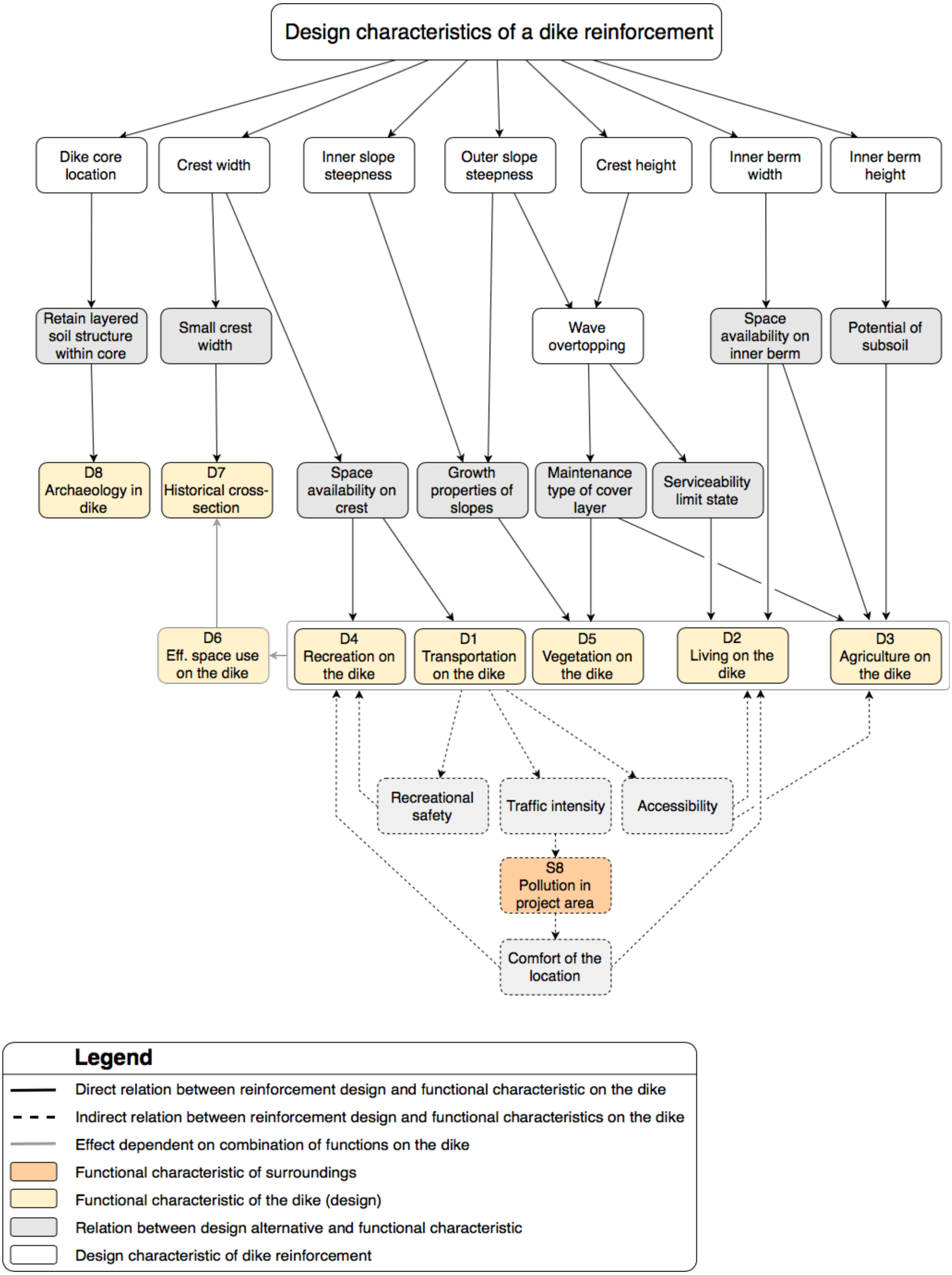


Figure 27: Evaluation model for influence of dike reinforcement design on the functional characteristics of the dike

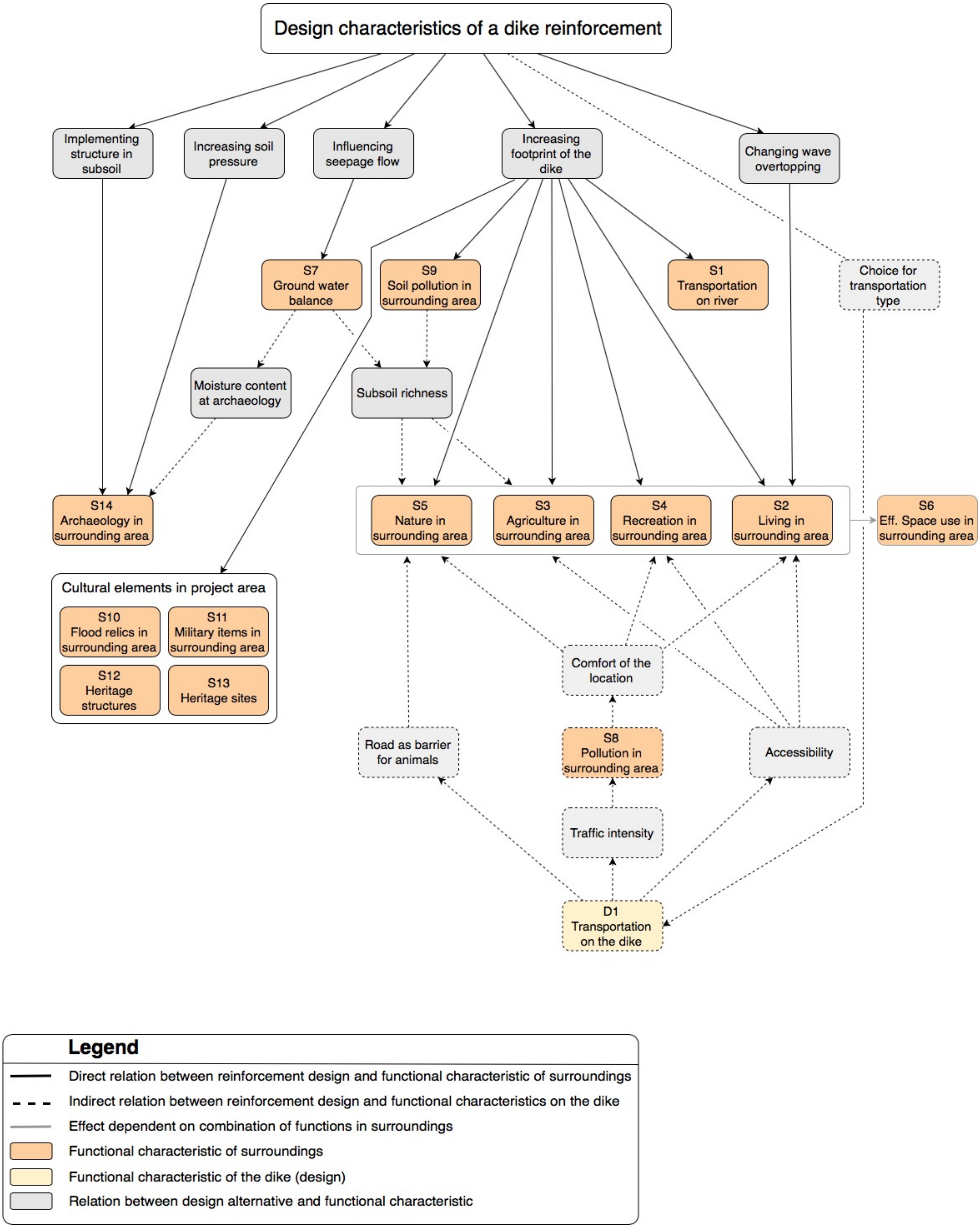


Figure 28: Evaluation model for influence of dike reinforcement design on its surroundings

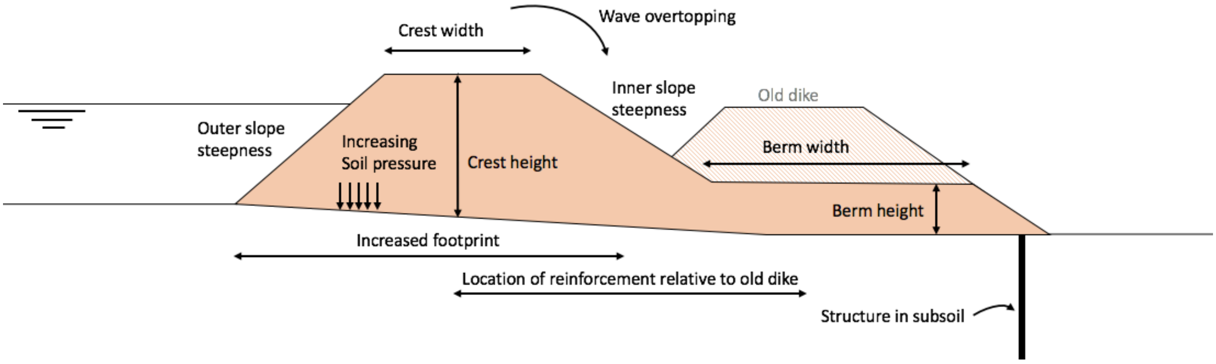


Figure 29: Design characteristics of dike reinforcements in rural areas

Using the conceptual evaluation model provides guidance in determining the interference of a certain dike reinforcement design on the existing functional characteristics of the project area. It should be started by identifying the applicable functional characteristics that occur at a certain location in the Netherlands. For these characteristics it can be determined how a dike reinforcement design influences the existing situation. This can be done by following the lines starting at "Design characteristics of a dike reinforcement" and ending at the functional characteristic of interest (orange or yellow boxes). Following the lines leads along grey boxes, indicating what causes an effect on the existing functional characteristic. Lastly, it should be determined what the importance of the retrieved effect is in the considered project area.

Example

Determine the influence on agriculture caused by a dike reinforcement design:

1. *Identify to elements related to agriculture: "D3 Agriculture on the dike" (Figure 27) and "S3 Agriculture in surrounding area" (Figure 28).*
2. *Going through Figure 27 identifies four relations between "D3 Agriculture on the dike" and the design of a dike reinforcement:*
    - *Potential of the subsoil on the inner berm*
    - *Space availability on the inner berm*
    - *Maintenance type of the cover layer*
    - *Accessibility of the agricultural land*
3. *Going through Figure 28 identifies four relations between "S3 Agriculture in surrounding area" and the design of a dike reinforcement:*
    - *Subsoil richness in surrounding area*
    - *Increasing footprint of the dike*
    - *Accessibility of the agricultural land*
4. *Determine the importance of the retrieved effects*
    - *For example, a dike is constructed without any structural measure. Then, it can be assumed that the subsoil richness in the surrounding area will not experience any interference from the design of the reinforcement.*

In Figure 27 and Figure 28, a deviation is made between direct and indirect relations. Direct relations are effects directly induced by the design characteristics of the dike reinforcement. In indirect relations, the dike reinforcement influences a certain functional characteristic due to the influence it has on another functional characteristic. A typical example of such indirect relation is the effect that the function "D1 Transportation on the dike" induces on the "S5 Nature in surrounding area". In the figures can be found that "D6 Effective space use on the dike" and "S6 Effective space use in the surrounding area" are dependent on function combination on the dike and in the surroundings of the dike. It is dependent on location specific ambitions to determine the target for effective space use in the project area. All retrieved relations illustrated in the conceptual evaluation models are based on a literature study into the functional characteristics of a project area. Section 4.2 describes the relations in more detail.

4.2. Relating functional characteristics of a project area and the design of a dike reinforcement

To determine the relation between the different functional indicators of a project area, and the dike reinforcement design, the functional indicators are divided in two groups; functional indicators of the dike design, and functional indicators of the surroundings. This is done to create an uncluttered overview on the dependencies between functional indicators, and the design of a dike reinforcement. In Section 4.2.1 and Section 4.2.2, the findings on the theoretical relations are described per identified element.

4.2.1. Functional characteristic of the dike

D1. Transportation function on the dike

- Space availability on crest

Explanation:

In the Scope Definition (Section 1.4), it is explained that roads on dikes in rural areas are normally located on the crest of the dike (when a road is available). Nevertheless, dike reinforcement projects provide the possibility to re-evaluate the required traffic function on the dike. Waterschap Hollandse Delta (2011) explains that safe transportation of large traffic intensities requires larger widths of roads, then low traffic intensities. This should be accounted for in the cross-sectional design of the dike.

D2. Living function on the dike

- Space availability on inner berm
- Serviceability limit state
- Accessibility of houses
- Comfort of the location (experienced pollution)

Explanation:

The attractiveness of living within the cross-sectional design of the dike is found to be dependent on four characteristics. Visser & Van Dam (2006) studied which factors influence the price of houses. It was found that houses in unpolluted areas, with a large accessibility on average have highest prices. Therefore, it is concluded that air-, and noise pollution negatively affect the comfort of the location. Also, large accessibility of the houses is found to be important. Nevertheless, it should be determined whether a road on a dike is critical to achieve accessibility.

According to The Water Act (Dutch National Government, 2017) additional activities within the cross-section of the dike may be applied, when these activities do not result in a reduction of the safety against flooding. Therefore, it is possible to construct on the inner berm of the dike (when it is chosen to design a berm to increase inner slope stability). To mitigate future reinforcement projects, construction of jack up (*opvijzelbare in Dutch)* houses on the dike can be considered (Tromp, Van den Berg, Rengers, Pelders, & Schmull, 2014). The availability of space, and the size of the houses determine the ability to construct houses on the berm of the dike. If houses are constructed within the cross-section, the serviceability of the house during storm conditions should be accounted for. In Jonkman et al. (2017), it is noted that there are several guidelines for maximum allowable overtopping discharges, to retain functions behind flood defences. From EuroTop (2007), can be retrieved that an average overtopping discharge larger 0.01 l/s/m will start inducing damage to buildings.

D3. Agriculture on the dike

- Space availability on inner berm
- Berm height
- Maintenance type of dike cover
- Accessibility of agricultural land on the dike

Explanation:
There are two types of agriculture, which can be applied within the dike's cross-section; light agriculture and intensive agriculture:

- Light agriculture: this type of agriculture focusses on combining agriculture with the maintenance of the grass cover layer located on the slopes of the dike. Maintaining the dike can, from agricultural perspective, be beneficial in two ways. The growing grass has to be mowed or grazed, to secure the strength of the cover layer. When grass is mowed by a farmer, this grass can be used as food for his animals. While grazing sheep on the dike can provide income by means of increased wool production. In both cases, the formed grass cover is a closed cover providing the same properties for strength against inner slope or crest erosion (Rijkswaterstaat & STOWA, n.d.). According to this study, agriculture with heavy animals (such as cows, and horses) cannot be performed on the slopes and crest of the dike cover, when the dike's crest allows wave overtopping. The reason is that the weight of these animals cause large gaps in the cover layer, resulting in an erosion-sensitive cover layer.
- Intensive agriculture: focusses more on the large scale agriculture, such as cultivation of food or livestock farming for human use. As explained above, the dike slopes and crest cannot facilitate these functions due to the erosion-sensitivity of the elements. As explained under "Living" multiple space use at the stability berm is allowed when this does not affect the water retaining structure. Therefore, an additional height can be applied on the minimal dimensions of the berm, to facilitate this type of agriculture on the stability berm (SWECO, 2018). The availability of agricultural land on the inner berm is dependent on the width of the inner berm. Also, the height of the inner berm is important. According to Huinink (2011), agricultural land is vulnerable for height differences, as it influences the moisture content near the ground level. In the study, it is also explained that mechanical activities (such as plowing) are more expensive in areas with gradients larger than twenty percent, due to the difficulties in operations.

D4. Recreation on the dike

- Recreational safety
- Space availability for recreational infrastructure
- Comfort of the location (experienced pollution)

Explanation:
The dike as an element also has a recreation function, which is focussing on cycling or walking in the area (Scope Definition, Section 1.4). According to Decisio (2017), the recreational attractiveness for cyclists is focussing on the attractiveness of the area (not in the scope of this study) and the comfort on the route. The study states that the comfort for a cyclist is dependent on the experienced safety at the cycling route, and the nuisance created by other functions in the project area. According to this study, the recreational safety will decrease when cycling or walking is combined with motorized traffic (and its velocities). Therefore, it is dependent on the road intensity, whether recreational safety is affected.

D5. Vegetation on the dike

- Maintenance type of dike cover
- Slope steepness of dike slopes

Explanation:
The variety of vegetation on the dike is an important measure for the ecological value of the dike. The appearance of species on the dike is dependent on the maintenance type (of the area), the composition of the subsoil, the slope that the cover layer has, and the exposure to the sun (Rijkswaterstaat & STOWA, n.d.). As the composition of the subsoil is, for every design alternative the same, it is not expected that this leads to distinctive effects on ecology. The slope of the cover layer, on the other hand, is important. It is concluded that steeper slopes have better properties to grow a specie rich cover layer, because these slopes are generally dryer. Specie rich grasslands develop best on steeper slopes, as herbs can resist draught

better than grasses. Also, the exposition relative to the sun is an important measure. Specie rich vegetation grows better when it is exposed to sunlight over many hours. Therefore, grow capabilities are better on southern slopes, than on northern slopes. The influence of the exposition is found to be larger than the steepness of the slope. Therefor it is concluded that, from vegetation point of view, it is better to construct shallow slopes in the north, because it is in this way more exposed to sunlight. While the southern slopes have the largest ecological potential when they are constructed as steep as possible (Rijkswaterstaat & STOWA, n.d.).

According to TAW (1994a), also the maintenance type is important for vegetation on the slopes of the dike. There are three maintenance types for slopes in a dike cross-section (Rijkswaterstaat & STOWA, n.d.):

- Nature maintenance: when maintenance is focussed on creating large nature values on the dike, a maintenance strategy is chosen which uses grazing or haying for the benefit of nature. When this type of maintenance is used, no fertilizers are used which can destroy natural values. The result of this type of maintenance is strong root structure in the cover layer, resulting in a large erosion resistance of the dike's cover, in overtopping conditions.
- Functional maintenance: when maintenance is focussed on small nature value, light agricultural or lawn maintenance is applied. This type of maintenance allows individuals to benefit from the to be maintained areas on the dike's cross-section. The light agricultural maintenance allows small amounts of fertilizers, resulting in a loss of nature values on the dike. While lawn maintenance results in more mowing activities, and thereby results in smaller nature values. The result of this maintenance type is that the roots are formed near the surface, resulting in a smaller strength of the cover layer, than in the case of nature maintenance.
- Agricultural maintenance: when agricultural maintenance is applied, the strength of the cover layer is lost for a large part. Due to the use of large amounts of fertilizer and intensive use by large animals, the roots of a grass cover do not get the ability to grow a strong cover. The heavy animals create pressure points in the cover layer. While also intensive use of fertilizer results in a cover layer with open places. The cover layer does not provide any additional strength to the core of the dike and the nature value in this ecological value will be low.

D6. Effective space use on the dike

- Combination of agriculture, living, recreation and nature within a design

Explanation:

The effective space use on the dike focusses on the possibility to allocate functions on top of the dike. According to AT Osborne & Deltares (2013), the effectiveness of space use focusses on combining functions that reinforce each other, while inefficient combinations are prevented. It is dependent on the combination of functions (living, agriculture, recreation, and nature) that the cross-section of the dike fulfils, whether the space use is efficient. This are typical design choices for a design team.

D7. Historical cross-sectional shape of the dike

- Small crest width
- Multifunctional design

Explanation:

According to TAW (1994a), the trace of the dike is, from culture historical perspective, more important than the cross-section of the dike. It reasons that cross-section properties are time dependent, caused by the gained knowledge on flood safety. As explained in the scope, the trace of the dike is set in this study, meaning that there will be no difference on this aspect in the considered design options. Nevertheless, there are differences in consideration of the preservation of culture historical values in the design of the dike.

TAW (1994a), reasons that from the past, a dike cross-section is a soil-only structure, therefore in the future a dike's culture historical value will be preserved when a soil reinforcement is constructed. This dike is a typical multifunctional element, in which the flood defence function is combined with for example light agriculture (for maintenance), living, or transportation on the dike. For the culture historical value of the dike it should be ensured that the dike does not get a solitary element, with large unused berms. Traditionally, on top of the soil structure, in the centre of the cross-sections crest, a small road structure has been located. This road structure (a vowel or gravel path) has been typed by its low traffic intensity and small dimensions. Due to the industrial revolution in the fifties, the traffic function on top of the dike is largely increased at many locations. The study concludes that the increased crest width, leads to much more damage to the culture historical value of the area, than the technically required cross-section. About the cross-section it is explained that the slopes of the dike are not an important consideration from historical perspective, as the slope was an indication of wealth in the project area (the shallower the slope, the wealthier the people). The wealth in the area has been changed over time, therefore the dike's cross-section can also adapt to this new situation. The preservation of steep slopes and stability berms, leading to limitations in the functional use of the dike, may not affect the historical character of a cross-section as a whole, which is a soil cross-section, with a gravel path located on the centre of the crest (TAW, 1994a).

D8. Archaeological values in the dike
- Excavation of the core

Explanation:
LoLa Landschapsarchitecten (2014), identified that the layered soil structure within the dike can have archaeological value. The layered soil composition provides information on the construction of past dike reinforcements. Due to the age and properties of materials in the dike, a good readable soil composition has been formed over the years. This archaeological value can be lost when (part of) the existing dike core is excavated for construction of the new reinforcement design. It is not necessarily the case that a dike's cross-section contains the layered composition of the core material, these values could have been lost in past dike reinforcements.

4.2.2. Functional characteristics in surroundings

S1. Transportation function on the river
- Footprint of the dike on the river

Explanation:
Inland waterway transport in the Netherlands is a large contributor for distributing goods within the Netherlands (CBS, 2016). This makes the Dutch rivers important transportation corridors. The corridor can be influenced by the construction of a dike reinforcement, when it results in limitations for waterway transport. When a dike is constructed in the waterway a bottleneck for transport among the river can be created, resulting in reduced transportation potential at the river. To determine the effect for river transportation, it should be known where the footprint of the dike influences the navigation channel, and what the quantity of the influence is.

S2. Living function in surrounding area
- Footprint of the dike on locations of buildings
- Experienced safety due to wave overtopping
- Comfort of the location (experienced pollution)
- Accessibility of houses

Explanation:
The access to the living function is dependent on the availability of houses in the surroundings of the dike. The influence of a dike reinforcement on the houses is dependent on the exact location of the reinforcement. When the footprint of the reinforcement is located within the footprint of the house, the house should be demolished to construct that particular design. Besides this quantitative measure, also the quality of living can be changed due to dike reinforcement projects.

One of these quantitative measures is wave overtopping of the dike. Heems & Kothuis (2012) explains that the experienced water safety of people is dependent on the myth of having "dry feet". This myth has been interfered with by constructing dike reinforcements based on a certain allowable overtopping discharge. It is no longer guaranteed, that people maintain the "dry feet" during large storm events. The larger the overtopping discharge, the more people feel threatened by the water.

The living area of people consists of a house with its garden, and comfort of the location (accessibility by road, pollution in the area, experienced safety (Visser & Van Dam, 2006)). The quality of the living function is, therefore dependent on design choices in the dike reinforcement project. In Section 4.2.1 (D2), is explained how design choices can affect accessibility, nuisance and air quality of the project area.

S3. Agriculture in surrounding area

- Footprint of the dike on agricultural land
- Accessibility of the agricultural land
- Changes in subsoil richness caused by changes in ground water balance

Explanation:
Within the scope of this study (dike reinforcements in rural areas), it is expected that agricultural land is an important use function in the area. Due to changing dimensions of the dike it can be interfered with the agriculture's quantity in the surroundings of the dike. Quantity is affected when the new footprint is located on agricultural land.

The quality of the agricultural land is dependent on other characteristics. Implementing a dike reinforcement at agricultural land can lead to loss in efficiency of agriculture in the project area. This can be caused by three reasons; the shape of the residual area after the reinforcement provides limitations for optimal operations of the land, the size of the land is not large enough to optimally perform its function, or the quality of the agricultural land is affected. As a dike can cut-of areas, it may be causing inefficient working areas. Illogical shapes, and small areas are difficult to operate for farmers, inducing that operation costs will rise. This may be causing that a part of the agricultural land will not be profitable anymore (Huinink, 2011).

Also, subsoil conditions determine the growth possibilities of agricultural land in the surroundings of the dike. According to Wesseling (1978), a linear relation can be assumed between water use and production of agricultural crops. Nevertheless, the water level in the soil should not be too high, as this decreases the oxygen level in the subsoil, causing unfavourable growth conditions. The study also points out that, under this conditions, the bearing capacity of the subsoil can limit the processing of the subsoil by agricultural machines. Based on the study of Wesseling (1978), can be concluded that large water level fluctuations in the subsoil can lead to a decreasing functionality of the agricultural land.

S4. Recreation in surrounding area

- Footprint of the dike on recreational area
- Accessibility of recreational area
- Comfort of the location (experienced pollution)

Explanation:
A dike reinforcement can influence the residential recreation in the surroundings of the dike, qualitatively and quantitatively. Similar as in agriculture, the effective use for recreational areas is dependent on the size of the area and the shape of the recreational space. But for recreation, also the comfort of the location plays an important role. Therefore, also the effect on the amount of nuisance, and pollution caused due to space use on the dike play an important role in the consideration of alternatives.

S5. Nature in surrounding area

- Footprint of the dike in vegetation area
- Changes in subsoil richness caused by soil pollution
- Changes in subsoil richness caused by changing ground water balance
- Pollution in the surroundings
- Road as barrier for animals

Explanation:
To preserve healthy living conditions for flora and fauna in an area, it is important that species can move freely through an area. In the Netherlands, Nature Network Netherlands has been developed to guarantee this safe passage of different species throughout the country (Natuurmonumenten, 2010). According to Reijnen & Koolstra (n.d.), this network should consist of small- and large vegetation areas to provide healthy living conditions for animals living in an area. Broekmeyer (2005) studied potential effects on these vegetation areas, caused by human interference. Based on his identified effects, a determination has been made to identify the potential influence of dike reinforcement projects:

- Effect on quantity of living area: An increased footprint of the dike located in an ecological structure reduces the size of the nature area. The natural habitat is replaced by a soil structure at the same location. It is dependent on the situation whether this structure provides good living conditions for the animals living in the nature area.
- Effect on quality of living area due to chemical factors: Chemicals in the subsoil reduce the ecological potential of the subsoil leading to limitations in the vegetation growth conditions of an area (Rutgers, Spijker, Wintersen and Posthuma, 2006). A dike reinforcement can influence this situation, as there is a possibility to clean up contaminated soils (explained under “S8 Pollution in the surrounding area”).
- Effect on quality of living area due to physical factors: According to Broekmeyer (2005), the effects due to a chance of physical factors is mainly dependent on the availability of water in the nature area. A dike reinforcement project can influence the water balance, and thereby the quality of the nature area. How soil conditions result in vegetation types has been shown in Figure 30.
- Effect on quality of living area due to nuisance: Also, factors such as air, noise, vibrations, and human activity (recreation) can influence the quality of the nature area. Within the scope of this study (long term effects on the existing spatial situation), it is dependent on the design choices for the reinforcement, whether effects on light, noise and human activity play a role. It is expected that vibrations play an important role during the construction of the reinforcement, but not after the construction.
- Effect on quality of living area due to spatial influence: Lastly, the quality of the nature areas can also be influenced by spatial barriers, causing obstacles for animals to move within and among nature areas. According to Broekmeyer (2005), typical barrier elements are roads, railways, channels, and locks. Infrastructure can be a physical barrier, as animals are not able to pass the infrastructure. Also, the infrastructure can cause an increase of animal casualties, due to accidents with for example cars.

As the ground near rivers is often fertile, a part of this ecological structure is located near the rivers in the Netherlands. As can be observed from the above provided influence categories it can be concluded that an ecological structure is vulnerable for interventions in the system, during and after the construction of a dike reinforcement. Although, these areas are vulnerable, due to spatial changes and design choices for the reinforcement, also positive effects can be experienced from ecological structures point of view. An example of such a positive effect is when a barrier (e.g. road) is removed from the dike to increase the safe passage for nature.

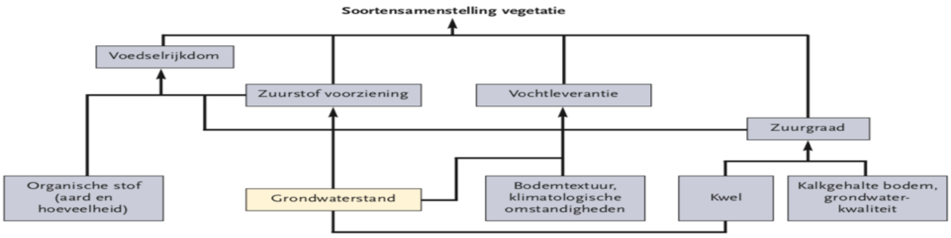


Figure 30: Relation between species composition and subsoil characteristics (source: Runhaar, et al., n.d.)

S6. Effective space use in surrounding area

- Effect on living in the surrounding area (S2)
- Effect on agriculture in the surrounding area (S3)
- Effect on recreation in the surrounding area (S4)
- Effect on nature in the surrounding area (S5)

Explanation:
In the Scope Definition (Section 1.4), it has been explained that the spatial planning consists of the combination of nature, agriculture, recreation, and living in the surrounding area. A dike reinforcement interferes this spatial system and thereby influences the efficiency of the use functions. The efficiency of space use of these functions is focussing on how the quality and quantity of the use function can be affected due to a dike reinforcement. It is only focussed on changing efficiencies caused by the dike reinforcement design. The influence of the dike reinforcement design on the space use in the surrounding area has therefore been explained at S2, S3, S4, and S5.

It should be remarked that a dike reinforcement not necessarily influences the situation negatively. According to HWBP-2 (2014), ground trade is also an option in such project. This gives the potential to create more efficient areas to perform the use functions on. For example, an unprofitable agricultural area can be converted into a nature area.

S7. Ground water balance in surrounding area

- Influence on seepage flow

Explanation:
The existing ground water balance is an important indicator for the ecological potential of the area, as it influences the oxygen supply, acidity, moisture delivery, and the food richness (Runhaar, Jalink & Bartholomeus, n.d.). Ground water levels in an area are dependent on several factors, such as rainfall and flow in the subsoil. Figure 30, illustrates that seepage is also coupled to the ground water level in the surrounding area. A dike reinforcement project can influence this seepage, due to an intervention in the subsoil leading to limitations in the ground water flow or by inserting structures that filter water from the subsoil. Within the scope of this study, it has been explained that only for piping, structural interventions have been considered. For these solutions should be considered how they influence the ground water balance.

S8. Pollution in surrounding area (air-, noise pollution)

- Changing traffic intensity on the dike crest

Explanation:
Air pollution is the presence of undesired gasses in the air causing unhealthy living conditions. According to Knol (n.d.) the three most important polluters are nitrogen dioxide, ozone, and sulphur dioxide. Sources producing these gasses are, for example, engines of cars or factories. As dikes often have a transportation function, the number of cars travelling over the dike influence the air pollution in the area.

The existing spatial planning is a cohesion of different use functions, which can produce noise in the area. The evaluated dike can contribute to this noise pollution, as use functions (e.g. traffic) on the dike in the current stage can produce certain noise. Design choices during the reinforcement can contribute to an increase or decrease of existing noise pollution. The main identified influencer within the scope of this study is the effect of a changing road type during the dike reinforcement project.

S9. Soil pollution in surrounding area

- Footprint of the dike located on bottom contamination

Explanation:
A polluted bottom can be caused by many different factors. According to Nieuwkoop (n.d.), soil contamination is often the result of incautious dealing with polluting materials in factories (in the past). Textile-, leather-, chemical-, metal-, and energy factories are identified as locations where pollution of the soil is expected. In dike reinforcement projects, soil contamination is correlated with the water quality in the subsoil. Due the governmental regulations on soil contamination, it is forbidden to decrease the quality of the bottom further in the future (Rijkswaterstaat, 2013). Also, contamination has to be cleaned, when future space use of the area might lead to health issues, due to soil contamination in the subsoil. When a dike reinforcement is constructed it is expected that excavations are required to remove weathered material. This gives a change to clean the contaminated soils.

S10. Historical flood relics in surrounding area

- Footprint of dike on flood relics

Explanation:
The LoLa landscape architects (2014), describes flood relics as important historical elements that tells the story of development of the flood defence structure. A typical indicator of past dike breaching is a pond (=*'wiel' in Dutch*). These ponds are caused by erosion due to the strong flow through a dike breached section. After such a dike breach, the dike was recovered, by constructing a new dike around the pond. Due to this effect, dikes in the Netherlands are often winding. To preserve this typical story of the dike, it is important to preserve the character of the ponds. This is affected, when the dike is constructed through the ponds, or relocated further away from the ponds, so that the story that the dike tells from the past to the future is no longer visible.

S11. Historical military expressions in surrounding area

- Footprint of dike on military elements

Explanation:
Similar as to the header "Historical indicators of floods", also the indicators of war tell an important part of the history of the dike. According to LoLa landscape architects (2014), dikes often have fulfilled strategic functions during wars. This is an important story, which from cultural point of view should be preserved. These structural elements located on- and close to the dike can be affected in dike reinforcements when the shape of the dike is interfered with at the location of the "military" element. According to TAW (1994a), the preservation of the elements are important culture historical values that have to be preserved.

S12. Heritage structures in surrounding area

- Footprint of dike on heritage structures

Explanation:
Besides the story that the dike tells in a project area, also other structural buildings provide interesting information that make an area valuable from cultural perspective. The influence of a dike reinforcement on the structural heritage is, from functional perspective, focussed on the interference of the increased footprint with the structural heritage element.

S13. Heritage sites in surrounding area

- Footprint of dike on heritage site

Explanation:

There can also be protected sites located within the project area. These protected sites can be interfered with when the dike is constructed within the protected site. The interference with a sight does not directly result in complete demolishment. More information is required to express the magnitude of the influence on the protected site.

S14. Archaeological values in surrounding area

- Additional soil pressure on archaeology
- Ground water level changes in subsoil
- Structural elements in subsoil at archaeology

Explanation:

The influence on archaeological values, is dependent on more factors. Construction projects can, according to Roorda and Stover (2016), be destructive for the archaeological values in the subsoil. Huisman et al. (2011) states that the archaeological value of an area is dependent on the type of assemble, the age of the assemble, and the origin and uniqueness of the elements. The difficulty is that this not always known on forehand, therefor an archaeological reconnaissance has to be obtained to identify the in-soil values in the area. The subsoil values can be affected by construction projects in different ways. Huisman et al. (2011), identifies four potential physical reasons in construction projects that can cause damage to the archaeological values in the subsoil. In the following it is determined, whether the identified physical effects can occur in dike reinforcement projects:

- *Disruption caused by excavation*: Excavation causes a total destruction of the archaeological values in the excavated area, when no extra attention is paid to research. In dike reinforcement projects, it is expected that only small weathered part of the subsoil layer is excavated for the construction of dike reinforcements. The size and the depth of the excavation are important measure for the magnitude of the lost values. In rural areas, the spatial planning consists for a large part of agricultural land. It is assumed that the weathered top layer (of the agricultural land) is constantly cultivated. Therefore, it is expected that archaeological values are already lost due to the use of the agricultural land.
- *Disruption caused by penetrating structural elements*: Structural elements penetrating through towards deeper soil layers can cause a local destruction of the archaeological values. In dike reinforcements, sheet pile wall may be used, causing this destruction. The magnitude of the effect is dependent on the size, depth and construction method of the wall.
- *Disruption caused by deformations of subsoil*: Deformations of the subsoil itself are not a destructive factor for archaeological values when they are homogeneous over a large area. A problem occurs when settlements are not even, causing unequal deformations in the subsoil. In dike reinforcement projects, this effect is expected to happen at the toe of the (berm of the) dike. At this location, gradients will be found in the layer in which the archaeological values are found. This can induce information loss of the archaeological values.
- *Disruption caused by changing moisture content in subsoil*: A change in the ground water level near archaeological values is identified as the effect that can cause the largest damage to the values. It is reasoned that a rise of the water level can lead to blushing, causing that the archaeological values deteriorate. On the other hand, lower the ground water table results in oxygen intruding in the ground. As oxygen induces a degradation process, the archaeological values might get lost. Lowering of groundwater, is often spread over a larger area, causing a large magnitude of destruction of values (Huisman et al., 2011).

It is found that dike reinforcements projects, potentially have a large influence on the archaeological values in the surroundings of the dike. These values are currently preserved in the soil, with as goal to use them in future archaeological researches.

4.3. Applying conceptual evaluation model to identify changes caused by a dike reinforcement design

The, in Sections 4.1 and 4.2, presented conceptual evaluation model to identify changes induced by a dike reinforcement design is in this section applied on an imaginary dike reinforcement. In this example it is assumed that the safety issues of the dike are solved by implementing a stability berm on the hinterland side of the dike. Constructing this stability berm induces changes to the project area. In Figure 31, it is explained how applying the conceptual evaluation model provides insights in changes in the project area initiated by the dike reinforcement design.

In Figure 31, a deviation is made between four stages of applying the model:

- It is started by identifying the existing function characteristics in a project area.
- Afterwards, the influence on these characteristic is determined by studying the effects of the reinforcement design.
- Third, it is evaluated which new chances for the project area are created due to the shape of the proposed cross-sectional design.
- Lastly, design choices are made to obtain a definitive design.

Studying the figures directly shows the changes induced by a dike reinforcement design when Image 1 is compared to Image 4. It can be observed that archaeological values and living in the surroundings of the dike disappear due to the influence of the dike reinforcement. On the other hand, it is found that extra functional characteristics are added to the project area by means of agriculture and vegetation on the dike. Image 2 and Image 3 provide a more detailed explanation on the effects of the reinforcement design. It should be noted that the effects on the existing situation (Image 2) and the chances for the new situation (Image 3) directly follow from the cross-sectional design (and the existing spatial situation). Afterwards, for the definitive design, choices have to be made to implement certain chances in the design of the dike reinforcement. Whether certain functional characteristics are included in the design is dependent on wishes and requirements for the project.

4.4. Concluding remarks

In this Chapter, a conceptual evaluation model is developed that couples technical design solutions (Chapter 2) to functional characteristics of the project area (Chapter 3). This evaluation model, presented in Figure 27 and Figure 28, identifies the influence on the existing functional characteristics in the project area, and explores the chances of adding functional characteristics to the project area. It should be noted that the definitive implementation of functional characteristics of the dike itself are always dependent on the wishes (ambitions) of the dike reinforcement project, including these functional characteristics can result in effective space use in the project area. The model only provides information to determine feasibility of including certain functional characteristics. Furthermore, the evaluation model does not include statements on the importance of certain functional characteristics in a project area. The evaluation model helps subject experts to judge one design alternative in a dike reinforcement project. As the research objective is to create a method to illustrate the effect of design choices on the functional characteristics of the project area, the developed conceptual evaluation model should be applied on a large variety of designs to identify the differences between the alternatives.

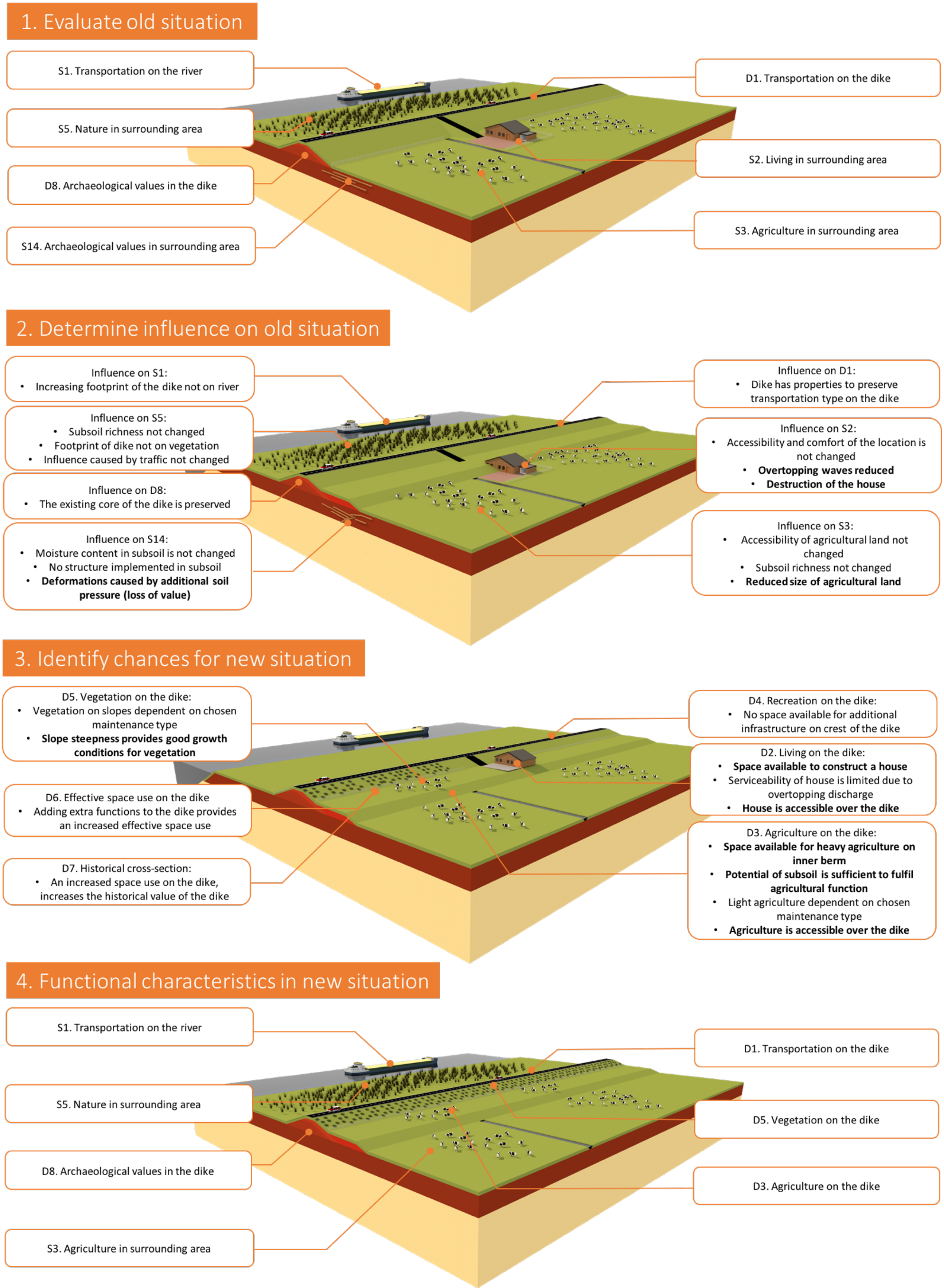


Figure 31: Application of conceptual evaluation model on imaginary dike reinforcement project

5. Method to illustrate effects of design alternatives

The goal of the study is to develop a method that is able to compare the influence of design alternatives (for a dike reinforcement) on the effects it induces on the project area for the purpose of initial selection of alternatives. In this Chapter, the fourth research question is answered by developing a method to illustrate the influence on the functional characteristics of the project area. The method uses the conceptual evaluation model, provided in Chapter 4, to identify the influence of a particular dike reinforcement design on the existing situation in the project area.

This Chapter is started by providing a brief description on the developed method in Section 5.1. Subsequently, from Section 5.2 to Section 5.7, a more elaborate explanation of the method is provided per step. In Section 5.8, it is explained which software used to guide the method. Finally, in Section 5.9, the chapter is ended with concluding remarks on the developed method.

5.1. Method to compare effects of design alternatives on the functional characteristics of the project area

This section briefly describes a method that results in the illustration of the effect that a design alternative induces on the functional characteristics of the project area (relative to all other design alternatives). The comparison between the different design alternatives is the result of going through the seven steps as provided in Figure 32. In the remainder of this section, it is per step shortly explained, what the purpose of the step is. An elaborate explanation on the steps is provided in Section 5.2 till Section 5.7.

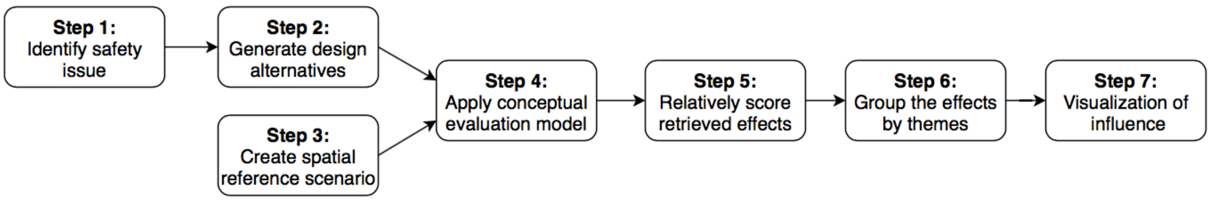


Figure 32: Required steps to visualize effect of design alternatives relative to other designs

Step 1: Identify safety issue
A dike reinforcement project is initiated by identifying a safety issue at an existing dike section. In this study, the safety issue can be caused by three failure mechanisms; “erosion of the inner slope”, “inner slope stability”, and “piping”. In the first step, the resistance against these failure mechanisms is determined and compared to the required strength of the dike section. When it is found that the resistance against one (or more) failure mechanism(s) is not sufficient a dike reinforcement project is initiated.

Step 2: Generate design alternatives
The identified safety problem in Step 1, is input for the generation of design alternatives to reinforce the dike section. In Chapter 2, it is explained which design parameters increase the resistance against a specific failure mechanism of the dike. Based on the identified relevant design parameters, design alternatives are created that solve the safety problem of the dike within the ambitions of the HWBP (faster, cheaper, and smarter (ENW, 2017)). The resulting

“evaluated” (large variety of) design alternatives are input for Step 4: Apply conceptual evaluation model.

Step 3: Create spatial reference scenario
Location specific data is required to apply the conceptual evaluation model on the design alternatives of the dike reinforcement. In this step, the required location specific data is generated for a specific project area. It is determined per functional characteristic of the project area which location specific data is relevant for applying the conceptual evaluation model.

Step 4: Apply conceptual evaluation model
The generated design alternatives (Step 2), and created spatial reference scenario (Step 3) are input for applying the conceptual evaluation model that is provided in Chapter 4. As there is a large variety of design alternatives, the application of the evaluation model should be an automated process. To provide automated measures on the effect caused by a design alternative, some additional assumptions are made. The output of applying the conceptual evaluation model is a large table providing measures on the influence of design alternatives on the functional characteristics of the project area.

Step 5: Relatively score retrieved effects
To compare the design alternatives, it is chosen to relatively score the effects of a particular design alternative compared to all other evaluated design alternatives. This means that the magnitude of an effect on a functional characteristic of the project area is scaled between the most positive observed value, and the most negatively observed value.

Step 6: Group the effects by themes
As there are many potential effects identified in the conceptual evaluation model, it is chosen to structure the effects by themes. The considered themes are: “living”, “agriculture”, “nature”, “culture”, “recreation”, and “transportation”. These themes are based on different perspectives that stakeholders can have within such projects. By using this structure, contradicting and reinforcing influences on the functional characteristics of the project area can be retrieved.

Step 7: Visualization of influence
The last step is the visualization of the relative effects of a design alternative relative to other design alternatives. An example of the representation of a design alternative is provided in Figure 33. The visualization consists of a top-view of the project area, cross-sectional view of the dike reinforcement, and a radar chart indicating the relative effects of the reinforcement design compared to other design alternatives. A further explanation is provided in Section 5.7.

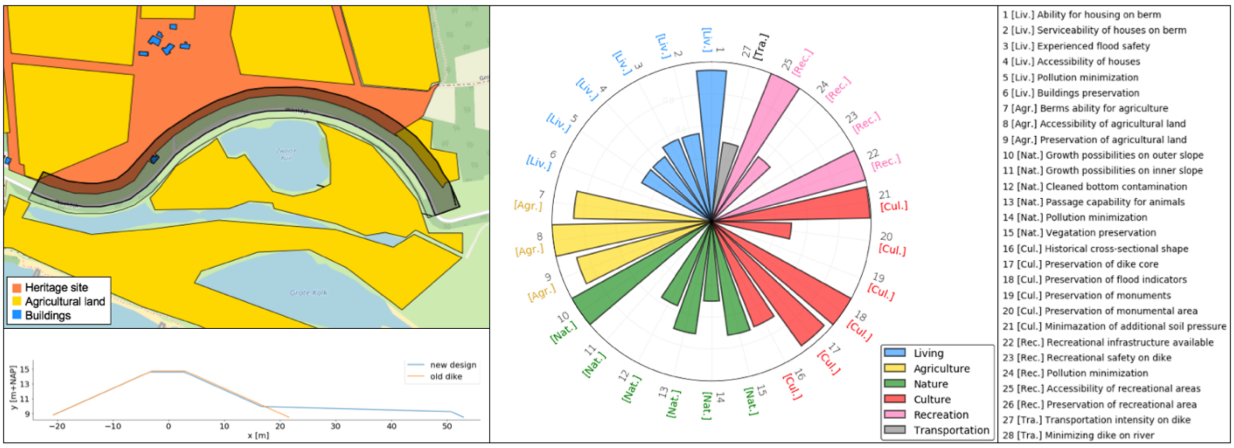


Figure 33: Example of visualization

5.2. Identify the safety issue and generate design alternatives (Step 1 & Step 2)

The first two steps focus on identifying and solving the safety problem of a certain dike section. In practice, a safety problem, in the Netherlands, is often detected in periodic assessment of the flood defence structures (ENW, 2017). Based on the hydrodynamic, and geotechnical boundary conditions a failure probability of the existing dike can be determined for the failure mechanisms “inner slope erosion”, “inner slope stability”, and “piping”. The urgency for the projects is determined, which eventually leads to the initiation of a dike reinforcement project.

In the second step, the design of the dike reinforcement is created based on the Design guidelines (“Ontwerpinstrumentarium 2014”) provided by the Dutch Government (Rijkswaterstaat, 2017). In Chapter 2, it is explained that there is a large variety of design options providing resistance against the considered failure mechanisms in this study. An example of the considered design variations for the dike reinforcement project “Wolferen-Sprok” is provided Table 3 (which is evaluated in the case study, Chapter 6). Multiplying all variations results in almost 370.000 unique geometries that have to be assessed on the resistance against “inner slope erosion”, “inner slope stability”, and “piping”. To limit the calculation time for the generation of design alternatives (with variations), assumptions have been introduced to limit the size of the safety assessments. The order of evaluating failure mechanisms is described in Figure 34.

Table 3: Example of design variations for cross-sectional design of dike reinforcement project (retrieved from case study “Wolferen-Sprok dike section 14”)

Name	Unit	Variations
Outer slope (s_{outer})	**[1:_]**	3, 4, 5
Critical Overtopping discharge (q_c)	**[l/s/m]**	1, 5, 10
Crest width (W_{crest})	**[m]**	3, 6, 10.4, 13.4
Inner slope (s_{inner})	**[1:_]**	3, 3.5, 4
Berm width (W_{berm})	**[m]**	15, 35, step size = 1m
Berm height (H_{berm})	**[m]**	1, 4, step size = 0.1m
Failure budget (w)	**[-]**	Scenario 1 (standard): $w_{erosion}$=0.24, $w_{stability}$=0.04, w_{piping}=0.24 Scenario 2 (shifted): $w_{erosion}$=0.04, $w_{stability}$=0.24, w_{piping}=0.24
Piping measure	**[-]**	1. Piping berm 2. Relief well 3. Vertical sand tight geotextile

First, the outer slope and crest height are determined based on the failure mechanism “Erosion of the inner slope”. The minimum required crest height is calculated per unique combination of overtopping discharge and outer slope angle, with the Hydra-NL software. The software is able to calculate the hydraulic loading level (*Dutch= “hydraulisch belastingsniveau”*), on which a pre-set critical overtopping discharge occurs, based on a specified outer slope angle. This results in crest heights for the dike, which are rounded at one decimal number. It occurs that different combinations of overtopping discharge and outer slope angle result in the same required crest height.

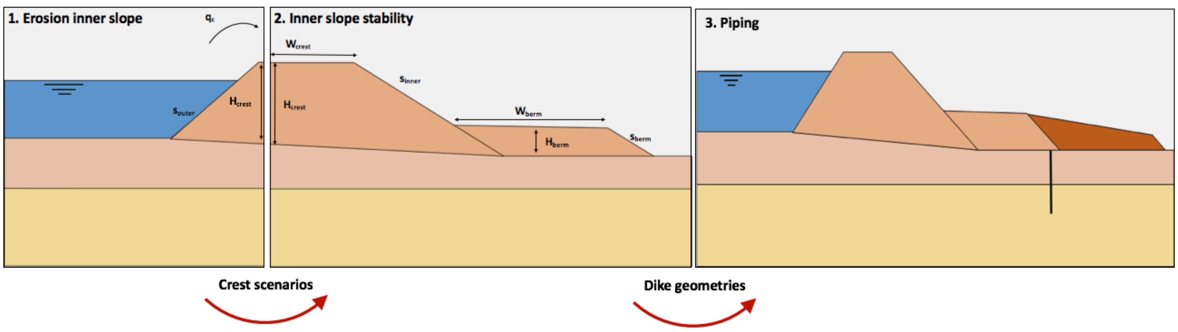


Figure 34: Evaluation strategy to solve safety problem

When the crest height scenarios have been retrieved from the failure mechanism "Erosion of the inner slope", it is started with evaluating the failure mechanism "Inner slope stability". It is assumed that the outer slope properties have negligible influence on the inner slope stability. This reduces the required calculations for inner slope stability, as outer slope variations are not considered (only differences in dike height). In the evaluation of inner slope stability, it is also assumed that crest width variations do not affect the stability of the inner slope. As explained in Section 5.4.1, there are different crest width scenarios used to apply the conceptual evaluation model within the developed method. The inner slope stability is calculated based on a crest width of six meters. This introduces some overestimation of the safety against sliding when the crest width is smaller than six meters. While, for larger crest widths, this can be observed as an underestimation. The magnitude of the effect is dependent on geo-hydraulic schematizations of water levels in and under the cross-sectional design of the dike reinforcement. A further explanation on the assessment of inner slope stability is provided in Appendix D.

Based on a unique combination of crest height and inner slope angle, the required berm dimensions are determined. This is done by determining the safety factor (for inner slope stability) for every combination of berm height and berm width in the proposed range. D-Geo Stability software is used to determine the safety against the formation of a sliding plane. An example of the results is shown in Figure 35a, which indicates the safety factor of a specific design by means of a colour. Within this study, only design alternatives that fit within the ambitions of the HWBP (smarter, cheaper, and faster) are evaluated as realistic. The organization states that only solutions are financed, that require the minimum investment (ENW, 2017). Therefore, it is aimed for a safety factor that is located close to the minimum required safety factor (indicated in Figure 35b). Higher berms are conservative, while lower berms do not provide sufficient safety. The last step is to retrieve the required berm height at a specific berm width, this is illustrated in Figure 35c. This process is repeated for every individual crest height retrieved from the evaluation of "Erosion of inner slope".

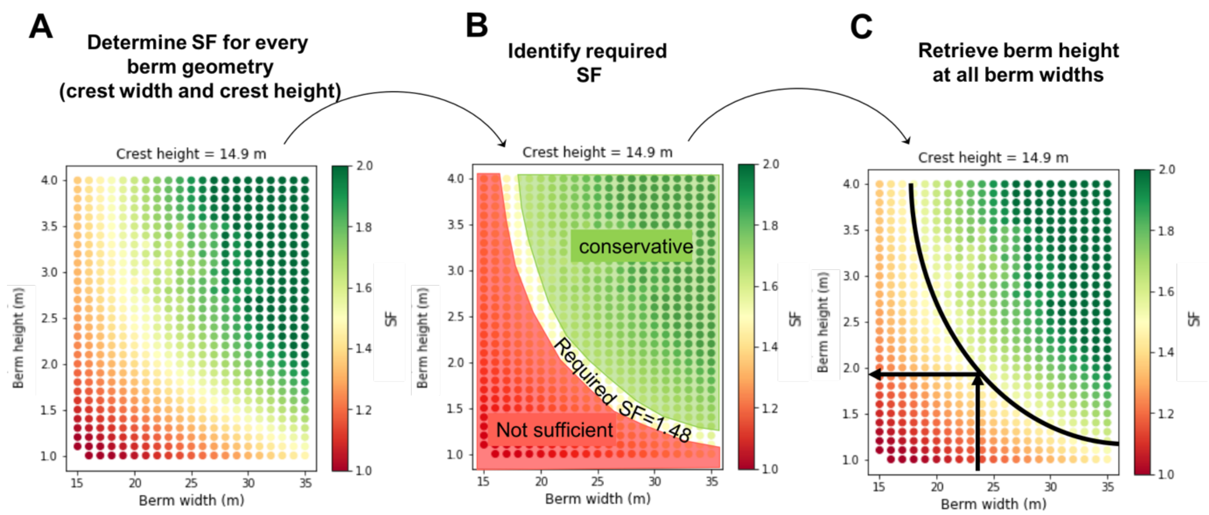


Figure 35: Determining minimum required berm height (example "Wolferen-Sprok dike section 14", for crest height = 14.9 m, and inner slope = 1:3)

After verifying design alternatives for inner slope stability, the evaluation of the safety is concluded by evaluating piping measures. Three piping measures are evaluated in the method; the piping berm, a sand tight geotextile, and a relief well. The piping berm is dimensioned based on the provided resistance against the physical phenomena; "Uplift", "Heave", and "Piping". This done by means of a deterministic calculation, resulting in one sufficient design preventing piping in the project area. Appendix D explains the details of this calculation. No structural designs have been calculated for the sand tight geotextile, and the relief wells. It is assumed that there is always a design that fulfils the safety requirements, while the influence on functional characteristics is not largely influenced.

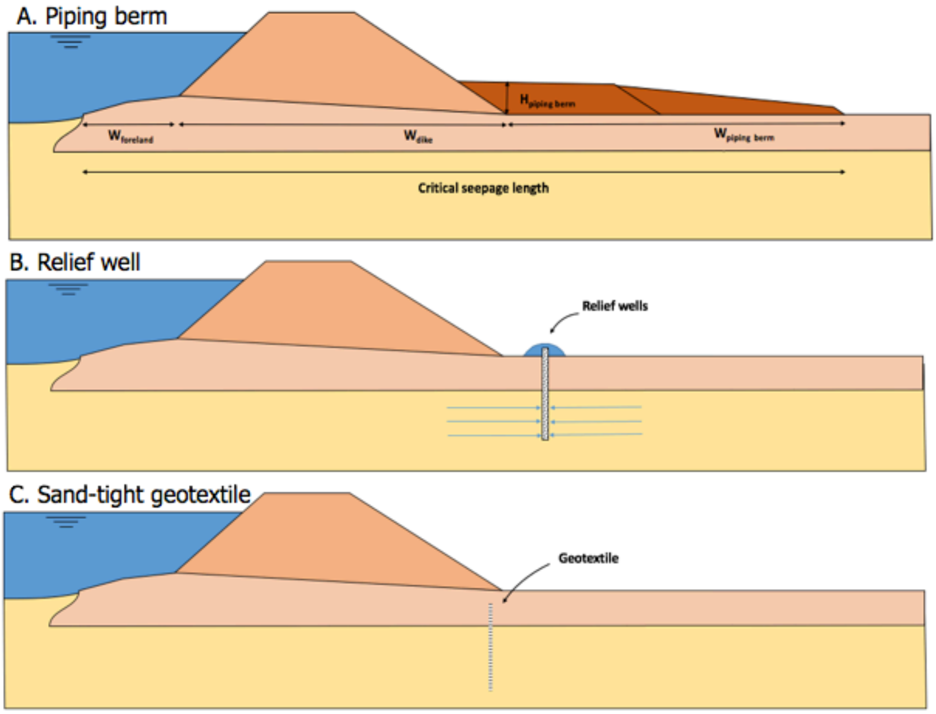


Figure 36: Piping solutions

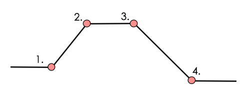
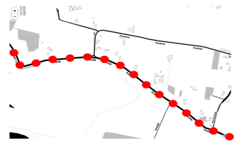
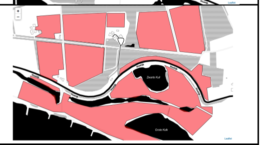
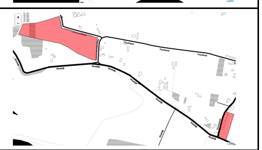
The large variety of designs is saved in a table that describes the geometry of a unique design alternative that is verified on the technical requirements. This table is used as input for Step 4 (Section 5.4), in which for every unique design alternative is evaluated what the influence on the functional characteristics of the project area is.

5.3. Create spatial reference scenario (Step 3)

To create a model that shows the influence on the functional characteristics of the project area, location specific data of the project area should be inserted. In this section, it is described which data is required input to illustrate the influence after applying the conceptual evaluation model to design alternatives (Step 4, Section 5.4). Table 4, describes which input data is required to correctly formulate the spatial reference scenario for the project. A note has to be made, that not every input element is necessarily located within a project area. From the provided list in Table 4, should be determined whether it is located within the project area.

Table 4, provides information on the location of the functional characteristics that are interfered by the following three effects; “increasing footprint of the dike”, “implementing structure in subsoil”, and “increased soil pressure” (retrieved from Figure 37, the presentation of the conceptual reasoning model). For these elements, the magnitude of the effects is dependent on the availability of the functional characteristic at an exact location (when a dike reinforcement is constructed at that location). As the input parameters are maps of the existing location of functional characteristics in the project area, it should be carefully dealt with the coordinate system of the maps. The application of the conceptual evaluation model (Step 4, Section 5.4) is created for an RD-coordinate system (EPSG: 28992), which is a x,y,z-coordinate system that is able to describe every location in the Netherlands.

Table 4: Required input data to perform functional indicator model

Element	Explanation	Example
Existing dike cross-section in the project area	To compare the shape of the existing (unsafe) dike with the shape of the design alternatives for the reinforcement, the cross-sectional shape of the existing dike will have to be inserted in the model. This is done by defining its characteristic points in a table with x, and y values. In the current model, one cross-sectional shape has to be defined per evaluated dike section.	
Existing trace of the dike in the project area	Besides the geometry of the existing dike, also the trace should be inserted in the model. This is done by creating a Point Shapefile layer in QGIS. The point shapefile should consist of points describing the trace of the existing dike.	
S2. Living in surrounding area	As input for the model, also the locations and shapes of buildings within the project area has to be identified. This information can be retrieved from visual data (such as satellite images), or predefined Shapefiles layers (by Governmental organizations). To limit the computation time of the model, input is per dike section created. The input for the model is a map showing the exact location and shapes of buildings within the project area.	
S3. Agriculture in surrounding area	Also a reference scenario for agriculture in the project area has to be generated. An example of such a map is provided in the next column. The required information on agriculture in the project area can, also be retrieved form visual data, or predefined data sets. Similar as in the case of "Buildings in project area", also for agriculture a reference scenario should be created per dike section.	
S4. Recreational area in surrounding area	A way to identify the location of recreational areas within the project area, is by using occupation maps of the land within the project area. An example of such a map is "Bestand Bodemgebruik 2008" (CBS, 2008), which identifies different use functions within an area. The information on recreation can be adopted in a Shapefile layer, that describes the shapes and the location within the project area.	
S5. Nature in surrounding area	As explained the Nature Network Netherlands is found to be an indicator of the nature areas within the project area. The exact location of the Nature Network Netherlands can for example be retrieved from PDOK Datasets (PDOK.nl). Input for the model is a map describing the exact locations of Nature Network Netherlands within the project area.	
S9. Soil pollution in surrounding area	To identify the soil pollution in the project area, in this model information on expected contaminated locations within the project area has be inserted. An example is the "Historisch Bodembestand"-database, which identifies suspicious locations based on historical soil use in areas. In this way, the required spatial data can be retrieved to make the influence of a dike reinforcement on contamination assessable.	
S10. Flood relics in surrounding area	The flood relics do mainly refer to ponds in the project area, these ponds can be recognized as water clusters ("small lakes"), often located near the dikes. Also, the ponds originating from floods can be identified by studying past maps of the project area (for example on topotijdreis.nl). The identified areas and locations on the pond will have to be illustrated on maps.	
S11. Military items in surrounding area	Military items, can be identified in a similar way as flood relics. In a site study, the locations of these elements can be identified. An illustration will have to be created on a map, showing the locations and shape of the elements.	
S12. Heritage structures & S13. Heritage sites	The heritage in the project area will have to be illustrated on two maps. One describing the locations of structural elements within the project area, and one describing the protected sites in the project area. Information on both can be retrieved from governmental databases (such as supplied in the PDOK Data server).	
S14. Archaeological values in surrounding area	At last, also the location of the archaeological values in the project area will have to be collected, and prepared as input for the model. These archaeological monuments can be retrieved in the same ways as, for example, heritage structures.	

5.4. Applying conceptual evaluation model (Step 4)

The verified design alternatives (Step 2) and the created reference scenario (Step 3) are input for applying the conceptual evaluation model that is presented in Chapter 4. This evaluation model requires small adjustments to apply it in the method (Section 5.4.1). Subsequently, it is explained how the location of the dike reinforcement designs is considered within the method (Section 5.4.2) and how a measure on the magnitude of the effects is provided (Section 5.4.3).

5.4.1. Applying the conceptual evaluation model within Influence demonstration method

The goal of applying the conceptual evaluation model is to provide a measure on the magnitude of the effects that a design alternative induces on the (potential) functional characteristics of the project area. This measure is used to compare (geometries of) design alternatives, not to express changes to the existing situation. Therefore, three additional demarcations are considered in the application of the conceptual evaluation model. The applied conceptual evaluation model for the purpose of the method is provided in Figure 37.

1. **Focus on the effects of a specific design alternative, without making design choices to include certain functional characteristics**

In Section 4.3, it is explained that the conceptual evaluation model first identifies influences on the existing situation, and chances of the evaluated design. The last step is to make choices on the actual implementation of new functional characteristics in the project area, this is dependent on wishes in the reinforcement project. The application of the conceptual evaluation model, within the method, is focused on identifying effects and chances of design alternatives. It is found that three functional characteristics are dependent on the choices of the designer to allocate a function within the design (independent on the cross-sectional shape). Therefore, the following three functional characteristics are not considered in the method:

- Effective space use on the dike (D6), because it is dependent on the introduction of functional characteristics within the reinforcement design (Transportation on the dike (D1), Living on the dike (D2), Agriculture on the dike (D3), Recreation on the dike (D4), and Vegetation on the dike (D5)).
- Historical cross-sectional design (D7), because this is dependent on the effective space use on the dike (D6).
- Effective space use in surrounding area (S6), because it is dependent on the desired function combinations within the project area.

2. **Focus on differences between influences of the (geometries of the) design alternatives, after applying the Dutch Design Guidelines**

Secondly, it is focussed on applying the conceptual evaluation model within the Dutch Design Guidelines ("Ontwerpinstrumentarium 2014", Rijkswaterstaat (2017)). The conceptual evaluation model is based on theoretical relations between the functional characteristics of a project area, and the design characteristics of a dike reinforcement alternative. Nevertheless, studying the Dutch Design Guidelines for determining the strength against the failure mechanism "Inner slope erosion" (height of the dike) results in the finding that function combination on the slopes of the dike (Vegetation on the dike (D5), and agriculture on the dike (D3)) does not lead to different requirements for the critical overtopping discharge of the cover layer. In the Dutch Design Guidelines, a deviation is made between an open sod, and a closed sod for grass cover layers. However, Rijkswaterstaat & STOWA (n.d) explain that ecological and agricultural maintenance of the cover layer both results in a closed sod. The maintenance type therefore becomes a design choice that is not restricted by a design characteristic of the reinforcement design. Indicating the effect will not provide interesting information, because every design alternative has the same possibilities to implement an ecological or agricultural maintenance type.

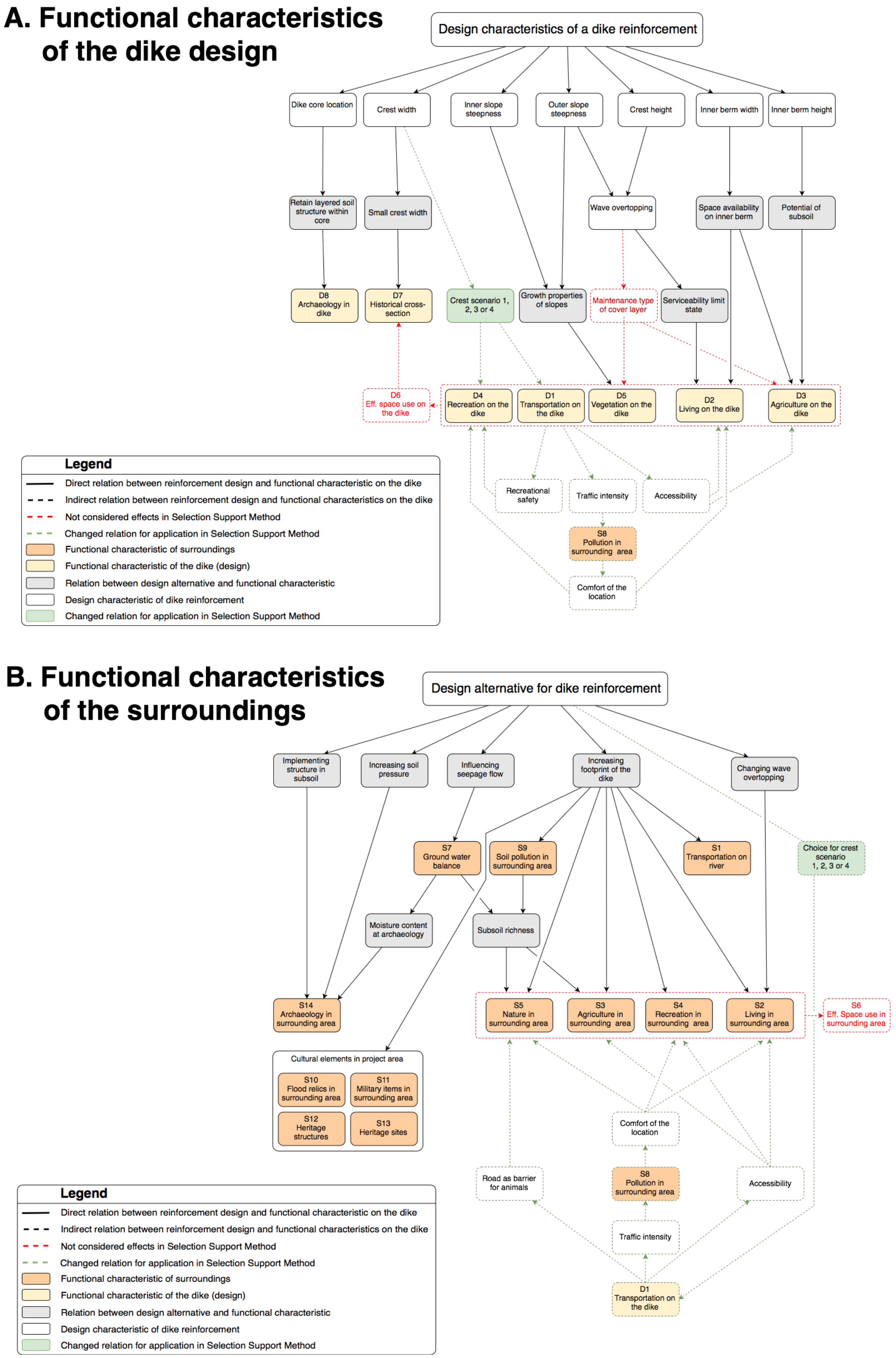
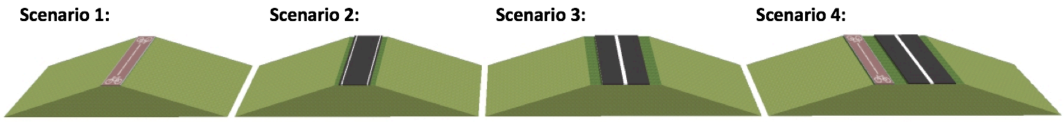


Figure 37: Application of conceptual evaluation model within the developed method

3. **Including scenarios to assess the functional properties of the dike's crest and influence it causes**

The goal of applying the conceptual evaluation model is to provide subject experts and stakeholders with information to assess the effect of a dike reinforcement design in the project area. To evaluate the influence of functions related to the crest width (on the other functional characteristics of the project area), four scenarios are developed for space use on the crest of the dike. These scenarios are illustrated in Figure 38.



	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Crest width:	3m	6m	10.4m	13.4m
Traffic intensity:	No motorized traffic	Low traffic intensity	Large traffic intensity	Large traffic intensity
Separate cycling path:	Yes	No	No	Yes
Cycling on dike:	Yes	Yes	No	Yes
Recreational safety:	Yes	No	-	Yes
Pollution due to traffic:	None	Small	Large	Large
Comfort of the location:	Large	Medium	Small	Small
Dike crest as a animal barrier:	Small	Medium	Large	Large

Figure 38: Crest width scenarios considered in developed method

In the Scope Definition (Section 1.4) is explained that transportation and recreation on the dike (D1 and D4), are always located on the crest of the dike. Within the method, four crest design scenarios (presented in Figure 38) are evaluated to account for combining the transportation and recreation function on the dike. The proposed scenarios are based on design standards for cycling paths and roads in the Netherlands (Table 5), resulting in minimal required crest dimensions. For every crest scenario is determined what the influence is on other functional characteristics of the project area (indicated in Figure 38). These measures are used to quantify the effects indicated with green lines in Figure 37.

Table 5: Determining crest width based on characteristics of roads and cycling paths (retrieved from Waterschap Hollandse Delta, 2011)

Scenario	Total road width	Required road surface	Required road berm	Cycling path width	Total crest width
1. No traffic function	-	-	-	3 m	3 m
2. Low intensity traffic function	6 m	4.5 m	2 x 0.75 m	-	6 m
3. High intensity traffic function without recreation	10.4 m	6.5 m	2 x 1.95 m	-	10.4 m
4. High intensity traffic function with recreation	10.4 m	6.5 m	2 x 1.95 m	3 m	13.4 m

For the crest width scenarios larger than three meters (Scenarios 2, 3, and 4) is assumed that they are only constructed in the case that the traffic and transportation function is implemented as suggested in the scenarios. This assumption is made, as there are no other functional characteristics of the dike coupled to the crest width of the dike (see Figure 37). The set condition does not hold for Scenario 1 (crest width of 3 meters). TAW (1994b) explains that a minimum crest width of three meters is also a maintenance requirement for the dike. Therefore, the implementation of the cycling path in this scenario, is a suggestion for using the space on the crest (another example for using the crest is light agriculture).

5.4.2. Variations of reinforcement location within the Influence demonstration method

Section 5.4.3 explains that increasing the footprint of the dike induces several effects on the existing situation in the project area. Therefore, it important to vary the location of the design alternatives relative to the existing dike. Three variations for the location of the design alternatives are considered in the method (shown in Figure 39).

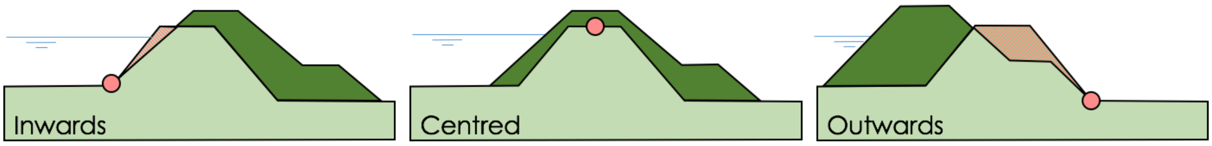


Figure 39: Considered design alternatives in model

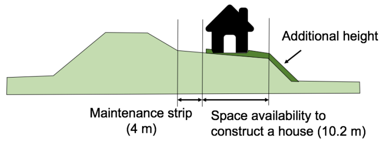
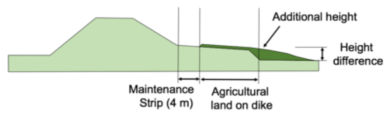
In the application of the conceptual evaluation model, three variations in the location of the dike reinforcement design are considered; inwards reinforcement, centred reinforcement, and outwards reinforcements. These location variations indicate the location of the dike reinforcement relative to the existing dike over the trace of a dike section. Figure 39 expresses the reference points on which the cross-sectional design alternatives for the dike reinforcement are implemented. The considered cross-sectional design alternatives are generated in Step 2 of the method (Section 5.2). To produce inwards dike reinforcements, the outer toe of the reinforcement design is set to the location of the outer toe of the existing cross-section. In the case of centred reinforcement, the middle of the crest is preserved at the same (horizontal) location with respect to the existing dike. An outwards dike reinforcement is produced, when the location of the inner toe is preserved at the same location.

5.4.3. Providing a measure on the magnitude of identified effects

To express the differences between design alternatives on the influence to the functional characteristics of the project area, in the developed method, a measure is provided on every identified relation between the design alternative and the functional characteristics of the area (based on the conceptual evaluation model presented in Figure 37). Afterwards, in Step 6 (Section 5.6) these measures are relatively scored to compare alternatives. Two types of measure are provided; measures that indicate the chances to implement functional characteristics within the considered cross-sectional design (following evaluation model of Figure 37a) and measures that indicate the influence of a dike reinforcement on the existing situation in the surroundings (following evaluation model of Figure 37b). It should be emphasized that these measures do not compare a reinforcement design to (functional characteristics of) the existing cross-section in the project area.

In Table 6 and Table 7, the functional characteristics of the dike and the functional characteristics of the project area is explained which measure is provided. The measures are based on mostly information retrieved from Section 4.2. It is also indicated whether a negative or positive relation between the functional characteristic and indicated measure is provided. It is spoken of a negative relation when an increasing magnitude of an effect, results in a larger negative influence. Based on these relations, differences between design alternatives are expressed in the remainder of the method.

Table 6: Providing measure on the effect on the functional characteristics of the dike (based on Section 4.2.1)

No.	Functional characteristic	Related to design characteristic by	Measure on effect	Relation[1]	Explanation/Visualization
D1	Transportation on the dike	Traffic intensity (in crest scenario)	*If traffic intensity large:* x = 1 *If traffic intensity small:* x = 0.5 *If no traffic intensity:* x = 0	Positive	The potential transporting goods through the project area can be dependent on the properties of the road located on the crest of the dike. In the crest scenarios, different road types have been proposed. The traffic intensity of the road is determined as the indicator of the transportation potential of the dike.
D2	Living on the dike	Space availability on inner berm	*If W_{berm} < 14.2 m:* x = 0 *If W_{berm} > 14.2 m:* $x = W_{berm} - 14.2$ m	Positive	It is required to retain a four-meter maintenance strip between the toe of the slope of the dike and the building that will be constructed on the stability berm (H+N+S, 2013). The required berm width to allow construction of buildings on the dike is the width of the maintenance strip plus the width of the house. According to EPN (n.d.), the average width of a detached house is 10.2 meters. This average is taken as the minimum required space to construct a house on a stability berm in this study (as some extra space is needed around the house). Larger berm widths increase the potential on constructing buildings on the berm. 
		Serviceability limit state	$x = q_c$	Negative	The amount of overtopping events leading to damage is found to be a measure for the serviceability limit state. From EuroTop (2007), can be retrieved that an average overtopping discharge larger 0.01 l/s/m will start inducing damage to buildings. This event occurs more often when the dike is designed based on a large maximum allowable overtopping discharge.
		Accessibility (in crest scenario)	*If traffic intensity large:* x = 1 *If traffic intensity small:* x = 0.5 *If no traffic intensity:* x = 0	Positive	According to Visser & Van Dam (2006), accessibility of the house (time to travel towards work for example), is an important indicator of the attractiveness of the location. In the crest scenarios three possible road types are considered, on the traffic intensity resulting in the described measure on the effect.
		Comfort of the location (in crest scenario)	*If traffic pollution large:* x = 1 *If traffic pollution small:* x = 0.5 *If no traffic pollution:* x = 0	Negative	The comfort of the location is dependent on the nuisance and pollution that is experienced in and near the house. A growing nuisance (mainly dependent on the road on the crest of the dike), makes the comfort of the location lower. Evaluating the crest scenarios results in the provided measures.
D3	Agriculture on the dike	Space availability on inner slope & Subsoil richness	$x = (W_{berm} - 4\text{ m})/H_{berm}$	Positive	When agriculture is applied on the stability berm, a space of 4 m should be reserved at the transition between the dikes slope and the stability berm for maintenance activities on the dike. The rest of the berm can be used for agricultural purposes. In Section 4.2, it is explained that the berm height determines the capabilities for maintaining land and growth of plants. 
		Accessibility (in crest scenario)	*If road available:* x = 1 *If no road available:* x = 0	Positive	For performing agriculture on the dike, also the accessibility of the berm can be important. As the traffic intensity of the road on the crest is not an important measure from agriculture point of view (tractors are slow traffic), only information is provided on availability of infrastructure.
D4	Recreation on the dike	Availability for recreational infrastructure (in crest scenario)	*If cycling possible:* x = 1 *If not possible:* x = 0	Positive	To determine whether recreational cycling is possible at the crest of the dike, it is retrieved whether recreational infrastructure is available. This is dependent on the crest scenario evaluated. It should be noted that this is not the same measure as for the availability of a cycling path.
		Recreational safety (in crest scenario)	*If separate cycling path:* x = 1 *If cycling on road:* x = 0	Positive	Combining cyclists and motorized traffic on the same road results, according to Decisio (2017), in a decreased safety feeling for the cyclists. In the crest scenarios, different combinations for combining recreation and transportation on the dike are proposed.
		Comfort of the location	*If traffic pollution large:* x = 1 *If traffic pollution small:*	Negative	Pollution and nuisance induced by traffic negatively influences the recreation attractiveness of the area. The magnitude of the pollution is assumed to be related to the magnitude of the traffic intensity. Every

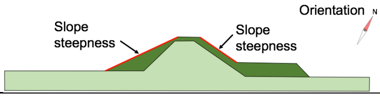
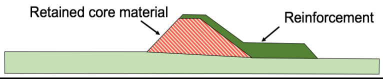
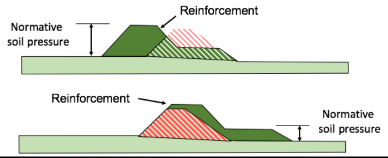
		(in crest scenario)	x = 0.5 *If no traffic pollution:* x = 0		crest width scenario has a different influence on the comfort of the location, which is assumed to be dependent on the traffic intensity of the road on the dike.
D5	Vegetation on the dike	Growth properties of slopes	*Determine orientation of inner and outer slope.* *For northern slope:* $x = s_{nothern\ slope}$ *For southern slope:* $x = s_{southern\ slope}$	*For northern slope:* Positive *For southern slope:* Negative	According to description in Section 4.2, the southern slope of a dike has the largest ecological value when the slope is steepest. A decreasing angle on the southern slope will therefore be considered as a negative influence on the ecology in the design of the reinforcement. For the northern slope, the effect is found the be opposite from the southern slope. Therefore, in this model, a shallow northern slope provides optimal ecological condition. This is decreasing when the slope gets steeper. 
D7	Historical cross-section	Crest width (in crest scenario)	$x = W_{crest}$	Negative	In Section 4.2, is explained that an historical dike is typed by its small crest dimensions, therefor it is assumed that the smallest crest width provides the best properties for a historical design. The disturbance is assumed to be largest, when the crest width is largest.
D8	Archaeology in dike	Preservation of dike core	$x = A_{retained\ core\ material}$	Positive	The core of the dike is identified as an important indicator that represents culture historical value (Section 4.2). The effect on the core, in this model is evaluated by the amount of core material, that can be retained at its existing location. Preserving the largest part of the core is, from culture historical perspective, the best for the design. The largest replacement of core material is set as the worst case scenario. 
[1]*Positive relation = The measure indicates that an increasing number is favourable for the functional characteristic* *Negative relation = The measure indicates that an increasing number is NOT favourable for the functional characteristic*					

Table 7: Providing a measure on the functional characteristics in the surroundings (based on Section 4.2.2)

No.	Functional characteristic	Related to design characteristic by	Measure on effect	Relation[1]	Explanation/Visualization
S1	Transportation on the river	Increased footprint of dike	$x = A_{overlapping\ dike\ \&\ river}$	Negative	Two important indicators are identified to assess the influence of a dike reinforcement project on the transportation function on the river: the location of the interference with the cross-section, and the size of the interference (Section 4.2.2). The location of the interference of a dike cross-section with the river will, in this model, be shown on a map of the project area. The quantity of the interference will be measured by determining size of the intersecting footprint of the dike interferes with the river.
S2	Living in surrounding area	Increased footprint of dike	$x = N_{buildings\ within\ footprint}$	Negative	The increasing footprint of the dike affects the existing living function when the footprint of the new dike is located, within the footprint of the building. In this model, it is for a dike reinforcement alternative determined how many buildings are located within the cross-section of the dike.
		Safety feeling	$x = q_c$	Negative	In the method, three overtopping discharges have been considered (1, 5, and 10 l/s/m). These overtopping discharges are based on design requirements for grass covers as provided in the Rijkswaterstaat (2017b). The smallest overtopping discharge, provides the largest safety feeling, while the largest overtopping provides the smallest safety feeling.
		Comfort of the location (in crest scenario)	*If traffic pollution large:* x = 1 *If traffic pollution small:* x = 0.5 *If no traffic pollution:* x = 0	Negative	See Table 6, functional characteristic "D2. Living on the dike".
		Accessibility (in crest scenario)	*If traffic intensity large:* x = 1 *If traffic intensity small:* x = 0.5 *If no traffic intensity:* x = 0	Positive	See Table 6, functional characteristic "D2. Living on the dike".
S3	Agriculture in surrounding area	Increased footprint of dike	$x = A_{overlapping\ dike\ \&\ agr.\ land}$	Negative	When a footprint of a dike is located on agricultural land, the use function of agriculture cannot be performed anymore at that location. To identify the quantity of this effect for a design alternative, the area of the dike's footprint interfering agricultural land is measured. In addition, it should be

					assessed whether residual shapes provide sufficient conditions to maintain the agricultural function at that location.
		Ground water balance	Related to the influence on S7		The decreasing quality of subsoil characteristics is dependent on the influence caused by the influence on the water levels at the agricultural land. This influence is found to be dependent magnitude on the water demands of crops and workability of the project area.
		Accessibility (in crest scenario)	*If road available:* x = 1 *If no road available:* x = 0	Positive	See Table 6, functional characteristic "D3. Agriculture on the dike".
S4	Recreation in surrounding area	Increased footprint of dike	$x = A_{\text{overlapping dike \& recr. area}}$	Negative	The quantitative reduction of the area is focussed on the overlapping part of the reinforcement design in the recreational area. The variety between the designs is indicated, by showing the maximum and minimum influence on the recreational area. In addition, it should be assessed whether the residual shapes provide favourable conditions for recreational areas.
		Comfort of the location (in crest scenario)	*If traffic pollution large:* x = 1 *If traffic pollution small:* x = 0.5 *If no traffic pollution:* x = 0	Negative	See Table 6, functional characteristic "D4. Recreation on the dike".
		Accessibility (in crest scenario)	*If road available:* x = 1 *If no road available:* x = 0	Positive	See Table 6, functional characteristic "D3. Agriculture on the dike".
S5	Nature in surrounding area	Increased footprint of dike	$x = A_{\text{overlapping dike \& nat. area}}$	Negative	In the method, it is assumed that the valuable vegetation in the project area is all located within assigned areas (Nature Network Netherlands). Due to a dike reinforcement, the vegetated top layer will have to be removed, causing a loss of valuable vegetation. The influence is most positive when the largest part of the vegetation is preserved.
		Ground water balance	Related to the influence on S7		A negative effect of the ecological potential results, in a negative effect on the existing vegetation in the project area. It is found that the ecological potential of the subsoil can be interfered by influencing the ground water balance (S7) and the soil pollution in the project area (S8). The measures indicting the influences are explained in S7 and S8.
		Soil pollution in surrounding area	Related to the influence on S8		
		Crest as animal barrier	*If barrier is larger:* x = 1 *If barrier is medium:* x = 0.5 *If barrier is small:* x = 0	Negative	The transportation function of the dike creates a physical barrier for animals travelling through the project area. In the method, the impact is taken as most positive when there is no transportation function available on the dike. The negative influence is largest in the case when the largest transportation function is available on the dike.
		Comfort of the location (in crest scenario)	*If traffic pollution large:* x = 1 *If traffic pollution small:* x = 0.5 *If no traffic pollution:* x = 0	Negative	See Table 6, functional characteristic "D4. Recreation on the dike".
S7	Ground water balance	Influencing seepage flow	*If influenced:* x = 1 *If not influenced:* x = 0	Negative	The influence on the ground water balance is dependent on water flow disturbing structures located in the subsoils. The assumption is made that a soil solution for the dike reinforcement will not cause disturbances on the existing ground water balance. It is also, assumed that the sand tight geotextile does not influence the ground water balance. Nevertheless, it is assumed that relief wells influence the ground water balance in the project area to prevent the occurrence of piping.
S8	Pollution in the surrounding area	Traffic intensity (in crest scenario)	*If traffic pollution large:* x = 1 *If traffic pollution small:* x = 0.5 *If no traffic pollution:* x = 0	Negative	See Table 6, functional characteristic "D4. Recreation on the dike".
S9	Soil pollution in surrounding area	Increased footprint of dike	$x = A_{\text{overlapping dike \& pol. area}}$	Positive	For soil pollution, it is found that increase of the footprint potentially leads to influence on the contamination sources (due to excavation activities during construction). This results in a positive effect on nature values in the project area. The larger the required clean-up, the more positive the effect.
S10	Flood relics	Increased footprint of dike	$x = A_{\text{flood relics within footprint}}$	Negative	The effect on physical cultural elements in the spatial planning is found to be dependent on the interference of the footprint of the dike, with the footprint of the cultural element. For the three functional characteristics (S10, S11, S12), it is evaluated whether the dike's cross-section is located
S11	Military items	Increased footprint of dike	$x = N_{\text{structures within footprint}}$	Negative	

S12	Heritage structures	Increased footprint of dike	$x = N_{\text{her. structure within footprint}}$	Negative	within in the footprint. It is counted how many cultural elements are interfered with the reinforcement design.
S13	Heritage sites	Increased footprint of dike	$x = A_{\text{site within footprint}}$	Negative	The effect on monumental areas (estates such as, castle gardens) is indicates by determining the size of the interfered area due to a certain reinforcement design. Experts can than, together with a provided map, assess whether the reducing area results in a large demolishment of the character of the monumental area.
S14	Archaeology in surrounding area	Structure in subsoil at archaeology	*If structure in subsoil:* x = 1 *If no structure:* x = 0	Positive	In the study, it is focused on soil solutions to reinforce the existing dike. Nevertheless, to reinforce against piping, it is assumed that sand-tight geotextiles and relief wells are design options. Both solutions interfere with the subsoil, which can cause negative effects for archaeology in the surrounding area.
		Increased soil pressure	*If outwards reinforcement:* $x = H_{crest}$ *If inwards or centred reinforcement:* $x = H_{berm}$	Negative	It is found that unequal settlements of the subsoil lead to damage to archaeological values in the subsoil. Therefore, in this model, the influence on archaeological values in this model has taken to be dependent on the increased soil weight on top of the subsoil. The provided measure is dependent on the reinforcement location and the dimensions of the reinforcement. 
		Ground water balance	Related to the influence on S7		A ground water change can be negative in both ways. Therefore, in this model, the effect on archaeological values is taken to be most positive in the case that the water level does not change. It is found that the ground water balance only changes due to the implementation of the relief wells in the method.
[1]*Positive relation = The measure indicates that an increasing number is favourable for the functional characteristic* *Negative relation = The measure indicates that an increasing number is NOT favourable for the functional characteristic*					

The measures provided in Table 6 and Table 7, provide the influence of a single design alternative for a dike reinforcement in rural areas. In the method, this is programmed in a Python-script that retrieves the measures for every single design alternative. The outcome of Step 4 is a large table indicating the influence of every design alternative on the functional characteristics of the project area. This is input for Step 5 (Section 5.5).

5.5. Relatively score retrieved effects (Step 5)

After the evaluation of alternatives in Step 4 (Section 5.4), in Step 5 the relative measures can be created. There are several ways to compare the magnitude of effects. In this method, the interval standardization method is used. This method represents values on interval between the minimum and maximal observed value in a data set. The observed score has a linear relation in between the minimum and maximum value (Figure 40). According to Reinshagen (2006) this scaling method is mainly interesting when the obtained scores are not proportional to the zero impact situation. As the goal of the design model is to compare design alternatives, these can be illustrated best in relative scales (interval standardization). Creating a scale between the zero and the maximum observed value can result in a large range, reducing the visibility of the effect of changing the design. From the data set created in the previous modelling step, it is therefore, per influence on the functional characteristics retrieved what the minimum and maximum observed value is.

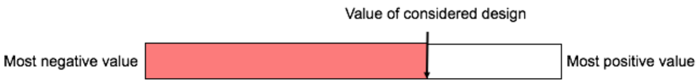


Figure 40: Interval standardization method

Table 6 and Table 7, provide the measures on the effects that have to be relatively scaled. In these tables is indicates whether are positive or negative relation is identified. A negative relation means that the lowest observed value is most positive. In the scaling method, it is determined whether a positive or negative effect was observed, so that a full scale bar (Figure 40) always indicates the most positive observed effect on the considered functional characteristic.

5.6. Group the effects by themes (Step 6)

It can be observed (in Table 6 and Table 7) that there is a large overlap in the effects on the functional characteristics. To reduce this overlap, it is decided to restructure the functional characteristics of the project area in six themes. The presented themes are based on the different angles of approach on functional changes that stakeholders are interested in, in dike reinforcement projects. The following themes are used in the representation of the results of the method:

- Living
- Agriculture
- Nature
- Culture
- Recreation
- Transportation

Representing the influence of a reinforcement design in these themes, guides the user of the model directly to the effects of its interest. Table 8, illustrates the division of the functional characteristics in themes. In Step 7 (Section 5.7), the effects of the design alternatives on the functional characteristics are illustrated in the six themes.

Table 8: Dividing functional characteristics of the project area in themes

Living	Agriculture	Nature	Culture	Recreation	Transportation
Functional characteristics of the dike (design)					
D2. Living on the dike	D3. Agriculture on the dike	D5. Vegetation on the dike	D7. Historical cross-section	D4. Recreation on the dike	D1. Transportation on the dike
D1. Transportation on the dike	D1. Transportation on the dike		D8. Archaeology in the dike	D1. Transportation on the dike	
Functional characteristics of the surroundings					
S2. Living in the surroundings	S3. Agriculture in the surroundings	S5. Nature in the surroundings	S10.Flood relics	S5. Recreation in surrounding area	S1. Transportation on the river
S8. Pollution in the surroundings	S7. Ground water balance	S7. Ground water balance	S11. Military items	S8. Pollution in the surroundings	
		S8. Pollution in the surroundings	S12. Heritage structures		
		S9. Soil pollution in the project area	S13. Heritage sites		
			S14. Archaeology in surrounding area		
			S7. Ground water balance		

It should be noted, that there is a small overlap in-between groups (for example on the topic transportation). This is caused by the perspective chosen to structure the results. In the current representation, the model provides the complete interests per theme, with as goal to inform the user of the model as fast as possible, and providing information on the spatial changes on the topics that the user is interested in (which is done in Step 7, Section 5.7).

5.7. Visualization of influences (Step 7)

The visualization of the influence of a design alternative on the functional characteristics of the project area is created in the last step (Step 7). Going through Step 1 till Step 6 provides all information to visualize the relative influence of a design alternative on the functional characteristics of the project area. Figure 41 illustrates this relative influence of a design alternative for a random design retrieved from evaluating the case study “Wolferen-Sprok” (Dike Section 14). This figure visualizes the outcome of the method, by assigning the effects on the functional characteristics to themes that illustrate effects from a certain stakeholders’ perspective. All identified effects on the functional characteristics of the project area are present in the provided radar plot. It should be noticed that a full scale bar always indicates the most positive score on the evaluated theme. In the remainder of this section explains the visualization of results in the method (Figure 41) per element in the plot.

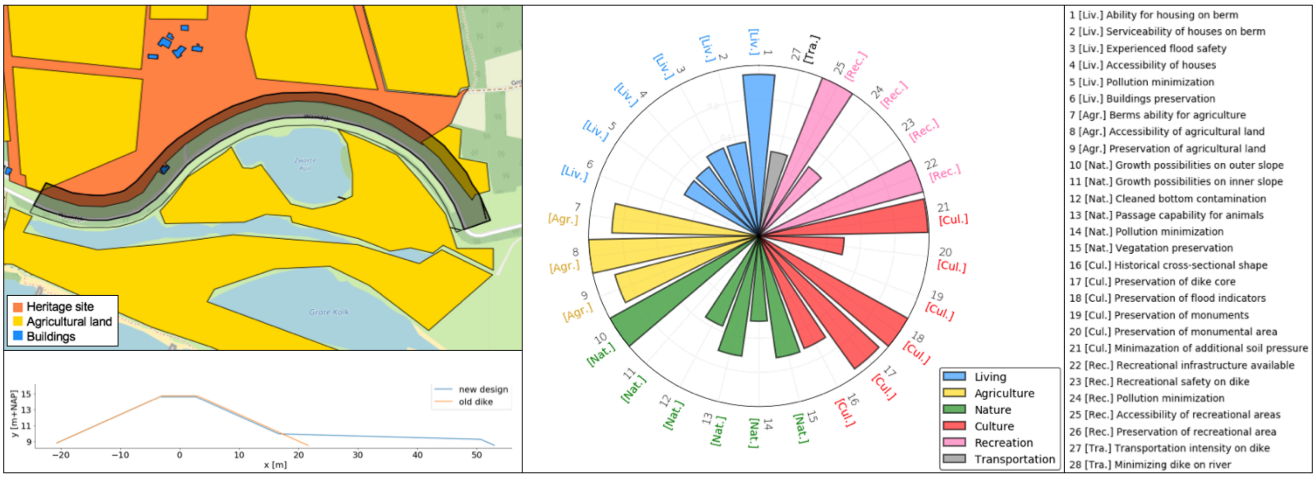


Figure 41: Visualization of outcome of method

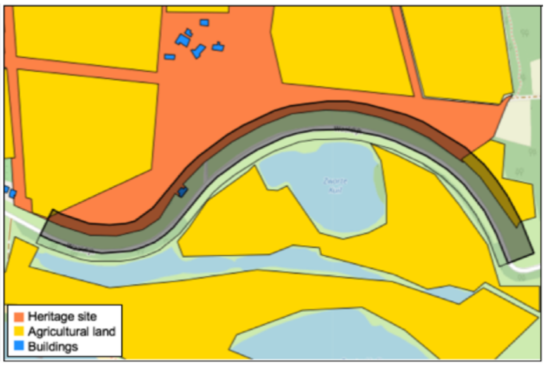


Figure 42: Top view of evaluated dike section

Top view of dike reinforcement (Figure 42)
This panel illustrates a top view of a studied design alternative for a dike reinforcement in rural area. As explained in Section 4.2.2, shapes of residual area are important indicators of the new effectiveness of the applicable functions in the project area. Therefore, the reinforcement design is illustrated relative to layers with important information of the project area. In the example three layers are shown; heritage site, agricultural land, and buildings.

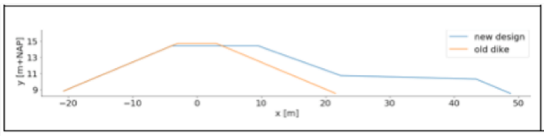


Figure 43: Cross-sectional view on dike reinforcement

Cross-sectional design (Figure 43)
The panel on the left shows the cross-sectional design of the dike relative to the existing dike in the project area. These two cross-sections are compared to determine where the dike reinforcement deviates from the existing dike.

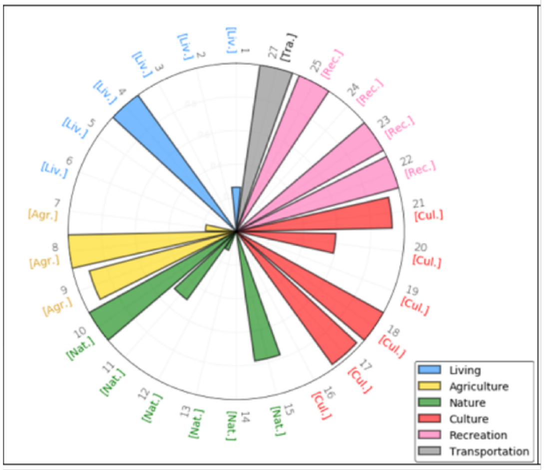


Figure 44: Relative influence on project area of evaluated design alternative

Influence of evaluated design relative to other design options (Figure 44)
The radar plot of Figure 44 shows the influence of a dike reinforcement design on the functional characteristics of the project area relative to all other design alternatives evaluated in the method. The six themes are illustrated in colour, which provides the possibility to directly get a first impression of the rough effect of the studied design alternative. Full scale bars illustrate positive effects. Meaning that the hypothetical optimal design, is the design that completely consists of full scale bars (which is only possible in theory). The radar plot compares effects on functional characteristics that have been identified in the project area. There is a chance that some of the, in Section 4.1, identified effects are not applicable in the studied project area.

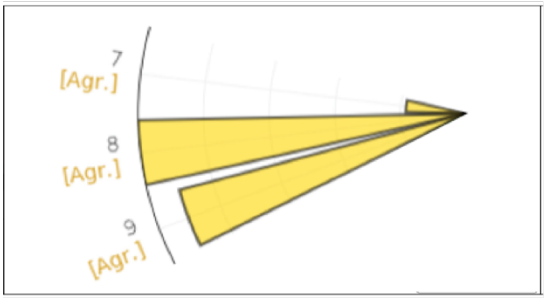


Figure 45: Illustration of influence on a theme

Illustrating the score of a theme (Figure 45)
After retrieving a rough overview of the effects on the different themes, a more detailed look can be obtained on a specific theme. The user of the model can determine the relevance of the indicated effects. For example, from agricultural perspective, it can be discussed whether agricultural on the stability berm is an ambition in the reinforcement project (number 7 in Figure 45).

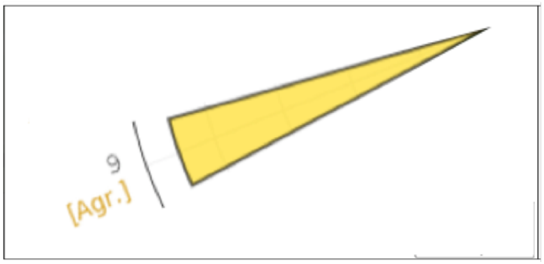


Figure 46: Illustration of single effect

Illustrating the score of a single effect on a functional characteristic (Figure 46)
Evaluating every single bar in the radar plot provides information to assess the changes to the functional characteristics in the project area (Figure 46). A full scale bar indicates the most positive effect, while no bar indicates the most negative effect. In Figure 46 can be found that the studied design alternative, scores quite good on “9. Preservation of agricultural land”. By studying every effect of the dike reinforcement (every scale bar in Figure 44), it can be determined whether a design alternative has a satisfying influence on the existing situation.

5.8. Required software support to execute the method

Software support is required to execute the method as explained in this chapter. The developed method is guided by a Python script that connects the steps. In addition, other programs are used to obtain the required information for a desired outcome of the method. This section explains per step which software is used.

Step 1: Identify safety issue
First, the safety issue is identified by determining the resistance of the existing dike against “Inner slope erosion”, “Inner slope stability”, and “Piping”. Three types of software are used to identify the safety issue of the dike:

- Hydra-NL for “Inner slope erosion”
- D-Geo Stability for “Inner slope stability”
- Deterministic calculation in Python for “Piping”

Step 2: Generate design alternatives
To generate design alternatives, first different outer slope and crest height scenarios are determined in Hydra-NL. The retrieved dike heights are input for a Microsoft Excel-file that is able to create a large variety of geometries. After the schematization of boundary conditions, this Microsoft Excel-file is able to create input files for D-Geo Stability for every unique geometry. Running the batch of D-Geo files, results in a safety factor for every evaluated geometry, that is returned in a table in Microsoft Excel. This table is imported in Python, and assessed on the minimum required safety factor, and the ambitions of the HWBP (Section0, Figure 35).

Step 3: Create spatial reference scenario
A spatial reference scenario is created in QGIS, by means of shapefiles describing a certain functional characteristic in the surroundings of the dike. The created layers, Point or Polygon shapefiles in the RD-Coordinate system, are imported in Python.

Step 4: Apply conceptual evaluation model
The application of the conceptual evaluation model is programmed in a Python-script that assess the influence of every design alternative created in Step 2. This is done by following the structure that is presented in Figure 47a. A separation is made between the shape of the dike and the influence on the spatial input data describing the functional characteristics of the surroundings. The influence caused by the shape of the dike is directly retrieved from the characteristic points of the dike.

To assess the spatial input data, the differences between designs are determined by comparing the characteristic points of the existing dike and the evaluated design alternative, as illustrated in Figure 47b. For the part of the design alternative that deviates from the existing dike is determined how it influences the existing functional characteristics of the surroundings (related to the footprint of the dike). Therefore, the reinforcement design is projected over the existing dike trace creating a Polygon-layer describing the design in the project area. Afterwards, it is assessed where this layer intersects the Polygon-layers describing the functional characteristics of the surroundings (retrieved from Step 3). Information (for example number of elements, or hectares) is retrieved from the intersected parts, with help of the GeoDataFrame-package in Python. All information is saved in a large table, describing the influence of the reinforcement.

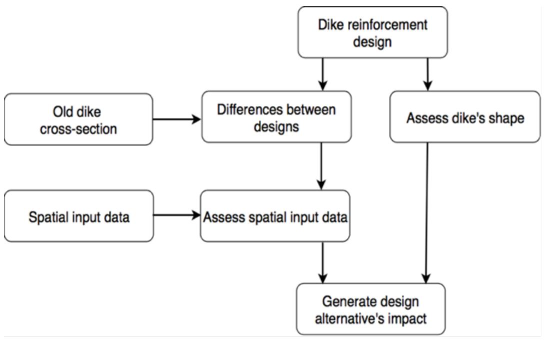


Figure 47a: Dike design assessment method

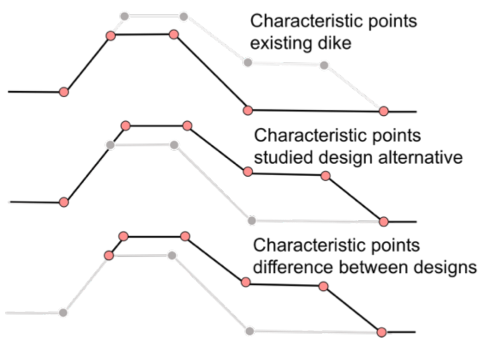


Figure 47b: Finding difference between designs

Step 5: Relatively score retrieved effects, Step 6: Group the effects by themes, and Step 7: Visualization of influence
The information retrieved in Step 4, is relatively scaled and grouped with help of a Python-script. Lastly, this information is visualized in Step 7 with help of the following Python packages:

- PyPlot-package to create the radar plot
- PyPlot-package to plot the cross-section of the existing dike and design alternative
- Folium-package to plot the top view of the dike

5.9. Concluding remarks

In this chapter, a method is developed that enables to compare design alternatives in early stages of a dike reinforcement project on the influence it has on the functional characteristics of the project area. The method consists of seven steps that eventually lead to a visualization of the differences between design alternatives. It should be noticed that the location specific input data has a limited level of detail, which makes quantitative assessment of the influence of a design alternative possible. However, the importance of qualitative effects is also important in such projects. To study these effects, the required input data on the functional characteristics of the project area should consist of a larger level of detail. The increased level of detail is, according to Voorendt (2017), obtained throughout the design process by doing detailing loops. As these detailing loops are not obtained in the method, the provided method is only suitable for initial selection and evaluation of design alternatives.

6. Applying the method: Case Study

In this chapter, the developed method of Chapter 5, is applied on the dike reinforcement project "Wolferen-Sprok". The developed method is applied on a case study to retrieve insights in the working of the method to provide information on the effects of design alternatives on the functional characteristics of the project area.

The chapter is started by introducing the case study (Section 6.1). Subsequently, the results of applying the developed method are presented in Section 6.2. Based on these results, it is in Section 6.3 and Section 6.4 explained what the capabilities and limitations of the method are. Section 6.5 explains the influence of the project location on the results of the method. Finally, concluding remarks on applying the method in dike reinforcement projects are provided in Section 6.6.

6.1. Introduction of the Case Study

The method is applied on a dike reinforcement project located in the eastern part of the Netherlands, near the city of Nijmegen. The project "Wolferen-Sprok" is initiated to reinforce fifteen kilometres of dike among the Waal river. The dikes, bordering the river, are part of the primary flood defence network in the Netherlands. Figure 48, shows the location of the dike reinforcement project by means of the red trace. The trace is divided in seventeen dike sections, which are based on comparable geotechnical and hydrodynamic conditions within the dike section (Soepboer, 2018).

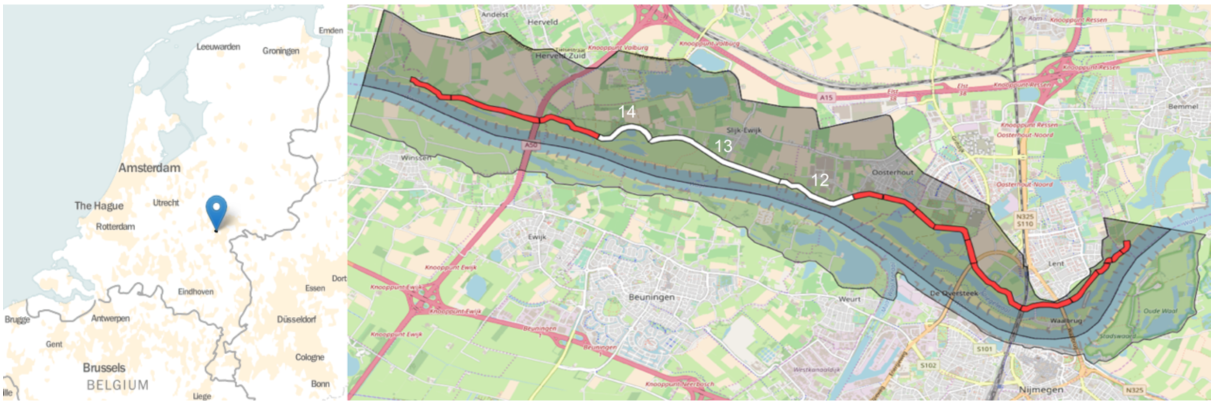


Figure 48: Location dike reinforcement project

In the case study, three dike sections are evaluated (illustrated in white, from right to left: Dike Section 12, 13, and 14). These dike sections are chosen as they fit within the scope of this study; dike reinforcements in rural areas. As the evaluated dike sections have different lengths and compositions of surrounding areas, it is expected that evaluating these three sections provide good insight in the working of the method, and the value of the outcome of the method. To assess the working of the method, the method is applied on Dike Section 14. Section 6.2, explains the retrieved insights of applying the method. Dike Section 12, and 13 are evaluated in Appendix D. In Section 6.5, the retrieved results for Dike Section 12, and 13 are compared to the results of Dike Section 14.

6.2. Results of applying the developed method for Dike Section 14

This section illustrates the results of applying the developed method on the dike reinforcement of Dike Section 14. In this section includes a step-by-step explanation on how the method is applied and what insights are retrieved by going through the method. Subsequently, in Section 6.3, the value of applying the method in dike reinforcement projects is explained in detail.

6.2.1. Step 1: Identify safety issue

The HWBP initiated the dike reinforcement project between Wolferen-Sprok, based on a safety analysis of the project area. For Dike Section 14, the main safety problem in the existing situation (based on governing conditions in 2025) was found to be inner slope stability, and piping. It was concluded that the height of the dike in Dike Section 14, is sufficient to prevent overtopping that causes destructive erosion of the inner slope (Bisschop & van Loon, 2017). The reinforcement project was initiated to make the dike future proof.

In the Dutch Water Act is stated that soil dikes should be designed to fulfil the governing conditions for the first fifty years after construction (Dutch National Government, 2017). Therefore, after the dike reinforcement project, the dike should be able to resist the governing conditions in 2075. For the dike segment in which the project area "Wolferen-Sprok" is located, a failure probability of 1/10.000 years is set (Soepboer, 2018). To identify the problems to resist these governing conditions (in 2075), a safety analysis is obtained on the existing situation. The safety analysis on inner slope stability, inner slope erosion, and piping is obtained by following the Dutch Design Guidelines for dikes ("Ontwerpinstrumentarium IO2014", Rijkswaterstaat (2017b)). Following these guidelines provides information for the schematization of the boundary conditions, and the physical behaviour of soil. In some cases, it was more convenient to use other schematizations. This is explained in Appendix D. The appendix explains the used geotechnical, and hydrodynamic schematizations to retrieve a measure on the safety of the existing cross-section of the dike. Figure49a provides geometrical conditions used for the safety analysis, while Figure 49b provides the retrieved safety measure for the three considered failure mechanisms. The dike in the project area consists of a clay core, with a grass cover layer on the slopes of the dike. For an elaborate explanation on the evaluation of the failure mechanisms is referred to Appendix D. The outcome of the analysis is explained in the remainder of this section. Table 9, provides the required safety factors for the project area for two failure budgets (see Appendix D). In this way can be determined what the influence is of changing the failure budgets within the dike segment.

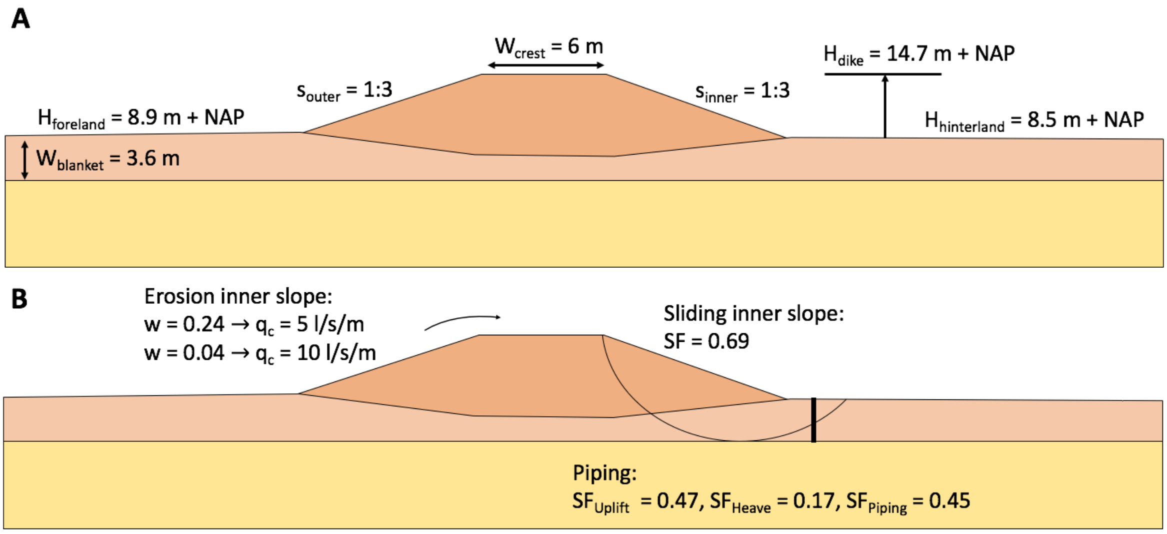


Figure 49: Safety problem in Dike Section 14 during governing conditions

Table 9: Required safety conditions for cross-sectional design of the dike (based on Table 33, Appendix D)

Name	Unit	Section 43-4	
Failure norm for segment	[1/year]	1/10.000	
Inner slope stability			
Failure probability budget $[\omega]$	[-]	0.04	0.24
Required Safety Factor [SF]	**$= \gamma_n * \gamma_m * \gamma_d * \gamma_s$ [-]**	**1.48**	**1.42**
Inner slope erosion (height)			
Failure probability budget $[\omega]$	[-]	0.04	0.24
Cross-section norm [$P_{eis;\,dsn}$]	**[1/year]**	**4.0e-6**	**2.4e-5**
Piping			
Failure probability budget $[\omega]$	[-]	0.04	0.24
Safety factor Piping $[\gamma_{pip}]$	**[-]**	**1.50**	**1.33**
Safety factor Uplift $[\gamma_{up}]$	**[-]**	**2.03**	**1.74**
Safety factor Heave $[\gamma_{heave}]$	**[-]**	**1.07**	**0.91**

The retrieved overtopping discharges (based on a Hydra-NL calculation, illustrated in Figure 49) for erosion of the inner slope, q_c = 5 l/s/m for w=0.24, and q_c = 10 l/s/m for w=0.04, are overtopping discharges determined for a dike height of 14.7 m + NAP, an outer slope of 1:3, and a set failure budget. The set failure budget and the norm of the dike segment result in a cross-sectional norm for hydraulic loadings on the dike (see Table 9). The norm results in an overtopping discharge of the existing dike, by predicting the hydrodynamic behavior of the river during these conditions. The overtopping discharge of 5 l/s/m is according to the design guidelines sufficient for a grass cover layer with an open sod (in small wave conditions). While the overtopping discharge of 10 l/s/m requires a closed grass sod. It is therefore concluded, that in the worst case, the quality of the grass sod should be reinforced to provide resistance during governing conditions. The height of the dike is not the main challenge of the dike reinforcement project in Dike Section 14.

Safety against sliding of the inner slope during governing conditions is found to be equal to 0.69. This value is obtained by analyzing the sliding behavior of the dike in DGeo Stability, based on the Uplift Van sliding model, and the CSSM material model. The required safety factors for sliding of the inner slope are 1.42 for a failure budget of 0.24, and 1.48 for a failure budget of 0.04, which is much larger than 0.69. It can be concluded that the inner slope should be reinforced to guarantee safety during governing conditions.

Third, the resistance against piping during governing conditions is assessed. Safety against piping is provided when safety against one of the three sub-mechanisms (uplift, heave, and piping) is sufficient. A deterministic assessment resulted in safety factors on the sub-mechanisms for the existing cross-section in Dike Section 14. It can be observed that the calculated safety factors of the existing cross-section (Figure 49) are smaller than the minimal required safety factors in the project area (Table 9). Therefore, a safety measure should be provided to mitigate the piping problem. In Step 2 (Section 6.2.2), it is explained which design alternatives are considered to solve the safety problem in Dike Section 14.

6.2.2. Step 2: Generate design alternatives

After identifying the safety problem (Section 6.2.1), in the second step design alternatives are created that provide safety against the governing conditions in 2075. In Section 5.2, has been explained how the safety analysis is automated for a large variety of input geometries of the dike. The considered design variations for Dike Section 14 are shown in Figure 50 and Table 10. Based on these geometries and the geotechnical and hydrodynamic boundary conditions is determined which geometries fulfil the safety assignment within the ambitions of the HWBP (smarter, cheaper, and faster (ENW, 2017)). For a description on the schematization of the boundary conditions for the assessment of the resistance in referred to Appendix D. In this appendix, is per failure mechanism described how a measure on the resistance can be retrieved. Similar as in Step 1 (Section 6.2.1), these calculations are based on the Dutch Design Guidelines ("Ontwerpinstrumentarium IO2014", Rijkswaterstaat (2017b)).

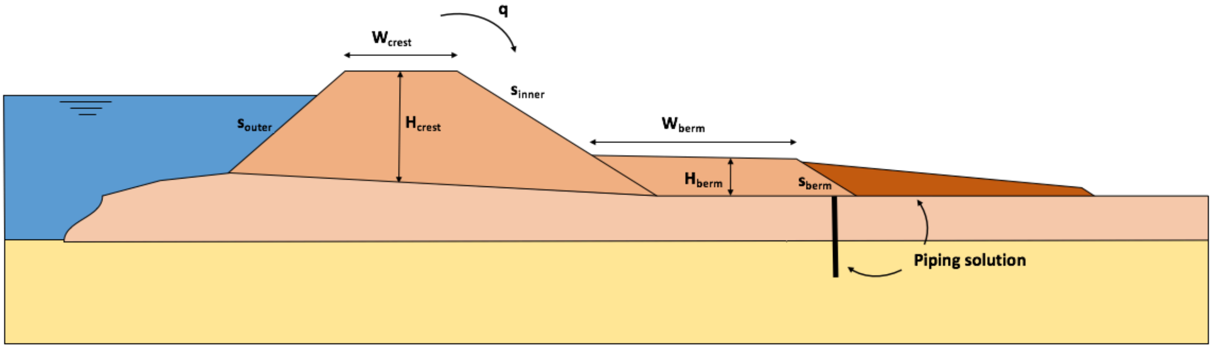


Figure 50: Illustration of possible design variations to reinforce Dike Section 14

Table 10: Considered design variations for Dike Section 14

Name	Unit	Variations Section 14
Outer slope (s_{outer})	**[1:_]**	3, 4, 5
Critical Overtopping discharge (q_c)	**[l/s/m]**	1, 5, 10
Crest width (W_{crest})	**[m]**	3, 6, 10.4, 13.4
Inner slope (s_{inner})	**[1:_]**	3, 3.5, 4
Berm width (W_{berm})	**[m]**	15, 35, step size = 1
Berm height (H_{berm})	**[m]**	1, 4, step size = 0.1
Slope inner berm (s_{inner})	**[1:_]**	3
Failure budget (w)	**[-]**	Scenario 1 (standard): $w_{erosion}$=0.24, $w_{stability}$=0.04, w_{piping}=0.24 Scenario 2 (shifted): $w_{erosion}$=0.04, $w_{stability}$=0.24, w_{piping}=0.24
Piping solution	**[-]**	1. Piping berm 2. Relief well 3. Sand-tight geotextile

In Table 10 can be observed that two failure budget scenarios are used in the generation of design alternatives. The failure budget of a dike should be equal throughout a dike segment. Failure budget scenario 1 is based on the standard failure budgets as described in ENW (2017). In addition, it is determined whether shifting the failure budget leads to a more convenient reinforcement project. As explained in Chapter 2, berms on the river side of the dike are not considered as a design measure, because it is expected berms are not efficient measures to reduce overtopping of the dike. In the remainder of this section, it has been explained what the design alternatives are for reinforcing Dike Section 14. The influence of the piping measure on the design alternatives is discussed separately.

Design alternatives to resist “inner slope stability” and “inner slope erosion”

Evaluating the design variations according to the method as provided in Section 4.2, results in the design alternatives that are illustrated in Figure 51 and Figure 52. The figures illustrate two times 1,919 different geometries that provide resistance against “inner slope stability” and “inner slope erosion” for Dike Section 14. These geometries are verified design alternatives to provide resistance against the two failure mechanisms; the verification is provided in Appendix D.

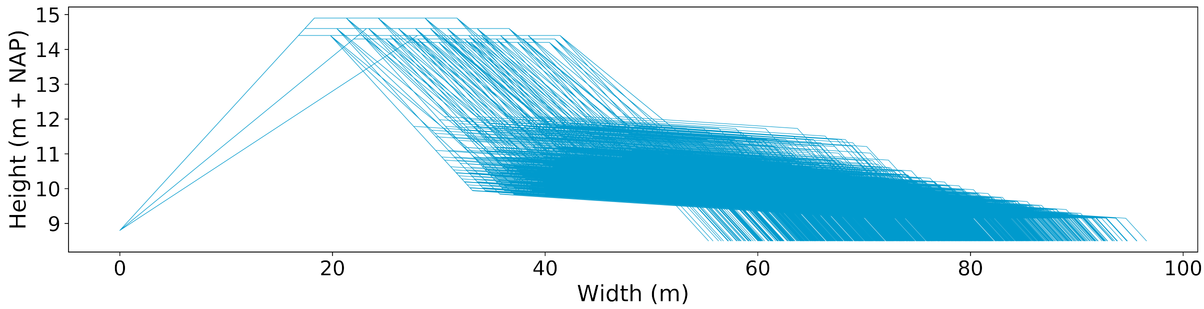


Figure 51: Design alternatives to reinforce Dike Section 14, with failure budget scenario 1

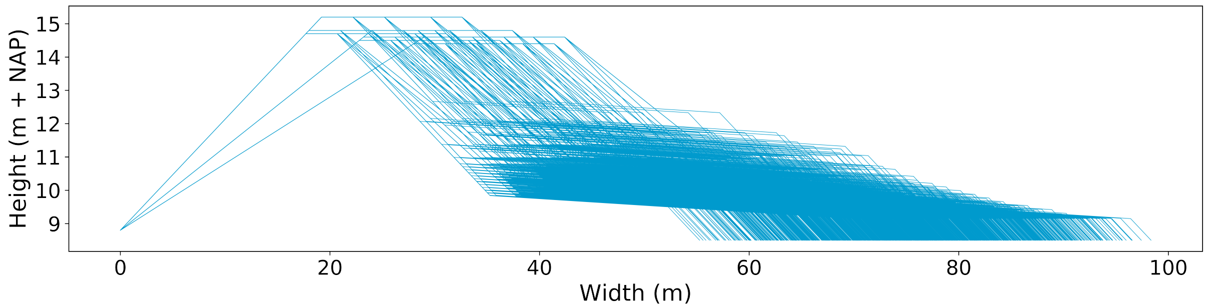


Figure 52: Design alternatives to reinforce Dike Section 14, with failure budget scenario 2

It can be observed that Figure 51 and Figure 52 show very similar geometries of the dike. Nevertheless, the design alternatives based on failure budget scenario 2 provide slightly higher cross-section. To illustrate the effects of design parameters on the total width of the dike boxplots are provided in Figure 53. The created boxplots are based on the design characteristics retrieved from the geometries provided in Figure 51 and Figure 52.

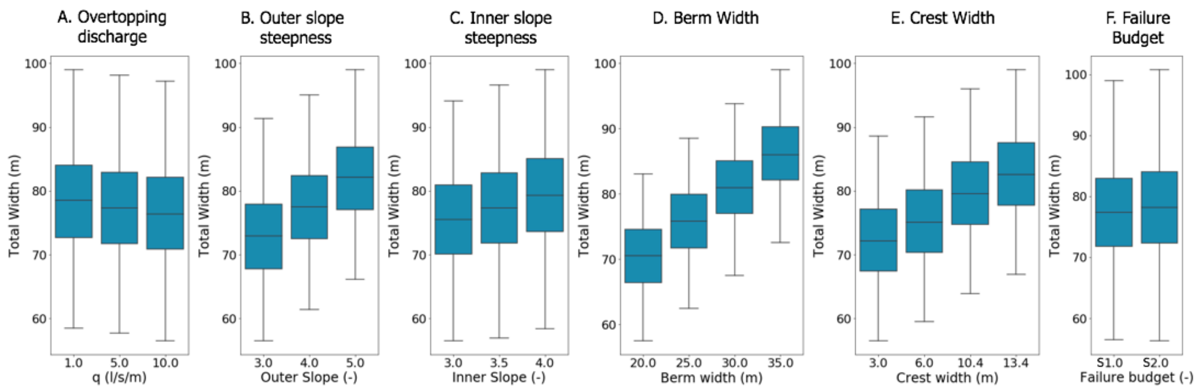


Figure 53: Influence of design parameters on the total width of the dike (for Dike Section 14)

Evaluating Figure 53 shows that changing the overtopping discharge, and inner slope steepness have a limited effect on the total width of the dike. This is interesting, as it means that functional characteristics coupled to these parameters can be implemented easily without affecting the footprint largely. The most important contributors to the total width of the dike are the outer slope angle, crest width, and berm width. These parameters can contribute largely to the multi-functionality of the design, but the designer should be aware of the consequences it can have on the existing situation in the project area.

The influence of changing the failure budget scenario, is found to have a small influence on the total width of the dike. Two failure budget scenarios have been reviewed (Scenario 1 (standard): $w_{erosion}$=0.24, $w_{stability}$=0.04, and Scenario 2 (shifted): $w_{erosion}$=0.04, $w_{stability}$=0.24). It can be found that the difference on the total width of the dike is negligible. As it is expected that this will not result in largely changing outcomes of the method, it is decided to set the failure budget in the complete project area to failure budget scenario 1 ($w_{erosion}$=0.24,

$w_{stability}$=0.04, w_{piping}=0.24). Failure budget scenario 2, will not further be considered in the in the case study.

Piping measures
Lastly, also resistance should be created against the failure mechanism piping. In Section 5.2 is explained that three piping measures are evaluated in the developed method (Figure 54). This section also explains that structural designs have not been created for relief wells and the sand-tight geotextile.

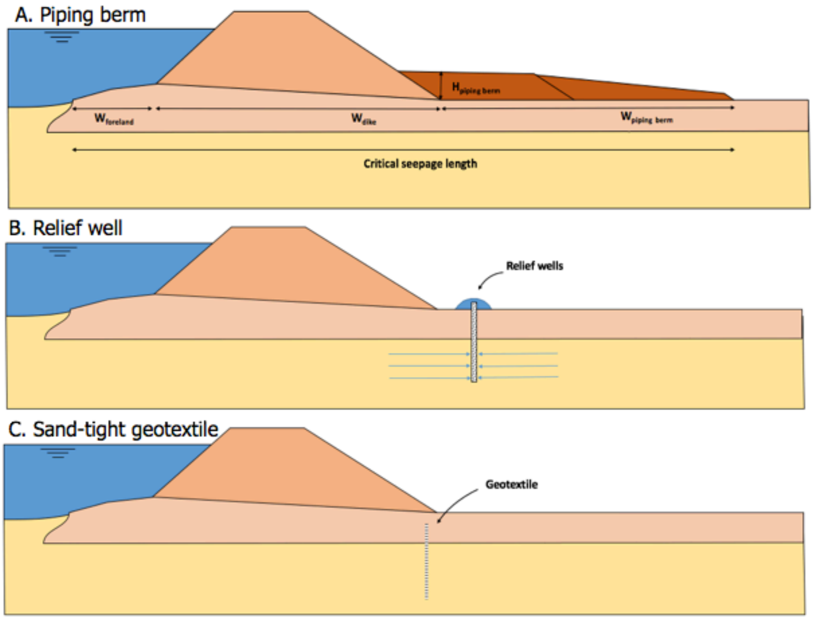


Figure 54: Piping measures

The required dimensions for the piping berm are retrieved from a deterministic calculation on the sub-mechanism "uplift", "heave", and "piping". The resulting dimensions of the piping berm are given in Table 43. It should be noted that the width of the piping berm is dependent on the total width of the dike that is provided in Figure 51. The maximum total dike width in this figure is about hundred meters. Constructing an additional piping berm 171 meters, is assumed to be not realistic. As the influence of providing resistance against piping is that large. The influence on the functional characteristics is assessed separately in the remainder of this chapter.

Table 11: Piping berm dimensions

	Dike Section 14
Critical seepage length [m]	281
W_{dike} + $W_{piping\ berm}$ [m]	271
$H_{piping\ berm}$ [m]	1.81

6.2.3. Step 3: Create spatial reference scenario

To determine the effect of reinforcement designs on the characteristics in the surroundings, a reference scenario is created describing the functional characteristics of the surroundings of the dike. Table 12 describes the sources that were used to illustrate the spatial reference scenario, that is illustrated in Figure 55 and Figure 56. Evaluating the input data shows "S4. Recreation in the surroundings" and "S11. Military items in surroundings" are not identified within the project area. On the other functional characteristics, a map is provided to represent the existing situation in the surroundings. These maps are used in Step 4 (Section 6.2.4) to evaluate the effect of design alternatives on the project area.

Table 12: Sources for spatial input data

Functional characteristic	In legend of Figure 56	Visualized data based on
Existing cross-section in Dike Section		Cross-section schematization of Witteveen + Bos (2018c)
Trace of existing dike		Based on air picture of the project area (Google Maps)
S2. Living in surroundings	Buildings	Based on air picture of the project area (Google Maps)
S3. Agricultural land in surroundings	Agricultural land	Data supplied by the PDOK Geocoder (Agragrisch Areaal Nederland, AAN)
S4. Recreational area in surroundings		No indicators identified in the evaluated area
S5. Nature in surroundings	Nature Network Netherlands	Province Gelderland (Opendata Gelderland, 2017)
S9. Soil pollution in surroundings	Soil pollution	HBB ("Historisch bodem bestand") locations retrieved from (Soepboer, 2018)
S10. Flood relics in surroundings	Flood relics	Retrieved from "Topotijdreis: 200 jaar topografische kaarten" (n.d)
S11. Military items in surroundings		No indicators identified in the evaluated project area.
S12. Heritage in surroundings	Heritage	Retrieved from (Soepboer, 2018)
S13. Heritage site in surroundings	Heritage site	Retrieved from (Soepboer, 2018)
S14. Archaeological values in surroundings	Archaeology	AMK ("Archeologische Monumenten Kaart"), retrieved from (Soepboer, 2018)

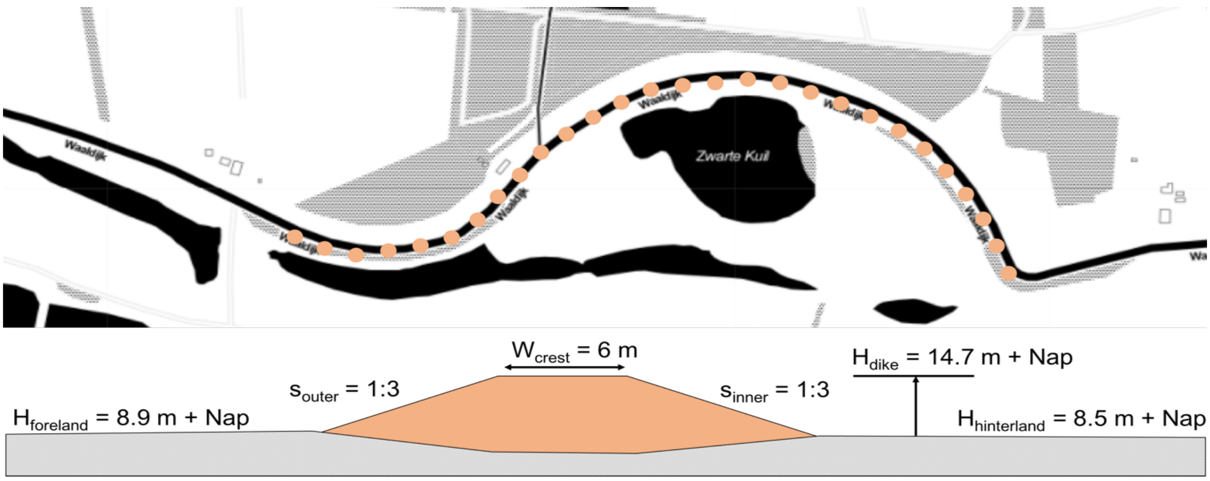


Figure 55: Characteristics of the existing dike

Figure 56: Characteristics of the project area

6.2.4. Step 4: Apply conceptual evaluation model

In the fourth step, information on the influence that the developed design alternatives (in Step 2) induce on the project area is retrieved by applying the model that is presented in Section 4.1. Required input for applying the conceptual evaluation model is retrieved from Step 3 (Section 6.2.3). The results of applying the conceptual evaluation model on the design alternatives of Dike Section 14 are explained in two phases. First, the effect of evaluating design alternatives resisting "inner slope stability" and "inner slope erosion is discussed. Subsequently, the influence of the piping measures is elaborated on.

Effect of design alternatives resisting "inner slope stability" and "inner slope erosion"

In Section 5.4. is explained that three reinforcement locations are considered in the application of the conceptual evaluation model, because the influence of the dike reinforcement is dependent on the location of the reinforcement with respect to the old dike. Therefore, the (in Step 2) created design alternatives that resist "inner slope stability" and "inner slope erosion" are projected on a reference point, to create outwards, centred, and inwards design alternatives. The resulting designs are shown in Figure 57, in which the design alternatives are illustrated with respect to the existing dike in the project area.

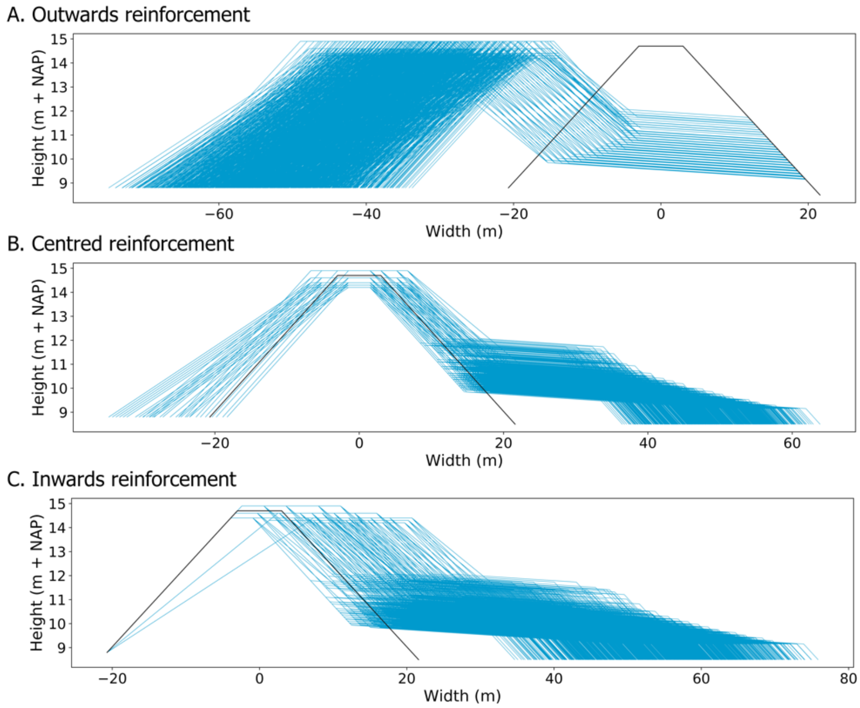


Figure 57: Design alternatives plotted relative to the existing dike (black line) in Dike Section 14

The design alternatives, illustrated Figure 57, are applied on the conceptual evaluation model to retrieve the chances to integrate functional characteristics within the new design, and to assess the effect on the functional characteristics of the surrounding area (Section 3.2). Information is retrieved from every single design alternative (blue line in Figure 57). Table 13 provides for every effect on the functional characteristics of the dike design the most positive and the most negative value observed in the evaluated design alternatives. These values indicate suitability of the design to include certain functional characteristics within the design of the dike reinforcement relative to the other evaluated designs. The most positive observed value of the measured effect has the most favourable influence to include or preserve a functional characteristic within the design. A similar table is provided to indicate the influence of the dike reinforcement on the functional characteristics in the surroundings of the dike (Table 14).

Table 13: Retrieved range of effect on functional characteristics of the dike

No.	Functional characteristic	Effect measured:	Most negative value:	Most positive value:	Dimension:
D1	Transportation on the dike	Traffic intensity (in crest scenario)	0	1	[-]
D2	Living on the dike	Space availability on inner berm	1.8 (=16 – 14.2)	20.8 (= 35– 14.2)	[m]
		Serviceability limit state	10	1	[l/s/m]
		Accessibility (in crest scenario)	0	1	[-]
		Comfort of the location (in crest scenario)	1	0	[-]
D3	Agriculture on the dike	Space availability on inner slope & Subsoil richness	3.9 (= (16 – 4)/3.1)	31 (= (35 – 4)/1)	[-]
		Accessibility (in crest scenario)	0	1	[-]
D4	Recreation on the dike	Availability for recreational infrastructure (in crest scenario)	0	1	[-]
		Recreational safety (in crest scenario)	0	1	[-]
		Comfort of the location (in crest scenario)	1	0	[-]
D5	Vegetation on the dike	Growth properties on outer slope (southern orientation)	3	5	[1:_]
		Growth properties on inner slope (northern orientation)	4	3	[1:_]
D7	Historical cross-section	Crest width (in crest scenario)	13.4	3	[m]
D8	Archaeology in dike	Preservation of dike core	35.2	144.2	[m^2]

Table 14: Retrieved range of effect on functional characteristics in the surroundings

No.	Functional characteristic	Effect measured	Most negative value:	Most positive value:	Dimension:
S1	Transportation on the river	Increased footprint of dike	-	-	-
S2	Living in surrounding area	Increased footprint of dike	1	0	[#]
		Safety feeling	10	1	[l/s/m]
		Comfort of the location (in crest scenario)	1	0	[-]
		Accessibility (in crest scenario)	0	1	[-]
S3	Agriculture in surrounding area	Increased footprint of dike	2.6	0.1	[ha]
		Ground water balance	-	-	-
		Accessibility (in crest scenario)	0	1	[-]
S4	Recreation in surrounding area	Increased footprint of dike	-	-	-
		Comfort of the location (in crest scenario)	1	0	[-]
		Accessibility (in crest scenario)	0	1	[-]
S5	Nature in surrounding area	Increased footprint of dike	9.0	3.4	[ha]
		Ground water balance	-	-	-
		Soil pollution in surrounding area	0	103.4	[m^2]
		Crest as animal barrier	1	0	[-]
		Comfort of the location (in crest scenario)	1	0	[-]
S7	Ground water balance	Influencing seepage flow	-	-	-
S8	Pollution in the surrounding area	Traffic intensity (in crest scenario)	1	0	[-]
S9	Soil pollution in surrounding area	Increased footprint of dike	0	103.4	[m^2]
S10	Flood relics	Increased footprint of dike	0.9	0	[ha]
S11	Military items	Increased footprint of dike	-	-	-
S12	Heritage structures	Increased footprint of dike	1	0	[#]
S13	Heritage sites	Increased footprint of dike	4.1	0	[ha]
S14	Archaeology in surrounding area	Structure in subsoil at archaeology	-	-	-
		Increased soil pressure	6.0	1.0	[m]
		Ground water balance	-	-	-

The ranges on the magnitude of the effect, provided in Table 13 and Table 14, are input for the next steps of the developed method. In Table 14 can be observed that no measure is provided on certain indicated effects. This can have two causes; the functional characteristic is not located within the surroundings of Dike Section 14 (in table: increased footprint on S1, S4, and S13), or the evaluated design alternatives do not interfere the subsoil by implementing structures (in table: “Structure in subsoil at archaeology”, and “Ground water balance”).

Applying the conceptual evaluation provides useful insights in the effect of the reinforcement assignment on the functional characteristics of the surroundings. Based on the information retrieved by measuring the effects of the increased footprint of the dike, boxplots can be provided describing the influence of location of the dike reinforcement relative to the existing dike in the project area. Evaluating the design alternatives and grouping the influence in outwards, centred, and inwards reinforcements provides the boxplots presented in Figure 58.

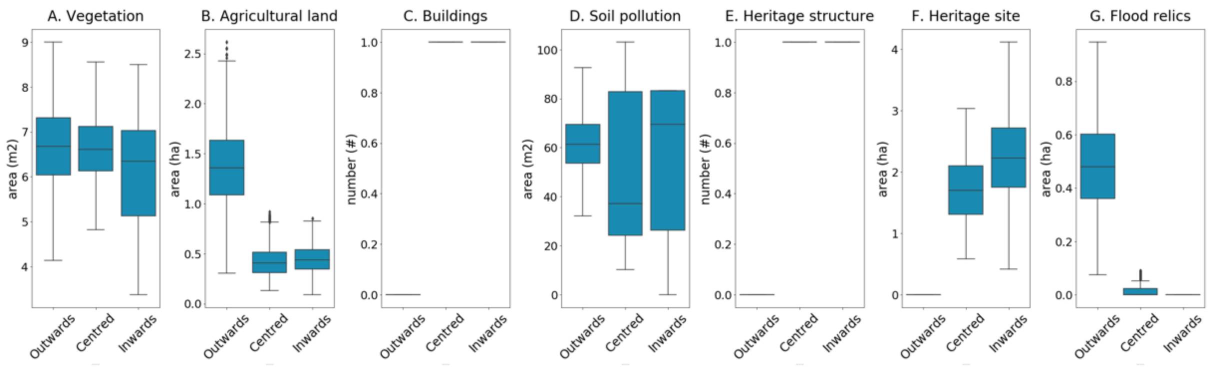


Figure 58: Influence of location relative to the existing dike in the project area

Observing Figure 58 provides insights in the influence of the location of the reinforcement. In Figure 58a and Figure 58d can be observed that the location choice of the dike reinforcement does not affect the magnitude of the influence largely. Nevertheless, it can be retrieved that the shape of design influences the magnitude of the effect largely for vegetation. The amount of interfered soil pollution in the project area is found to be relatively small.

It is found that the location choice for the dike reinforcement design is an important consideration for agricultural land and buildings within the project area (Figure 58b and Figure 58c). The amount of agricultural land interfered by the footprint is much larger for outwards reinforcements, than for inwards, and centred reinforcements. Nevertheless, it can also be observed that a large part of the agricultural land can be preserved in the case, that the footprint of the dike is minimized in an outwards reinforcement. For buildings of the project area can be observed that no range is found. Inwards and centred reinforcement result in demolishment of the buildings, while an outwards reinforcement preserves this building.

The influence of the location of the reinforcement on the cultural indicators of the project area, show a contradiction (Figure 58e, Figure 58f, and Figure 58g). It can be observed that, to preserve the monumental building in the project (heritage), an outwards reinforcement is required. But to preserve the pond in the project area (flood relics), it is required to do an inwards, or centred reinforcement of the dike. The observation states that within the evaluated reinforcement designs, it is not possible to preserve the complete existing culture historic situation. Meaning that either, the structural solution should be constructed (quay wall), or a part of the cultural values will be lost.

Remarkable is the shape of the “centred” box in the figure that indicates the effect on the elements of floods. It can be observed that the median is located on the same location as the bottom of the box. This means that at least fifty percent of the provided alternatives will not influence the historical pond of the project area, while constructing a centred reinforcement.

Effect of design measures to resist piping
In Step 2 (Section 6.2.2) is explained that piping measures leads to unrealistically large berm dimensions. Therefore, this piping berm is not considered to be a design solution in the project area. It is explained that relief wells, and sand-tight geotextiles are other solutions that were considered to increase the resistance against piping. The conceptual evaluation model has been applied on these two measures to indicate the different effects on the functional characteristics of the project area. Relief wells, and the sand-tight geotextile do not interfere with the geometry of the dike that provides resistance against the failure mechanisms "inner slope stability", and "erosion of the inner slope". The influence they induce on the project area focusses on the effect on the water balance and constructing in the subsoil.

Table 15: Rough assessment of piping measure in project area

No.	Functional characteristic	Effect measured	Relief well	Geotextile
S3	Agriculture in surrounding area	Ground water balance	Influenced	Not influenced
S5	Nature in surrounding area	Ground water balance	Influenced	Not influenced
S7	Ground water balance	Influencing seepage flow	Influenced	Not influenced
S14	Archaeology in surrounding area	Structure in subsoil at archaeology	Influenced	Influenced
		Ground water balance	Influenced	Not influenced

The difference on the influence on the functional characteristics induced by the geotextile and relief well, is found in the effect that the filter construction (relief well) has on the water balance. The filter structure will affect the flow from the river towards the hinterland of the dike (TAW, 1999), which can result in negative effects for agriculture, nature, and culture. It should be noted that the magnitude of the influence should be assessed by a subject expert. In addition, the danger for using the geotextile, is that it is a relatively new solution and the working of the method has some uncertainties (Van den Berg, 2013). Therefore, applying this measure has some risks.

Using the method to assess the piping solution does not express the advantage of the developed functional indicator model, because the design options are limited and could easily be reviewed by obtaining a study to discuss different solution types. This is different for providing resistance against erosion and stability of the inner slope, as there is a large variety of design alternatives providing the same safety. Therefore, in the remainder the application of the method, will be fully focused on evaluating the effect of geometrical design choices induced by the design alternatives provided in Figure 57. As the piping solutions do not interfere the functional characteristics of the dike (Table 13) and induce effect on the existing surroundings in only two manners, it is not useful to express the influence in a visualization.

6.2.5. Step 5: Relatively score retrieved effects & Step 6: Group the effects by themes

For illustration of the results, in Step 5 and Step 6 of the developed method, the retrieved measures on the functional characteristics (Table 13 and Table 14) are relatively scored and grouped by themes. It should be noticed that the effect of the piping measures is not included in the visualization of the effects. The identified effects on the functional characteristics in project area for reinforcing Dike Section 14 are grouped in the themes described in Section 5.6. The groups are created to reduce the overlap between identified effects, but provide a complete indication on the effect of a reinforcement design for a certain angle of approach. It should be noticed that also the considered effect for evaluation of Dike Section 12, and 13 are provided in this table as this makes the results easier interpretable. In Table 16 is illustrated which effects are included in the themes, and what the name is for the visualization of the results in Step 7. Names are changed, to enhance that a positive bar in the radar plot are always positive effects.

Table 16: Grouping effects on functional characteristics by themes

Effect	Name in visualization
Living	
Space availability on inner berm	1. Ability for housing on berm
Serviceability limit state	2. Serviceability of houses on berm
Safety feeling	3. Experienced flood safety
Accessibility (in crest scenario)	4. Accessibility of houses
Comfort of the location (in crest scenario)	5. Pollution minimization
Increased footprint of dike on buildings	6. Buildings preservations
Agriculture	
Space availability on inner slope & Subsoil richness	7. Berms ability for agriculture
Accessibility (in crest scenario)	8. Accessibility of agricultural land
Increased footprint of dike on agricultural land	9. Preservation of agricultural land
Nature	
Growth properties on outer slope (southern orientation)	10. Growth properties on outer slope
Growth properties on inner slope (northern orientation)	11. Growth properties on inner slope
Increased footprint of dike on soil pollution	12. Cleaned soil pollution
Crest as barrier for animals	13. Passage capability for animals
Comfort of the location (in crest scenario)	14. Pollution minimization
Increased footprint of dike on vegetation	15. Vegetation preservation
Culture	
Crest width (in crest scenario)	16. Historical cross-sectional shape
Preservation of dike core	17. Preservation of dike core
Increased footprint of dike on flood relics	18. Preservation of flood relics
Increased footprint of dike on heritage	19. Preservation of monuments
Increased footprint of dike on heritage sites	20. Preservation of monumental area
Increased soil pressure	21. Minimization of additional soil pressure
Recreation	
Availability for recreational infrastructure (in crest scenario)	22. Recreational infrastructure available
Recreational safety (in crest scenario)	23. Recreational safety on the dike
Comfort of the location (in crest scenario)	24. Pollution minimization
Accessibility (in crest scenario)	25. Accessibility of recreational areas
Increased footprint of dike on recreational area	26. Preservation of recreational areas
Transportation	
Transportation intensity	27. Transportation intensity on the dike
Increased footprint of dike on river	28. Minimizing dike on river

6.2.6. Step 7: Visualization of influence

Based on going through Step 1 till Step 6 of the developed method, a visualization can be created in Step 7 that illustrates the influence of a reinforcement design on the functional characteristics of the project area relative to all other design alternatives. An example of a visualized design alternative is provided in Figure 59. The evaluated design alternative has the characteristics that are presented in Table 17. The figure provided three separate plots; a cross-sectional representation of the reinforcement, a top view of the project area, and a radar plot. The radar plot expresses the score of the evaluated reinforcement on the functional characteristics of the project relative to all other design alternatives (illustrated in Figure 57). A visualization, such as Figure 59, can be automatically created for every evaluated reinforcement design. In the remainder of this section is explained which information can be retrieved from the provided visualization.

Table 17: Technical characteristics of evaluated design in Figure 59

Name	Unit	Target image
Outer slope (s_{outer})	**[1:_]**	3
Critical Overtopping discharge (q_c)	**[l/s/m]**	10
Crest width (W_{crest})	**[m]**	13.4
Inner slope (s_{inner})	**[1:_]**	3
Berm width (W_{berm})	**[m]**	23
Reinforcement location	**[-]**	inwards

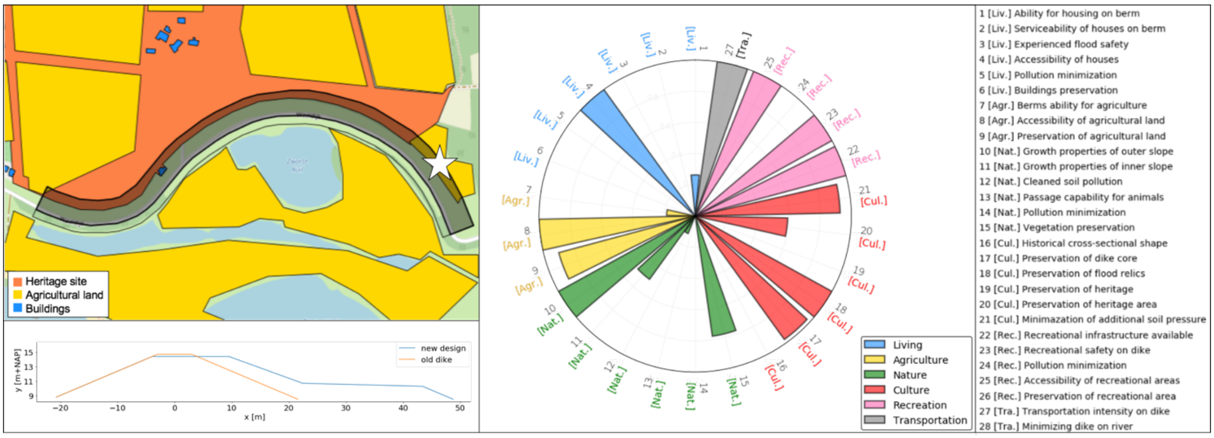


Figure 59: Influence of a random geometry on the functional indicators of the project area

Figure 59 represents a top-view illustration of the design alternative within the project area (top left). In this top-view, the location of the reinforcement design (illustrated in black) is shown relative to the spatial reference scenario as created in Step 3. Information on the effect of a design alternative on the existing situation of the project area can be retrieved from this illustration. It can be thought of assessing whether residual areas provide suitable conditions for effective use of the project area. For example, a small agricultural area is located at the white star within the top-view. The effect of the considered design alternative is a reducing size of this area, causing an illogical residual shape. It should be assessed whether this shape is still suitable for performing agriculture. This is also dependent on the properties of the dike to combine flood protection with agriculture on the stability berms. Therefore, below the top-view representation, a cross-sectional representation of the reinforcement design is plotted relative to the existing dike in the project area. The panels illustrating the cross-section, and top-view of the dike can be used to qualitatively assess the influence of a dike reinforcement on the project area. Third, a radar plot is provided that compares the evaluated design alternative to the other verified design alternatives in the project area.

This section focusses on the data that can be retrieved from the radar plot. This plot represents the influence of a dike reinforcement on the existing functional characteristics in the surroundings, and identifies the suitability of the dike to introduce new functional characteristics within the design. The radar plot includes effects that were identified within the project area for which different measures are retrieved (in the application of the conceptual evaluation model) within the evaluated designs. Two effects that do not meet these two conditions are "26. Preservation of recreational areas", and "28. Minimizing dike on river". There are no recreational areas located within this section, and the dike has such a large foreland, that it will not interfere the waterway for transportation purposes in case of an outwards reinforcement (note that the numbers are indicated in the legend as this are elements applicable for Dike Section 12, and Dike Section 13).

The themes created in Step 6, can directly retrieved by means of the colour in the radar plot. A first impression can be retrieved on the influence on the different themes. In Figure 59 can be observed that there is almost no blue colour plotted, this indicates that the influence of this particular design alternative compared to others is quite negative. On the other hand, is observed that transportation and recreation within the project area score relatively good (many full scale bars are observed). Comparing the themes results in points of attention, which can be focused on in the further evaluation of the radar plot.

After the rough comparison between the different themes, the effects that the design alternative induces is studied in more detail. It can for example be focussed on agriculture in the project area (yellow bars in Figure 59). Three effects are indicated with a relative score; ability to perform agriculture on the berm, accessibility of the agricultural land, and the preservation of the agricultural land. In this stage, should be determined what the importance of the individual expressed effects is. This is dependent on the composition of a specific project area. For example, it is not efficient to construct a stability berm which provides space for agriculture, when on the hinterland side of the dike no agriculture is located. Also, it can be questioned whether the agricultural land requires accessibility by a road within the cross-section of the dike. A road could be located somewhere else within the project area. The user of the visualization (of the developed method) can, based on the composition of the project area, determine which effects are valued. Retrieving data from radar plot provides the information to assess whether the induced influence by a design alternative leads to satisfying result in the project area. The influence on the other themes can be retrieved in a similar manner as explained for agriculture. When such analysis is done for every theme, the influence of a design alternative on the existing situation in the project area can be assessed relative to the other design alternatives. Evaluating multiple designs within a project team provides a framework to discuss the desirable influence of a dike reinforcement on the project area. In Section 6.3 is explained how the outcome of the method can be used to include the influence of a design alternatives in early stages of a dike reinforcement project.

6.3. Application of the method within dike reinforcement project in rural areas

In this section is explained how the visualization of the developed method can provide new insights for the discussion and selection of design alternatives for dike reinforcement projects in rural areas. Three possible applications of the model are discussed in this section; using the method to assess the vision of the landscape architect (Section 6.3.1), using the method for illustrating the effects of changing requirements (Section 6.3.2), and using the method to make the stakeholder or subject expert a designer (Section 6.3.3).

6.3.1. Assessing the vision of the landscape architect

The value of applying the method in dike reinforcement projects is found in the large variety of design alternatives that is assessed on the influence on the functional characteristics of the project area. As explained in Section 1.2, in the current dike reinforcement project, the vision on design alternatives is largely dependent on the landscape vision and technical vison on the project. Afterwards, the influence on the functional characteristics of the project area can be included. Using the method in this stage, provides the possibility to include the effect on the functional characteristics of the project area before the vision of design alternatives. One application of the (visualization of the) method is to review effects of the desirable landscape vision on the reinforcement design. In this section is evaluated what the effect of applying the landscape vision is for Dike Section 14.

In early phases of the project “Wolferen-Sprok”, a target design has been formulated for the project. This target image focusses on retaining the typical character of the project area (mainly focusing on the aesthetics). Soepboer (2018), explains that the desired design of the dike reinforcement in the project area is a continuous ribbon through the project area. It is aimed to maintain the existing dike core throughout the project area. Furthermore, it is desired to construct slope angles of 1:3 (vertical : horizontal) in the cross-sectional design. For the design of the stability berm it is aimed to create a berm that smoothly evolves in to the ground level in the hinterland. Besides the smooth transition, the ambition is set that the stability berm has a secondary function, up to the toe of the dike core. Together this results in the design goals as presented in Figure 60.

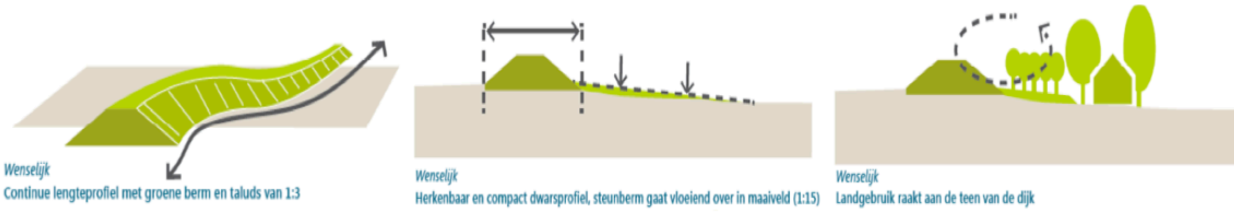


Figure 60: Target design for implementation of reinforcement design in project area (source: Soepboer, 2018)

Table 18: Design dimensions of target image

Name	Unit	Target image
Outer slope (s_{outer})	**[1:_]**	3
Critical Overtopping discharge (q_c)	**[l/s/m]**	5
Crest width (W_{crest})	**[m]**	6
Inner slope (s_{inner})	**[1:_]**	3
Berm height (H_{berm})	**[m]**	1
Reinforcement location	**[-]**	inwards

To evaluate the effect of the target design (illustrated in Figure 60) on the functional characteristics of the project area, it is assumed that the target design has the cross-sectional properties as presented in Table 18. The critical overtopping discharge of the target design is set to 5 l/s/m, which is retrieved from Van den Akker, Buckers, & Drost (2018). Inserting the design characteristics of Table 18 in the visualisation of the method provides Figure 61.

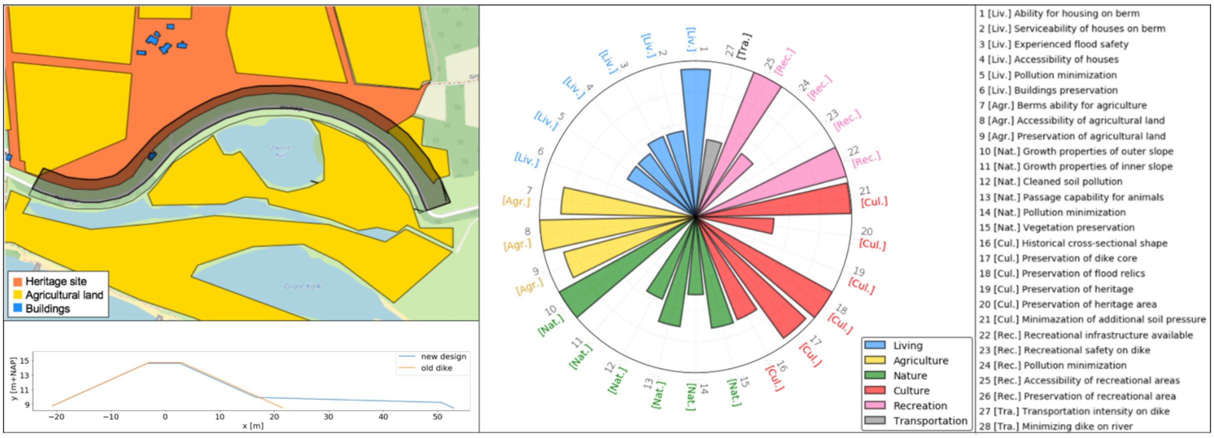


Figure 61: Influence of target design on functional indicators in project area

Observing the results of evaluating the target design, provides insight in positive and negative influences that the design alternative induces. First of all, it can directly be observed that the design alternative scores quite good in the category agriculture; the footprint of the dike only has a small interference with the agricultural land, the agricultural land is accessible from the dike, and the stability berm provides space to use it for agricultural purposes (Number 7). Nevertheless, it is questionable whether agriculture on the stability berm is an interesting chance for this project area, because only a small part of the agricultural land is located in the hinterland close to the dike (observed in the top-view of the project area).

From the figure is also observed that one monumental building, is located within the new cross-section of the dike (Number 19). Due to the large stability berm, it might be possible preserve the building, by doing a jack-up operation (*opvijzelen in Dutch*). In this way the indicated large negative impact on “Building preservation” (Number 6 in radar plot) and “Preservation of monuments” (Number 19), changes from the most negative to the most positive value. When this operation is performed, it could be found that the score on the cultural characteristics in the project area is relatively large with respect to other designs. Only the interference with the heritage side located in the hinterland is quite large (Number 20), and the crest width is not minimized. It is questionable whether minimization of the crest width is realistic, because the dike loses the traffic function in that case. Nevertheless, it remains a design choice to construct a road on the dike.

It seems that the influence of the reinforcement on the nature in the project area is quite large. The growth possibilities on the outer slope are maximized (Number 10), but other effects on nature in the project area is relatively negative; the growth possibilities on the inner slope are not maximized (Number 11), and the nature area interfered with is quite large (Number 15). It is the question for the ecologist, whether the interference with the nature area is indeed destructive for the nature function in the project area. An improvement compared to the old situation is achieved by cleaning a part of the bottom contamination (about 50 m^2).

The influence of the dike reinforcement design on the recreation and transportation is not changed compared to the old situation, a road is located on the crest of the dike, creating certain recreational and transportation capabilities. This is also indicated in the radar plot.

6.3.2. Illustrating the effect of setting additional or changing requirements to the design

In the previous section, it is discussed what the effect on the functional characteristics of the project area is when the landscape vision on the reinforcement project is evaluated. However, blindly following the prescribed vision of the architect could result in inconvenience for stakeholders. Adding or changing requirements might be desirable. In Step 7 of the developed method, it is easy to adapt characteristics of the evaluated design alternative and it can directly be observed how the influence on the project area of the dike reinforcement design changes. In this section an example is given, that illustrates the effect of changing requirements in the project area.

In Section 6.3.1 is found that the target design (from landscape vision, Figure 61) showed some inefficiencies in the category “Nature”. To increase the natural properties of the project area, it might be valuable to consider fading of the inner slope to a slope of 1:4. Also, it was identified the jacking up of a house might be a realistic alternative to preserve a monument, and maintain the living function, without having to consider an outwards reinforcement (which does not fit in the target image). For the serviceability of the house constructed on the berm, it is favourable to decrease the overtopping discharge to 1 l/s/m. The evaluated geometries that illustrates the effect of the additional requirement are set in Table 19.

Table 19: Input geometries to evaluate the effect of setting additional requirements

Name	Unit	Target image	Target image with additional requirements
Outer slope (s_{outer})	**[1:_]**	3	3
Critical Overtopping discharge (q_c)	**[l/s/m]**	5	1
Crest width (W_{crest})	**[m]**	6	6
Inner slope (s_{inner})	**[1:_]**	3	4
Berm height (H_{berm})	**[m]**	1	1
Reinforcement location	**[-]**	inwards	inwards

The effect of setting the extra requirements to the geometry of the dike results is illustrated in Figure 62. As expected, the changing requirements lead to a positive effect on “Serviceability of houses on berm” (Number 2), “Experienced flood safety” (Number 3), and “Growth possibilities on the inner slope” (Number 13). It can also be observed, changing the design parameters for the overtopping discharge, and inner slope angle, does not have a large reducing effect on other functional characteristics of the project. Observing the two figures, directly provides the user of the model information, on whether changing design parameters leads to a desired outcome for the design.

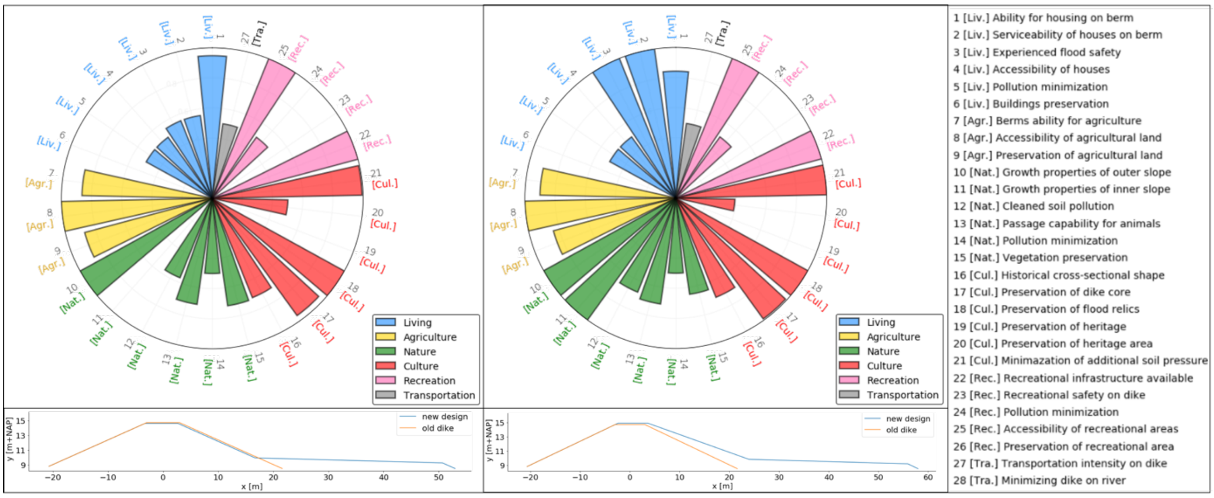


Figure 62: The effect of changing and setting additional requirements

6.3.3. Making the subject expert/stakeholder a designer

Traditionally, the specialist on specific topics (for example: Nature, Culture, or Recreation) are in the design process mainly used to reflect on the provided design, created by a landscape architect and an engineer (TAW, 1994b). In the previous sections is shown how the landscape vision on the project area, effects the functional characteristics of the project area. Applying the developed method provides possibilities to instantly adapt the design, and assess the differences on the expressed effects. Iterations provide the possibility to create a design which is desirable for (most of) the stakeholders in the project.

Applying the method on a dike reinforcement project also provides the possibility to do reversed engineering. The specialist can retrieve a design alternative based on the desired influence on the functional characteristics of the project area. This means that an expert will not have to set the technical design parameters of the dike to design the dike reinforcement that is desirable from the experts' perspective. The design follows from fixing the observed effects induced by a design alternative to a desired value. In this section is explained how different angles of approach can provide a design with help of reversed engineering.

A target influence is created for the themes agriculture, nature, culture, and living. It should be noted that this is a hypothetical target image, because specialist on the topics should weigh the importance of the presented effect on the functional characteristics of the project area. No target design is prepared for recreation and transportation, because setting a target design based on the influence on the functional characteristics of these themes allow many degrees of freedom in the geometrical design. Nevertheless, it's also possible to search for design alternatives having certain properties on the influence on these themes.

Agriculture
For agriculture, it is aimed for maximum preservation of the agricultural land, while the land is accessible by a road constructed on the dike. The multi-functional use of the inner berm is initially not considered, because only a small amount of agriculture is located on the hinterland side of the dike. Setting these two requirements for agriculture leads to the design as presented in Figure 63. In the figure can be found, that setting these requirements, leads to a design which scores quite good for culture as well. The influence on nature, and living is expected to cause larger inconvenience for stakeholders interested in these topics.

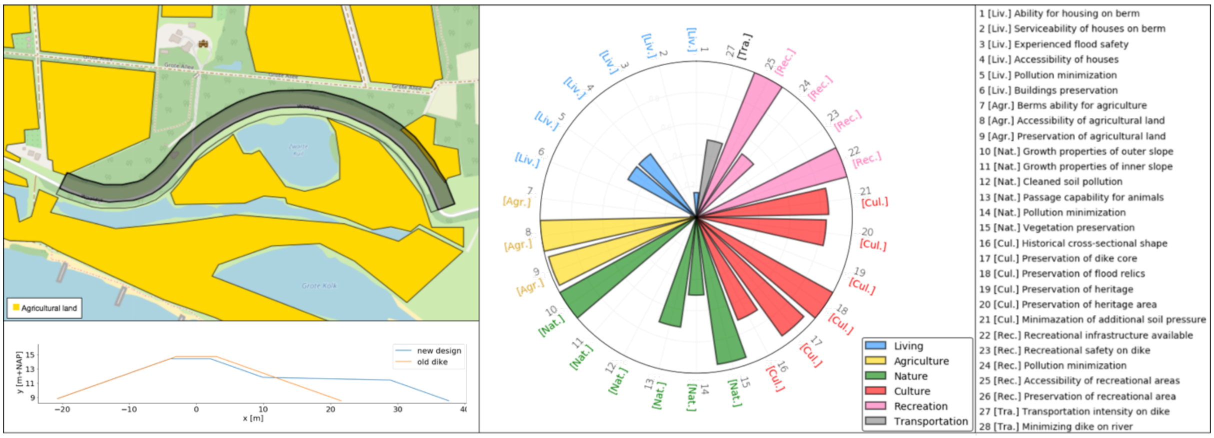


Figure 63: Target design for agriculture

Nature

A convenient influence of the reinforcement project on the topics nature, is assumed to have five specific characteristics. The design of the reinforcement consists of maximum growth properties on the inner and outer slope, and a safe passage for animals over the crest of the dike. Also, it is aimed to minimize the pollution in the project area, and to preserve the largest amount of vegetation (taking into account the earlier set requirements). The resulting design is shown in Figure 64. Bottom contamination is not set as a requirement, because the amount of bottom contamination within the considered section is small. Since, in this project area, cleaning bottom contamination is contradicting with preservation of nature, it is assumed that preservation of nature is more important to create a comprehensive design from ecological perspective.

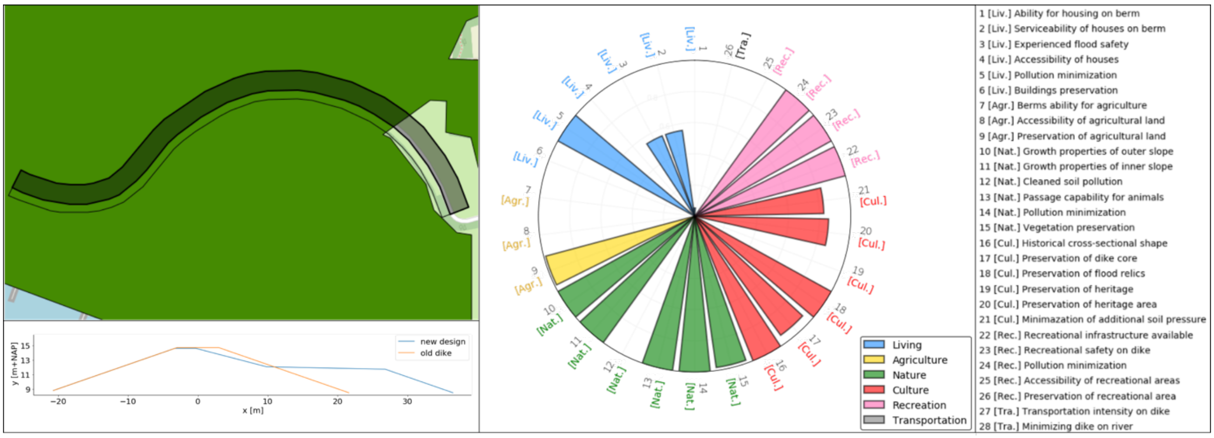


Figure 64: Target design for nature

In Figure 64, can be found that the target design for nature, results in demolishing the road, providing a negative effect for transportation, living, recreation, and agriculture. Whether the effect on recreation is positive or negative is dependent on the wishes on accessibility of recreational areas. When this is not needed, the effect on recreation is assumed to be positive. It can also be remarked, that the target design for nature, does not lead too large in efficiencies in culture.

Culture

Reviewing the effect on "Culture" shows that a choice should be made between, constructing in monumental sites, or constructing in a pond (Figure 58). A specialist should determine the preferred alternative from cultural point of view is. The contradiction between the location of the pond, and the heritage site is expressed by creating two design alternatives for the theme culture. The first design, focusses on creating a historical cross-sectional shape, that preserves the pond (indicators of floods), while the core of the dike is maximally preserved, and the additional soil pressure is minimized. The results can be found in Figure 65. It is found, that the retrieved design combines relatively good with the influence on the themes “Nature” and “Living”.

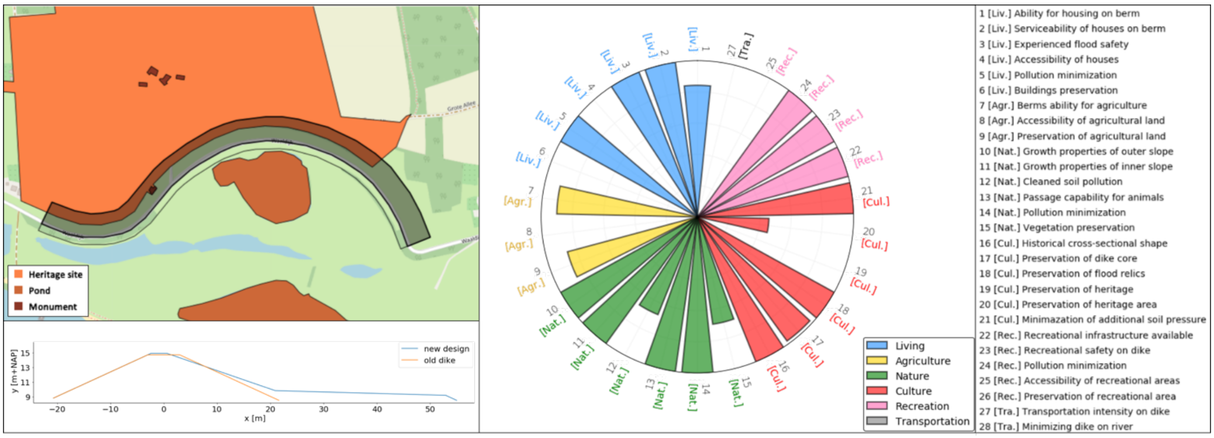


Figure 65: Target design 1 for culture

The second normative design, also consists of a maximum historical cross-sectional shape, that aims for maximization of the dike core. The design of the dike should be defined in such a way, that the monumental area and monumental building are preserved. In Figure 66, the second target design has been presented. Compared to the design presented in Figure 65, it can be found that this topic scores generally worst on nature, while the influence on living is completely different.

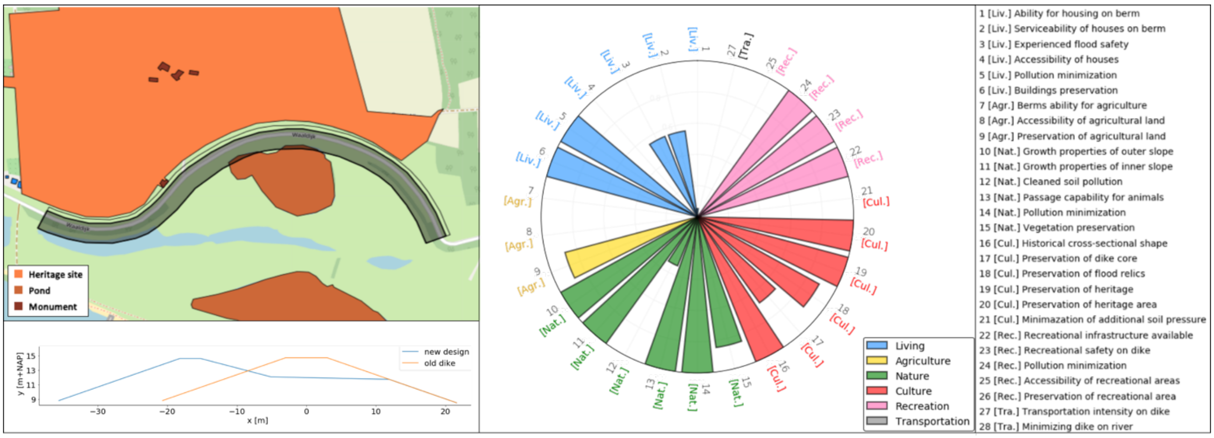


Figure 66: Target design 2 for culture

Living

Lastly, a target design is created for the theme “Living”. This design focusses, on preserving the buildings in the project area, and maximizes the experienced safety behind the dike. It is chosen to construct a low traffic intensity road on the dike to create accessibility for the houses, but limiting the pollution. The corresponding design is shown in Figure 67.

The resulting design, as presented in Figure 67, shows that setting the target design for living, results in relatively large (negative) effect on the nature in the project area. It is also observed that influence, that the design initiates on agriculture, is generally positive when multi-functional berm use is not an ambition (Number 7). An outwards reinforcement is not necessarily devastating for agricultural function in the project area (Number 9).

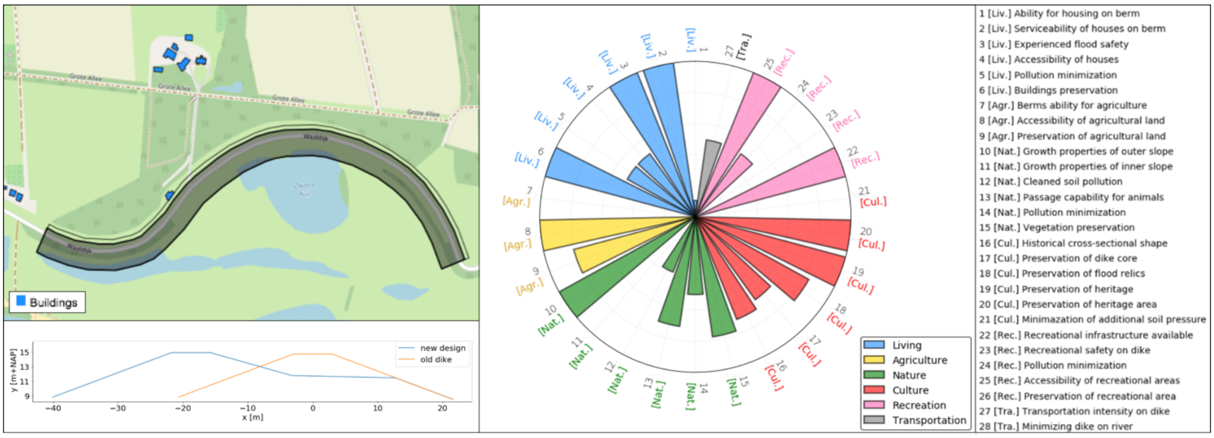


Figure 67: Target design for living

Using the developed method, provides the possibility for subject experts to develop a vision on the dike reinforcement project, without requiring knowledge on the safety issue and design options. Differences between the different angles of approach on the desired design alternative are retrieved from comparing the influence of the cross-sections on the functional characteristics of the project area (Figure 63 to Figure 67). The different designs can be a starting point for the discussion, in which the subject experts already assessed which characteristics of the project area are valued from their perspective.

6.4. Limitations of the method within dike reinforcement projects in rural areas

Applying the method in a case study, also results in the observation on limitations for using the model. Three types of limitations are identified; the design options are limited, automated optimizations result in inconvenient outcomes, and the accuracy of the outcome is rough. In this section it is per limitation, explained how it could induce undesired project results.

6.4.1. Considered design options

The results of the developed method only provide the effect for dike reinforcement options that are constructed completely in soil within a specified range of geometrical dimensions. Since, customized (structural) solutions are not considered in the method, the user of the model should be aware of other technical design solutions. The outcome of the method can then be discussed, and potential mitigating solutions can be suggested to create a more desirable results. An example, on how the model can be used in combination with customized technical design measures is explained in Section 6.3.1 (Assessing the vision of the landscape architect). The discussed influence on the functional characteristics of the project area, is first evaluated. Afterwards, it is determined which customized possibilities there are to mitigate the negative influences. Applying the method in that case helps, identifying the location, which requires specific attention. Nevertheless, when these additional technical options are not considered, a reinforcement design might be created which not optimally exploits the chances within the project area.

6.4.2. Accuracy of the results

Secondly, it should be remarked that the outcome of the model is a rough indication on the effects on the functional characteristics related to the increased footprint of the dike. The calculation on the overlapping areas induces some error, because in this calculation it is assumed that the existing (normative) cross-section of the dike in a project area has the same geometry throughout the section. This is not necessarily true, as settlements and height differences within a dike section are not considered within the method. A second example is provided by buildings constructed close to the dike. A building (constructed close to the dike) could be constructed on a higher ground level, to allow sufficient space for future dike reinforcement projects. As only a normative existing dike geometry is included in the method, it might cause that the model indicates that the house is located within the footprint of the design alternative. A demolishment of the building is then unjustified indicated in the model.

6.4.3. Automated optimizations

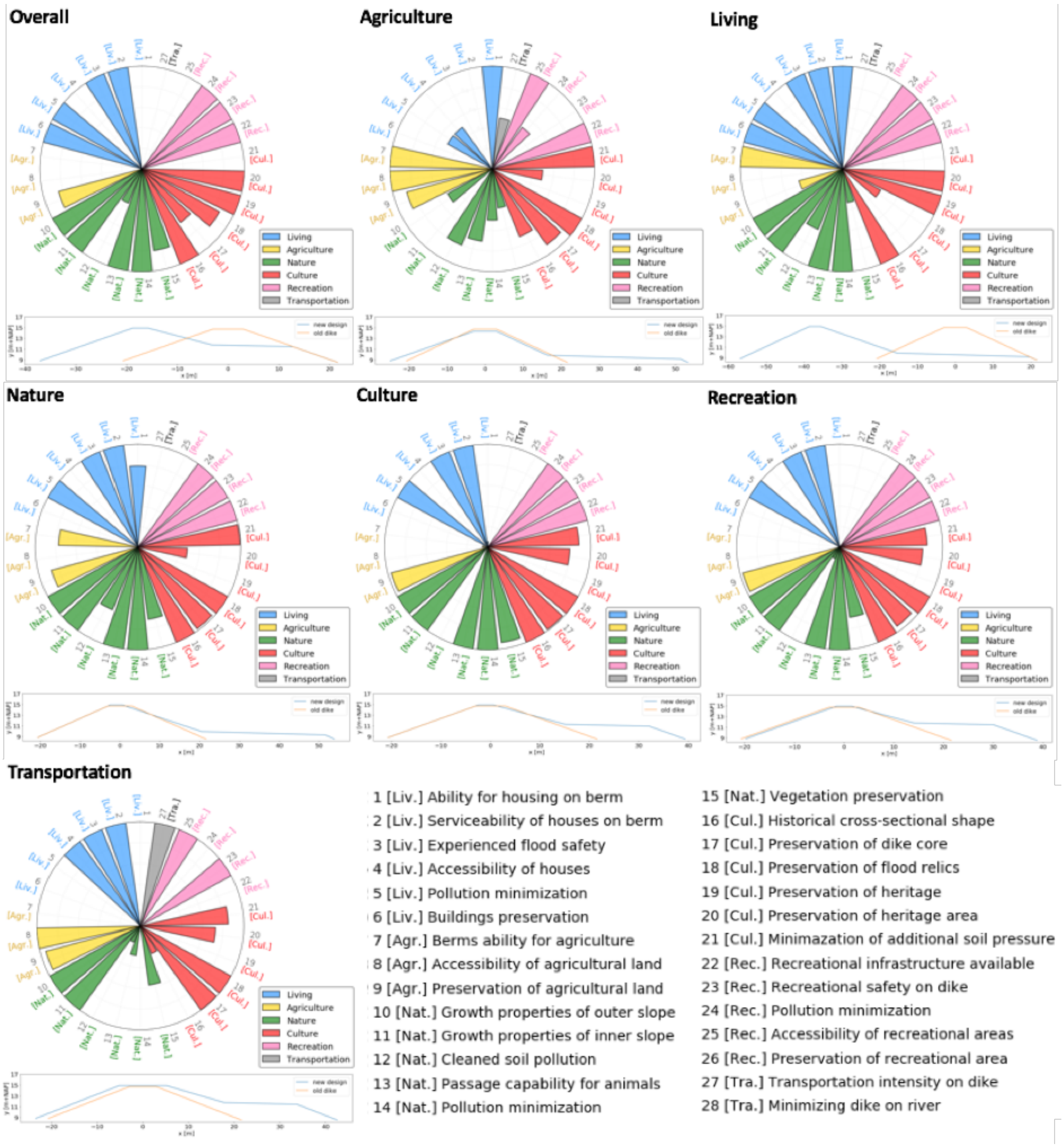


Figure 68: Results of automated optimizations on the different topics

The third limitation, is found in creating optimized geometries without studying the importance of the indicated effects on the functional characteristics (of a theme). An automated optimization on a certain topic can result in an inconvenient design on that topic, due to contradictions within the topic. With automated optimizations is meant, that the model gets the task to find the largest value for the sum of the relative impacts on a certain topic. The outcomes of the blind optimization runs are presented in Figure 68.

An automated optimization, that searches for the largest value of all effects (plot: “Overall” in Figure 68), is found to be a dike without a road located within the cross-section of the dike. It is expected that the resulting design alternative leads to large inconvenience, because accessibility over the dike is lost. It is concluded that optimizing on all indicators, leads to a design which does not pith the matter on the right effects induced on the functional characteristics of the project area. This is also something which can be observed in the plot “Nature”. It is found that the amount of soil pollution in the project area was not very large, while the nature area in the project area is very large. It is therefore, more logical to focus fully on preserving nature. For “Culture” can be observed, that the specialist is not able to study the importance of the effects induced on culture, the software of application makes an automated choice. This undesirable outcome is prevented when carefully studying the influence of the reinforcement design on the project area.

In the previous paragraph is explained that automated optimization results in geometries that give too much value to effects of small importance. A second danger of such optimization, is that there can be multiple geometries providing desired effects on the project area. Best example of this effect is found in the optimized results of “Transportation”. In fact, optimizing on transportation only sets a requirement to the crest width (leaving several possibilities to fluctuate in outer slopes, inner slopes, overtopping discharges, and berm designs). The model automatically provides a solution that fulfils the set requirement, leaving more than 2.000 geometries undiscussed. This induces wrong choices, when subject experts are tenacious on “their” target design.

6.5. Comparing locations

In the previous sections is explained what insights are retrieved while applying the method on the dike reconstruction in section 14. The method is also applied to illustrate the influence on the functional characteristics, when designing to reinforce Dike Sections 12, and 13 (in the project area “Wolferen-Sprok"). In this section it is evaluated, what additional insights this provides for using the developed method.

To retrieve additional insights, first the safety issue per dike section is identified (Step 1 of the method). Based on the parameters provided in Table 19, and the schematization assumptions provided in Appendix D, a measure is retrieved to indicate the safety problems per dike section. Evaluating these measure (presented in Table 21), results in the finding that the safety issue for the three sections is similar. The main problems are inner slope stability and piping, while the height of the dike is sufficient to resist erosion of the inner slope. For more information on the interpretation of the numbers presented in Table 21 is referred to Section 6.2.1 and Appendix D.

Design alternatives are created to decrease the probability of failure of the dike sections (Step 2 of the method). It should be noted that Piping is not considered in the evaluation of alternatives (explained in Section 6.2.4). The considered design variations, provided in Table 22, are used to create the design alternatives per dike section. These design alternatives are illustrated in Figure 71. In addition, a spatial reference scenario is shown in Figure 72. This scenario is based on data retrieved from sources as explained in Table 12. The developed design alternatives and spatial reference scenario are input for the application of the conceptual evaluation model (Step 4). The measured effects of Step 4 are similar as provided in Table 13 and Table 14. Only effects related to the footprint of the dike differ per dike section. This is illustrated in Figure 73. Boxplots per dike section (and reinforcement location) are provided to illustrate the influence of all design alternatives on the functional characteristics related to the footprint of the dike.

Step 1: Identify safety problem

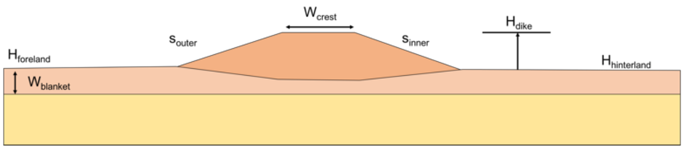
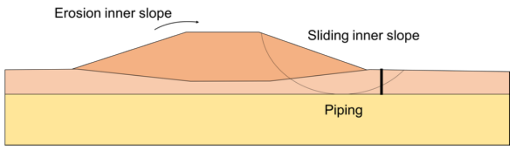


Figure 69a: Design parameters



69b: Failure mechanisms

Table 20: Geometrical parameters of the existing dike

Dike parameter	Unit	Dike Section 12	Dike Section 13	Dike Section 14
Outer slope (s_{outer})	[1:_]	3	3	3
Crest height (H_{dike})	[m + NAP]	15.2	15.1	14.7
Crest width (W_{crest})	[m]	6	6	6
Inner slope (s_{inner})	[1:_]	3	3	3
Thickness blanket ($W_{blanket}$)	[m]	5.7	5.8	3.6
Height foreland ($H_{foreland}$)	[m + NAP]	8.9	9.8	8.9
Height hinterland ($H_{hinterland}$)	[m + NAP]	9.1	8.9	8.5

Table 21: Identified safety issues

Failure mechanisms	Unit	Dike Section 12	Dike Section 13	Dike Section 14
Erosion inner slope	q_c [l/s/m]	5	5	5
Inner slope stability	SF [-]	0.63	0.77	0.69
Piping				
- Uplift	SF [-]	0.87	0.89	0.47
- Heave	SF [-]	0.33	0.32	0.17
- Piping	SF [-]	0.54	0.54	0.45

Step 2: Generate design alternatives

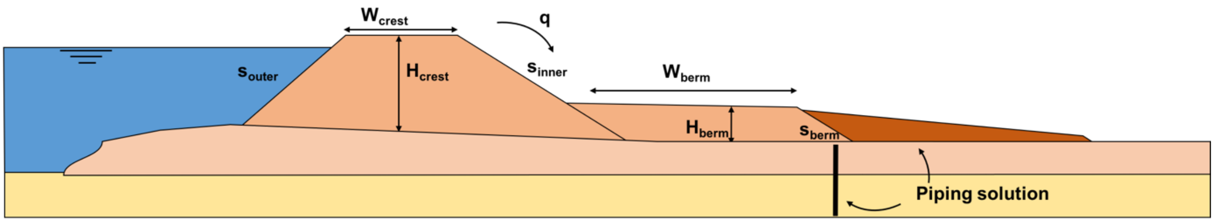


Figure 70: Design parameters for dike reinforcement

Table 22: Design variations per dike section

Name	Unit	Variations Section 12	Variations Section 13	Variations Section 14
Outer slope (s_{outer})	**[1:_]**	3, 4, 5	3, 4, 5	3, 4, 5
Overtopping (q_c)	**[l/s/m]**	1, 5, 10	1, 5, 10	1, 5, 10
Crest width (W_{crest})	**[m]**	3, 6, 10.4, 13.4	3, 6, 10.4, 13.4	3, 6, 10.4, 13.4
Inner slope (s_{inner})	**[1:_]**	3, 3.5, 4	3, 3.5, 4	3, 3.5, 4
Berm width (W_{berm})	**[m]**	20, 38, step size = 1	20, 40, step size = 1	15, 35, step size = 1
Berm height (H_{berm})	**[m]**	1, 4, step size = 0.1	1, 4.5, step size = 0.1	1, 4, step size = 0.1
Piping solution		Not considered (explained in Section 6.2.4)		
Failure budget (w)	**[-]**	$w_{erosion}$=0.24, $w_{stability}$=0.04	$w_{erosion}$=0.24, $w_{stability}$=0.04	$w_{erosion}$=0.24, $w_{stability}$=0.04

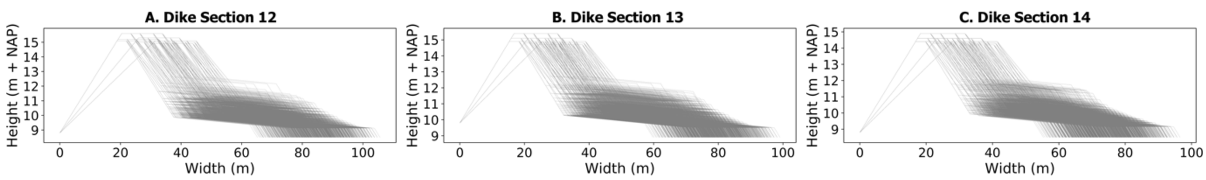


Figure 71: Design alternatives to reinforce Dike Section 12, Dike Section 13, and Dike Section 14

Figure 72: Reference situation

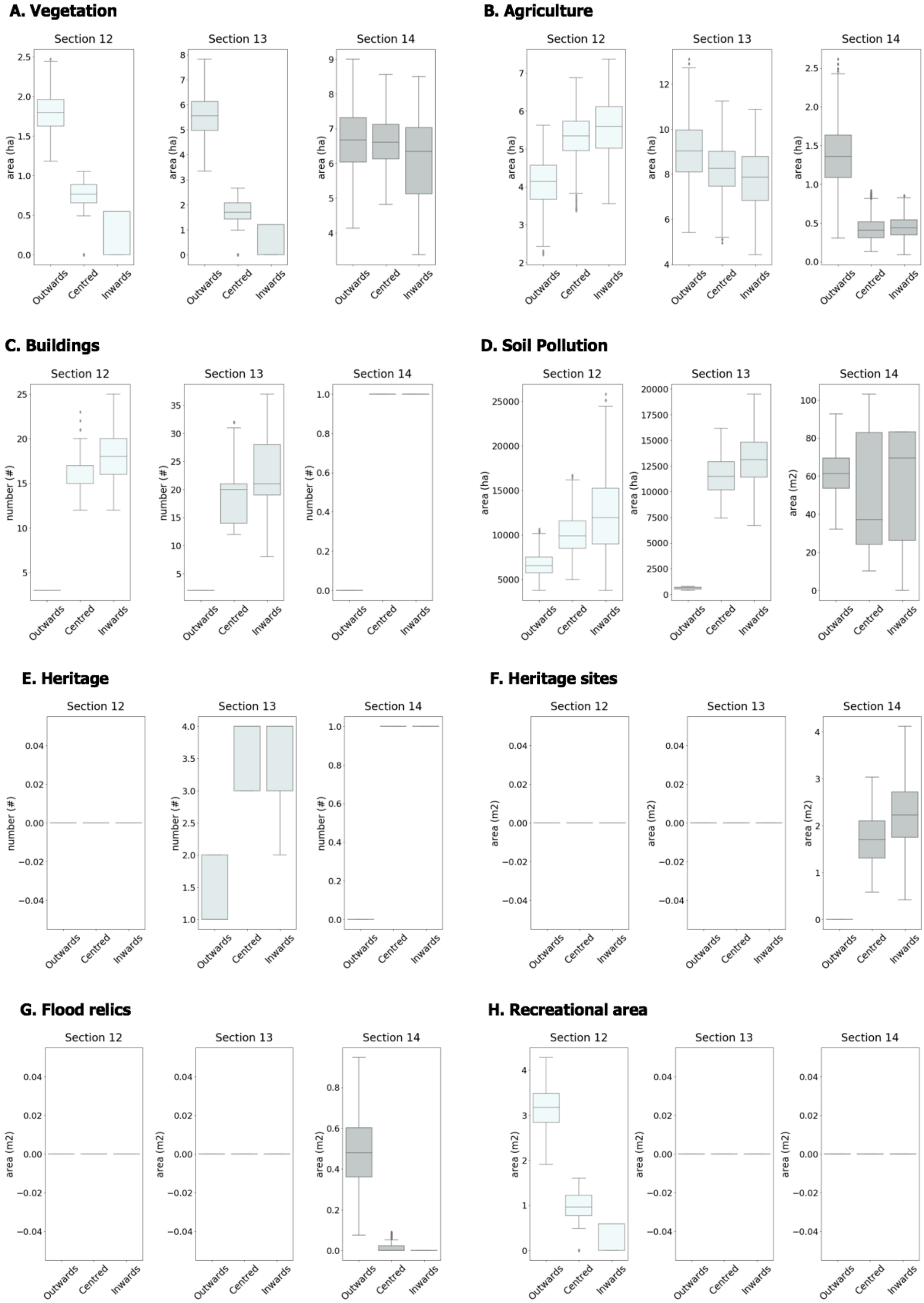


Figure 73: Influence of location of design alternative per dike section

In Figure 73 is observed, that every dike section has its own characteristics. For example, Dike Section 12 is the only section in which the design alternatives interfere with a recreational area. It is also found that the design alternatives do not interfere with physical cultural elements (heritage, heritage area, or flood relics). This is completely different for section 14, in which all these cultural elements are found in the spatial planning. The differences between the sections, make it necessary that a different focus is required to design a solution which is suitable for most stakeholders and subject experts.

Besides the occurring functional characteristics in the project area, it is (in Figure 73) also observed that the magnitude of the influence is different for every studied dike section. The best example is provided by the influence on the soil pollution in the project areas. Influence on the soil pollution in Dike Section 14 is very small when it is compared to the influence on the soil pollution in Dike Section 12, and Dike Section 13. Furthermore, also the location of the functional characteristics relative to the dike can be retrieved from the provided boxplots. For example, the location of the Nature Network Netherlands (Figure 73a), within the project area is relatively independent on the location of the reinforcement design in Dike Section 14. This does not hold for Dike Section 12, and Dike Section 13, in which it is preferred to construct an inwards reinforcement to preserve the vegetation in the project area.

After applying the conceptual evaluation model (Step 4), the retrieved information is relatively scored (Step 5), and divided in themes (Step 6). Based on this information the influence of a design alternative on the functional characteristics of the project area is expressed relative to the other considered design alternatives (Step 7). In this section, the differences between dike sections are retrieved by evaluating three scenarios; the implementation of the landscape vision, an agricultural target design, and a target design for nature;

- landscape architect's design: as provided in Table 18.
- agricultural target design: preserves the maximum amount of agricultural land in the project area, under the condition that the agricultural land is accessible by a road over the dike.
- natural target design: preserves the maximum amount of vegetation in the project area, in a design which has a steep outer slope, and a shallow inner slope.

The resulting effects on the functional characteristics for the evaluated scenarios are presented in Figure 74, Figure 75, and Figure 76. These figures show the relative score of the reinforcement design of the magnitude effect on the functional characteristics of the project area. In these figures, the light grey bars, indicate effects which are not identified in the evaluated project area. When reviewing the influence of the target designs, it is observed that inwards design alternatives are, in the three considered scenarios, most favourable in eight of the nine cases. It should be noted that this can be completely different when other scenarios are considered.

In the provided radar plots is observed that target designs (per dike section) have a very similar influence on the functional characteristics in the project area (when only topics are evaluated that occur in every section). This is mainly caused by the functional characteristics that are coupled to the cross-sectional design of the dike. However, an important observation is made when reviewing effects of a design alternative related to the footprint of the dike. This observation is explained based on Figure 74. Implementing the landscape vision as a design alternative, results in the observation that "6. Buildings preservation" is influenced negatively for every considered dike section. The boxplots in Figure 73c, express that the amount of buildings potentially demolished in a dike reinforcement project, is much larger for Dike Sections 12, and Dike Section 13, compared to Dike Section 14. It is treacherous, that the magnitude of the observed effect cannot directly be retrieved from the provided radar plots. Therefore, the user of the model should be aware of the magnitude of the effect before adding value to a scale bar in the provided radar plots.

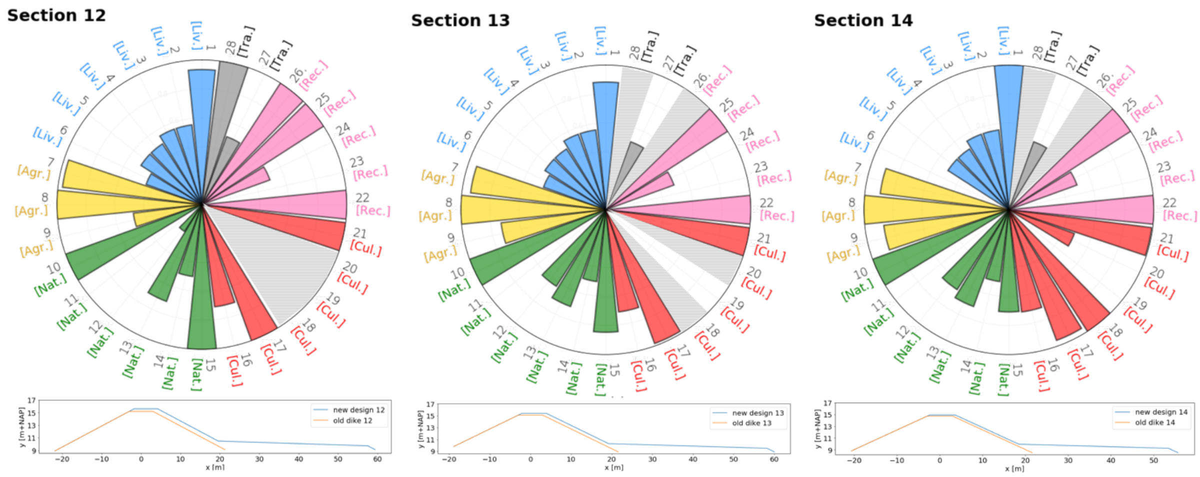


Figure 74: Target design for landscape architecture

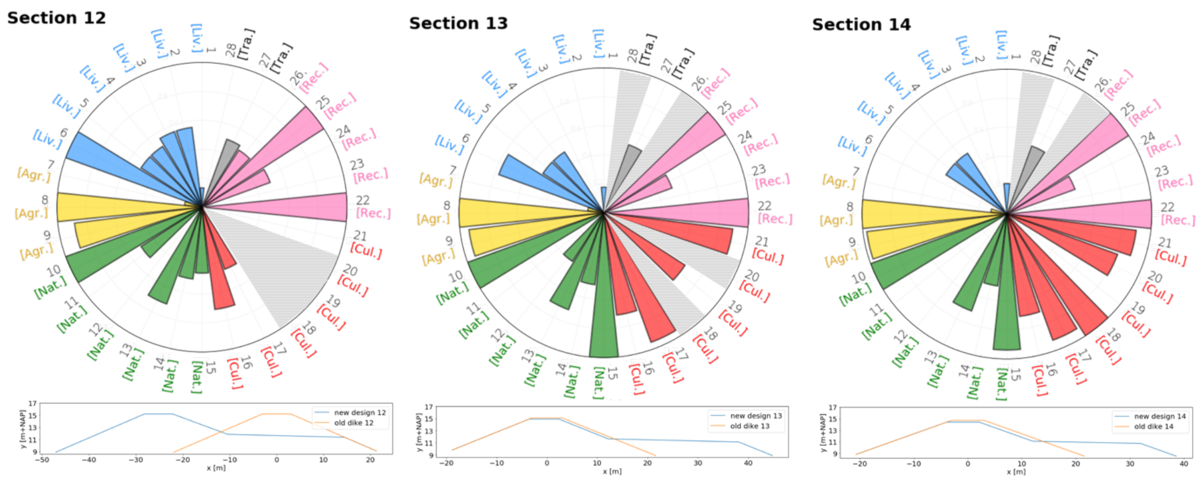


Figure 75: Target design for agriculture

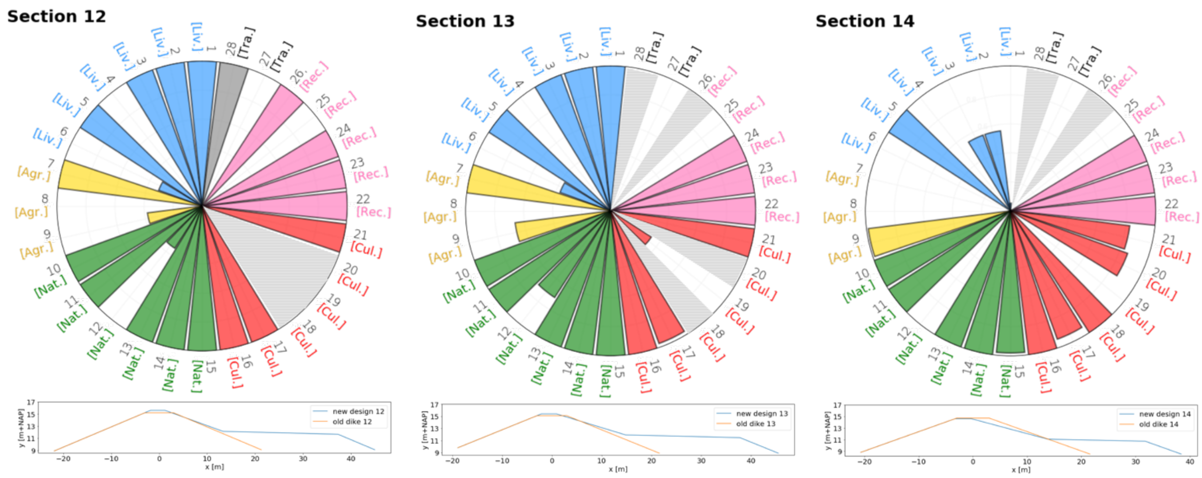


Figure 76: Target design for nature

1 [Liv.] Ability for housing on berm
2 [Liv.] Serviceability of houses on berm
3 [Liv.] Experienced flood safety
4 [Liv.] Accessibility of houses
5 [Liv.] Pollution minimization
6 [Liv.] Buildings preservation
7 [Agr.] Berms ability for agriculture
8 [Agr.] Accessibility of agricultural land
9 [Agr.] Preservation of agricultural land
10 [Nat.] Growth properties of outer slope
11 [Nat.] Growth properties of inner slope
12 [Nat.] Cleaned soil pollution
13 [Nat.] Passage capability for animals
14 [Nat.] Pollution minimization
15 [Nat.] Vegetation preservation
16 [Cul.] Historical cross-sectional shape
17 [Cul.] Preservation of dike core
18 [Cul.] Preservation of flood relics
19 [Cul.] Preservation of heritage
20 [Cul.] Preservation of heritage area
21 [Cul.] Minimazation of additional soil pressure
22 [Rec.] Recreational infrastructure available
23 [Rec.] Recreational safety on dike
24 [Rec.] Pollution minimization
25 [Rec.] Accessibility of recreational areas
26 [Rec.] Preservation of recreational area
27 [Tra.] Transportation intensity on dike
28 [Tra.] Minimizing dike on river

Living
Agriculture
Nature
Culture
Recreation
Transportation

6.6. Concluding remarks

Applying the method on the case study “Wolferen-Sprok” gave the chance to assess the value of the developed method. The visualization in Step 7 of the method provide insights in the relative effect of a design alternative on the functional characteristics of the project area (compared to all other generated design alternatives). A method to facilitate the discussion for the selection of design alternatives is developed, as the method provides the information to compare design alternatives. A created landscape vision on the reinforcement project can be assessed on the rough influence it has on the functional characteristics of the project area. Inconvenient designs can be adapted, and the influence of the adapted design can be compared to the influence of the initial design. The method also allows to apply a reversed reasoning, which provides a design alternative for the dike reinforcement by requiring a certain (relative) influence on the functional characteristics of the project area. A subject expert or stakeholder becomes a designer, that can create a design that influences the project area as he desires.

Every considered design alternative is a unique composition that describes the influence on living, agriculture, nature, culture, recreation, and transportation within a project area. The decomposition of effects on the complete project area provides the possibility to have structured discussion on the inclusion of wishes in the various design alternatives in the project area. Using the method in project teams, assuming a good and transparent communication within the team, provides the possibility to include the effects on the existing situation in early stages of dike reinforcement projects. However, there are some limitations in the application of the method. The method only focusses on soil solutions to increase the safety against inner slope stability and inner slope erosion, other (structural) solutions are not considered in the provided method. Also, the method should always be applied by people with knowledge on the project area, as they can indicate the importance of illustrated effects.

7. Conclusions, Discussion & Recommendations

In this chapter, conclusions on the development of a method that compares insight on the impact of design alternatives on an existing situation are presented and explained (Section 7.1). Furthermore, discussion and recommendations for further research are provided (Section 7.2). The chapter is then finalized by providing recommendations on the practical use of the method (Section 7.3).

7.1. Conclusions

A “research through design” study is obtained to develop a method that compares the influence on the functional characteristics of a project area, caused by design alternatives for a dike reinforcement in rural area. The definition of a functional characteristic is set as a characteristic that an individual can value while being in or using an area, in the present, and in the future (one might think of social economic-, ecological-, and cultural elements). This section provides an answer to the research questions of this study. Subsequently, conclusions are drawn on the research objective of this study.

How can safety, against the failure mechanisms “inner slope erosion”, “inner slope stability”, and “piping”, be provided in design alternatives of dikes in rural areas?
It is concluded that there is a large design freedom when the only requirement is to design a dike that provides safety against governing conditions. The analysis on the failure mechanisms “inner slope erosion”, “inner slope stability”, and “piping”, resulted in the finding that every geometrical parameter of the cross-section of a dike (consisting of a soil body) contributes to the resistance against one of the three failure mechanisms. This results in a large variety of soil geometries that can fulfil the safety requirements of the dike. In addition to the soil solutions, solutions constructed in the subsoil, can be considered to resist the failure mechanism “piping”.

What are the functional characteristics of a project area, that can be interfered with, in dike reinforcement projects in rural areas?
An inventory is made of functional characteristics that together describe the existing situation in rural project areas. The twenty-two identified characteristics are divided in two groups; functional characteristics of the design of the dike, and functional characteristics of the surroundings. Functional characteristics of the design focus on elements that are (potentially) located within the footprint of the dike, while the functional characteristics of the surroundings focus on the elements that are located close to the dike. The retrieved functional characteristics of a project area are indicated in Figure 77 by yellow (for characteristics of the dike) or orange boxes (for characteristics of the surroundings). It is found that the identified functional characteristics are a break-down of natural, cultural, and social-economic functions of rural areas in the Netherlands.

How can functional characteristics of rural areas be influenced by design alternatives of dike reinforcements in rural areas?
The influence of a design alternative on the functional characteristics is provided by going through the developed conceptual evaluation model. In this model, presented in Figure 77, the

effects on functional characteristics of the project area are directly related to characteristics of design alternatives. It is dependent on the composition of functional characteristics in the project area, and the details of the design alternative, what the exact impact will be.

Figure 77 provides two flowcharts that guide the identification of influences on the existing situation in the project area. These flowcharts identify the influence on the functional characteristics of the dike design (Figure 77a) and the influence on the functional characteristics of the surroundings addressed (Figure 77b). Four steps are explained to retrieve information for the evaluation of effects on (the functional characteristics in) the existing situation, caused by a dike reinforcement design:

1. Retrieve the functional characteristics of the existing situation in the project area.
2. Determine the influence of a design alternative on the existing situation in the project area.
3. Identify chances to include functional characteristics in the new situation
4. Integrate desired functional characteristics in a definitive design.

An important remark is that the definitive implementation of functional characteristics in a final design (going from Step 3 to Step 4) is always dependent on the ambitions in the dike reinforcement project.

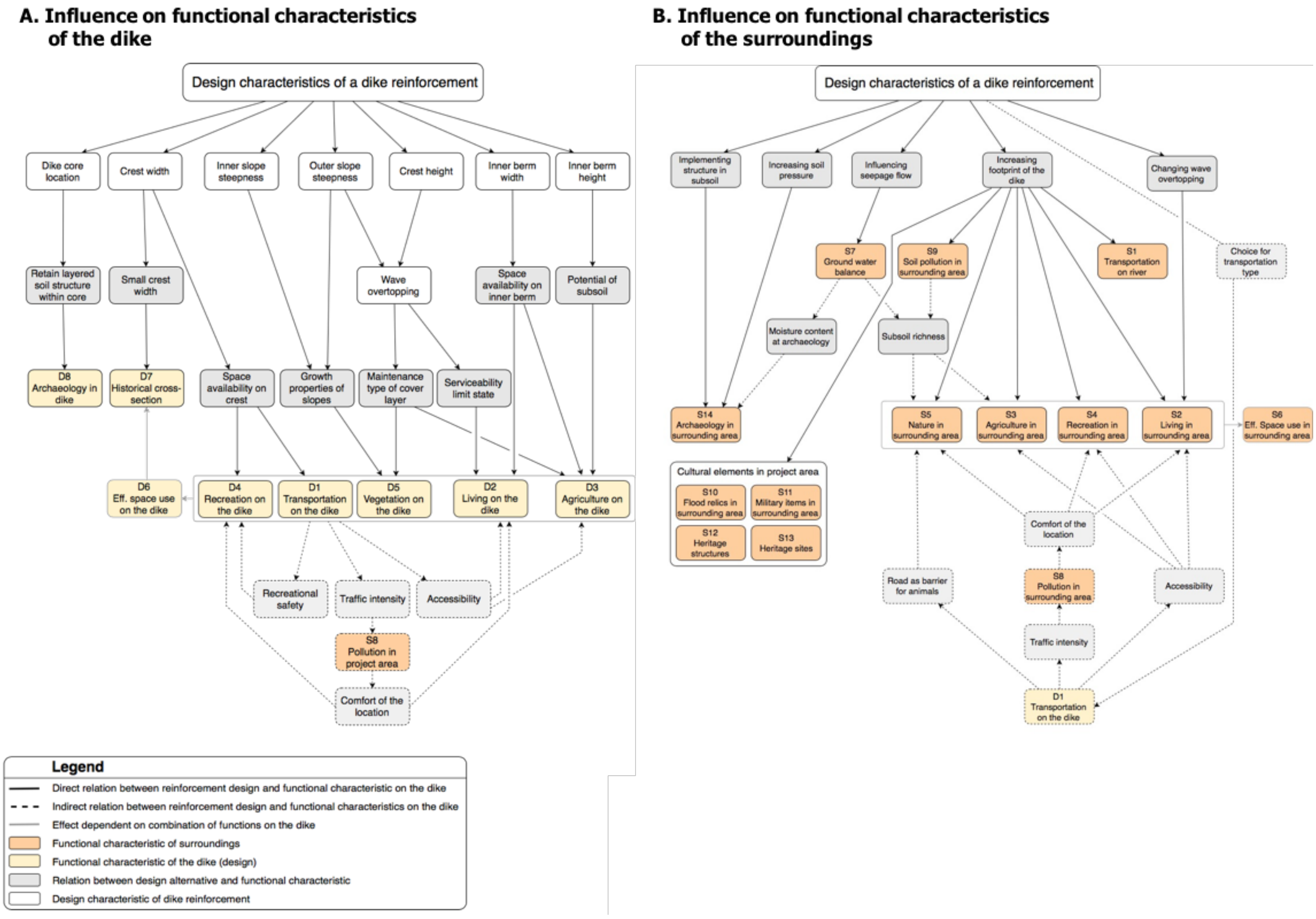


Figure 77: Conceptual evaluation model

What is a method that compares the effects of various design alternatives on the functional characteristics of rural areas?

Based on the findings in the first three research questions a method is developed that provides the possibility to compare design alternatives for dike reinforcement projects in rural areas. This method consists of the seven steps presented in Figure 78.

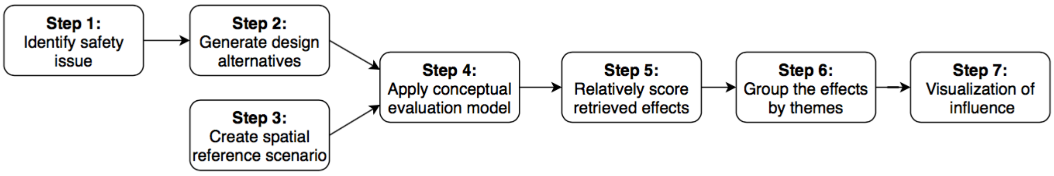


Figure 78: Method to compare design alternatives

In the method, it is first focussed on providing information to apply the conceptual evaluation model for a large variety of design alternatives. This is done by generating verified design alternatives that resolve the identified safety problem (Step 1 & Step 2). Next, a spatial reference scenario is created to provide the required information for the application of the conceptual evaluation model (Step 3). In the fourth step, the conceptual evaluation model is applied on the generated design alternatives and data is retrieved that identifies the effect on the functional characteristics of the project area. The retrieved effects are relatively scored and divided in six interest groups (living, agriculture, nature, culture, recreation, and transportation), that represent different angles of approach that stakeholders can have in a project area (Step 5 & Step 6). The outcome of the method is a visualisation of the influence of a randomly chosen design alternative on the functional characteristics of the project area, compared to all other evaluated design alternatives (Step 7). The visualization of the influence of a design alternative is illustrated in Figure 79. This figure consists of a top-view of the evaluated design alternative in the project area, a cross-sectional view of the design alternative relative to the existing dike, and a radar plot indicating the influence of a design alternative relative to all other design alternatives. In this radar plot, a full bar indicates the most positive observed effect, while an empty bar indicates the most negative observed value. Such visualization can be created for every generated design alternative.

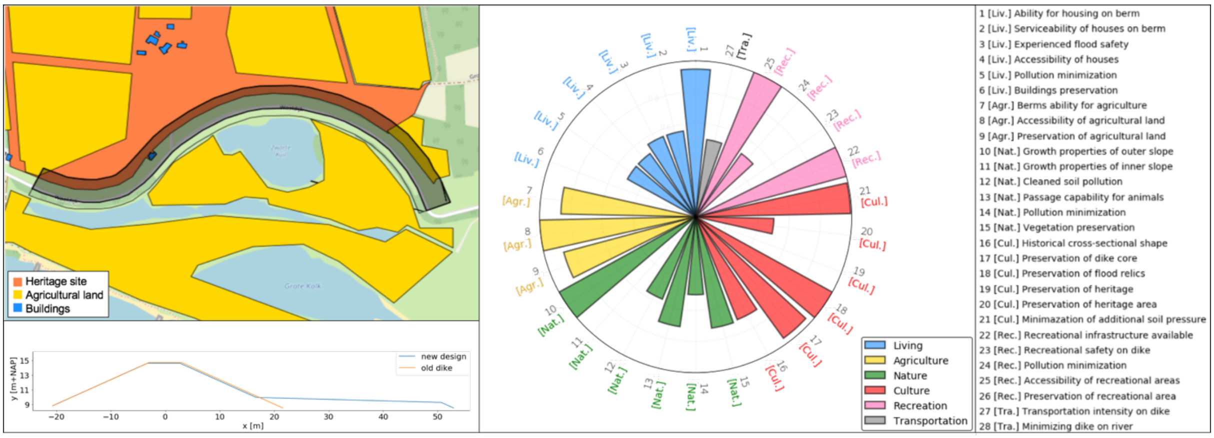


Figure 79: Visualization of a design alternative in dike reinforcement project "Wolferen-Sprok" (Dike Section 14).

What is the value of the method that compares the effects of design alternatives for designing dike reinforcements in rural areas?

Application of the method on the case study "Wolferen-Sprok" resulted in findings on the value of the method for the design of a dike reinforcement. The value of the model is that contradictions between themes (living, agriculture, nature, culture, recreation, and transportation) can be retrieved by using the visualization of the method (Figure 79) to reflect on different design alternatives. The method uses raw data that can be retrieved from a project area in early stages of a project. Using the method provides information on the identified effects induced by a design alternative. The user should determine whether the proposed design influences the existing situation as desired. Inconvenient designs can be adapted, and the influence of the adapted design can be compared to the influence of the initial design. The method also allows to apply a reversed reasoning, that provides a design alternative for the dike reinforcement by requiring a certain (relative) influence on the functional characteristics of the project area. Searching for the desired influence results in a design alternative to reinforce a dike section.

After having discussed the answer to all research questions, it is determined whether the research objective is achieved in this study.

Develop a method which provides information, that can be used by subject experts, to compare effects that various design alternatives induce on the existing situation in a project area.
It is concluded, that a method is developed that provides subject experts the possibilities to compare the effects on the existing situation, for the purpose of evaluation and selection of design alternatives, in dike reinforcement projects in rural areas. The method, as proposed in Figure 78, provides the framework that is used to identify and compare the effects on the existing situation. The visualization of the outcome of the method (Step 7) provides information to the subject experts. This information makes it possible to assess effects of a design alternative compared to the other design alternatives solving the safety problem in the project area.

7.2. Discussion

This section discusses the conclusions drawn in Section 7.1. The discussion is started by explaining the influence of the research strategy on the development of the method. Subsequently, the provided visualization of the method is discussed. Followed by discussing how the method can be used for the selection of design alternatives in dike reinforcement project. Finally, the limitations of the research are discussed.

Influence of research strategy on retrieved results
The research strategy explained that iterations were required to develop a method that provides useful insights on the effects on the existing situation. In the executed research, mainly iterations were made between the identification of functional characteristics and the effects on that can be induced by a dike reinforcement design, leading to a conceptual evaluation model that is applied in the provided method. This conceptual evaluation model is based on a literature study to the effects on the functional characteristics of the project area.

For further development of the method, it is recommended to do an additional design iteration for the method from the beginning (identification of functional characteristics). In the next design iterations, it is recommended to include subject experts in the development. The different approach of these experts towards dike reinforcement projects, can provide useful information to express the influence of a reinforcement design on the existing situation. This study is a first application that uses a parametric dike design to evaluate the spatial integration of design alternatives in a project area.

Visualization of data in the developed method
A visualization of the outcomes of the developed method is required to compare the design alternatives on the induced influence on the existing situation. In the provided visualization is focused on showing the relative effects, and providing an indication of the complete influence on every theme (see Figure 79). This means that the magnitude of the effect is not directly visible from the provided polar plot. Based on the retrieved results at Step 4 of the developed method, the user of the model has to indicate the importance of identified effects.

The visualization provides a rough comparison between themes by means of the amount of color that is observed. However, it is not desirable to cluster the effects per theme in one bar that indicates a total score. Clustering the effects in one bar would results in the loss of a lot of information on the spatial integration of the reinforcement design.

Using the method to select design alternatives

The provided method gives subject experts the information to pro-actively participate in the development of design alternatives in the project area. In existing dike reinforcement projects, the developed design alternatives are mainly determined by a landscape architect and a civil engineer. Design alternatives are created that fulfil their requirements. Using the developed method provides the possibility to include wishes and requirements of subject experts in the design alternatives. It is expected that this results in more convenient influence on the existing situation for design alternatives in the Environmental Impact Assessment.

The, in this study, retrieved functional characteristics of rural areas mainly focus on the natural, cultural and social economic functions in project areas. TAW (1994a) explains that influence on landscape values, maintainability and costs should be added to retrieve the complete influence of a design alternative for a dike reinforcement project. This should be kept in mind while using the developed method for the evaluation and selection of design alternatives in a dike reinforcement project in rural areas. It can be convenient to study how a similar method can be developed to express the influence of a design alternative on the maintainability and costs of the dike. A method to illustrate changing landscape value is already available, by the "VR-Dijken"- tool (Witteveen+Bos, n.d.).

In the scope of this study is explained that it is focused on river dike reinforcement projects in rural areas. Due to the large complexity of the existing situation in urban areas, the developed method cannot be used in dike reinforcement projects in urban areas. Nevertheless, it would be interesting to develop such a method for urban areas, as interests of stakeholders in such areas might even be larger. Also, it would be interesting to develop a method that is not fixed to the existing dike trace in the project area.

Limitations

This paragraph elaborates on the limitations of the developed method in this research.

- The method is not designed to determine the optimal dike reinforcement design for a specific project area. The user of the model should always provide a value judgement on the provided effects on the existing situation. This value judgement determines whether a certain design has a desired influence on the existing situation.
- Only quantitative measurements of the effects on the existing situation are provided in this study. It is expected that a quantitative measure cannot always indicate the exact influence on a functional characteristic of the project area.
- The input data to apply the method on a dike reinforcement project does not indicate the importance of certain characteristics within an area. It is expected that this is sufficient for the first evaluation of the functional characteristics, but further in the design process more detailed information on the project area should be assessed. The provided method is not able to guide this more detailed information.
- A demarcation is set that safety against inner slope stability, and inner slope erosion is provided by a soil solution. However, it is not unusual to apply customized (structural) solutions near remarkable elements in the spatial planning. This is not considered in this study, but it should be kept in mind while evaluating the model outcomes.
- The method assumes that the existing dike has a uniform cross-section throughout a dike section. However, deviations from a uniform cross-section can occur in a project area. This decreases the accuracy of the generated results in the method.
- In this study is focused on indicating differences between design alternatives that influence the existing situation on the long-term. It is expected that short term effects during the construction phase are also important effects that should be considered.

7.3. Recommendations

In the Discussion (Section 7.2) is reflected on the developed method. This resulted in recommendations for the application of the method in the design process of a flood protection project:

- Before using the developed method, it should be determined whether the provided method fits within the scope of the flood protection project. It should be a dike reinforcement project in rural areas, in which it is required to retain a dike at the location of the existing dike in the project area.
- The application of the method requires technical knowledge on how to design dike reinforcements. The verification of the created design alternatives requires knowledge on the dike design. This technical knowledge is also required to indicate which structural solutions may be applied to preserve important values in the project area.
- The relevance of the indicated effects on the existing situation should be evaluated by persons with knowledge on (themes in) the project area. The value of the indicated effects should be assessed, and it should be determined what a desirable result is.
- The use of the method to include the effects on the existing situation within design alternatives requires a transparent communication within a project team. This should result in mutual understanding on the reinforcement assignment and the potential problem. Together consensus can be achieved on design alternatives that are worth considering in the Environmental Impact Assessment.
- The developed method is only suitable for the initial evaluation and selection of design alternatives. In further stages, more qualitative effects on the functional characteristics in the project area should be considered.

The developed method can be applied to include the existing situation in the project area in the evaluation and selection of design alternatives in dike reinforcement projects in rural areas. It is expected that application of the method in design teams provides new input for further improvement of the method.

Appendices

Appendix A
Dutch design practice

A.1. Design process of dike reinforcement projects in the Netherlands

The design is described based on information retrieved from ENW (2017). In the Netherlands, the design process of a dike reinforcement is initiated by observing that a dike section is not fulfilling a set required safety level, which is established in the Water Act. The rejected dike sections are collected in the High Water Protection Program (HWBP), and clustered into potential projects (Ministerie van Verkeer en Waterstaat, 2017). The HWBP determines the urgency of a project by reviewing the probability of flooding and economical damage resulting from a flood. This results in a list with the most urgent project, which will be adopted in the reinforcement program for the next years. For these designated projects the design process is initiated. The typical design process in the Netherlands consists of three phases; the draft design phase, the preliminary design phase, and the detailed design phase. In the following paragraphs it is per design phase explained what activities are involved.

The design process is started with the draft design. This phase is initiated by doing an extensive site characterization on technical and environmental boundary conditions at the projects location. The exploration to potential solutions is started and the wishes and requirements from stakeholders are identified in the context process. Next, it is determined which wishes and requirements fit within the scope of the project. The potential solutions and the effect on the potential wishes and requirements are communicated with the stakeholders. Dependent on the reaction of the stakeholder further studies can be done to set satisfying requirements and wishes for the project.

When the draft design phase is completed, it is started with the preliminary design phase. In this phase the potential solutions are further developed into preliminary designs. If needed, further research on the site conditions will be obtained and obstacles for the project are identified. The preliminary designs are prepared in such a way that it can be determined what the dimensions and costs of the solutions are. In this stage, it is also important to determine whether a preliminary design is feasible on permit application. The stakeholders are informed on the possible alternatives for the dike reinforcements, and it is determined if the presented solutions are satisfying for the stakeholders. If not, the presented designs will be reviewed, before the formal public consultation procedure starts. Eventually, an official decision on the preferred alternative is made and the detailed design phase can start.

In the detailed design phase, the preferred alternative is further developed into a detailed design that can be used for tendering the project. This phase can be seen as providing the information that is required for the construction of the project. Further investigations are conducted to reduce the technical risks of the project. Also, direct involved stakeholders are consulted to prepare a plan that creates a satisfying result for the project. If the stakeholders agree on the detailed the design, the construction of the project can start.

Voorendt (2017) studied the design process of flood defence projects, and developed the integrated design method (Appendix A). This method is developed to combine the safety issue with the spatial quality of an area, with as goal to improve the integration of the flood defence design in its environment. If the Dutch design process of dike reinforcements is compared to the different design processes, it can be concluded that the design process is comparable to a typical civil engineering approach. The main difference between the integrated design approach and the typical engineering approach is the emphasis that is put on creativity in the early design stages. Starting the design process with a large analysis, setting requirements, and setting boundary conditions for the project leads to limitations in creativity throughout the design process, because the solution space is limited from the beginning. For this reason, in the integrated design method, the research on specifications is obtained after the development of concept. Also more emphasis is placed on the spatial design in the integrated design method, compared to the civil engineering method. By allowing creativity and emphasizing spatial design in the design process, stakeholder resistance could be reduced by developing a more appropriate design at a specific location (Voorendt, 2017).

A.2. Procedures in dike reinforcement projects in the Netherlands

As explained, the public has the right to give its opinion on infrastructural projects. In the Water Act, two formal procedures are set, the project proposal procedure and the environmental impact procedure, to reflect on the proposed plans. In Figure 80, these are represented in a flow chart. The flow chart is based on information provided in Waterschap Hollandse Delta (2013), Jonkman et al. (2017) and Witteveen + Bos (2013) and is further explained in the remainder of this section.

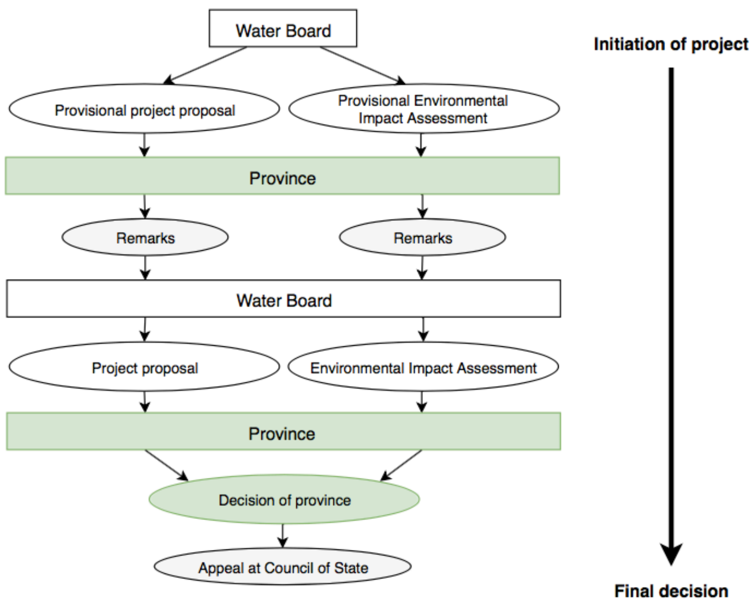


Figure 80: Procedures in dike reinforcement projects

The formal procedures are started after the draft design phase, when it is officially announced that a project to reinforce a dike section is proposed. Documents are prepared on how the project will be approached and how environmental impact will be determined in the project. To make sure that the all environmental elements are considered in the design process of a dike reinforcement project, TAW (1994a) did research into this topic. The result of the research was a guideline that recommends to take six topics into account in the consideration of alternatives of a flood protection project:

- social economic functions,
- costs,
- maintenance,
- landscape-,
- natural-, and
- cultural values

More information on what is involved in these topics is given in Appendix B. This appendix describes how the above six criteria can be valued in dike reinforcement projects.

After analysing the problem and creating preliminary designs, the results are documented in a provisional project proposal and a provisional environmental impact assessment. These documents are submitted to the province, who is responsible for notifying the public about the plans to reinforce a dike section. For the dike reinforcement project, a large number of permits is required to obtain all legal documents that are required for the reinforcement project. These permits, for example on nature compensation or spatial planning, are open for inspection for a period of six weeks. During these six weeks, every citizen has the right to submit official remarks on the provisional project proposal and environmental impact assessment.

The remarks on the plan, collected by the province, are given back to the Water Board, that discusses the remarks and can adjust the project proposal or environmental impact assessment if desired. Afterwards the definitive versions of the two documents are submitted at the province, and the Provincial Executive makes its decision on the project. When the decision or argumentation of the Provincial Executive on the project is not satisfying for citizens, they can appeal the decision of the province at the Council of State when they submitted remarks in earlier stages to the provisional project proposal or environmental impact assessment. That is an undesired situation, as such procedures are expensive and delay the project. To prevent this from happening in early stages of the project, stakeholders are already integrated in the design process, by means of the context process.

A.3. Environmental Impact Assessment

Since there were many troubles in dike reinforcements from 1960 till 1994, the Dutch Government decided to study the impact of dike reinforcements on its environment (see Section 1.1.1). In the nineties, research was done on evaluation criteria for dike reinforcement projects, and this resulted in a set of criteria that were able to be scored. These criteria were presented in a guideline (TAW, 1994a). In this section the criteria are described per subject and it is explained how should be dealt with each criterion, according to the provided guideline.

Landscape-values

It is advised to value the landscape at three levels; the dike in the region, the dike in its direct environment, and the dike as element. The integration of the dike reinforcements on these three levels can be judged by assessing five characteristics of the dike:

- Do the landscape patterns and elements match each other?
- Does the shape of the reinforcement match its intended functions?
- Is the proportion between human induced shapes and natural shapes changed?
- Is the development process of the landscape history visible?
- Is there visual coherence between sizes and positions of elements in its landscape?

Nature-values

Also, for nature it is advised to take the three levels, as proposed under landscape, into account. The value of a dike reinforcement can be scored on the following five criteria:

- The amount that ecosystems and species are integrated in the dike design.
- The presence and impact of the dike design on rare ecosystems and species.
- The number of species per homogeneous dike section.
- The presence of chances to improve and preserve species and ecosystems at the dike section.
- The time that is required to enable establishment of ecosystems and species.

Culture historical-values

Again, the dike is advised to be assessed on regional, direct environment and element level. The culture history is divided in four sub criteria:

- Archaeology
- Historic geography
- Building and art history
- History of the area.

These criteria are being valued based on its rarity of the element, the authenticity of the element, the amount that an element of a larger unity, the characteristic value of an element in its environment, and the symbol that a specific element has on local, national or international level.

Social-economic functions

The criteria that focus on social-economics are describing the impact of the dike reinforcement on human functions of the environment. For living, it is assessed how many houses vanish because of the construction of the dike reinforcement. Agriculture can be assessed by the change in accessibility of the farm ground and the accessibility of emergency grounds for animals. The impact on industry is also focussed on the impact on its accessibility, but also on the protection level of the industrial area and the available space for industry. The recreational impact of the reinforcement is tested on the attraction, accessibility and change of the dike environment due to the project. Lastly, the changes in the traffic situation are assessed by reviewing traffic safety, nuisance and accessibility.

Maintenance

The maintenance criteria should be judged on two elements; the water retaining structure and the river. For the water retaining structure, it should be assessed how good the possibilities for inspections or maintenance are during periodic controls or high water situations. Also, the possibility for future reinforcement is assessed per alternative. For the river it is mainly focused on the impact the dike reinforcement has on the flow area of the river. Is this area not changed, and if it is changed is it compensated along the segment of the dike reinforcement?

Costs

The last criterion that is taken into account are the costs for the dike reinforcement project. This can be divided in five categories:

- Costs for creating the design of the dike reinforcement.
- The costs for the acquisition of required areas and compensation for damage.
- Cleaning costs for polluted soil.
- Construction costs of the reinforcement.
- The inspection and maintenance costs of the reinforced dike.

Appendix B:

Applying the Workbench Method to identify functional characteristics of rural areas

In this appendix, the Workbench Method has been applied to define the functional characteristics of the project area. This done by, introducing spatial quality and defining its definition in Section B.1. Afterwards, in Section B.2, the set definition is conceptualised with the help of the Workbench Method. In Section B.3, this made specific for dike reinforcement projects. Finally, in Section B.4, it reflected on this approach for defining spatial quality.

B.1. Defining spatial quality

Spatial quality is a definition which is not unambiguously described in the literature. Janssen-Jansen, Klijn & Opdam (2009) concludes that there are roughly three possibilities to define spatial quality. The spatial quality of an area is:

- The visual experience of that area.
- The quality of the living environment in that area.
- The sustainable development of that area.

The definition of spatial quality which is commonly used in the Netherlands is as follows: spatial quality is the sum of the user value (the possibilities of the area in relation to the using wishes of people), perceived value (the way how people experience an area), and future value (the adaptability to the future situation) of an area (Janssen-Jansen et al., 2009). The difference between the three definitions for spatial quality can easily be explained based on this definition. Sustainable development can be seen as the total of user, perceived and future value of a project area. In this definition, the perceived value can be seen as the visual experience in the area. While the quality of the living environment can be seen as the user value plus the perceived value.

In the Netherlands, emphasis is put on the sustainable development of project areas in current projects (Janssen-Jansen et al., 2009). Therefore, in the review on spatial quality at dikes in rural area, this definition is considered. Table 23 provides an explanation on the terms user, perceived and future value based on (Diemont, Cilliers, Stobbelaar & Timmermans, 2010).

Table 23: Definition of user, perceived, future value (Diemont, Cilliers, Stobbelaar & Timmermans, 2010)

User value	Suitability	The appropriateness of the investment that comes with the project.
	Functionalism	The design of the project is focussed on the use function of the area.
Perceived value	Identity	The uniqueness of the project area.
	Diversity	The inclusion of interests of different groups in the project area.
	Beauty	The aesthetic quality of a project area.
Future value	Sustainability	The way that the ability of future generations to meet their own needs is interfered with.
	Adaptability	The quality of being able to adjust to different demands or situations.
	Manageability	The quality of the project area to be manageable in the future.

B.2. Spatial quality according to the Workbench Method

The in Section B.1 defined definition of spatial quality is still open for interpretation. To conceptualize this definition for construction projects, the Workbench Method has been developed (Hooimeijer et al., 2001). In this method the spatial assignment is approached from four perspectives for which the spatial quality can be assessed: economic-, ecological-, cultural-, and social perspective. Per perspective the method prescribed terms on which the user, perceived and future value of the perspective can be described. Table 24 presents these terms, that together describe the total impact on spatial quality. In the table, also a short explanation on each term has been included.

Table 24: The Workbench Method (Hooimeijer et al., 2001)

	Economic	Social	Ecologic	Cultural
User value	**Allocation-efficiency:** A location has access to certain resources, which can attract specific economic functions.	**Access:** The project area should be easy accessible for everybody wanting to enter the area.	**Ecological structures:** The planning of an area contributes to the cohesion of living environment of plant and animal.	**Freedom of choice:** In the spatial planning it should be accounted for the different interests of different people. The space should be developed in such a way that everybody can chose something that interests them.
	External effects: Are effects that indirectly affect economic value of the area in a positive or negative way. These effects are related to the other themes: social, ecological, and cultural.	**Distribution:** This element focusses on the fair distribution of costs and revenues from the development and maintenance of the project area.	**Clean environment:** A clean environment is a condition for different use functions of a project area.	
	Accessibility: The accessibility of (parts of) a project area determines a part of the attractiveness of a location.	**Participation:** The area shows that everybody was able to participate in the decision making process in such way that these choices can be identified.	**Water in balance:** The planning of the area has a water balance which prevents flooding or desiccation.	**Cultural variety:** The variety in culture enriches an area, because it tells the story of an area from the past to the present.
	Multi-purpose: A location is characterized by interaction-patterns between actors that strengthen or conflict each other. This contributes to an efficient space use.	**Choice:** There should be place for everybody in the spatial planning, in such a way that people from different groups have the possibility to identify themselves in the project area.	**External safety:** The society should be as safe as possible, people living in a project area should be as least as possible be confronted with risks which are not caused by themselves.	
Perceived value	**Image/Attractiveness**: From economic perspective attractiveness and image of an area contributes to the economic value of the area. 'Site', 'Situation', 'Composition' and 'Planning', determine the image and attractiveness of an area	**Inequality:** The spatial planning of an area is valued positively when people notice that spatial wishes of people/groups are considered in equal amounts	**Healthy living environment:** The feeling of living in a healthy environment is important for the people.	**Contrast in environment:** A space with contrasts can be unique and therefore be valued. People can think of the contrast between building environment and nature, or agriculture.
		Connectedness: People feel emotionally connected to the project area.	**Beauty of nature:** Many people are touched and motivated by the beauty of nature of an area.	**Beauty of culture:** Many people are touched and motivated by the beauty of culture of an area.
		Safety: The safety feeling of people in the public space.	**Peace and space:** The area has possibilities to enjoy the peace and space of the area.	**Singularity:** A special character of a project area should be safeguarded and utilized.
Future value	**Stability/flexibility**: For the future economic value of the area it is important to create a stable and flexible environment to enhance sustainable growth of the area.	**Social support:** The support for projects in a region should be sufficient to prevent degradation of the amount of services provided in that region.	**Ecological stocks:** The space in a project area represents the ecological stocks of the area. These ecological stock can differ in quality, which is depending on the area.	**Heritage:** Cultural heritage is an irreplaceable quality, a source of information. This information is lost when the element is gone.
	Agglomeration: Agglomeration effects are effects in which people and companies concentrate in the same areas.			**Integration:** New cultural expressions get a place in the public area, leading to new development areas for culture.
	Cumulative attraction: Attraction in a project area is determined by the combination of learning, entertainment, relaxing and aesthetic activities in a project area. A combination of those four in a project area gives an economic attractive location	**Cultures of poverty:** The theory which states that disadvantaged groups within a generation will also be disadvantaged in future generations.	**Healthy ecosystems:** Healthy ecosystems are an important condition for the survival of stocks in the project area.	**Cultural innovation:** By implementing new cultural elements an attractive area can be created.

The underlying idea of the Workbench Method is that spatial quality is different at every location and for every individual (Hooimeijer et al., 2001). In the method, emphasis is put on how an individual can experience the spatial quality. This can also be observed when the themes in Table 24 are critically evaluated. For example, under the theme ecological is a topic positioned, called external safety. This topic explicitly focusses on the safety of humans. The link to the ecologic perspective is made, as these external risks are caused by natural conditions (such as a flooding). Also, it could be argued, whether the economic perspective is something individual, as from political viewpoint some people might say that economic growth should not be a purpose on its own. Therefore, it is important not to put too much value the provided names for the categorization (economic-, social-, ecologic-, and cultural perspective), as this could cause misunderstanding in what is actually meant with the subtopics in these categories.

The strength of the Workbench Method is found in the provided decomposition of the complex term spatial quality. It is not difficult for an individual to value a design on the different topics in Table 24. This helps triggering the discussion on spatial quality in construction projects. Developing a method, which identifies the spatial quality from individual perspective, leads to a good indication of how people value the project area. The goal of this study is to develop a model that provides information on the functional changes in the spatial system of the project area, caused by a dike reinforcement project in rural area. Therefore, first it is identified which values are found in rural areas near dikes. Due to its composition, the Workbench Method seems an appropriate method to identify these values. Afterwards in Section B.3, it explained how the identified values lead to functional indicators of the project area.

B.3. Spatial quality for dikes in rural areas (Workbench Method)

In this section the categorization, as provided in Section B.2, is used to express values of dikes in rural areas among primary rivers in the Netherlands. The following paragraphs provide per Workbench Method category a reasoning on the potential influences on subtopics in that category. A topic is interesting when a different dike design leads to a different impact on that topic.

B.3.1. Economic perspective

The economic interest in spatial planning focusses on how the economy can be affected due to a dike reinforcement projects in rural areas. Table 25 reasons from theoretical perspective which economic values may be endangered in these projects, based on the Workbench Method provided by Hooimeijer et al. (2001). This results in a set of spatial quality indicators.

Table 25: Economic values in dike reinforcements (based on Hooimeijer et al. (2001))

	Term	Dike design in rural area	Indicator
User value	**Allocation-efficiency:** A location has access to certain resources, which can attract specific economic functions.	As dike reinforcements are discussed in this study, the location of the project area is already set. Besides that, a dike is a structural element which does not need economic functions to be well-functioning. Therefore, allocation-efficiency does not play a role in dike reinforcement projects.	**No changes experienced**
	External effects: Are effects that indirectly affect economic value of the area in a positive or negative way. These effects are related to the other themes: social, ecological, and cultural.	Like already explained in the previous column, the effects on the other subtopics in social, ecological, cultural values can result in an economic effect. For example, the attraction of an area can partly be lost when cultural heritage is lost in the area. Which can eventually result in a decreasing income for the catering industry. This is a negative example; the influence of the project can also be experienced positive. It should be kept in mind that these effects are indirect.	**All indicators mentioned in Table 25 till Table 28**
	Accessibility: The accessibility of (parts of) a project area determines a part of the attractiveness of a location.	A dike often has a transportation function located in the cross-section. When a dike is reinforced, the necessity of this function can be re-evaluated. Following in different requirements for the cross-sectional design of the dike. Besides the transportation function of the dike, the river also has a transportation function which may be important for inland waterway transportation.	**Transportation function of the dike** **Transportation function of the river**
	Multi-purpose: A location is characterized by interaction-patterns between actors that strengthen or conflict each other. This contributes to an efficient space use.	Multi-purpose focusses on the efficiency of space use in the project area. The efficiency of the spatial planning is dependent on the dike in two ways. First, the dike contributes to this system, as it is a typical example of multifunctional element in spatial planning. When function combination in the design stage is considered, it is possible to provide space for additional functions within the footprint of the reinforcement's cross-section (such as agriculture, transportation, living, and recreation).	**Effective space use on the dike** **Effective space use in the project area**

		Second, the influence of the dike design on the existing spatial planning is important indicator of the efficiency of the project area. To exploit land optimally, sufficient space, logical shapes, and appropriate subsoil characteristic are required.	
Perceived value	**Image/Attractiveness**: From economic perspective attractiveness and image of an area contributes to the economic value of the area. 'Site', 'Situation', 'Composition' and 'Planning', determine the image and attractiveness of an area	The topics image and attractiveness are topics that are endangered in the dike reinforcement design. A dike is a landmark, which is valued due to its specific character (TAW, 1994a). The appearance of this landmark is something that might change in dike reinforcement project.	**The experienced image/attractiveness of the project area**
Future value	**Stability/flexibility**: For the future economic value of the area it is important to create a stable and flexible environment to enhance sustainable growth of the area.	Flexibility and stability from economic perspective, in a dike reinforcement projects, focusses on the technical design of the dike. It is set in the Dutch legislations, that for example a sheet pile wall requires a longer lifetime, than a soil reinforcement (Dutch National Government, 2009). This lifetime difference is caused by the flexibility and stability of certain solutions. As this effect is studied and set by law, it is assumed that there are no great differences between alternatives.	**Lifetime of the design of the dike**
	Agglomeration: Agglomeration effects are effects in which people and companies concentrate in the same areas.	The agglomeration effects concentrate more on development of complete areas, such as the location of a new district. This is not directly connected to dike reinforcement projects, as these projects are initiated from a safety perspective.	**No changes experienced**
	Cumulative attraction: Attraction in a project area is determined by the combination of learning, entertainment, relaxing and aesthetic activities in a project area. A combination of those four in a project area gives an economic attractive location.	The effect of dike reinforcement projects in rural area on cumulative attraction is expected to be limited, as rural areas are not complex system of many different functions. This topic has an added value for dike reinforcement projects in urban areas, where the learning, entertainment, relaxing and aesthetic activities are situated close to each other	**No changes experienced**

When Table 25, is evaluated it can be concluded that identified indicators for economic values in the project area are mostly dependent on the presence of use functions within the design, and the effect on the existing use functions within the project area. The allocation of functions within the cross-section of a dike is a typical design choice, which in a typical civil engineering design method is based on requirements, and wishes for such projects (Voorendt, 2017).

B3.2. Social perspective

In the social perspective it is aimed to create an area in which the social values are fairly distributed over the people living in the area. According to Hooimeijer et al. (2001), social justice is defined as the equality in access to work, living, and healthcare for all people in the society. In Table 26, it is reasoned if, and how, the social values of a rural area can be affected due to a dike reinforcement in that area.

Table 26: Social values in dike reinforcement projects (based on Hooimeijer et al. (2001))

	Term	**Dike reinforcement design in rural area**	**Indicator**
User value	**Access:** The project area should be accessible for everybody wanting to enter the area.	Access in the social context refers to the access to work, living and healthcare (Hooimeijer et al., 2001). In rural areas, this access is mainly interfered with due to the potential demolishment of buildings or work areas as result of a construction project.	**Living in project area** **Agriculture in project area**
	Distribution: This element focusses on the fair distribution of costs and revenues from the development and maintenance of the project area.	As dike reinforcement projects are governmental projects, regulations are set for the costs liability in these projects (ENW, 2017). It does not mean that this topic is not interesting to consider. Individual interests of people in certain projects are evaluated and it is determined whether these wishes or requirements are included in the project. It should be the project team's goal to create a set of requirements for the project that fairly distributes the interests of people.	**Finance structure of the project** **Stakeholder analysis**

	Participation: The area shows that everybody was able to participate in the decision making process in such way that these choices can be identified.	The public participation process is interesting in dike reinforcement projects, as it can increase the stakeholder's satisfaction on a specific design. This is a process which definitely deserves a large role in dike reinforcement projects, as miscommunication or forcing solutions initiates dissatisfaction for a project. The dissatisfaction in that case, does not even has to do with the provided design plans for the dike (Lammers, 2015).	**Public participation plan**
	Choice: There should be place for everybody in the spatial planning, in such a way that people from different groups have the possibility to identify themselves in the project area.	Dike reinforcement projects in general do not focus on the social issues between different groups in the population. In densely populated areas, a dike reinforcement project may be combined with certain functions to address social wishes. The scope of this project is dike reinforcements in rural areas, therefor this topic will not be considered.	**No changes experienced**
Perceived value	**Inequality:** The spatial planning of an area is valued positively when people notice that spatial wishes of people/groups are considered in equal amounts	Dike reinforcement projects in general do not focus on the inequality between different groups in the population. The primary goal of such projects is to increase safety against flooding, which does provide equal safety conditions for people living in the project area.	**No changes experienced**
	Connectedness: People feel emotionally connected to the project area.	People can be used to a specific location, such as a dike and its current design. When this is changed sentimental value can be lost, as the design of the dike does not show its specific characteristics anymore.	**The experienced connectedness to a dike**
	Safety: The safety feeling of people in the public space.	The safety feeling of people can be affected due dike reinforcement projects. A specific example is the allowable overtopping discharge. When during a design storm a large amount of water overtops the dike, people can get anxious. This is reinforced by the study of Heems & Kothuis (2012), as they explain that people consider water safety, as "dry feet" at their houses during storm conditions.	**The experienced safety feeling at a dike** **Overtopping discharge of the dike**
Future value	**Social support:** The support for projects in a region should be sufficient to prevent degradation of the amount of services provided in that region.	The influence of dike reinforcement project on the social services in a region are assumed to be negligible.	**No changes experienced**
	Cultures of poverty: The theory which states that disadvantaged groups within a generation will also be disadvantaged in future generations.	It is assumed that dike reinforcement project cannot change the societal chances for people living in the project area. The primary goal is to provide safety against flooding.	**No changes experienced**

From the in Table 26 provided influences on the social values in rural areas, can be concluded that the effect of a dike reinforcement does not change the future (social) values within the project area. The effect of a dike reinforcement on the use value on the other hand is significant. Often, agricultural land is located close to the dike, while houses might even be located within the dike's cross-section. This was, according to TAW (1994a), a past measure to provide safe living space for poor people in an area that is sensitive for floods.

B.3.3. Ecological perspective

In the Workbench Method the ecological perspective is referred to as the interests of the human in the natural environment (Hooimeijer et al., 2001). In Table 27, it is described what is meant with these terms and how it will be dealt with these terms in the remainder of this study.

Table 27: Ecological values in dike reinforcements (based on Hooimeijer et al. (2001))

	Term	Dike reinforcement design in rural area	Indicator
User value	**Ecological structures:** The planning of an area contributes to the cohesion of living environment of plant and animal.	Ecological structures are green structures aimed at increasing the liveability of flora and fauna in an area (Bredenoord, Van Hinsberg, De Knegt, & Leneman, 2011). To prevent degradation of nature in the Netherlands, a nationwide ecological structure has been developed (Nature Network Netherlands). Locations that provide good living qualities for flora and fauna are therefor protected by law. A part of this system is located near rivers (and dikes), as water level fluctuations and ground water flow provide characteristic living conditions for	**Ecological structures in project area**

		certain species. Increasing the strength of the dike, may interfere this system.	
	Clean environment: A clean environment is a condition for different use functions of a project area.	A clean environment from spatial quality point of view refers to functional limitations of an area caused by pollution due to human activity. There are different types of pollution, for dike reinforcements the following have been identified in this study: • Bottom pollution • Air pollution • Water pollution • Noise pollution Dike reinforcement can contribute positively and negatively on this term due to design choices made in these projects. In the Netherlands, it is set by law that further degradation of the bottom/water is not allowed (Kattenberg & Van der Gun, 2012). In construction projects contaminated soils have to be cleaned when the soil might endanger the health of people.	**Bottom pollution** **Air pollution** **Water pollution** **Noise pollution**
	Water in balance: The planning of the area has a water balance which prevents flooding or desiccation.	A dike reinforcement project is initiated to reduce the probability of flooding; this is the 'Safety assignment'. Besides flooding, also desiccation in bordering areas can be the result of certain design measures.	**Ground water balance**
	External safety: The society should be as safe as possible, people living in a project area should be as least as possible be confronted with risks which are not caused by themselves.	As explained in the previous column external safety mainly focusses on external risks which are not caused by people. For dike reinforcement projects, this focusses fully on the safety assignment that has to be fulfilled in these projects. The safety assignment is the same for every design and will therefore not be leading to a deviating score on this topic.	**No changes experienced**
Perceived value	**Healthy living environment:** The feeling of living in a healthy environment is important for the people.	As dike reinforcement projects interfere with the existing living environment, this provides chances to create a better living environment. On the other hand, it is also possible that a healthy environment is destroyed due to a certain design.	**The experienced healthiness in the project area**
	Beauty of nature: Many people are touched and motivated by the beauty of nature of an area.	When specific characteristics of a nature area are destroyed, this could lead to a negative influence of a dike reinforcement design on the perceived value of the environment. This term focusses on the value (beauty) that elements have in a natural system.	**The experienced natural beauty in the project area**
	Peace and space: The area has possibilities to enjoy the peace and space of the area.	Same as “beauty of nature”. When specific characteristics of a nature area are destroyed, this could lead to a negative influence of a dike reinforcement design on the perceived value of the environment. The experience of people is dependent on the value that they give to a certain element.	**The experienced natural peace in the project area**
Future value	**Ecological stocks:** The space in a project area represents the ecological stocks of the area. These ecological stock can differ in quality, which is depending on the area.	The future “ecological” value of an area is partly dependent on the ecological stocks that are available in the area. This something that is typically endangered in dike reinforcement projects.	**Vegetation in the project area** **Vegetation on the dike**
	Healthy ecosystems: Healthy ecosystems are an important condition for the survival of stocks in the project area	According to Christian (n.d.), an ecosystem can be decomposed in three components: • The abiotic system • The biotic system • Interaction between abiotic and biotic system This is a large and complex system, which provides certain indicators to measure the value and quality of ecosystems in an area. Janssen-Jansen, Klijn, & Opdam (2009), states that for the abiotic system, soil moisture and altitude are important boundary conditions. The biotic system is presented by the vegetation in the area, which also indicates when the abiotic system changes. This therefor provides a measurement on the functioning of the ecosystem. Dike reinforcement interfere these systems.	**Vegetation in the project area** **Vegetation on the dike**

As follows from the reasoning in Table 27, dike reinforcements in rural influence many aspects with respect to ecological values of the project area. It can be concluded, that besides the design itself, also the future activities on the dike can provide a large impact on the existing ecological situation in the project area.

B.3.4. Cultural perspective

The same as for economic-, social-, and ecological perspective is done for the cultural perspective of spatial quality. Based on the terms identified in the Workbench Method, it is explained what describes the cultural value of a project area (Table 28).

Table 28: Cultural values in dike reinforcements (based on Hooimeijer et al. (2001))

	Explanation	Dike reinforcement design in rural area	Indicator
User value	**Freedom of choice:** In the spatial planning it should be accounted for the different interests of different people. The space should be developed in such a way that everybody can chose something that interests them.	The topic freedom of choice is moreover a consideration for complex and builded environments, because there is a large variety of activities at that locations. For dike reinforcements in rural areas, this is not the case.	**No changes experienced**
	Cultural variety: The variety in culture enriches an area, because it tells the story of an area from the past to the present	The cultural variety of an area, tells the story of the area from the past to the future. According to the LoLa landscape architects (2014) this story, is a story of floods and army defence lines among Dutch rivers, which is typically a multifunctional element. This character of the dike can be heavily interfered with, when a dike reinforcement is constructed.	**Culture in design** **Historical elements indicating floods** **Historical elements illustrating war**
Perceived value	**Contrast in environment:** A space with contrasts can be unique and therefore be valued. People can think of the contrast between building environment and nature, or agriculture.	A dike is a contrast between a flowing river, which is natural, and a builded environment (polder). This characteristic is valued in dike reinforcement projects, and showed by means the existing dike design (TAW, 1994a). The typical character of the dike can be changed when the design of the dike is changed.	**The experienced contrast in the project area**
	Beauty of culture: Many people are touched and motivated by the beauty of culture of an area.	The beauty of a landscape is valued by people. This beauty is caused by a certain composition of the landscape. A landscape is a composition of remarkable structures, such as a flood defence network bordered by cultural and natural expressions. Due to a reinforcement of a dike, this system is interfered.	**The experienced cultural beauty in the project area**
	Singularity: A special character of a project area should be safeguarded and utilized.	A dike reinforcement is unique cultural landscape which is, according to TAW (1994a), valued because it is illustrates the dense mix of different use functions with a historical character. This unique composition is interfered (positively or negatively) during dike reinforcements. Influence is negatively experienced, when the flood defence structure is decoupled from other use functions of the area.	**The experienced cultural singularity in the project area**
Future value	**Heritage:** Cultural heritage is an irreplaceable quality, a source of information. This information is lost when the element is gone.	Cultural heritage is an important value in living environments. These elements describe life in past generations. Due to the design of a dike reinforcement it may be required to destroy some elements.	**Heritage in project area**
	Integration: Cultural elements get a place in the public area, leading to new development areas for culture.	Integration of cultural expressions focusses on the design of the dike in its environment. A characteristic design can be the new attractor of the area.	**Culture in design**
	Cultural innovation: By implementing new cultural elements an attractive area can be created.	The scope of dike reinforcement projects in rural areas is providing certain safety for the people living in the hinterland. This is not related to creating new cultural expressions.	**No changes experienced**

In many areas among Dutch rivers, cultural aspects play an important role. By reflecting the provided cultural terms of the Workbench Method on dike reinforcement projects it can be concluded there are two types of cultural expressions. A large part of the identified indicators focussed on the past development of the dike within an area (such as floods), expressing the origin of the area. Besides the dike related indicators, also other heritage elements are important, as these elements tell a story about the past use of the area.

B.4. Setting functional spatial quality indicators

As discussed in Section B.1, spatial quality is a definition which is not unambiguously defined in literature. In Section B.3, it is reasoned how dike reinforcements can influence these spatial quality, when it is defined as sustainable development. The identified influence of a dike reinforcement project on the spatial quality in a project area, can be roughly divided in three groups:

- The aesthetical qualities of the area,
- The process related qualities of project, and
- The functional qualities of the project area.

As explain in the scope of this study, it has been focused on developing a model that expresses the changes on the functional qualities within the project area, caused by dike reinforcement projects (Section1.4). To identify the functional quality indicators of the project area, in Table 29, the identified spatial quality indicators from the Workbench Method have been separated in the three groups. In the remainder of this study, aesthetics and process related indicator will not further be studied.

Table 29: Dividing the identified indicators in the Workbench Method

Category	Aesthetics related indicators		Process related indicators		Functional indicators	
	Workbench Term	Indicator	Workbench Term	Indicator	Workbench Term	Indicator
Economic values	Image/ attractiveness	The experienced image/attractiveness of the project area			Accessibility	Transportation function on the dike
						Transportation function of the river
					Multi-purpose	Effective space use on the dike
						Effective space use in the area
					Stability/flexibility	Lifetime of the dike design
Social values	Connectedness	The experienced connectedness to a dike	Distribution	Finance structure of the project	Access	Living in the project area
				Stakeholder analysis		Agriculture in the project area
	Safety (feeling)	The experienced safety feeling at a dike	Participation	Public participation plan	Safety (feeling)	Overtopping discharge of the dike
Ecological values	Healthy living environment	The experienced healthiness in the project area			Ecological structures	Ecological structures in the project area
	Beauty of nature	The experienced natural beauty in the project area			Clean environment	Bottom pollution
						Air pollution
						Water pollution
						Noise pollution
	Healthy ecosystems	The experienced natural peace in the project area			Water in balance	Ground water balance
					Ecological stocks	Vegetation in the project area
						Ecology on the dike
					Healthy ecosystems	Vegetation in the project area
						Ecology on the dike
Cultural values	Contrast in environment	The experienced contrast in the project area			Cultural variety	Culture in design
						Historical elements indicating floods
	Beauty of culture	The experienced cultural beauty in the project area				Historical elements illustrating war
					Heritage	Heritage in project area
	Singularity	The experienced cultural singularity in the project area			Integration	Culture in design

Appendix C:
Review on designing against failure mechanisms

In this chapter, it will be focussed on the safety assignment that has to be fulfilled in dike reinforcement projects. Section C.1 introduces how the design of the dike is approached in the Netherlands. Afterwards, in Section C.2 it is per considered failure mechanism physically explained how failure is caused and how resistance against failure can be increased.

C.1. Design rules for dike reinforcement projects in the Netherlands

To determine the required dimensions of a dike, a probability of failure of a dike section is set by the Dutch government. This probability of failure is based on the resistance against the applicable failure mechanisms at the location of the dike reinforcement project. The designer of the reinforcement is free to choose the distribution of the probability of failure per failure mechanism, as long as the sum of all failure mechanisms together is equal or lower than the required probability of failure set by the Dutch government. This probability of failure is chosen for a dike segment, which is the length of a dike for which the Dutch government set the required safety level (ENW, 2017).

If the failure probability per failure mechanism is set, the segment is divided in sections that have the same hydraulic and geotechnical characteristics (Figure 81). The required dimensions for the dike per section can be calculated by adding a length factor to a cross-sectional design, that is based on the set failure probabilities per mechanism (ENW, 2017).

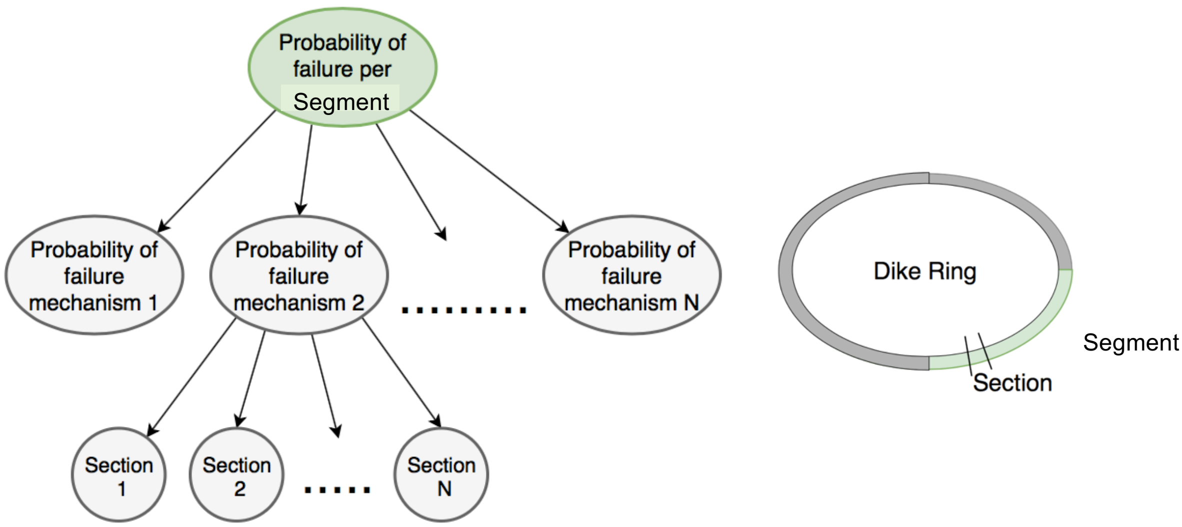


Figure 81: Determination of probability of failure per segment

C.2. Designing against failure mechanisms

To determine the required dimensions of the dike that meets the safety requirements, resistance should be created against physical processes that potentially cause breaching of the dike. There are many possible causes for dike failure, this study focusses on three of them;

- erosion of the inner slope/crest,
- stability of the inner slope,
- piping

Each failure mechanism is caused by a different process. In this section, the processes of the considered failure mechanisms are explained. Based on this physical description it is also, per failure mechanism reasoned how the resistance against that failure mechanism is changed, when changing certain design parameters (as shown in Figure 82). Only the parameters are discussed, that can logically be changed in dike reinforcement projects, as set within the scope of this study.

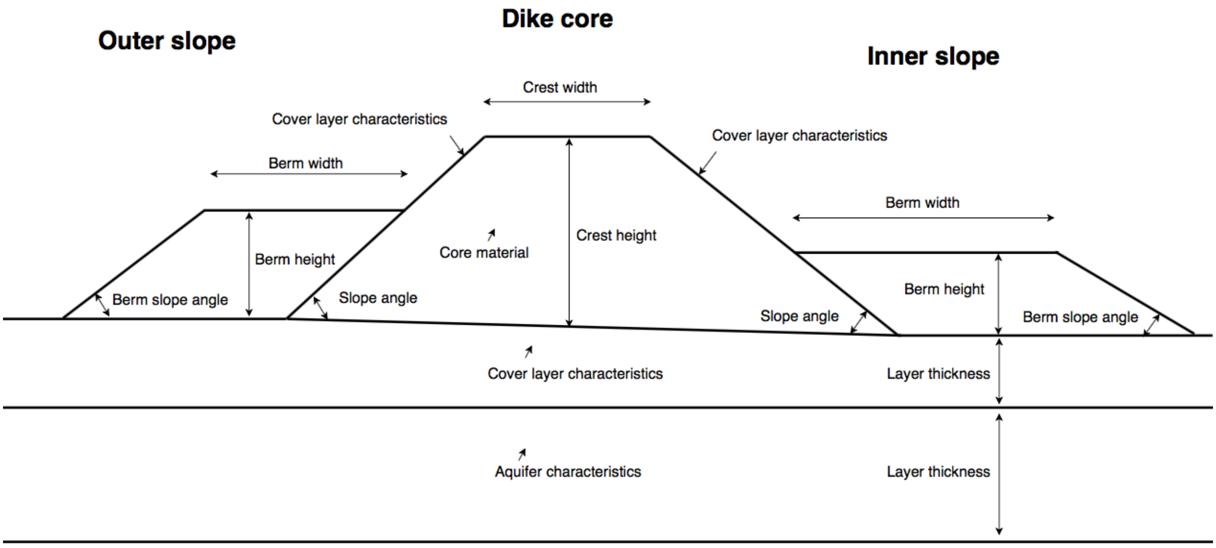


Figure 82: Design parameters of a dike cross-section in soil

C.2.1. Erosion of the inner slope/crest

Resistance against erosion on the inner slope and crest is an important boundary condition in the determination of the crest height of the dike. Erosion on the inner slope or crest can be caused by overtopping waves or overflow of the dike. Overflow is the phenomenon that occurs when the water level in the river is higher than the crest height of the dike. This phenomenon is only normative when there are no waves under design storm condition of the dike. Otherwise, wave overtopping is the phenomenon that causes erosion on the inner slope (Jonkman et al., 2017).

Wave overtopping occurs when the run-up of the waves exceeds the crest level of dike. The overtopping amount of water will flow over the crest and inner slope into the hinterland. This high velocity and turbulent flow over the crest and inner slope exposes the cover layer to large water pressures differences, which can initiate erosion of the cover layer. When, at one location, the cover layer is completely eroded, the core of the dike is exposed to overtopping discharge and erosion of the core will be initiated. Erosion of the core has been started, and a gap on the inner slope will be growing, which can eventually lead to instability and breaching of the dike section (Figure 83).

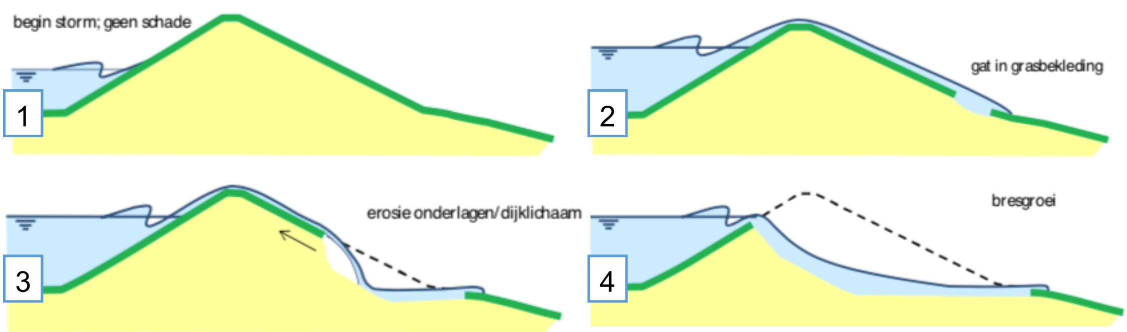


Figure 83: Schematization of breaching due to erosion inner slope ('t Hart., De Bruijn, & De Vries, 2016))

Design parameters

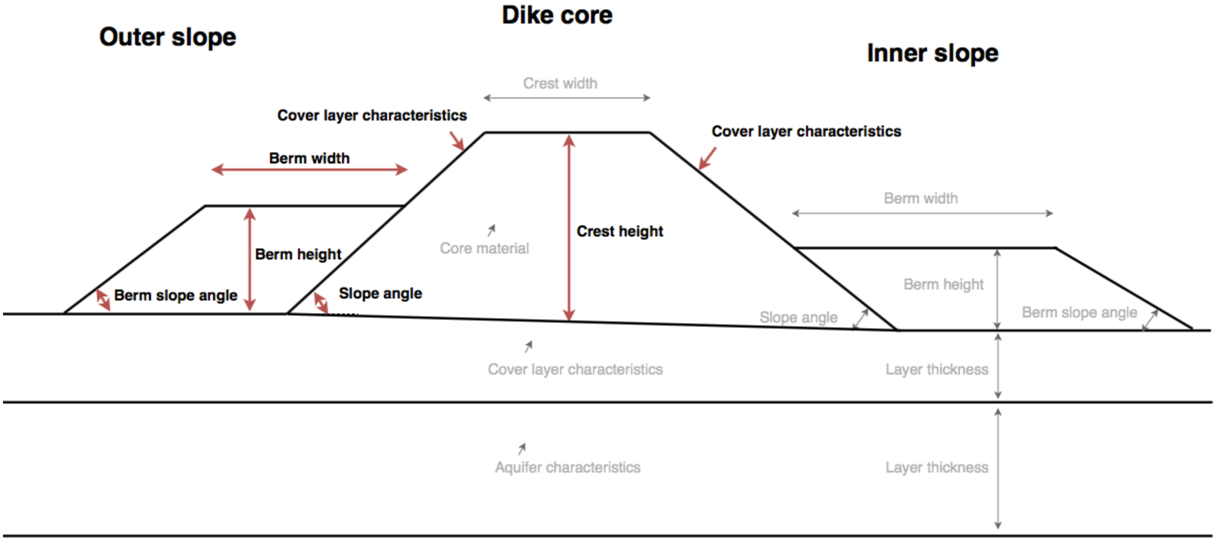


Figure 84: Parameters that provide resistance against erosion of the inner slope

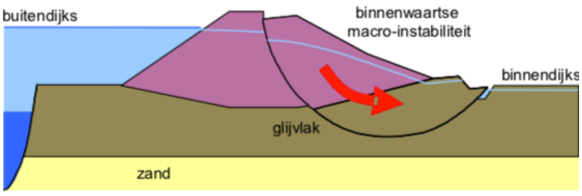
Occurrence of erosion of the inner slope or crest is dependent on two factors; the amount of wave overtopping, and the strength of the cover layer on the crest and the inner slope. Figure 84, shows which parameters influence the strength of the design on this failure mechanism. Table 30 explains per parameter, how the resistance against that failure mechanism can change.

Table 30: Effect of changing design parameters, based on Jonkman et al. (2017).

Design parameter	Influence by	Explanation
Outer slope angle (dike)	Resistance against overtopping	The angle of the dike influences the wave run-up. Steeper slopes provide smaller resistance against waves, leading to a higher run-up level.
Cover layer characteristics (outer slope)	Resistance against overtopping	The roughness of the cover layer at the outer slope provides resistance to the waves flowing over the slope of the dike. When this roughness increases, the resistance increases, leading to a decrease in wave run-up.
Crest height	Resistance against overtopping	The amount of overtopping water is dependent on the wave run-up and the crest height of the dike. When the crest height increases, the amount of water reaching the crest reduces, reducing the amount of overtopping.
Cover layer characteristics (crest & inner slope)	Resistance against erosion	The properties of the cover layer on the inner slope, determine the resistance against erosion of the inner slope. For grass covers this is dependent on the quality of the grass. Good quality grass can be exposed to a larger overtopping amount than pore quality grass.
Inner slope angle	Resistance against erosion	When the inner slope angle gets steeper, the gravitational acceleration in the flow gets a larger influence, increasing the flow velocities on the inner slope. It is expected that the forces on the inner slope increase, leading to a more vulnerable situation for the cover layer at the inner slope (Rijkswaterstaat, 2018)
Outer berm height	Resistance against overtopping	Whether the outer berm contributes to the resistance against overtopping is dependent on the height of the outer berm. When the outer berm is located in-between the water level minus two times the significant wave height and the maximum run-up level, the berm provides resistance against wave run-up. This resistance is maximum when the berm height is equal to occurring water level. The further the berm is located from the water level, the less the influence of the berm is on the run-up of the waves.
Outer berm width	Resistance against overtopping	When a berm is located in-between the water level minus two times the significant wave height and the maximum run-up level, also the berm width provides extra resistance. The resistance against run-up grows when the width of the berm grows, since the length on which friction on the wave is applied is larger.
Outer slope angle (berm)	Resistance against overtopping	When the berm is located such that it provides resistance against run-up, also the slope of the berm contributes to the resistance against run-up. Shallow slopes provide more friction than steep slopes, this is cause by the longer length of the slope.

D.2.2. Stability of the inner slope

The instability of the inner slope, is the failure mechanism in which a large part of the inner slope collapses due to the loss in effective stresses in the soil (dike and sub-layers). This failure mechanism focusses specifically on deep sliding planes that cause breaching of the cross-section, with a minimum depth of one meter below the ground level. Shallow sliding planes are evaluated in other failure mechanisms, such as micro-instability or shearing of the cover layer.



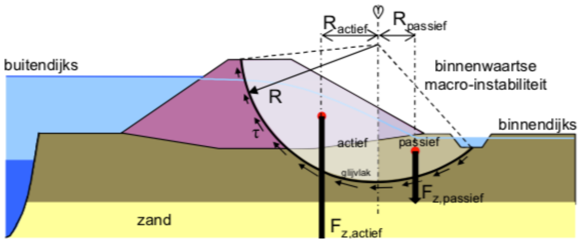


Figure 85a: Schematization of inner slope instability *85b: Forces on a sliding plane*

Instability of the inner slopes often occurs when the water level in the river rises during a long period. Due to high water levels, water will start infiltrating the dike core and sub-soil under the dike. This infiltration causes an increasing pore water pressure in and under the dike, resulting in a decreasing effective stress in the soil in the core and sublayers of the dike. Whether the soil will be sliding is dependent on the momentum equation between three forces; the active soil pressure, the passive soil pressure, and the shear stress (Figure 85b). When the driving moment (soil weight in the active zone), exceeds the resisting moment (soil weight in the passive zone plus the shear strength), a sliding plane will be developed and the stability of the inner slope is lost. The sliding will be formed at the location of minimum resistance; this is not a fixed location in the cross-section of the dike ('t Hart et al., 2016).

Soil behaviour

To understand the physical effects of sliding planes, some more insight in soil behaviour is needed. The two extremes in soil behaviour are drained and undrained behaviour. Soil behaves drained, when the soil immediately adapts to the new loading situation, without limitations caused by the permeability of the soil. Soil behaviour is called undrained, when pore water cannot be drained out of the pores, making consolidation difficult. A change in soil stress will in this situation, for the largest part be absorbed by the water pressure in the pores, leading to over- or under pressure in the pores of the soil. An overpressure is created when a saturated material is compressed, but water cannot flow out of the sample. The added pressure on sample is absorbed by the water, this is called overpressure. Under pressure is the opposite phenomenon of overpressure. Whether the soil behaves drained or undrained, is dependent on the speed of the load change and the permeability of the soil. Soil, such as clay and peat are known as a soils with a small permeability, and will therefor earlier react undrained when compared to sand (which has a high permeability) (Verruijt, 2001).

Soil behaviour during sliding is also an important measure in determination of the shear strength at the sliding plane. When soil on the sliding plane behaves drained, the deformation in the soil does not lead to water under- or overpressures at the sliding plane, because the soil can respond quick enough to the deformations. As the effective stress is not affected by water pressures, the shear strength can be related to the cohesion of the soil, the effective stress in the soil, and the internal friction angle. This is different in the case of undrained soil responses. Due to a water flow limitation during sliding, water is not able to escape or enter the pore within the same time as the deformation develops. This causes over- or under pressures of the water in the pores. These pressures affect the shear strength of soil, because effective stresses of the grains are affected. In highly over consolidated soils (in which the vertical yield stress is much larger than the in-situ effective stress), soil has the tendency to loosen a bit at the sliding plane. This is called dilatant behaviour, causing under pressure in the pores, increasing the effective stress in the soil. On the other hand, in mild over consolidated soil, the soil has the tendency to consolidate during sliding, causing over pressure in the pores, reducing the effective stress at the sliding plane (Rijkswaterstaat., 2016).

Loads
In determination of the resistance against sliding of the inner slope, two types of loads can be distinguished; hydraulic loads and top loads. Hydraulic loads are caused by infiltration of the water into the dike core and by infiltration of the water into the aquifers under the dike. Due to the rising phreatic surface in the dike core, pore water pressure increases, resulting in a decreasing effective stress in the dike. When the head in the aquifer rises due to the increasing water level, the same phenomenon occurs. In addition, also the cover layer near the inner toe of the dike can be exposed to uplift conditions, in which the pore water pressure in the aquifer is larger than the weight of the cover layer. The cover is lifted in this situation, which causes that the shear stress between cover layer and aquifer is lost. This makes the stability of the inner slope of the dike less stable. In uplift conditions, a ditch near the toe of the dike will be unfavourable, since the resistance against uplift is smaller at this location due to the "gap" in the cover layer (Rijkswaterstaat., 2016).

Besides the hydraulic loads, also top loads on the crest of the dike influence the stability of the inner slope negatively. An example of a top load on the dike the load caused by traffic. Due to fast movements of traffic on the crest, the soil has no time to respond to the new situation, causing that soil behaviour under this load is typically undrained. Depending on the yield stress of the soil (consolidation of soil in the dike), this can lead to a large negative influence on the sliding resistance of the soil. In the momentum equation a large force will be added to the crest, while the shearing capacity of the soils grows with a smaller factor (Rijkswaterstaat., 2016).

Design parameters

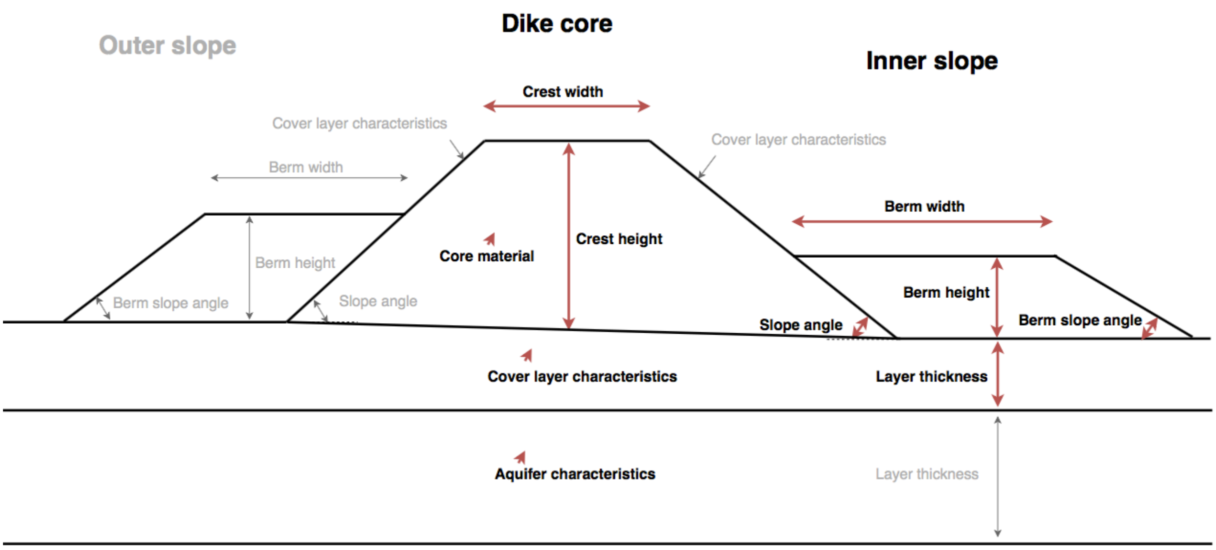


Figure 86: Parameters that provide resistance against sliding of the inner slope

As explained, the occurrence of instability of the inner slope is dependent on the momentum equilibrium between three forces, the shear strength, the active soil weight, and the passive soil weight. Figure 86, shows which parameters influence the strength of the design on this failure mechanism. It is dependent on the sliding planes location, what the contribution of different parameters is to the resistance against the failure mechanism. When soil is added to the cross-section the existing equilibrium situation is changed, since soil weight is added on the active and/or passive side of sliding plane. Changing these weights, also changes the shear strength of the soil among the sliding plane, leading to a new safety against sliding. When soil is added on the passive site of the sliding plane, the resisting moment and shear strength under the reinforcement increase, leading to an increasing resistance against sliding. It is more complicated when soil is added on the active site. In this situation, the relation between the increase in shear strength and the added weight is important. This is dependent on the behaviour of the soil on the sliding plane in saturated conditions:

- **Overpressure at sliding plane**: when there is overpressure at the sliding plane, the water pressure at the sliding plane, reduces the shear strength at the sliding plane. As explained, overpressure at the sliding plane occurs in mild over consolidated soils (*in Dutch: contractant gedrag*). Added weight at this location leads to a negative influence on safety, as the momentum increase due to soil weight is larger than the momentum increases due to the increase in shear strength.
- **Neutral pressure at sliding plane**: in the neutral situation, the pore pressure will not change due to the deformation among the sliding plane. Added weight at this location has no influence on safety, as the momentum increase due to soil weight is equal to the momentum increase due to the increase in shear strength.
- **Under pressure at sliding plane**: when there is under pressure at the sliding plane, the water pressure at the sliding plane, increases the shear strength at the sliding plane. As explained, under pressure at the sliding plane occurs in highly over consolidated soils (*in Dutch: dillatant gedrag*). Added weight at this location leads to a positive influence on safety, as the momentum increase caused by the soil weight is smaller than the momentum increase caused by the increase in shear strength.

For the above described soil reactions on the active side of the sliding plane, it is assumed that the consolidation process of sub-layers is finished, before the normative high water conditions occur. Therefore, no additional effects on shear strength are considered as result of consolidation effects of the subsoil.

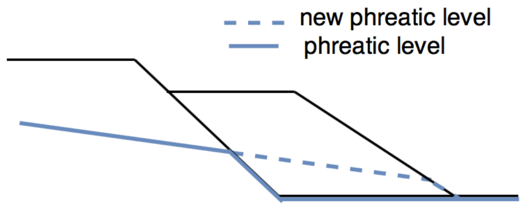


Figure 87: Adaptation of the phreatic line

The earlier described three situations assume an unchanged phreatic level in the dike, after the construction of the soil reinforcement. This is not necessarily the case, as there also may be a phreatic level in the reinforced dike section (Figure 87). In that specific case, shear stresses in the soils also reduce due to an increased water pressure, compared to the old situation. When this is on the active site of the sliding plane, the increased water pressure, results in a decreased effective stress in the soil, creating an unfavourable momentum growth at the sliding plane.

Based on the above described physics behind sliding planes, in Table 31, it is per parameter explained, how the resistance against that failure mechanism can change, due to variations in the design.

Table 31: Effect of changing design parameters, based on Jonkman et al. (2017) and 't Hart et al. (2016)

Design parameter	Influences	Explanation
Cover layer characteristics (outer slope)	Shear strength	The permeability of the cover layer on the outer slope is important for the phreatic level that occurs in the core of the dike. Smaller permeability, results in a lower phreatic level in the dike. If the phreatic level is lower, effective stresses in the core of the dike will be larger, providing larger shear strength of the dike.
Crest width (dike)	Active soil weight, Passive soil weight & Shear strength	When the crest width is growing, this will lead to an overall increase of the width of the dike (not to steeper slopes). Depending on the sliding plane, the soil will be added to the active and passive side of the sliding plane. If the increase in shear strength plus the increase of soil weight on the passive is larger than the increase in active soil weight (in the momentum equation), an increasing dike width leads to a growing safety against sliding of the inner slope
Crest height (dike)	Active soil weight & Shear strength	When the crest height is increased, it is supposed that the crest width will decrease (nothing changes to slopes). When sliding planes through the crest are considered, adding extra height to crest will increase the soil weight on the active side. Also the shear strength will be increased, but is dependent on the soil behaviour whether the resulting moment is positive or negative for the stability (as explained earlier this section). An additional effect of heightening is decreasing the overtopping. When overtopping is decreased, the phreatic surface in the dike core will be lowered. A lower phreatic surface, has a positive effect on the shear of the dike. This increases stability of the slope.
Core material (dike)	Active soil weight & Shear strength	Different soils have different properties. Therefore, a change of core material can have effects on the shear strength of the slope and the phreatic surface within the dike.
Inner slope angle (dike)	Active soil weight, Passive soil weight & Shear strength	When the inner slope angle of the dike gets shallow (but the height of the dike remains constant), soil will have to be added to the inner slope. In large sliding circles (where soil is only added to the active side), this can negatively influence the stability of the inner slope. When also a part of the reinforcement is placed on the passive site, this part will contribute positively to the resistance against sliding of the inner slope.
Inner berm height	Active soil weight, Passive soil weight & Shear strength	It is dependent on the width of the berm and the normative sliding plane, what the effect of berm height is on the resistance against sliding of the inner slope. Extra height of the berm is only favourable in the situation, where the soil is located on the passive side of the sliding plane.
Inner berm width	Active soil weight, Passive soil weight & Shear strength	The width of the berm has a positive influence on the resistance against sliding when it is located in the passive zone of the sliding planes. The influence of the berm width is optimal when it covers the total passive zone of the normative sliding planes.
Inner slope angle (berm)	Active soil weight, Passive soil weight & Shear strength	A shallower inner slope of the inner berm results in a larger soil weight in the soil under the slope. When this is located in the passive zone of the sliding plane, the resistance against sliding will increase. While constructing in the passive side, decreases the stability.
Cover layer thickness		The cover layer thickness has effect on the resistance against uplift. In an uplift situation, the shear strength on the edge between the cover layer and aquifer is assumed to be zero, because resistance is lost when to cover layer is lifted.
Cover layer characteristics		Due to low permeability of the cover layer, the soil will behave undrained in the sliding plane, dependent on the pre consolidation of the soil this can negatively influence the shear strength.
Aquifer characteristics		Due to the high permeability of the aquifer, the water head in this aquifer will rise corresponding to the water level in the river. This creates an upward force on the cover layer, which is unfavourable for the stability of the cover layer.

Besides the above mentioned soil parameters, also structural intervention can increase the resistance against the failure mechanism "Sliding of the inner slope". An example of a structural intervention is the construction of a sheet pile wall in the inner toe of the dike. This structure increases the shear strength, because it blocks potential sliding planes (when the wall is sufficiently strong).

C.2.3. Piping

Piping is the mechanism in which sediment is washed away from under the dike into the hinterland. Breaching of the dike section occurs when a continuous “Pipe” is formed between the river side and the hinterland, leading to a structural collapse of the dike due to erosion of the subsoil.

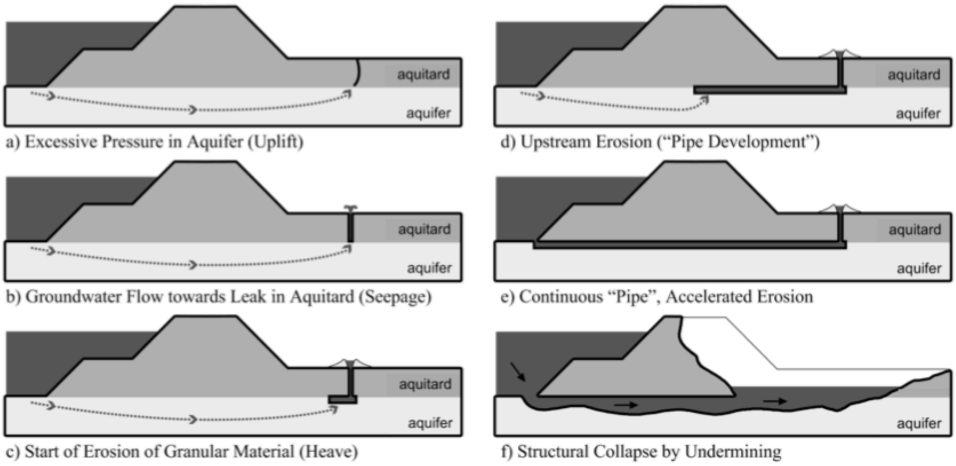


Figure 88: Piping process (source: Jonkman et al. (2017))

The mechanism piping can be described based on the six steps represented in Figure 88. Due to a large water level difference between the water level in the river and the water level in the hinterland, water pressure is built up in the aquifer under the dike and in the hinterland. When this water pressure is larger than the weight of the cover layer, the cover layer can crack (uplift, Figure 88a). This can initiate a concentrated water flow between the subsoil and the ground level in the hinterland (seepage, Figure 88b). When the hole gets large, and the water flow is strong enough, grains from the aquifer can be transported through the cover layer towards the ground level (heave, Figure 88c). As water flows towards the point of the least resistance, the flow will be concentrated on the place where erosion occurred and more material starts eroding from that location. A “pipe” will be formed on the edge between the cover layer and the aquifer (Figure 88.d). The erosion in this pipe will be accelerated, due to the resistance loss when material is washed away from the aquifer. When, eventually, the dike is completely undermined, this hollow pipe will be broadened by the flow from the river into the hinterland and eventually the dike section will breach (Figure 88f) (‘t Hart et al., 2016).

Design parameters

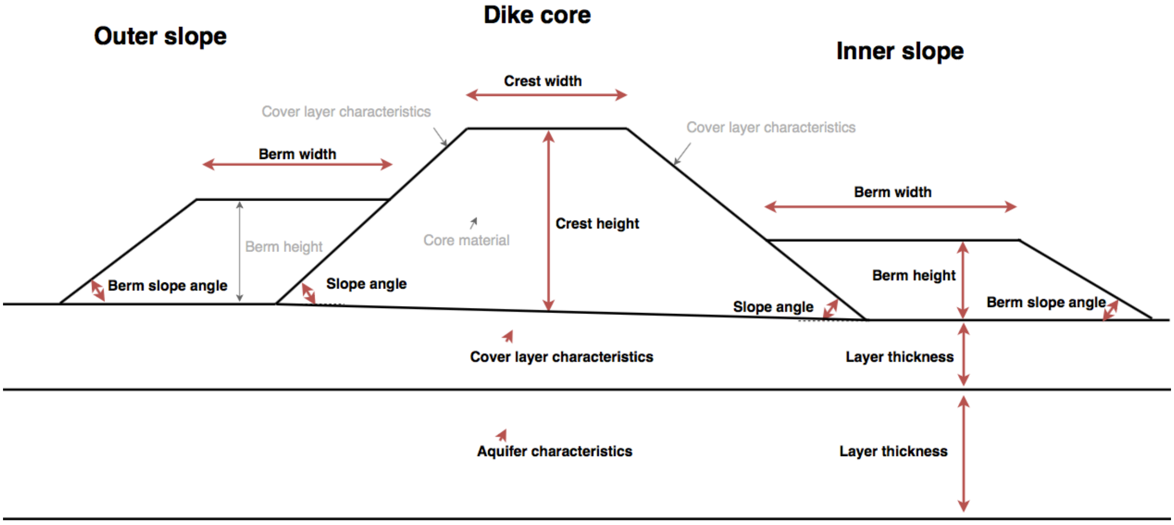


Figure 89: parameters that influence the resistance against piping

There are several design options that create resistance against failure due to the failure mechanism piping. Figure 89, shows which parameters of a soil dike contribute to the resistance against piping. Piping causes failure of a dike section when three processes occur consecutively: uplift, heave, and piping. In the following paragraphs it is per process, explained how resistance is dependent from design location characteristics. Table 32 describes potential interventions that increase the resistance against piping.

Uplift

Uplift is the first mechanism occurring when piping potentially compromises the safety of the dike. This phenomenon occurs at the toe of the dike when the water head in the aquifer, is larger than the downward pressure caused by the weight of the cover layer. The vulnerability of the subsoil against uplift can be determined based on the water head in the subsoil and the resisting force by means of the own weight of the cover layer (TAW, 1999).

Heave

Due to upward seepage, the water pressure in the cover layer gets larger than the hydrostatic pressure. This overpressure causes, a decrease in effective stresses. When the over pressure is equal to the effective stresses, the sand will be liquefied, which makes it easy to flow towards the top of the cover layer (TAW, 1999).

Piping

The head difference between the river and hinterland is important for the mechanism piping. When the hydraulic gradient at the gap in the cover layer is sufficiently large, the grains are mobilised and flow towards the exit point (gap in the cover). A pipe will be created on the edge of the aquifer and the cover layer. This process accelerates due to the friction loss in the aquifer, increasing the length of the pipe (Jonkman et al., 2017)

Table 32: Piping measures (source: TAW, 1999)

Measure	Example	Uplift	Heave	Piping
Increasing horizontal seepage length	Piping berm width in hinterland Increasing dike width Add clay cover to foreland	Decreases water pressure in aquifer, decreasing upward pressure under cover layer.	Decreases water pressure in aquifer, increasing effective stresses in the cover layer.	The seepage length is longer when the berm is constructed, decreasing the hydraulic gradient in the subsoil. Decreasing the forces on grains, just below the cover layer.
Increasing vertical seepage length	Seepage screen	Due to the extra seepage length, the water pressure on the hinterland side will decrease.	Due to the extra seepage length, the water pressure on the hinterland side will decrease.	Increases the seepage length, creating a lower hydraulic gradient. This decreasing the forces on grains, behind the screen (in the hinterland).
Preventing uplift in critical seepage length	Piping berm height in hinterland	Due to extra downward force, the resistance against the water pressure in the aquifer increases	The effective stress in the cover layer increases due to the berm. Resistance against fluidization of sand increased.	No effect.
Reducing head difference between river and hinterland	Decrease river water level Increase hinterland water level	Increasing hinterland water level, increases weight of the cover layer due to saturation of the cover layer. Chance on uplift decreases	Effective stress in the cover layer decreases, decreasing the resistance against fluidization of the grains flowing through the cover layer.	When the head difference decreases, the mobilization forces on the grains in the pipe decrease. Reducing the probability of occurrence of piping.
Prevent transportation of sand to ground level	Filter construction	No effect.	An extra resistance is created to prevent soil from flowing towards the ground level.	No effect.
Prevent pipe formation	Vertical geotextile Vertical gravel column	No effect.	No effect.	An obstacle blocks the formation of a pipe in the direction of the river side. Undermining of the dike will therefore not occur.

Appendix D:
Technical assignment in developed method & case study

In this chapter, it has been explained how the technical assignment is evaluated in this study. This evaluation is started in Section D.1, this section describes what the required safety levels for the designs of the dike reinforcements are. Afterwards, in Section D.2, it has been explained how the failure mechanism erosion of the inner slope is evaluated in this study. This is followed by the evaluation of the failure mechanisms “Stability of the inner slope” (Section D.3), and “Piping (Section D.4). Section D.5, explains the design variations considered in this study, while Section D.6 clarifies the strategy for the evaluation of the safety assignment. Eventually, in Section D.7, the obtained results are verified.

D.1. Safety standards for failure mechanisms

For assessing the safety assignment, it should per failure mechanism be known what the required safety demands are. The Dutch Water Act (2017) prescribes that dikes should be designed based flood probabilities (this has been explained in Appendix C). The total failure probability is distributed over the applicable failure mechanisms, this distribution is equal throughout a dike segment. As in this study, only three failure mechanisms have been considered, it is assumed that the failure budget is on the other failure mechanisms is not interfered with. According to ENW (2017), the following failure probability budgets are standard for the (in this study) considered failure mechanisms:

- Piping: 24%
- Erosion of the inner slope: 24%
- Stability of the inner slope: 4%

In Table 33, it has per failure mechanism been determined how the standard failure budgets result in a failure mechanism specific safety condition. The calculation of the safety condition has been based on Rijkswaterstaat (2017), which explains the relations between failure probabilities and the safety conditions of the different failure mechanisms. Also, it has been determined what the influence on the safety conditions is when the failure budget has been changed. For stability of the inner slope the failure probability has also been considered when the failure budget is shifted to 24%, while for piping and erosion of the inner slope also the required safety conditions corresponding to a failure budget of 4% are considered.

Table 33: determining safety requirements for case study Wolferen-Sprok

Name	Unit	Section 43-4	
Failure norm for segment	[1/year]	1/10.000	
Inner slope stability			
Length effect [N_{dsn}]	$= 1 + \frac{a_l * L_{traject}}{b_l}$ [-]	17.0	
Mechanism sensitive fraction of segment length [a_l]	[-]	0.033	
Value showing the intensity within mechanism sensitive length of the dike [b_l]	[m]	50	
Segment length [$L_{traject}$]	[m]	25,800	
Failure probability budget [ω]	[-]	0.04	0.24
Cross-section norm [$P_{eis;\,dsn}$]	$= \frac{\omega P_{eis}}{N_{dsn}}$ [1/year]	2.3e-7	1.4e-6
Reliability index [$\beta_{eis;\,dsn}$]	$= -\phi^{-1}(P_{eis;\,dsn})$ [-]	5.04	4.68
Damage factor [γ_n]	$= 0.15 * \beta_{eis;\,dsn} + 0.41$ [-]	1.17	1.11
Material factor [γ_m]	[-]	1.00	
Model factor [γ_d]	Uplift Van [-]	1.06	
Schematization factor [γ_s]	[-]	1.20	
Safety Factor [SF]	**$= \gamma_n * \gamma_m * \gamma_d * \gamma_s$ [-]**	**1.48**	**1.42**
Height			
Length effect [N_{dsn}]	[-]	1	1
Failure probability budget [ω]	[-]	0.04	0.24
Cross-section norm [$P_{eis;\,dsn}$]	**$= \frac{\omega P_{eis}}{N_{dsn}}$ [1/year]**	**4.0e-6**	**2.4e-5**
Piping			
Length effect [N_{dsn}]	$= 1 + \frac{a_l * L_{traject}}{b_l}$ [-]	77.4	
Mechnanism sensitive fraction of segment length [a_l]	[-]	0.90	
Value showing the intensity within mechanism sensitive length of the dike [b_l]	[m]	300	
Segment length [$L_{traject}$]	[m]	25,800	
Failure probability budget [ω]	[-]	0.04	0.24
Cross-section norm [$P_{eis;\,dsn}$]	$= \frac{\omega P_{eis}}{N_{dsn}}$ [1/year]	5.2e-8	3.1e-7
Reliability index cross-section [$\beta_{eis;\,dsn}$]	$= -\phi^{-1}(P_{eis;\,dsn})$ [-]	5.32	4.98
Reliability index segment [β_{max}]	$= -\phi^{-1}(P_{eis})$ [-]	3.72	3.72
Safety factor Piping [γ_{pip}]	**$= 1.04 * e^{0.37 * \beta_{eis;\,dsn} - 0.43 * \beta_{max}}$ [-]**	**1.50**	**1.33**
Safety factor Uplift [γ_{up}]	**$= 0.48 * e^{0.46 * \beta_{eis;\,dsn} - 0.27 * \beta_{max}}$ [-]**	**2.03**	**1.74**
Safety factor Heave [γ_{heave}]	**$= 0.37 * e^{0.48 * \beta_{eis;\,dsn} - 0.30 * \beta_{max}}$ [-]**	**1.07**	**0.91**

D.2. Erosion of the inner slope

Erosion required safety for erosion on the inner slope is an important condition for determining the required crest height of the dike. To evaluate the strength of the dike designs on erosion of the inner slope, governmental regulations on the design have been followed (Rijkswaterstaat, 2017). These regulations describe that the inner slope has a certain strength, which is based on the material and composition of the cover layer at the crest and the inner slope of the dike. The strength is expressed by means of the critical overtopping discharge in the Dutch design regulations (Water Act, 2017). The crest height of the dike should be designed on the height at which the overtopping discharge during the design storm is smaller than the critical overtopping discharge.

$$q_c > q_{occuring} \qquad \text{[Eq.1]}$$

D.2.1. Critical overtopping discharge

Four scenarios of overtopping discharge have been set for the design of a dike (see Figure 90). It is assumed that a critical overtopping requirement of 0.1 l/s/m is not a realistic design dimension for dike reinforcements in rural areas. Therefore, this value is not considered in the remainder of this study. The other critical overtopping discharges are used to set crest height and outer slope scenarios for the dike reinforcement. Higher overtopping discharges in general lead to higher maintenance requirements for the inner slope.

q_c (l/s/m)	Toepassingsvoorwaarden voor grasbekleding op kruin en binnentalud (aan alle voorwaarden moet voldaan worden)
0,1	• geen eisen
1	• gesloten of open zode[a] op klei[b] • voldoende stabiliteit[c] Bij 1 l/s/m gelden geen eisen aan objecten en overgangen op kruin en binnentalud.
5	• Toepasbaar in twee mogelijke gevallen: – gesloten zode[a] op klei[b] en H_{m0} < 4 m[d] **of** – open zode[a] op klei[b] en H_{m0} < 2 m • taludhelling flauwer dan 1:2,3 • voldoende stabiliteit[c] Bij 5 l/s/m gelden geen eisen aan objecten en overgangen op de kruin. Indien op het talud objecten groter dan 0,15 x 0,15 m^2 en/of overgangen aanwezig zijn, dan dient hier in het ontwerp rekening mee te worden gehouden.
10	• gesloten zode[a] op klei[b] • taludhelling flauwer dan 1:2,3 • H_{m0}<4 m[d] • voldoende stabiliteit[c] Bij 10 l/s/m gelden geen eisen aan objecten en overgangen op de kruin, behalve in het bovenrivierengebied. Indien op het talud objecten groter dan 0,15 x 0,15 m^2 en/of overgangen aanwezig zijn, dan dient hier in het ontwerp rekening mee te worden gehouden. Voor het bovenrivierengebied geldt dit voor talud én kruin.

[a] Een gesloten zode is een op het oog gesloten grasmat, zonder grote (0,15 m x 0,15 m) open plekken[10].
[b] Minimale gegarandeerde kleidikte van 0,4 m, geen eisen aan kleikwaliteit.
[c] Controle van de geotechnische stabiliteit van de bekleding op het binnentalud en de binnenwaartse macrostabiliteit. Dit kan leiden tot aanvullende eisen ten aanzien van kleilaagdikte, kleikwaliteit, het aanbrengen drainage, aanpassing van de taludhelling etc.
[d] Bij H_{m0} > 4 m dient advies over de lokaal te hanteren kritieke overslagdebieten ingewonnen te worden bij de Helpdesk Water (www.helpdeskwater.nl).

De randvoorwaarden die aan de golfhoogte H_{m0} worden gesteld (bijvoorbeeld H_{m0}<2m of H_{m0}<4m) kunnen worden afgelezen uit het illustratiepunt van de Hydra-berekening. Hierbij kan H_s gelijk worden gesteld aan H_{m0}.

Figure 90: Critical discharges of crest and inner slope (Rijkswaterstaat, 2017b)

D.2.2. Crest height calculation

The above described overtopping scenarios are used to determine the required crest height of the dike. As explained, the occurring overtopping discharge during normative conditions should be equal or smaller than the set critical overtopping discharge. In this study, the "Hydra-NL"-software has been used to determine the required crest height that is related to the critical overtopping discharge. This done with a semi-probabilistic calculation that determines the so-called hydraulic loading level (HBN, *in Dutch: Hydraulisch belastingniveau*). This HBN is dependent on the combination of the still water level and the wave run-up occurring at the same moment in time, caused by tides, winds, and river discharges. As the dike reinforcement project is located in the "Bovenrivierengebied", it can be assumed that water levels and wave height in the project area are not dependent on tidal influences and storm conditions at sea. River discharges and wind conditions are the dominant drivers in the calculation of hydraulic loads on the dike (Chbab & De Waal, 2017).

Water level in river

In Chbab & De Waal (2017) it has been found that, river discharges are dominant for determining the water level in the river in the "Bovenrivierengebied". This is caused by the fact that there are only small fetches in the river branches, limiting the influence of wind on the occurring water level in the river. The water level scenarios that are used in Hydra-NL are based on a WAQUE-model of the "Bovenrivierengebied". This model calculates water levels and flow velocities in rivers based on river discharge scenarios. These river discharge scenarios are based on the statistical analysis of 30-years of measurements on rainfall (supplied by the GRADE-model). Applying this method is common practice in the Netherlands, and according to Chbab & De Waal (2017) resulting in realistic water levels in the "Bovenrivierengebied". This water level model has been compared to other models, and it was found that deviations were not large than ten to fifteen centimetres.

Wave characteristics
To determine the HBN, occurring water level should be combined with wave run-up. This run-up is dependent on the wave spectrum in the river. In the Hydra-NL software, these wave heights have been based on the Bretschneider-formulas for determining the wave growth at a specific location in a river. There are some clear limitations for using these formulas to determine the wave characteristics, but it has been concluded that this method provides a good description on "wave growth induced by wind". This conclusion makes the method applicable for the "Bovenrivierengebied", in which the dike reinforcement project has been located. To determine the wave characteristics, three location specific parameters are required; the water depth, fetch, and wind velocity. Resulting in wave characteristics for relatively deep water.

Wave characteristics at outer toe
For determining wave overtopping at the dike, wave characteristics should be known at the outer toe of the dike. In this study, the assumption has been made that the wave spectrum has not been influenced by the foreland. According to TAW (2002), the influence of the foreland on the wave spectrum is negligible when the water depth on the foreland is about three to four times larger than the significant wave height. A smaller water depth provides favourable conditions for wave overtopping, as the largest waves will break before reaching the dike. To determine the validity of the assumption it has per evaluated dike section been determined whether this requirement holds, the results can be found in Table 34.

Table 34: Influence of foreland

	Significant wave height	Normative water level	Ground level		
	h_s [m]	H_{mhw} [m+NAP]	$H_{GL\ outwards}$ [m+NAP]	3* h_s [m]	H_{mhw}- $H_{GL\ outwards}$ [m+NAP]
Section 12	1.8	14.6	8.9	5.4	5.7
Section 13	1.6	14.4	9.8	4.8	4.6
Section 14	1.5	13.9	8.8	4.5	5.1

In Table 34, can be found that at Section 12 and 14, the water depth is larger than three times the significant wave height. However, in Section 13, it can be observed that the value is slightly below three time the significant wave height. At this section there will be a small overestimation of the wave characteristics at the toe of the dike.

Wave overtopping
When the water level and wave characteristics near the outer toe of the dike are, wave overtopping can be calculated. This is in Hydra-NL done with the overtopping formula provided by Van der Meer (2014). This overtopping-formula uses several parameters to determine the overtopping:

- Significant wave height
- Outer slope of the dike
- Wave steepness
- Crest free board (difference between still-water level and crest of the dike)
- Reduction factors for berms, slope roughness, oblique waves, and wall on the crest

It was found that the "Van der Meer"-formula provides a good description on the occurring mean overtopping discharge during design conditions (Jonkman et al., 2017). The HBN is derived from specifying a critical overtopping discharge, resulting in a required crest free board.

As the Hydra-NL software uses a semi-probabilistic method to determine the required the HBN, different combinations on water levels and wave characteristics have been sampled to find the HBN at which the set norm is not exceeded. The, in this section, described calculation method is automatically obtained by a Hydra-NL calculation. Hydra-NL is developed in such way that it is in line with the set governmental regulations (Duits, 2018). The required input for the dike reinforcement project "Wolferen-Sprok" is limited to the angle of the outer slope, and the desired overtopping scenario. The cover layer is in every design constructed from grass. Also, the database on hydraulic loadings of the applicable dike segments are added to have the wave and water level scenarios available in Hydra-NL (Segment 43-4, and 43-5 within the Dutch flood defence system).

D.3. Inner slope stability

For determining the normative 'safe' cross-sectional designs, also the inner slope stability has to be determined. To determine the resistance against sliding, a number of design principles should be set. In this study, the design principles used are based on regulations set in WTI 2017 (Water Act, 2017), unless differently mentioned. In this paragraph, it has been explained what these design principles are set and which boundary conditions have been used.

D.3.1. Boundary conditions

Geotechnical boundary conditions

Research on the soil properties and layering in the project area "Wolferen-Sprok" shows that the soil layering is typical for the "Bovenrivierengebied" in the Netherlands. This typical layering structure consists of an impermeable cover layer on top of a Pleistocene sand layer (Figure 91). The dike body is constructed from clay.

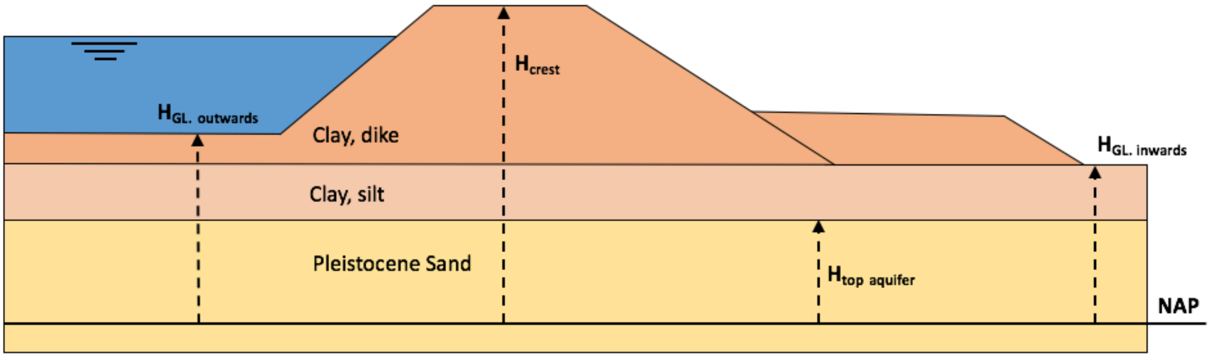


Figure 91: Soil layering in project area

In Figure 91, it can be that the material "Clay, dike" is also used as foreland material. It has been schematized in this way, as the used software for generating cross-sections in D-Geo Stability is only able to process horizontal lines. Nevertheless, it is expected that this schematization does not affect the results for inner slope stability, as it is expected that the shearing plane is initiated in the crest of the dike. Another geotechnical assumption that is made, is that the constructed dike reinforcement consists of material of the same strength as the existing material in the dike.

To evaluate the stability of proposed reinforcement designs, a number of geotechnical parameters need to be set. The normative geotechnical data per section has been based on data supplied by Witteveen + Bos (Witteveen + Bos, 2018-1, Witteveen + Bos, 2018-2, and, Witteveen + Bos, 2018-3). This normative data is the result of research on the longitudinal variability within a section. In Figure 91, can be observed that the layering in the subsoil is dependent on four different parameters; ground level outwards ($H_{GL\ outwards}$), ground level inwards ($H_{GL\ inwards}$), crest height of the dike (H_{crest}). and height of the top of the aquifer ($H_{top\ aquifer}$). These values are expressed relative to NAP. These parameters are only used to schematize the subsoil (and dike core material), not to set the geometry of the dike reinforcement itself. The retrieved parameters on the normative cross-sections per dike section can be found in Table 35.

Table 35: Cross-sectional soil layering (Witteveen + Bos, 2018-1, Witteveen + Bos, 2018-2, and, Witteveen + Bos, 2018-3).

		Section 12	Section 13	Section 14
H_{crest}	[m+NAP]	Dependent on height scenario		
$H_{GL\ outwards}$	[m+NAP]	8.9	9.8	8.8
$H_{GL\ inwards}$	[m+NAP]	9.1	8.9	8.5
$H_{top\ aquifer}$	[m+NAP]	3.4	3.1	5.5

As in this case study, the safety analyses will be performed based on drained soil behaviour (explained in Section D.3.2), information on the internal friction angles and unit weight of the subsoil materials is required. As also the CSSM failure model has been used for the calculations, cohesion of the materials will not play a role. From CPT's in the project area, it is found that soil properties are uniform over the project area. The properties of the three used materials are described in in Table 36. For the stability analysis of the inner slope, unit weights and the internal friction angle are important parameters.

Table 36: Soil properties (Witteveen + Bos, 2018-1, Witteveen + Bos, 2018-2, and, Witteveen + Bos, 2018-3)

Material	Internal friction angle [°]	Unit weight (above phreatic surface) [kN/m^3]	Unit weight (below phreatic surface) [kN/m^3]
Pleistocene sand	30.5	18.0	20.0
Clay, silt	29.3	18.2	18.2
Clay, dike	30.7	18.7	18.7

Hydraulic boundary conditions

For determining the inner slope stability also, water changing geo-hydraulic conditions play an important role. Increasing water pressures in the subsoil, and dike core induce a reduction of effective stress in the soil bodies near, and in the dike. This results in a smaller bearing capacity of the subsoil against shear stresses. How the geo-hydraulic properties are modelled in this study is explained in Section D.3.2. To find the water stresses during normative conditions, it should be known what the water level in the river, and hinterland is during normative conditions. The water level in the river is found based on the Hydra-NL calculations on the water level in the project area. As input for the inner slope stability assessment it has been assumed that the effect of wave height on the geo-hydraulic conditions is negligible. The water level in the hinterland, in this study, has been taken on the ground level in the hinterland. TAW (2004), states that if there is no ditch located near the dike, it is safe set the water level in the hinterland equal the to the ground level in the hinterland.

Table 37: Normative hydrodynamic conditions (for water level hinterland: Witteveen + Bos, 2018-1, Witteveen + Bos, 2018-2, and, Witteveen + Bos, 2018-3)

	Water level in river H_{MHW} [m+NAP]	Water level in hinterland $H_{WL\ inner\ toe}$ [m+NAP]
Section 12	14.6	9.1
Section 13	14.4	8.9
Section 14	13.9	8.5

D.3.2. Calculation principles

Soil failure model (CSSM)

In this study, the Critical State Soil Model (CSSM) has been used to describe the soil behaviour under the normative conditions. The model is explained in the remainder of this paragraph based on Van Duinen (2014). CSSM is a description of the soil behaviour, that couples the behaviour of compression, swelling, volume change, shearing, and pore-water-interaction to effective stresses in the subsoil. By using this method, it can be accounted for:

- differences between peak strength, and the critical state shear strength,

- differences between over-, and normal consolidated soils,
- differences between drained, and undrained soil responses.

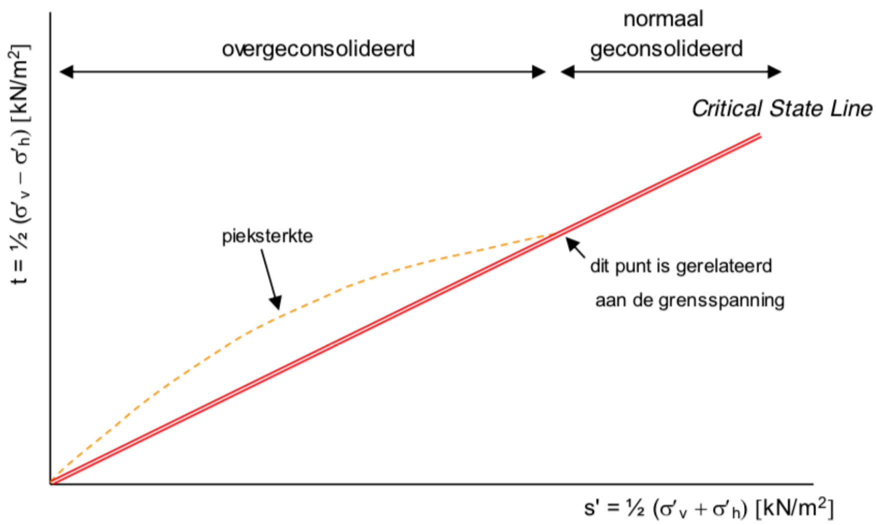


Figure 92: CSSM soil behavior model (Van Duinen, 2014)

The Critical State Line, as shown in Figure 92, is dependent on the following formula:

$$t_{max} = s' \sin \varphi'_{cs} \qquad \text{[Eq. 2]}$$

in which: t_{max} = the maximum mobilizable shear strength (kN/m^2)
s' = vertical effective stress (kN/m^2)
φ'_{cs} = internal friction angle (°)

It can be observed that the cohesion does not play a role in determining the strength against sliding. Nevertheless, the cohesion of soil can be found in the over-consolidation ratio of the subsoil, as it results in a peak strength that is larger than the value found on the Critical State Line (peak strength is the orange line in Figure 92).

When the CSSM model is compared to the Mohr-Coulomb soil behaviour model, it can be observed that there are two mayor differences. CSSM is developed to facilitate undrained soil behaviour in the application of stability analyses, while the Mohr-Coulomb model focusses on drained soil behaviour only. Also, the CSSM considers the maximum mobilizable shear strength as ultimate state of the soil, while the Mohr-Coulomb model determines the maximum mobilizable shear strength as the shear strength that initiate plastic deformations. As soils in, and near dikes often have varying properties, it seems that the CSSM model is a more realistic model to determine the shear strengths that leads to failure due to sliding.

Soil behaviour (drained)
Besides the choice of failure model, also the soil response is an important consideration in the assessment of stability on the inner slope. Two type of responses can be identified; drained and undrained soil behaviour (Figure 93). Undrained soil behaviour means that water pressure is generated due to mobilization of shear strength and deformation of the grain skeleton. The water does not have sufficient time to flow out of the pores, causing an extra over or under pressure effect. Drained soil behaviour, is found when the permeability of the soil is sufficiently large, so that water “escapes” faster than the movement of the grains (Van Duinen, 2014). Figure 93, shows the difference between drained and undrained behaviour caused by water pressure during sliding (u).

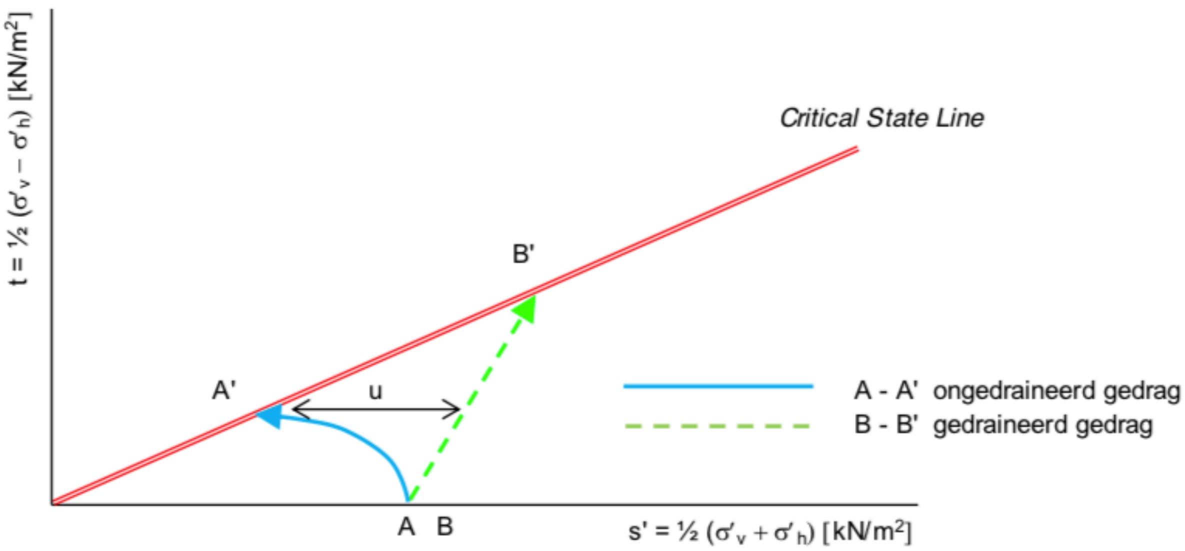


Figure 93: Drained vs. undrained soil behavior (Van Duinen, 2014)

Drained behaviour during sliding of the inner slope, typically occurs in a slow sliding process, or in soils with a large permeability (such as sand). Undrained soil response occurs in fast sliding processes and in soils with small permeability (such as peat, and clay). Undrained soil behaviour is in the Netherlands described with the following shear strength model:

$$s_u = \sigma'_{vi} * S * OCR^m \quad \text{with} \quad OCR = \sigma'_{vy}/\sigma'_{vi} \qquad \text{[Eq. 3]}$$

in which: s_u = maximum mobilizable shear strength (kN/m^2)
σ'_{vi} = effective stress (kN/m^2)
S = Shear strength ratio (-)
OCR = over consolidation ratio (-)
m = strength increase exponent (-)
σ'_{vy} = yield stress (kN/m^2)

While for drained calculations the following shear strength model can be applied:

$$\tau_f = \sigma'_n * \tan \varphi'_{cs} \qquad \text{[Eq. 4]}$$

in which: τ_f = maximum mobilizable shear strength (kN/m^2)
σ'_n = vertical effective stress (kN/m^2)
φ'_{cs} = internal friction angle (°)

When reviewing the two formulas ([Eq. 3] and [Eq. 4]), it can be observed that the drained calculations requires less information on the characteristics of the soil. For a proper schematization of undrained soils, information on the loading history, in situ situation and soil characteristics is of large importance. This makes that assessing stability of undrained soils is more complex and time consuming. Also, there is not much of experience with undrained calculations of soil behaviour under sliding conditions. For years, inner slope stability has been calculated with drained soil properties, making the uncertainties rather small.

In the safety assessment of the case study Wolferen-Sprok, the soil behaviour has been schematized as drained. Research of Lammers & Van den Akker (2018) on the soil behaviour in the project area resulted in a conclusion that a drained calculation would results in more realistic dimensions for the design of the dike reinforcement. This conclusion is based on the finding that the Pre-Overburden-Stresses (POPs) in the subsoil are relatively conservative, leading to a relatively small yield stress, and shear strength of the subsoil. Therefore, it is recommended to apply a drained calculation for determining inner slope stability.

Sliding model (Uplift-Van)
To perform the sliding plane analysis, the used software (D-Geo Stability) provides three possibilities to determine the normative sliding plane; Bishop, Uplift Van, and Spencer. Provided information on the three sliding models has been retrieved from Jonkman et al. (2017).

- Bishop: This sliding plane method is most commonly used in slipping planes analysis. The method checks the moment equilibrium along circular sliding planes.
- Uplift Van: Uplift Van differs from Bishop, as it uses two circles connected by a line to describe the sliding plane in the subsoil. This method is mainly applicable when uplift of the cover layer is a problem in the project area.
- Spencer: The main advantage of the Spencer method, is that the sliding plane is not forced into a certain shape. It is searched for the sliding plane within a pre-defined grid. A disadvantage of this method is the relatively little experience in using this method.

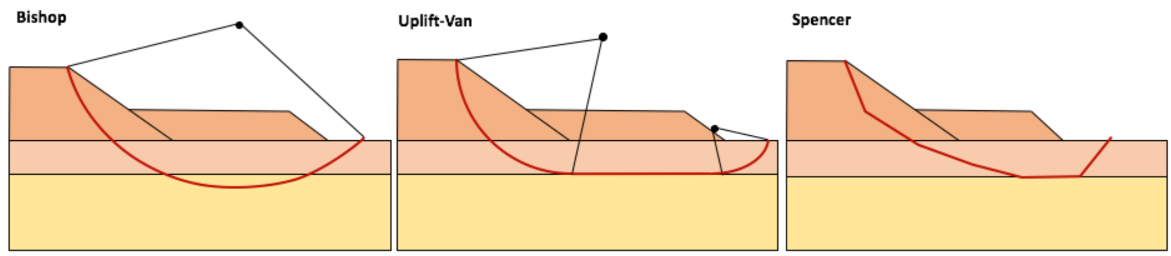


Figure 94: Sliding models

In this study, it chosen to use the Uplift-Van sliding plane model, as the geotechnical conditions in the project area show that this is a case where uplift is typically large. This is caused by the soil layering in the “Bovenrivierengebied”. The aquifer is located relatively close to ground level (see Section D.3.1.). When the Bishop method was used, this could have resulted in unrealistic sliding planes through the Pleistocene sand layer (Figure 94).

To use the Uplift-Van method, two separate grids should be defined from which is determined where the normative sliding plane is located. In Table 38 is described which grid settings have been used. At the location where the safety factor for inner slope sliding is found to be lowest, it is searched whether a lower factor is found nearby.

Table 38: Grid setting for Uplift Van calculations

Location	Unit	Uplift Van (left)	Uplift Van (right)
Grid X_{left}	[m]	Middle of dike crest	Inner berm toe – 7 m
Grid X_{right}	[m]	Middle of dike crest + 30 m	Inner berm toe + 3 m
Grid X_{number}	[-]	15	5
Grid Y_{top}	[m+NAP]	Crest height + 35 m	Ground level + 10 m
Grid Y_{bottom}	[m+NAP]	Crest height + 35 m	Ground level
Grid Y_{number}	[-]	15	5
Tangent Y_{top}	[m+NAP]	Top of the cover layer	
Tangent Y_{bottom}	[m+NAP]	Top of the cover layer	
Tangent Y_{number}	[-]	1	

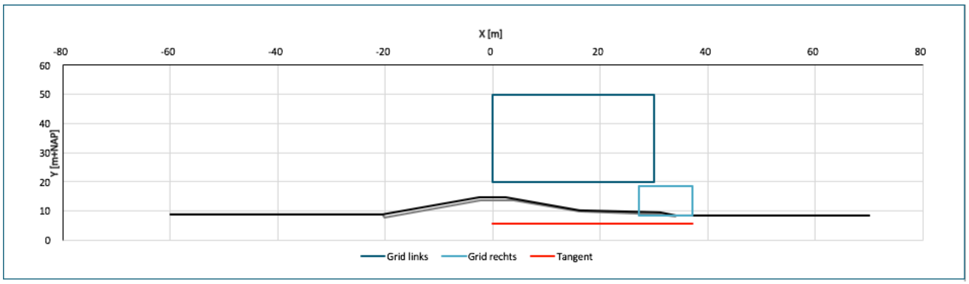


Figure 95: Sliding plane definition

Loading on crest (no traffic loading)
The dike often facilitates traffic on the crest of the dike. This causes an extra loading that influences the inner slope stability. According to Rijkswaterstaat (2016), this additional force is not considered in WTI 2017. It is reasoned that during normative storm conditions traffic functions on the dike cannot be performed. The only traffic that will be using the road has as purpose to repair the dike when necessary (small truck). According to Rijkswaterstaat (2016), this force is negligible as the force of a driving truck only acts a few seconds at the same location. This time is too short to induce sliding of the inner slope.

Traffic loads cause unfavourable conditions, as an additional driving force is added to the moment equilibrium. Therefore, it is expected that geometries of the dike will smaller than in the case that traffic loading is applied on the dike.

Geo-hydraulic schematization
Water in the subsoil and core of the dike can have a large influence on the stability of the inner slope of the dike. During normative high water conditions, water pressure changes in the soil system. In the following paragraphs it will per layer be explained how water pressures can be schematized.

Phreatic line (dike core)
The water level in the dike core is described by the phreatic line. As the dikes in the "Wolferen-Sprok"-reinforcement project are constructed from a clay core the phreatic line is schematized as shown in Figure 96. This schematization has been retrieved from the report "Waterspanningen bij Dijken" (TAW, 2004).

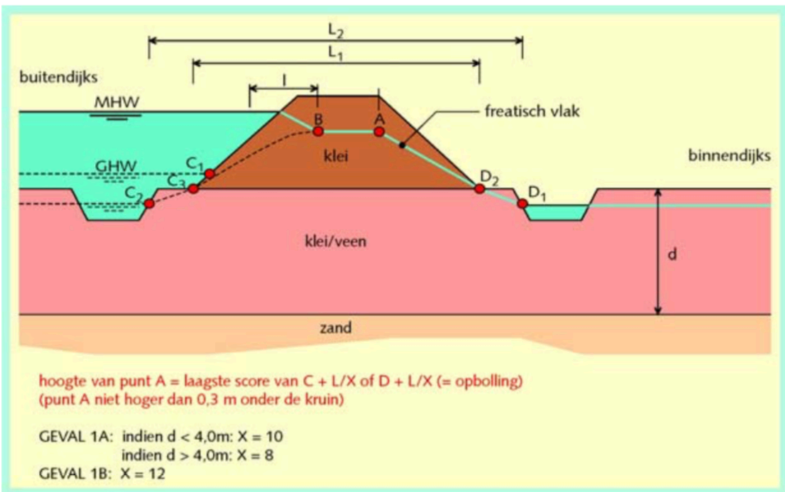


Figure 96: Schematization phreatic line in clay dike

In TAW (2004) has been noted that this water level schematization is only legitimate when the resistance against inner slope is roughly calculated (not for detailed design). There is no ditch located near the dikes in section 12, section 13, and section 14, therefore the height of the phreatic level at the inner toe of the dike is set on the ground level (D_2 in Figure 96). The entry point is taken on the mean high water level (under normative conditions). Point A (in Figure 96), can be determined based on the formula's shown in the figure. It is assumed that Point B, is located on a linear line between the entry point and Point A. By setting this assumption, it has been assumed that the duration of the high water peak is long enough for the phreatic level to adjust towards a new equilibrium situation, which is in line with the normative mean high water level. As these assumptions are set, the provided schematization is a conservative approximation of the phreatic level. Since there is no location specific data available, this assumption has been used to describe the phreatic lines in the dike.

Water head in aquifer (Pleistocene sand)

Also, the schematization of the water head in the aquifer is based on TAW (2004). The considered case is based on the situation where the aquifer is located under an impermeable cover layer. There are two typical situations under these conditions:

- No uplift of cover layer: when the weight of the cover layer (in the hinterland) is sufficiently large to compensate the upward water pressure acting from the aquifer on the cover layer, it is found that uplift is not a problem in that situation. According to TAW (1994c), in this case it can be assumed that the water head near the inner toe of dike is equal to the normative high water (MHW).
- Uplift of cover layer: when the cover layer is not heavy enough to resist the water force acting from the aquifer on the cover layer. The water head acting near the inner toe can be reduced to the limit potential (the point when the upward water force exceeds the downward gravitational force of the cover layer).

To determine whether water pressure causes uplift, it is calculated what the normative upward and downward (limit potential) forces are ([Eq. 5] and [Eq. 6]). Table 39 describes the outcomes of the calculation per section. For this calculation it has been assumed that the friction loss in the aquifer is negligible, causing that the water head at the inner toe of the dike is equal to the normative water level during design conditions.

$$Upward\ pressure = (H_{MHW} - H_{top\ aquifer}) * \rho_w \qquad \text{[Eq. 5]}$$

$$Downward\ pressure = D_{cover\ layer} * \rho_{cover\ layer} \qquad \text{[Eq. 6]}$$

Table 39: Determining forces acting on bottom of cover layer

	H_{MHW}	$H_{Top\ aquifer}$	ρ_w	$\rho_{cover\ layer}$	$D_{cover\ layer}$		
Section	**Normative high water [m+NAP]**	**Top of aquifer [m+NAP]**	**Density of water [kN/m^3]**	**Density of the blanket layer [kN/m^3]**	**Cover layer thickness [m]**	**Upward pressure [kN/m^2]**	**Downward pressure [kN/m^2]**
12	14.6	3.4	10.0	18.2	5.7	112.0	103.7
13	14.4	3.1	10.0	18.2	5.8	113.0	105.6
14	13.9	5.5	10.0	18.2	3.6	84.0	64.8

In Table 39 can be found that, in dike section 12, 13 and 14 uplift is a problem in the sections, therefor the water head in the aquifer will be described as shown in Figure 97. It is assumed that the entry point is at the outer toe of the dike, as it is uncertain whether the foreland cover material is permeable. The water head in the aquifer will than linearly decrease towards the inner toe of the dike. At this location the water head is described by its limit potential, which is equal to the in Table 39 described upward force divided by the density of water. After the inner toe has been reached, a constant water head has been assumed for the hinterland. This head is also equal to the limit potential.

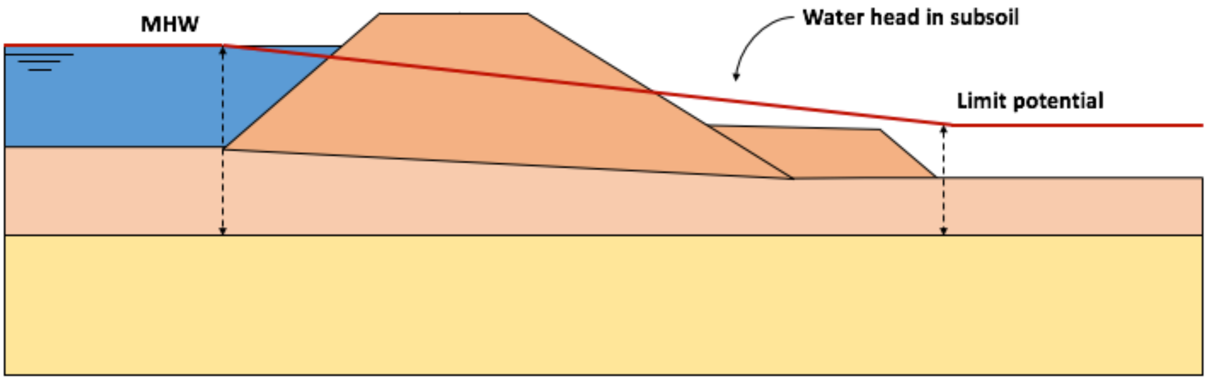
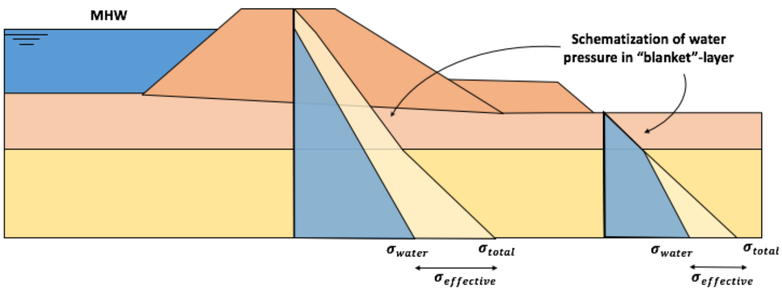


Figure 97: Water head schematization in the aquifers of section 12, 13 and 14.

The assumptions made in schematizing the water heads in the aquifer are conservative, nevertheless, the "Bovenrivierengebied" is known for its good permeable aquifers (TAW, 2004). Therefore, it is expected that this water pressure schematization is realistic for the calculated sections.

Water head in impermeable "blanket"-layer (Clay, silt)

Also the water head in the impermeable "blanket"-layer have been described on information supplied in TAW (2004). This report states that, in the "Bovenrivierengebied", the high water peaks are sufficiently long that the water head has sufficient time to reach its steady state. This steady state means that the water pressure increases linear in the blanket layer, towards the water pressure acting in the subsoil (shown in Figure 98b). Due to the low permeability of the "blanket", some time is needed to reach this equilibrium state. In the "Bovenrivierengebied" is the time to reach this state smaller than the time for the high water peak to pass a certain location along the river.



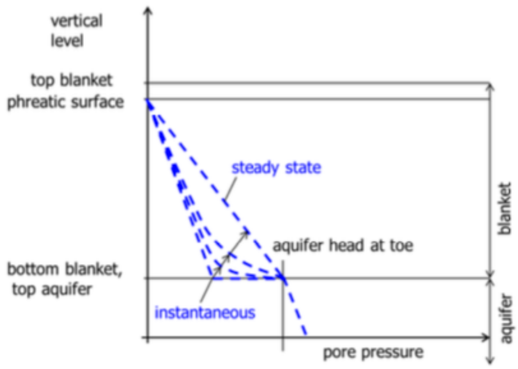


Figure 98a: Water pressure schematization in "blanket *98b: Dependency between water pressure and time*

D.4. Piping

By some people it has been doubted whether piping can endanger dike stability. Vrijling et al. (2010) researched this topic, and concluded that piping is a realistic danger in the Netherlands. To assess stability against piping, an evaluation method including three processes has been used in the Netherlands; uplift, heave, and piping. The safety assessment describes failure caused by piping as the result of the occurrence of all these three processes during the same high water event. To provide safety against piping, it is sufficient to prevent the occurrence of one process during normative storm conditions (Rijkswaterstaat, 2017a). In this section, it is described how the resistance against failure of the separate processes has been determined for soil solutions. Applying these rules eventually leads to required dimensions of a piping berm. Also other piping solution will be evaluated. In Section D.4.6, it will be explained how these solutions are considered in this study.

D.4.1. Determining water potential in the hinterland

Before explaining the assessment method for the applicable processes considering piping, it has been started with explaining the used schematization of the water potential in the hinterland. This schematization is important for determining the resistance of a location against Uplift, and Heave (Jonkman et al., 2017). The Water Act provides freedom for the schematization of the water potential in the hinterland, as it is dependent on available information, and detail level in the project (Rijkswaterstaat, 2017a). Available methods to determine the water potential in the subsoil are for example, numerical ground water models, site measurements, and analytical formulas.

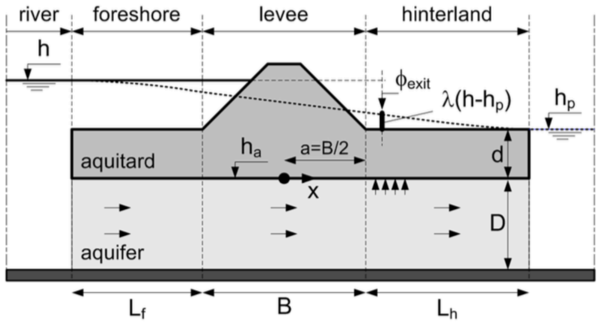


Figure 99: Schematization of water potential in aquifer (Jonkman et al., 2017)

In this study, a numerical model based on Dupuit flow has been applied to determine the damping factor for water potential at the exit point (Eq. 7). This damping factor relates the water level in the river to the water potential at the exit point (Eq. 8) and the gradient (in the blanket) at the exit point (Eq. 9). The formulas have been retrieved from Jonkman et al. (2017):

$$\lambda = \frac{\lambda_h}{L_f+B+\lambda_h} * e^{\left(\frac{0.5B-x_{exit}}{\lambda_h}\right)} \qquad \text{[Eq. 7]}$$

in which:
- λ = damping factor (-)
- λ_h = leakage factor (m) = $\sqrt{(k * D * d)/k_h}$
- L_F = length of the foreshore (m)
- B = width of the dike (m)
- x_{exit} = distance from exit point to centre of the levee (m)
- k = hydraulic conductivity of the aquifer (m/day)
- D = aquifer thickness (m)
- d = blanket thickness (m)
- k_h = hydraulic conductivity of blanket layer (m/day)

$$\phi_{exit} = h_p + \lambda(h - h_p) \qquad \text{[Eq. 8]}$$

in which: ϕ_{exit} = ground water potential (m+NAP)
h_p = water level in hinterland (m+NAP)
h = water level in river at normative conditions (m+NAP)

$$i = \lambda(h - h_p)/d \qquad \text{[Eq. 9]}$$

in which: i = heave gradient (-)
h_p = water level in hinterland (m+NAP)
h = water level in river (m+NAP)

To find the damping factor (and ground water potential, and gradient in the blanket) at the exit point, location specific data on the hydraulic and geotechnical conditions has to be obtained. The geotechnical information has been retrieved from Witteveen + Bos (Witteveen + Bos, 2018-1, Witteveen + Bos, 2018-2, and, Witteveen + Bos, 2018-3), while water levels during normative conditions (storm event occurring 1/10.000 years) have been calculated with Hydra-NL. The values can, per section, be retrieved from Table 40.

Table 40: Relevant geotechnical data for determining water potential in subsoil

	Section 12	Section 13	Section 14
L_F [m]	0	5	10
k [m/day]	113	113	113
D [m]	54	54	54
d [m]	5.7	5.8	3.6
k_h [m/day]	0.01	0.01	0.01
h_p [m+NAP]	9.1	8.9	8.5
h [m+NAP]	14.6	14.4	13.9

In Table 40 can be found that the length of the foreland in all the sections is assumed to be short. This is, for section 13, and 14, caused the observation that ponds (*Dutch: wielen*) are located close to the toe of the dike. These ponds are usually quite deep (at a depth were sand is located), which makes it possible for water to intrude in to the aquifer. The foreland at section 12 is taken as 0, because a part of the section is directly bordering the river.

It has been assumed that, for all sections, the most vulnerable location for piping can be found at the inner toe of the dike. This assumption has been set, as there are no ditches located close to the dike in the reviewed project area. Therefore, x_{exit} has been set equal to the value B/2 in Eq. 7. Applying the set data and assumptions to Eq 7, Eq 8, and Eq 9 results in a relation in which the damping factor is just dependent on the width of the dike.

D.4.2. Uplift

In the Netherlands, the sensitivity of the subsoil against Uplift of the blanket layer is determined by the safety criterions are presented in Eq.10 (Rijkswaterstaat, 2017a). This criterion determines whether the weight of the soil body on top of the aquifer is strong enough to resist the upwards force applied by the water potential.

$$\Delta\phi \leq \frac{\Delta\phi_{c,u}}{\gamma_{up} * \gamma_{b,u}} \qquad \text{[Eq. 10]}$$

in which: $\Delta\phi$ = water potential difference over blanket layer (m)
$\Delta\phi_{c,u}$ = critical water potential difference (m) = $\frac{D_{blanket}(\gamma_{sat} - \gamma_{water})}{\gamma_{water}}$
γ_{sat} = 18.2 [kN/m^3] = volumetric weight of saturated blanket
γ_{water} = 10 [kN/m^3] = volumetric weight of water
γ_{up} = safety factor for uplift (-), can be found in Table 33

$\gamma_{b,u}$ = modelling factor
$D_{blanket}$ = blanket layer thickness (m)

When the evaluation criterion (Eq. 10) is reviewed, it can be observed that only the modelling factor is unknown. According to Rijkswaterstaat (2017a), the modelling factor is dependent on the level of detail on which piping is evaluated. As the calculations in study are based on rough data of the project area, it is assumed that a modelling factor is equal to 1.3 (which is applicable for piping evaluations with relatively large uncertainties). Applying this modelling factor causes that the uplift evaluation is quite conservative. The introduced uplift criterion can also be used to design piping berms. In this case soil is added on top of the blanket, creating increased dimensions of the blanket layer.

D.4.3. Heave

Similar as for Uplift, also a design criterion for Heave has been provided by Rijkswaterstaat (2017b). This criterion evaluates whether the occurring water potential difference between the top and bottom of the blanket is large enough to initiate transportation of grains through the cover layer. Whether this occurs is dependent on soil properties and geo-hydraulic conditions. Dutch regulations evaluate this process with help of Eq. 11. This formula has also been used in this study to evaluate the occurrence of heave.

$$i \leq \frac{i_{c,h}}{\gamma_{he} * \gamma_{b,h}} \qquad \text{[Eq. 11]}$$

in which: i = occurring heave gradient in the blanket layer (-)
$i_{c,h}$ = 0.3 = critical water potential difference (-)
γ_{he} = safety factor for heave (-), can be found in Table 33
$\gamma_{b,h}$ = modelling factor (-)

It can be observed that the critical heave gradient in this study has been taken to be 0.3. This value has been based on the schematization regulations as provided in Rijkswaterstaat (2017a). Jonkman et al. (2017), explains that there are many methods for calculating the critical heave gradient, which differentiate in outcome. Nevertheless, the applied values in Dutch regulations, seems a bit conservative, as based on field observations and experiments, it has been concluded that the value would be located somewhere between 0.5 and 0.9. The modelling factor for Heave is taken as 1.3. This value has been taken for the same reasons as the modelling factor for Uplift.

When designing a piping berm, it required to provide sufficient resistance against of the three processes initiating piping. In Rijkswaterstaat (2017a), it has been explained that in most cases, the subsoil is more sensitive for heave than for uplift. It states that when the volumetric weight of the blanket layer is smaller than 13.0 kN/m^3 the strength against heave is larger than the strength against uplift. In these cases, it may be favourable to design based on the heave criterion. As the volumetric weight of the cover layer in the project area is about 18 kN/m^3, this is not considered as a realistic design option for a piping berm.

D.4.4. Piping

The last considered process, is the formation of a pipe under the dike. In the Dutch regulations the assessment of piping is based on the formulas supplied by Sellmeijer (Rijkswaterstaat, 2017b). Eq.11 provides the safety requirement for piping, as set in the Water Act.

$$(\Delta H - 0.3d) \leq \frac{H_c}{\gamma_{pip} * \gamma_{b,p}} \qquad \text{[Eq. 11]}$$

in which: ΔH = water level difference (m)

H_c = critical water level difference (m)
d = blanket thickness (m), can be found in Table 40
γ_{pip} = safety factor for piping (-), can be found in Table 33
$\gamma_{b,p}$ = modelling factor (-)

The critical value for the water level difference has been based characteristic parameters of the subsoil. In Figure 100, it can be found how the critical water level difference for a project location can be determined. The modelling factor ($\gamma_{b,p}$) has been taken as 1.3, due to the large uncertainty in the soil layering and characteristics at the start of a project (which is the case in the case study Wolferen-Sprok".

$$H_{c,p} = F_1 F_2 F_3 L$$
$$F_1 = \eta \left(\frac{\gamma_s}{\gamma_w} - 1 \right) \tan\theta$$
$$F_2 = \frac{d_{70m}}{\sqrt[3]{\frac{\nu k L}{g}}} \left(\frac{d_{70}}{d_{70m}} \right)^{0.4}$$
$$F_3 = 0.91 \, (D/L)^{\frac{0.28}{(D/L)^{2.8}-1}+0.04}$$

where

L seepage length [m]
γ_s volumetric weight of sand grains (=26.5 kN/m^3)
γ_w volumetric weight of water (=10 kN/m^3)
θ bedding angle [deg]
D thickness of the aquifer [m]
η drag factor coefficient
ν kinematic viscosity of water (=1.33 10^{-6} m^2/s)
d_{70} 70%-fractile of the grain size distribution [m]
d_{70m} reference value for d_{70} [m]
g gravitational constant (=9.81 m^2/s)
k specific conductivity [m/s]

Figure 100: Piping evaluation with Sellmeijer (retrieved from Jonkman et al., 2017)

Besides the in Figure 100 explained standard values for parameters, also values have to be obtained for the other parameters. Most parameters have been set in Rijkswaterstaat (2017b), and are restricted in the Dutch design procedure. The, in Table 41, presented parameter for the grainsize distribution (d_{70}), has been based on the Stochastic Soil Schematization (SOS) provided in DSoil-Model. Values for the specific conductivity (k), and aquifer thickness (D) can be found in Table 40.

Table 41: Parameters for piping evaluation

Parameter	Value
η [-]	0.25
d_{70} [m]	$4.1*10^{-4}$
d_{70m} [m]	$2.08*10^{-4}$
θ [°]	37

Using all provided parameters, makes it possible to relate the formation of piping to the dimensions (footprint) of the dike. The footprint of the dike can be determined for which, the formation of a pipe under a dike does not lead to undermining of the dike anymore. The common practice in the Dutch design process is using the Sellmeijer formulas to describe the occurrence of piping in the subsoil. According to Jonkman et al. (2017), this method has resulted from a theory based on the flow pattern caused by head differences, and is afterwards tested and adjusted based on scale experiments.

D.4.5. Occurrence of piping

Based on the in Section D.4.1 till Section D.4.2 provided schematizations, it can be concluded that the project area is sensitive for the failure mechanism piping. This has been expressed by the calculated (deterministic) safety factors during the normative conditions in Table 42. In this table also, the required safety factors can be found. Although it should be noted that the schematization for determining the probability of failure for piping is conservative, it is clear that during the normative conditions, piping can cause failure of the dike. Therefore, design measures have to be provided to increase the strength against piping. This is done in Section D.4.6.

Table 42: Assessing safety factors for piping

	Required safety factor $\gamma_{mech} * \gamma_{model}$	Section 12	Section 13	Section 14
Uplift	2.64	0.87	0.89	0.47
Heave	1.39	0.33	0.32	0.17
Piping	1.95	0.54	0.54	0.45

D.4.6. Piping measures

In this section it is described, which measures are considered to evaluate piping within the project area. As explained in Section D.4.5 there are many possibilities to reinforce a dike against piping. In this study, three alternatives are considered; a piping berm (located in the hinterland), relief wells, and a vertical sand tight geotextile. In the remainder of this section, it is per solution type explained what its characteristics are. Structural designs of the relief wells and vertical sand tight geotextiles have not been included in this study. Nevertheless, it is expected that enough can be provided, to assess the difference in influence of the design options.

Piping berm

For the design of the piping berm, it is, in this project area, important to create sufficient safety against uplift, within the critical seepage length (see Figure 101). According to Förster, Van den Ham, Calle & Kruse (2013), it is realistic to design the height of a piping berm, in such a way that it can withstand normative uplift conditions times 1.2. This is a difference with the evaluation method as used to determine the uplift safety of the cover layer, as used in Section D.4.2.

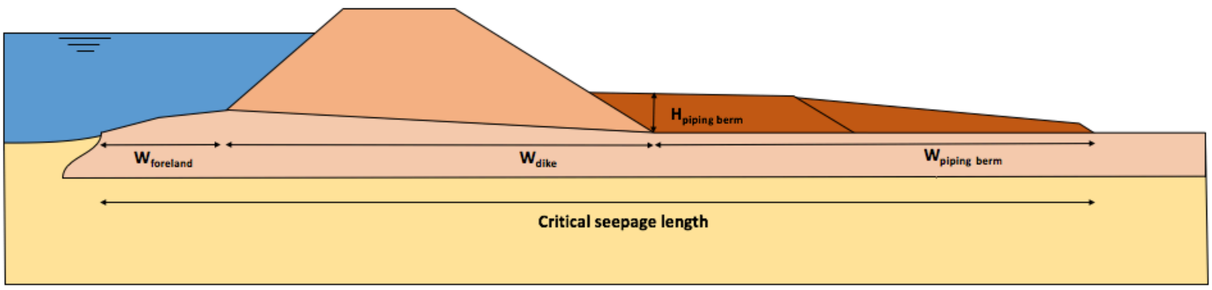


Figure 101: Piping berm design

The provided required length of the piping berm has been based on the Sellmeijer-formulas as presented in Section D.4.4. The required length of the piping measure is expressed from the outer toe of the dike, till the inner toe of the piping berm. This is done, as the geometries of the dike providing safety against overtopping and inner slope sliding will be varying. The found berm dimensions are presented in Table 43. The piping berm height in this table can gradually decrease towards the inner toe of the piping berm, because the water potential in the subsoil also decreases.

Table 43: Piping berm dimensions

	Section 12	Section 13	Section 14
Critical seepage length [m]	232	230	281
$W_{dike} + W_{piping\ berm}$ [m]	232	225	271
$H_{piping\ berm}$ [m]	0.75	0.71	1.81

Relief wells

A relief well is a filter construction that can be implanted near the inner toe of the dike. The relief well, reduces the water potential in the hinterland during high water conditions. The has to be constructed in the aquifer, to obtain the desired result. Jonkman et al. (2017) states that, when designing relief wells, it is important to determine the distance between two relief wells, as the relieving effect disappears with distance from the well. Figure 102, illustrates a relief well.

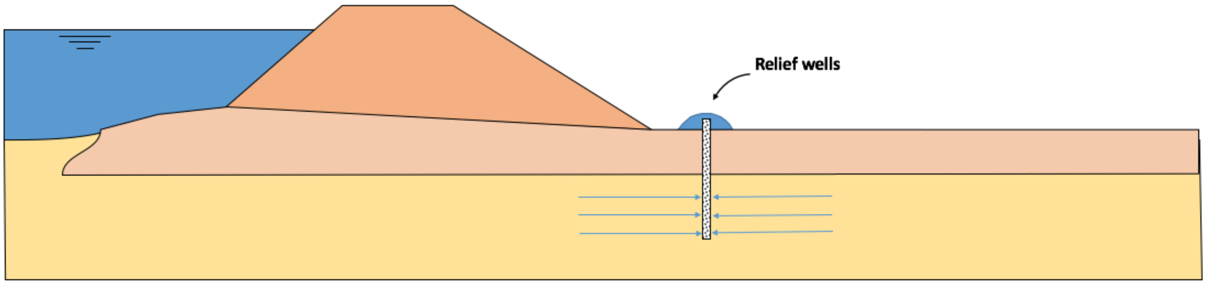


Figure 102: Relief well

Vertical sand tight geotextile

The third considered design option is the vertical sand tight geotextile (VZG). This method of preventing piping focuses on stopping the pipe formation under the dike during normative storm conditions. This is done by a geotextile that allows water to flow through the material, while it is not possible for sand to pass the geotextile (from river side to the hinterland). The geotextile should be constructed in such a way that the clay blanket stays impermeable, otherwise the geotextile will be undermined (Taal, 2017).

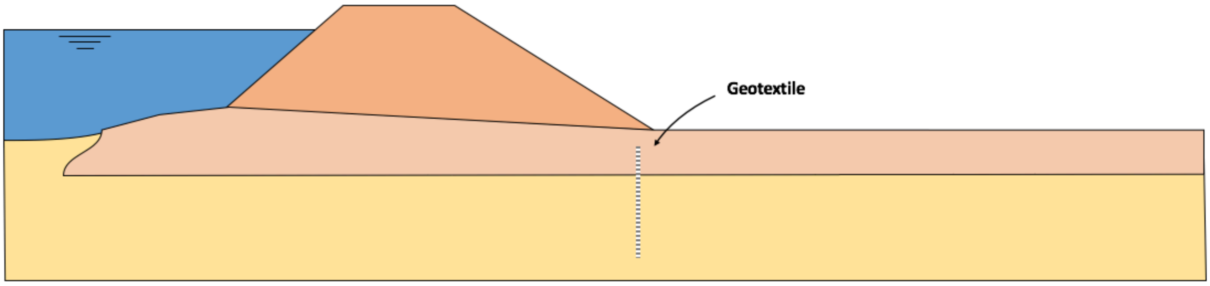


Figure 103: Vertical sand tight geotextile

D.4. Design variations

There are several ways to provide safety against the applicable failure mechanisms of this study. It has been set, in the scope of this study, that the focus for fulfilling the safety assignment lays on a dike reinforcement constructed in soil. There are many geometrical parameters that increase the strength against one or more failure mechanisms, these parameters are shown in Figure 104.

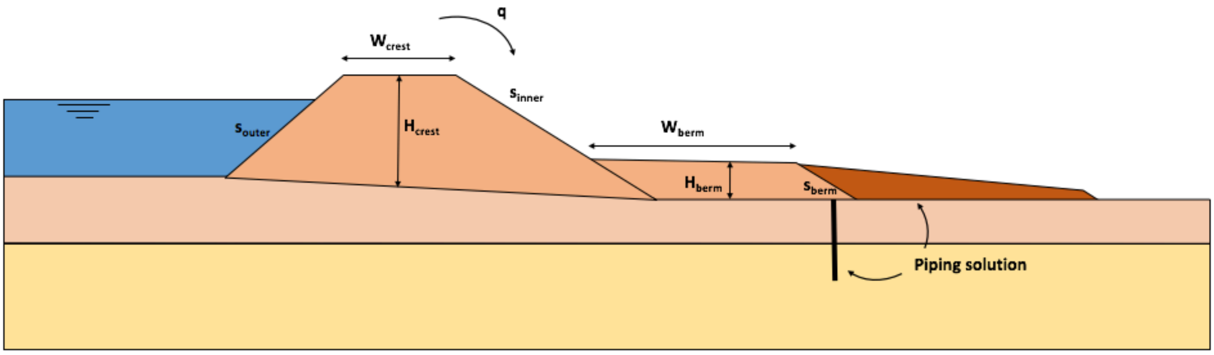


Figure 104: Design variables of a dike in rural area

In principle, there is an infinite amount of possibilities to increase the strength of the dike against failure mechanisms. The goal of this study, is to show the difference in influence on the functional aspects in the project area. But, calculating all these variations will take too long, therefore, a space has been defined in which is searched for a "safe" dike reinforcement design. This solution space is based on variations in geometric design parameters of a dike. How every parameter has been varied is found in Table 44.

Table 44: Design variations for dikes in rural areas

Name	Unit	Variations
Outer slope (s_{outer})	**[1:_]**	3, 4, 5
Critical Overtopping discharge (q_c)	**[l/s/m]**	1, 5, 10
Crest width (W_{crest})	**[m]**	3, 6, 10.4, 13.4
Inner slope (s_{inner})	**[1:_]**	3, 3.5, 4
Berm width (W_{berm})	**[m]**	Range between 0 and W_{berm} for which H_{berm}= 1m, step size = 1m
Berm height (H_{berm})	**[m]**	Range between H_{berm}= H_{crest} – 1m and H_{berm}= 1m, step size = 0.1m

The parameter slope of the inner berm (s_{berm}), is set to a slope of 1:3. No variations are considered for this parameter, as it is expected that varying this parameter will not lead to significant change in the impact on the functional qualities in the project area. For the design of the outer slope, berms are not considered, as these berms are usually constructed when also outer slope instability is an applicable failure mechanism. Variations in the piping solutions, that will be considered in this study are, a piping berm, a geotextile, and a relief well.

D.5. Evaluation strategy

To limit the calculation time for the evaluation of the safety assignment, with the design variations as proposed in Section D.4, some extra assumptions have been introduced in the evaluation of the safety assignment. The order of evaluating failure mechanisms has been described in Figure 105.

The evaluation of the safety assignment is started by evaluating the failure mechanism "Erosion of the inner slope". Minimal required crest height can be calculated per unique combination of overtopping discharge and outer slope angle. This results in crest heights of the dike, which are rounded at one decimal number. It occurs that different combinations of overtopping discharge and outer slope angle result in the same required crest height.

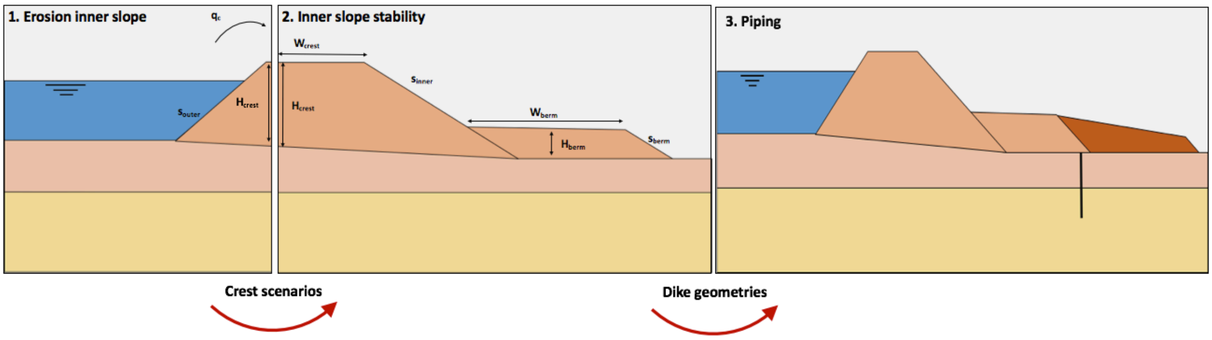


Figure 105: Evaluation strategy

When the crest height scenarios have been retrieved from the failure mechanism “Erosion of the inner slope”, it is started with evaluating the failure mechanism “Inner slope stability”. It has been assumed that the outer slope design has negligible influence on the inner slope stability. This reduces the required calculations for inner slope stability. For outer slope and overtopping scenarios that have an equal crest height, the inner slope stability has only been calculated once (this is done with a slope steepness of 1:3). In the evaluation of inner slope stability, it has also been assumed that crest width variations do not affect the stability of the inner slope. As explained in Section 5.4, there are different crest width scenarios used in the developed functional indicators model. The inner slope stability has been calculated based on a crest width of six meters. This induces some under estimation of the safety against sliding when the crest width is smaller than six meters. While, for larger crest widths, this can be observed as an overestimation. It should be noted that due to the, in Section D.3.1, set geo-hydraulic schematizations, it is expected that the variations will not lead to large differences in found safety levels. This is expected as the phreatic level in the dike will always reach to the inner toe of the dike (which is a conservative assumption for dikes with a large crest width). Also, the head in the subsoil are linearly decreasing towards the inner toe of dike, at which uplift takes places.

The calculation results for inner slope stability are shown by means of safety factors. The required safety factors are retrieved from Table 33. In this study, only design alternatives that fit within the scope of the HWBP are evaluated (smarter, cheaper, and faster). The organization states that they do not finance solutions, that require more investment than the minimum investment. Therefore, it is determined what the minimum berm height is, at a certain berm width. Higher berms (with higher safety factors) are not further considered in this study

After considering inner slope stability, the evaluation of the safety has been concluded with evaluating piping measures. Three piping measures are evaluated in this study; the piping berm, a geotextile, and a relief well. The effect of these piping measures will be explained separately for the spatial assignment, because have a large influence on the dike dimensions.

D.6. Verification of results

The results of the design calculations on determining the dimensions of the dike should be verified, before using them in the spatial assignment. The question answered in this section is; does fulfilling the safety assignment as explained in this chapter, result in realistic dimensions for design options for dike reinforcement projects in rural areas. It is questioned whether physical processes occur as expected.

D.6.1. Section 14

In this section, the results on the obtained calculations to assess inner slope erosion, inner slope stability, and piping calculations for section 14 have been verified. It is explained why these results are realistic design dimensions for fulfilling the safety assignment in this section.

First, erosion of the inner slope has been discussed. Afterwards the results of inner slope stability and piping have been valued.

Erosion of the inner slope

To verify the outcome of the erosion on the inner slope caused by wave overtopping of the dike, Figure 106 is supplied. This figure shows the relation between the crest height of the dike and the horizontal distance from the outer toe to the crest, based on a set overtopping scenario. In the left figure, the results are shown for outer slope scenarios base on a standard failure budget (w=0.24) for erosion of the inner slope. The right figure shows the effect a shifted failure budget (w=0.04). It can, for both cases, be observed that an overtopping discharge of q=10 l/s/m, combined with an outer slope s=1:3, is from land use point of view the most favourable design option. This is a logical outcome for the case study “Wolferen-Sprok”, as it has been explained that the system is dominated by the fluctuating water level, combined with “small” wind waves. A shallower outer slope does not affect the water level, and therefor does not lead to a large reduction of the required crest level of the dike. Nevertheless, the effect of a shallow outer slope can be found in the required crest levels of the dike. Applying a slope of 1:5, instead of 1:3, can lead to a reduction of the crest height till sixty centimetres.

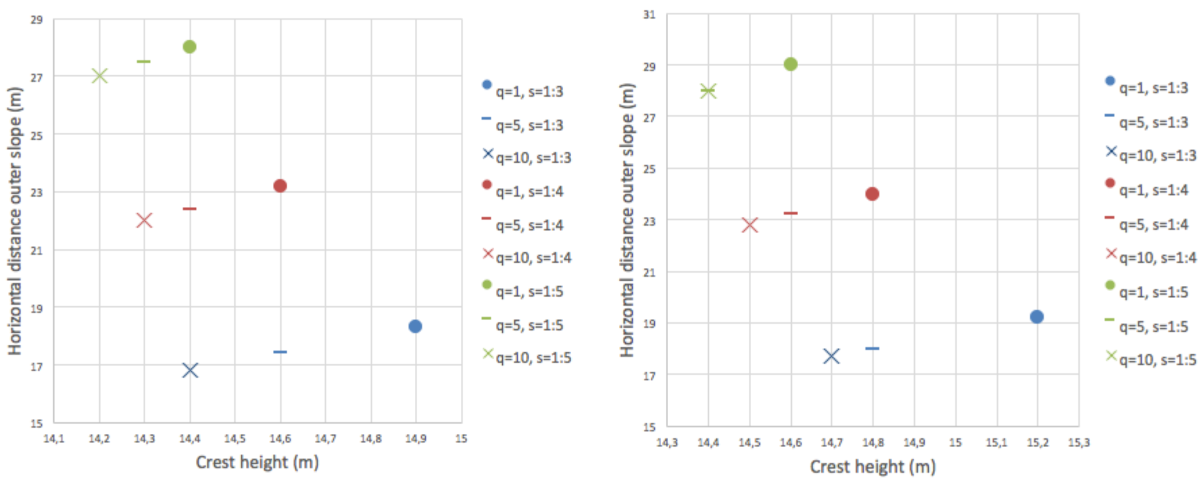


Figure 106a: outer slope scenarios (standard) *106b: outer slope scenarios (failure budget = 0.04)*

Also the effect of increasing, or decreasing the overtopping discharges can be observed in Figure 106. Increasing the overtopping discharge from 1 l/s/m, till 10 l/s/m, can lead to a crest height reduction of half a metre. The step between an overtopping discharge of 1 l/s/m top 5 l/s/m, is larger than the step from 5 l/s/m to 10 l/s/m. This makes sense, as overtopping of larger waves should be prevented. These more extreme waves require more resistance (among the outer slope of the dike) to restrict the wave height to a maximum of 1 l/s/m. In Figure 106b can be observed that for a slope of 1:5, the required crest height is equal for an overtopping of q=5 l/s/m and q=10 l/s/m. This is caused by the rounding of the number. Overall, it can be concluded, that the retrieved values for the crest-height are in line with the expectations.

Stability of the inner slope

The verification of the inner slope stability is more complex, as there are about 16,000 evaluated cross-sections for inner slope stability. Therefore, it is first explained what the typical sliding circle in the project area Wolferen-Sprok looks like. Afterwards, a verification of all calculated geometries has been obtained.

Typical sliding circle

The typical sliding circle in the case study “Wolferen-Sprok” is shown in Figure 107. The shown sliding circle has the following characteristics:

- Outer slope: 1:3
- Inner slope: 1:3
- Crest height: 14.9 m
- Crest width: 6 m
- Berm height: 1.8 m
- Berm width: 19.0 m

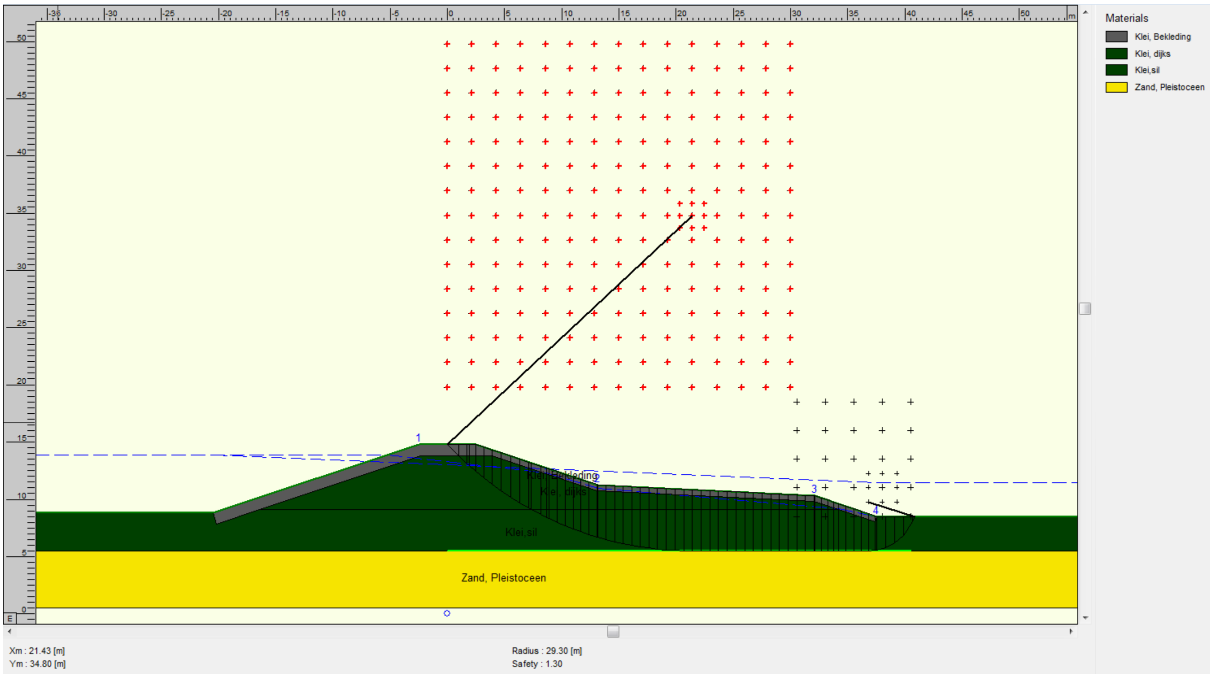


Figure 107: Typical sliding circle case study "Wolferen-Sprok" Section 14

After reviewing many sliding circle, it has been concluded that the in Figure 107 showed sliding plane is a typical result of the inner slope stability analysis as done in the program D-Geo Stability. The sliding plane starts in the crest of the dike, and ends near the inner toe. In between the start and the end, a horizontal part is observed on the border between the Pleistocene sand and the clay layer. This is typical for an Uplift case, as the border between the two layers is the location where least friction is found. The observed sliding planes, are the expected outcomes of the stability calculation performed in D-Geo Stability.

Verifying all design parameters

As explained, many safety assessments on inner slope stability have been obtained. To determine whether the outcomes are physically logical, Figure 108 (for slope 1:3), Figure 109 (for slope 1:3.5), and Figure 110 (for slope 1:4) are provided. These figures show the safety factor relating to a certain inner slope angle, crest height, berm height and berm width. There are a few remarkable things in this figure. First thing that is noticed while observing Figure 108, is that there are red points in the upper right corner when the crest height is smaller than 14.8 m. These red points indicate a safety factor of one or lower. The points in the upper right corner are red, as there are invalid geometries at these locations; the berm height exceeds the crest height of the dike (due to the 1:20 slope over the width of the crest).

It can also be observed that the safety factor is increasing when the berm width is increasing. This is exactly what is expected, as an increasing berm width provides a larger weight at the resisting part of the sliding circle. About the same effect has been observed for berm height, only it seems that the effect of adding height to the berm reduces when the berm height gets larger than 2.5 meters. This can be observed best when it is focussed on the yellow part of the figures. In all figures, an almost vertical line is observed (at a safety factor of about 1.5) till a berm height of 2.5 meters. Afterwards, the berm height decreases gradually when the berm width increases (keeping the safety factor constant). Almost a parabolic shape has been observed at the safety factor of 1.5. The observed effect is further discussed later in this paragraph, at headers “effect of berm width”, and “effect of berm height”.

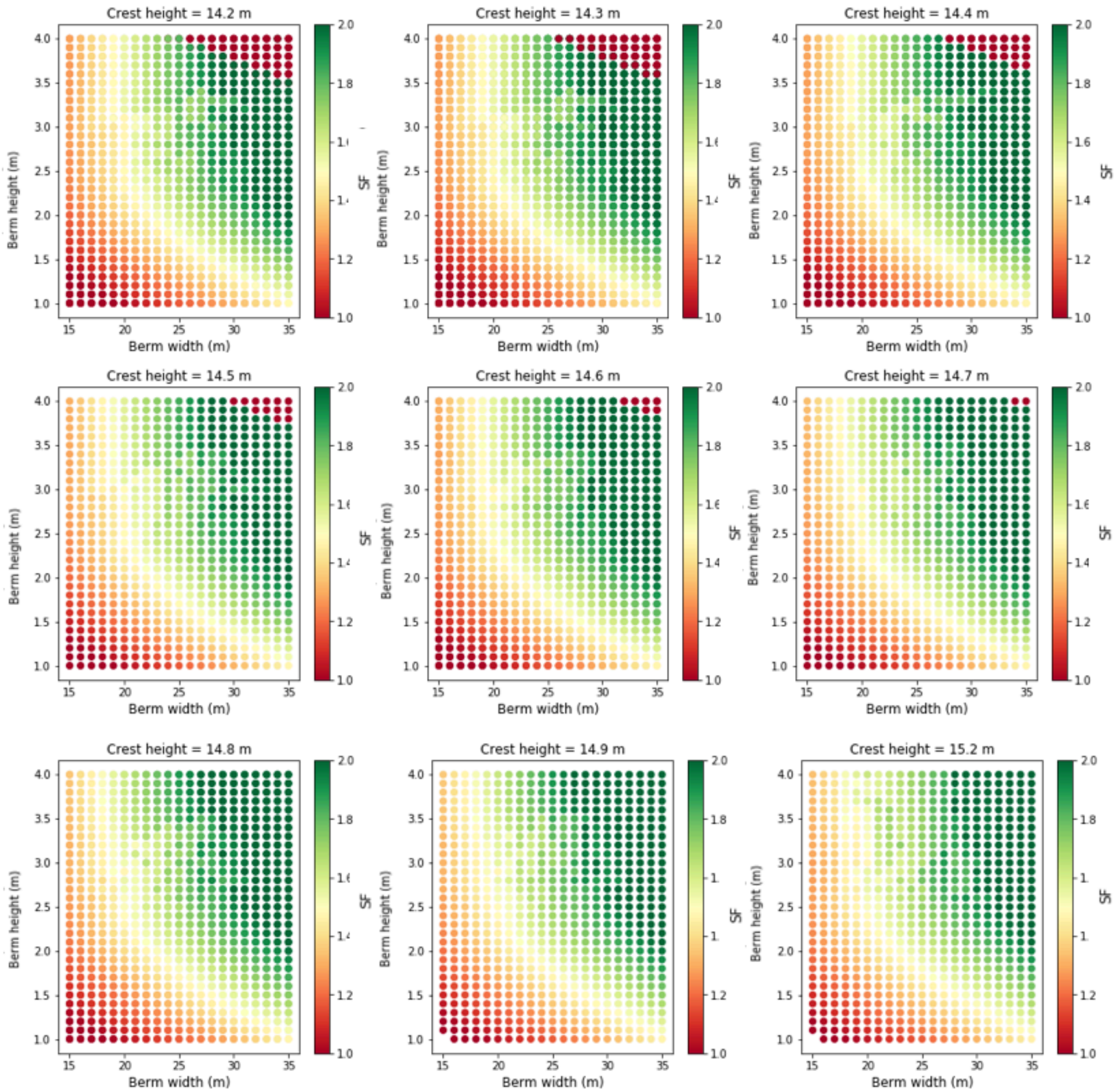


Figure 108: Section 14, inner slope 1:3

The, in the previous paragraph mentioned parabolic shape is also observed, for safety factors lower than 1.5. It is observed that safety factors gradually increase with berm width and berm height; this is the expected outcome of the safety assessment. When safety factors are larger than 1.5, this effect can also be observed, but it can be found that there are some irregularities in the figure (at the upper right half of all figures). An example is Figure 109, scenario: Crest height = 14.3 m. It can be observed that the smooth parabolic shape of a certain safety factor larger than 1.5, is interfered by jumps in green colour. The colour gets lighter for a few values, and then continues as expected. This jump in colour indicates an abrupt decrease in the safety factor. These jumps are most probably caused by the grid settings in the safety assessment, which causes jumps of the normative sliding circles. As these jumps are only observed in larger safety factors (larger than 1.5), it is not a problem for the case study. The required safety factor for a specific design is 1.48 for the standard failure budget (w=0.24), and 1.42 for the failure budget (w=0.24).

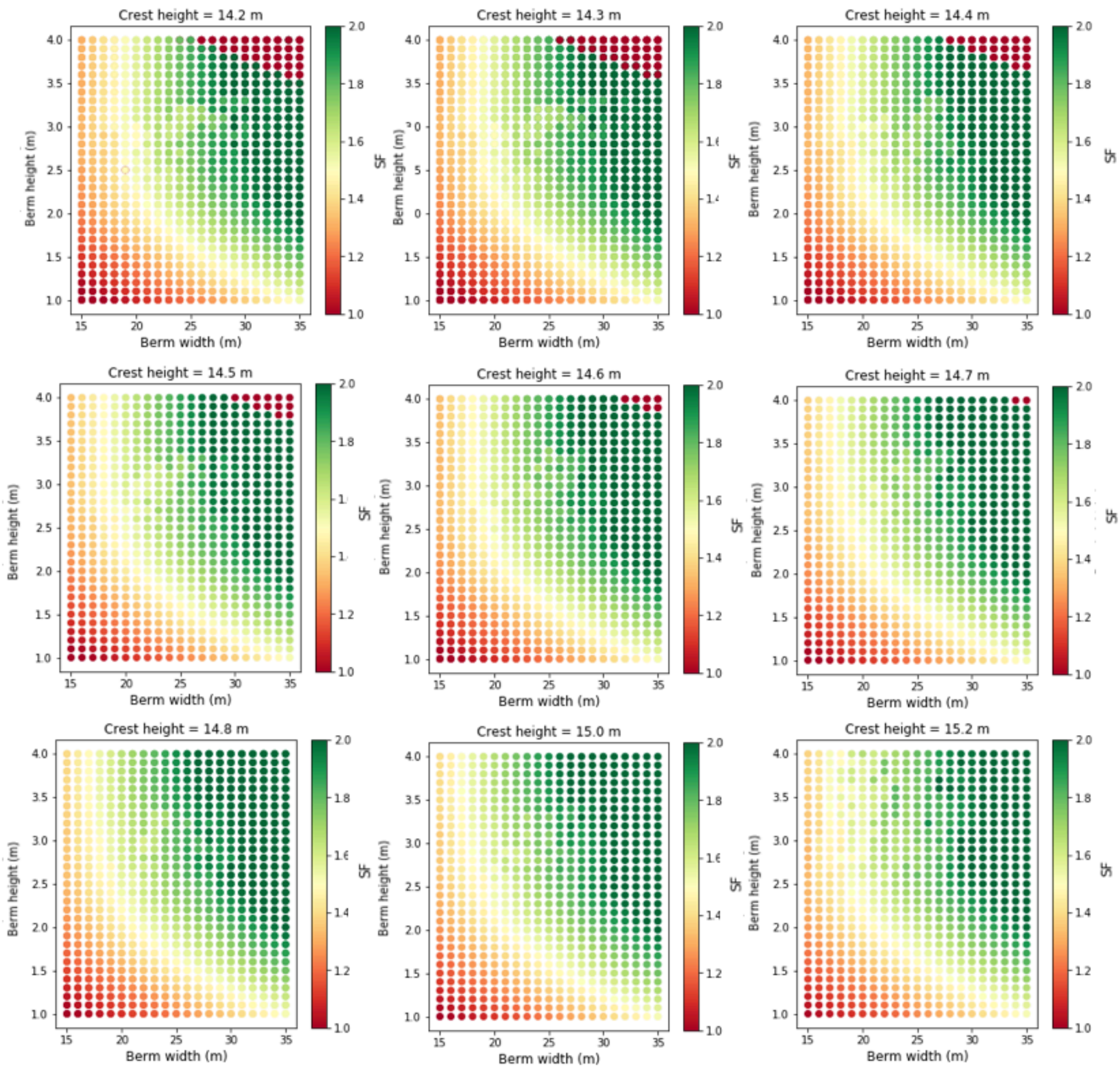


Figure 109: Section 14, inner slope 1:3.5

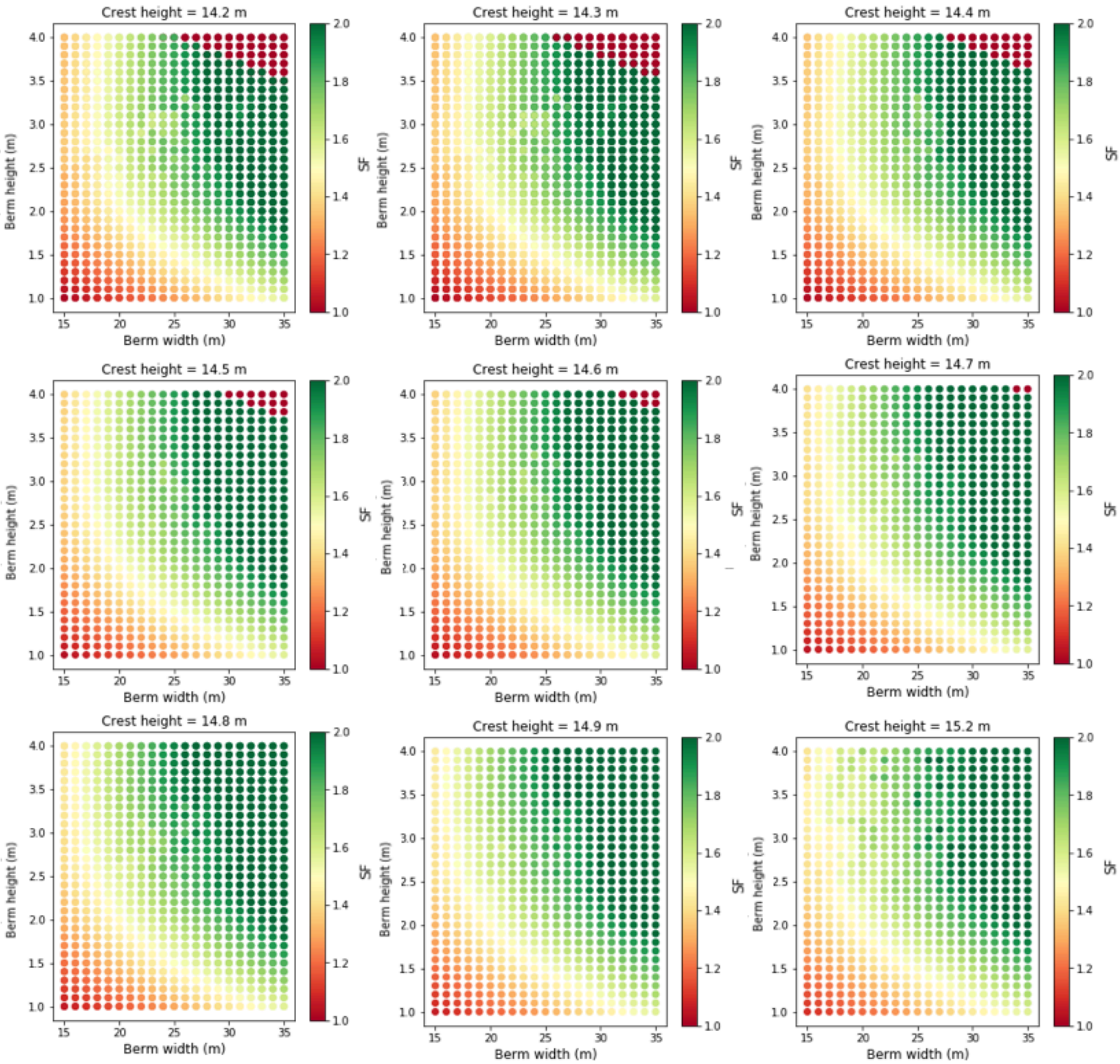
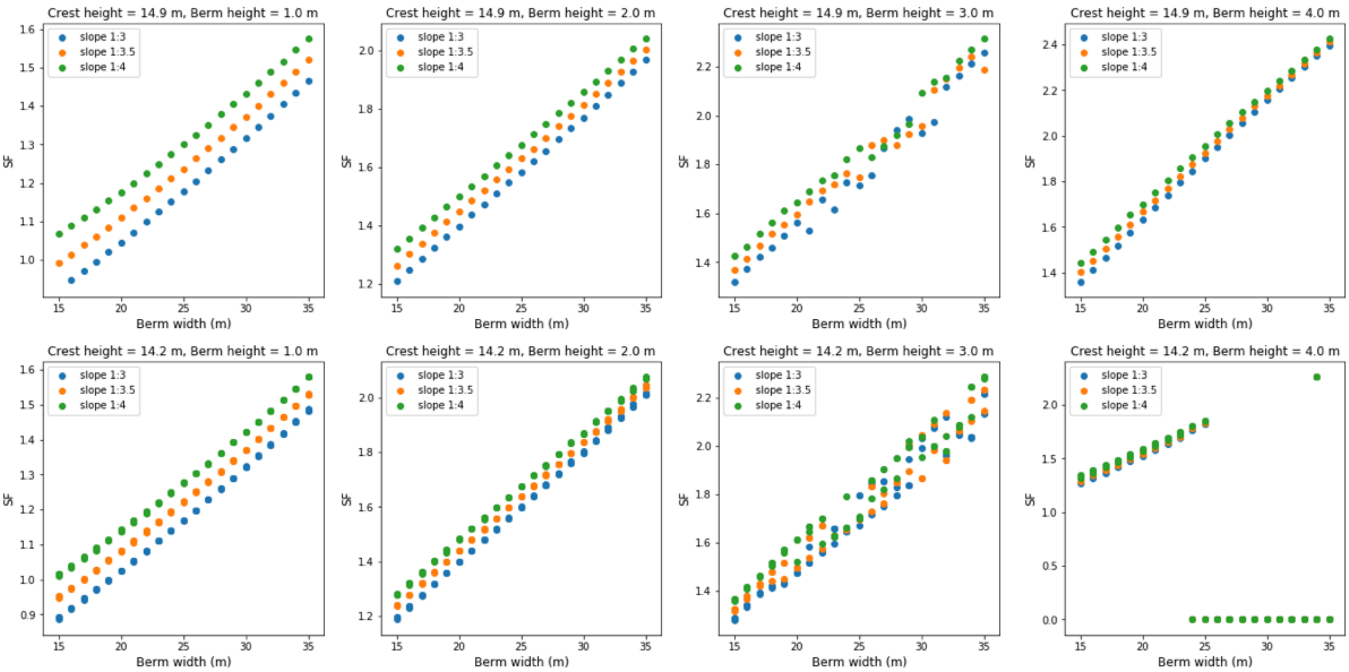


Figure 110: Section 14, inner slope 1:4

To conclude largest changes in safety factors are found, in changing the dimensions of the berm. Reviewing the safety assignment as proposed in this chapter, leads to comprehensive results, which can be used for evaluating the spatial assignment. Overall, it can be found that the safety factor changes gradually, when the berm height or berm width is changed. This observation is found in every single provided figure, based on a unique combination of crest height, and inner slope angle. From Figure 108 (for slope 1:3), Figure 109 (for slope 1:3.5), and Figure 110 (for slope 1:4), it is difficult to observe the effect of changing the inner slope, and the crest height of the dike. Nevertheless, it is found that these parameters have some influence on the safety against failure. This is discussed in the remainder of this section.

Effect berm width

In Figure 111, the effect of changing the berm width can be observed. In these figures, the effect is illustrated for two crest heights (14.9 m, and 14.2 m), and four berm heights (1 m, 2 m, 3 m, and 4 m). An almost linear relation, can be observed between the berm width, and the safety factor. It is realistic to observe that the safety factor increases with the berm width of the dike, because increasing the berm width would leads to an extra resisting force against sliding (weight on the passive side of the sliding plane). It can be found in the figures that a berm width of 15 m, and a berm of 35 m have a safety factor difference of 0.8.



Another thing which is observed in Figure 111, is the reducing difference between the inner

Figure 111: Effect of changing berm width

slopes scenarios when the berm height is increasing. This is caused by the reducing length on which the inner slope scenario acts. As explained in Section D.5., the slope underneath the berm is fixed to 1:3, causing that an increasing berm height, increases the influence of the slope of the inner berm, and reduces the effect of the inner slope scenario.

Lastly, also the risk of using automatic generated safety calculations can be found in the figure. In the figures which show the safety factors, when a berm height of 3.0 m is used, it can be observed that the results are not so smooth as in the other figures. The expected cause, is found in the way it is searched for the minimum safety factor. To reduce computation time, grids are set at a certain location, in which the centre point of the turning circle is expected. When a minimum is found in at the border of a grid, the grid is adjusted to a new location. This search method can eventually lead to unrealistic sliding planes. Therefore, the observed sliding planes should always be valued by an engineer. In this case this was not needed, because the observed values (at the disturbances) where above the minimum required safety factor of 1.48 (for the standard failure budget, minimum factor for the shifted budget = 1.42).

Effect berm height

Also the effect of the berm height is evaluated separately. The observed effects are described based on Figure 112. This figure shows the effect of gradually changing berm height for a crest height of 14.9 m, and 14.2 m, and a berm width of 15 m, 25 m, and 35 m.

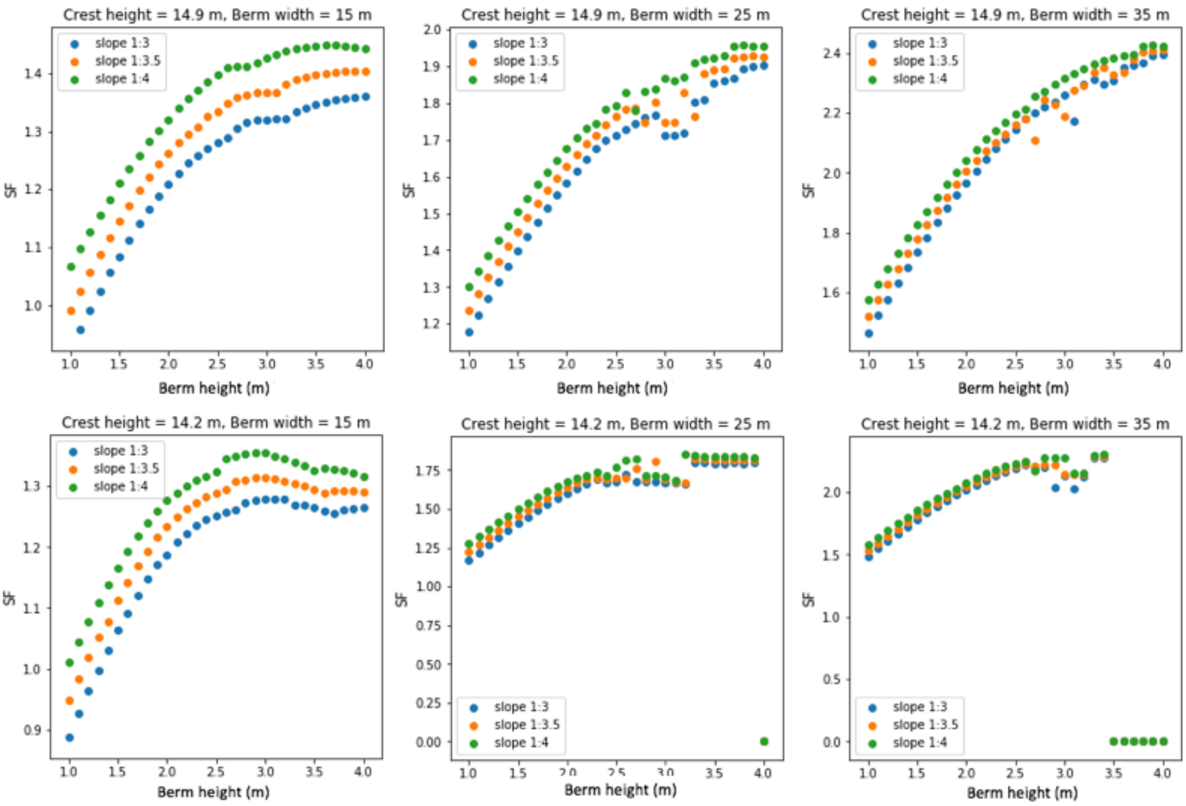


Figure 112: Effect of changing berm height

In general, it can be observed that the effect of the berm height decreases gradually when the berm gets higher. It can even be found that the safety factor slightly decreases (in the case the berm height is 14.2 m and berm width is 15 m) when the berm height approaches four meters. The observed effect of influencing the safety factor is largest when the berm width is 15 meters, while the effect is smallest at the widest berm (35 m). The cause of the observed effect is found in the part of the berm that contributes to the active and passive side of the normative sliding circles. In the case of a crest height of 14.2 m, a berm width of 15 m, and berm height of 4 m, the added extra height decreases the efficiency of the berm due to the added weight on the active side of the sliding plane. This effect is not observed at larger berm widths (25 m, and 35 m), as the influence of the extra height of the berm on the active side, is smaller than the influence on the passive side. The wider the berm, the more weight is added on the passive side, the larger the safety factor.

Effect crest height

At last, also the influence of the changing crest height has been evaluated. In Appendix D , it has been reasoned why it is expected that the crest height will not be a large influencer of the safety factor. In Figure 113, it is founded that this is indeed the case. This figure show for different berm height and inner slope scenarios, the relation between the crest height (horizontal axis), berm width (colour range), and the safety factor (vertical axis). It can be observed, that the safety factor increases slightly with the crest height when a small berm is evaluated, while the safety factor decreases slightly in case of a large berm. For berm heights of 1 m, 2 m, and 4 m, a nice gradual increase of the safety factor can be observed with an increase of the berm width. For berm heights of 3 m, again disturbances are observed.

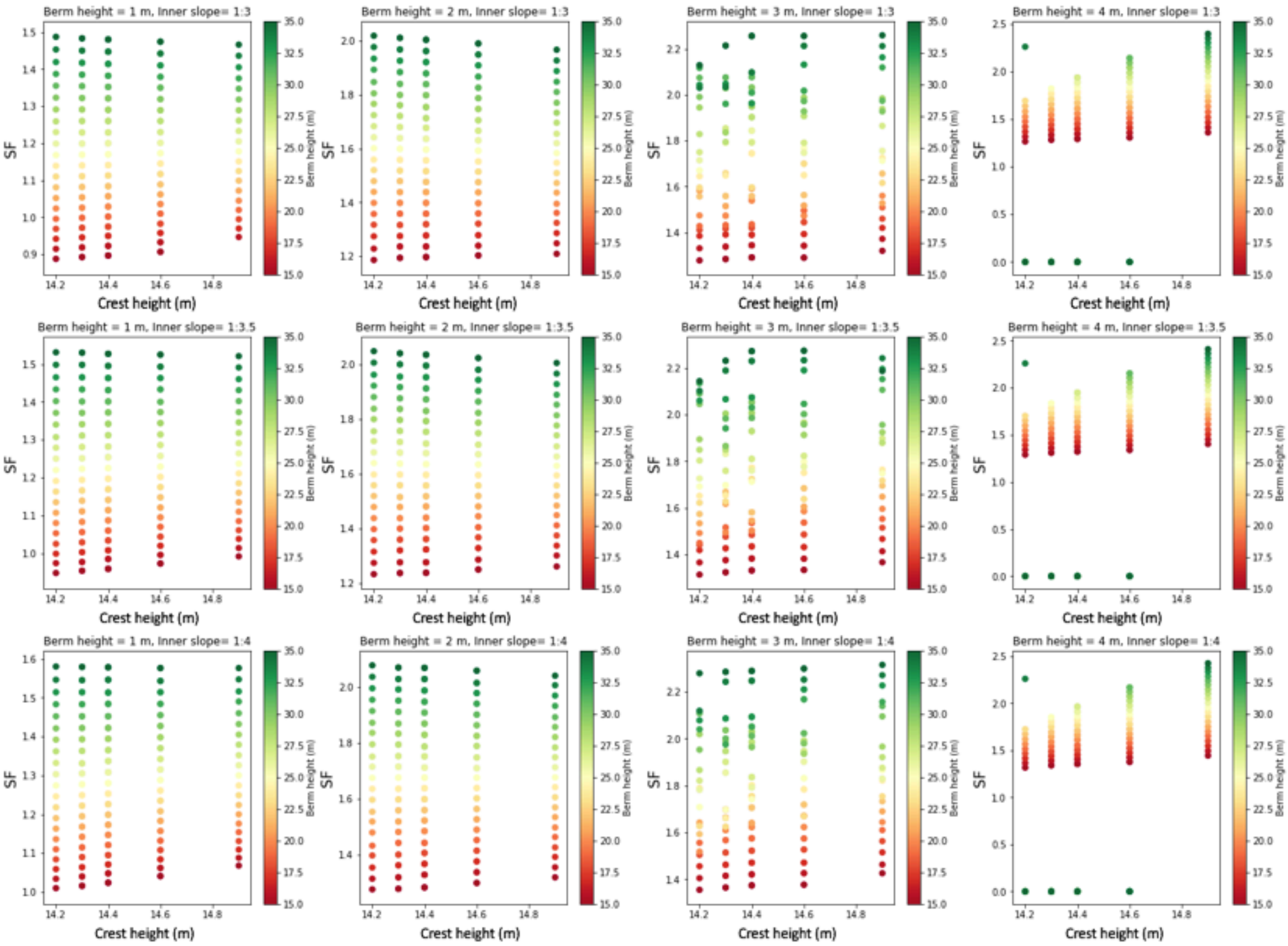


Figure 113: Effect of changing crest height

Piping

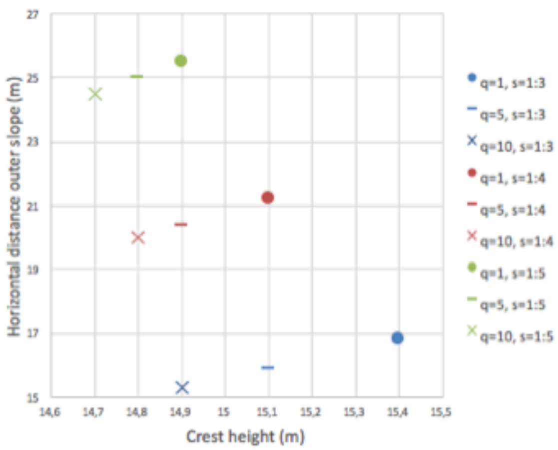
Initially, the provided design dimensions for piping are found the be large. Nevertheless, this is a familiar outcome for dike reinforcement projects in the “Bovenrivierengebied”. According to Rijkswaterstaat (2017b), this is caused by the piping sensitive soil composition in this area of the Netherlands. Besides the soil composition, also the duration of the high waters is an important reason. It is explained that a high water waves takes at least two weeks to pass a location in the “Bovenrivierengebied”. Due to this long duration, the water in the subsoil has the time to adapt completely towards the new equilibrium for water pressures in the subsoil. High water heads in the subsoil, then cause piping sensitive circumstances in the hinterland. It can be concluded, that although the found piping berms seem large, they are realistic dimensions for a typical location (the evaluated case study) in the “Bovenrivierengebied”. This conclusion holds also for the other sections (12 and 13), and will therefore not be discussed in the verification of these sections anymore.

G.6.2. Section 13

Besides for section 14, also the technical assignment has been fulfilled for section 13, and 12. In this paragraph, the results of section 13 are verified. As explained Piping in Section D.6.1, piping will not separately be verified for section 12, and 13. This paragraph is started by verifying the outcome of the determined shape of the outer slope (erosion of the inner slope). Afterwards the stability of the inner slope has been verified.

Erosion inner slope

The obtained results for assessing erosion of the inner slope caused by wave overtopping in section 13, are comparable with the outcome of section 14 (as described in Section D.3). The results are present in Figure 114a (outer slope scenarios for a standard failure budget), and Figure 114b (outer slope scenarios at a failure budget of w=0.04). This figure shows the relation between the crest height of the dike and the horizontal distance from the outer toe to the crest, based on a set overtopping scenario. It can, again, be observed that an overtopping discharge of q=10 l/s/m, combined with an outer slope s=1:3, is from land use point of view the most favourable design option. A stricter overtopping requirement does not lead to a large increase in horizontal distance over the outer slope, a decreasing slope angle (from 1:3 to 1:5) has large influence on the horizontal length of the outer slope. In Section D.6.1, it has been explained why this is a typical outcome for the case study “Wolferen-Sprok”.



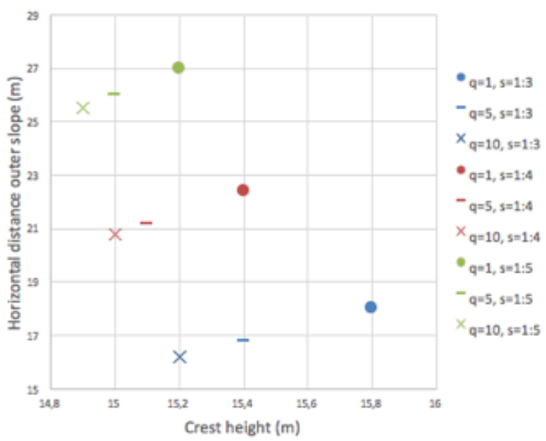


Figure 114a: outer slope scenarios (standard) *114b: outer slope scenarios (failure budget = 0.04)*

Inner slope stability

To verify the outcome of the stability analysis for inner slope stability, again for every unique combination of crest height, and inner slope angle a plot has been made that shows the safety factor for a certain berm height and berm width. The results are presented in Figure 115, Figure 116, and Figure 117. These plot are provided as it can immediately be observed whether the safety factor changes in a logical way. It is observed that this is indeed the case. When the results are compared to the outcome of section 14, it can be concluded that the results are more smooth. This can especially be observed when in the figures berm heights close to three meters are evaluated. In section 14, fluctuations of the safety factor were observed at this location, while in this section, the results show a nice gradual increasing behaviour. Again an almost parabolic behaviour is observed between berm height and berm width, when a certain safety factor is set. This is caused by the decreasing efficiency of adding extra height to the berm (as earlier explained in Section D.6.1). Based on the provided figures, it is concluded that the behaviour of the safety factor changes in a logical manner, when changing the berm height or berm width. The effect of changing the crest height and inner slope, is discussed in the remainder of this section.

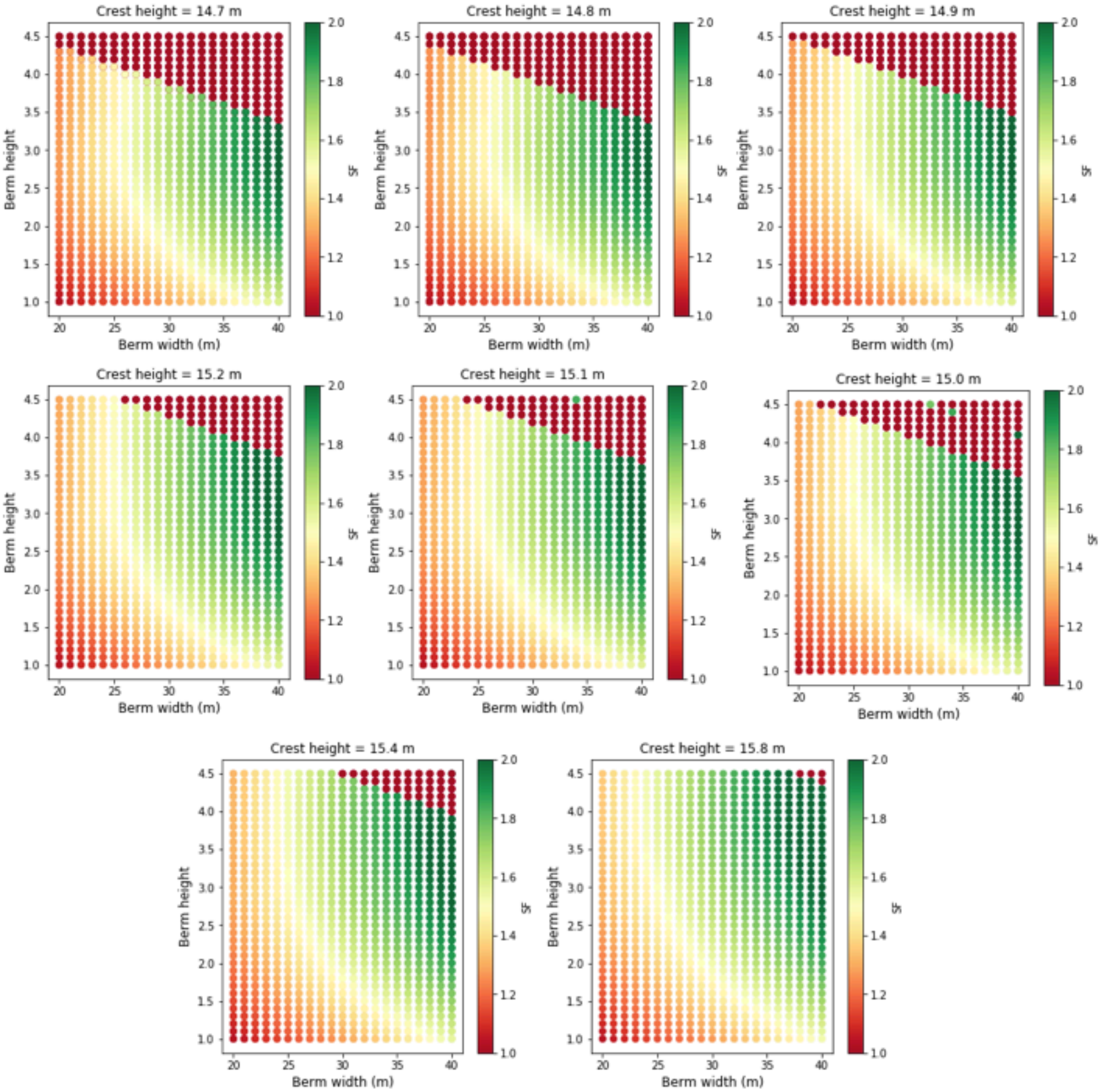


Figure 115: Section 13 slope 1:3

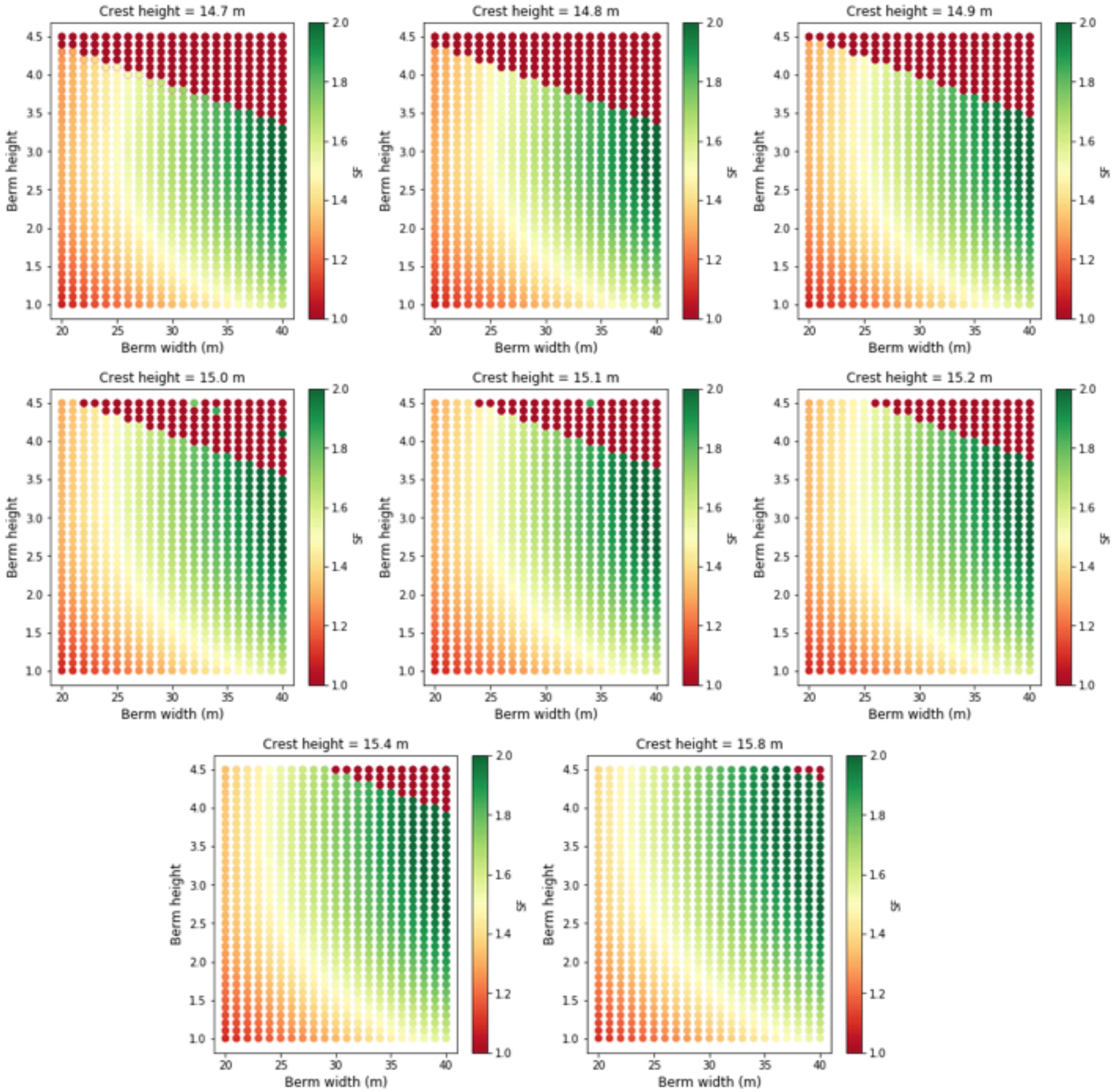


Figure 116: Section 13 inner slope 1:3.5

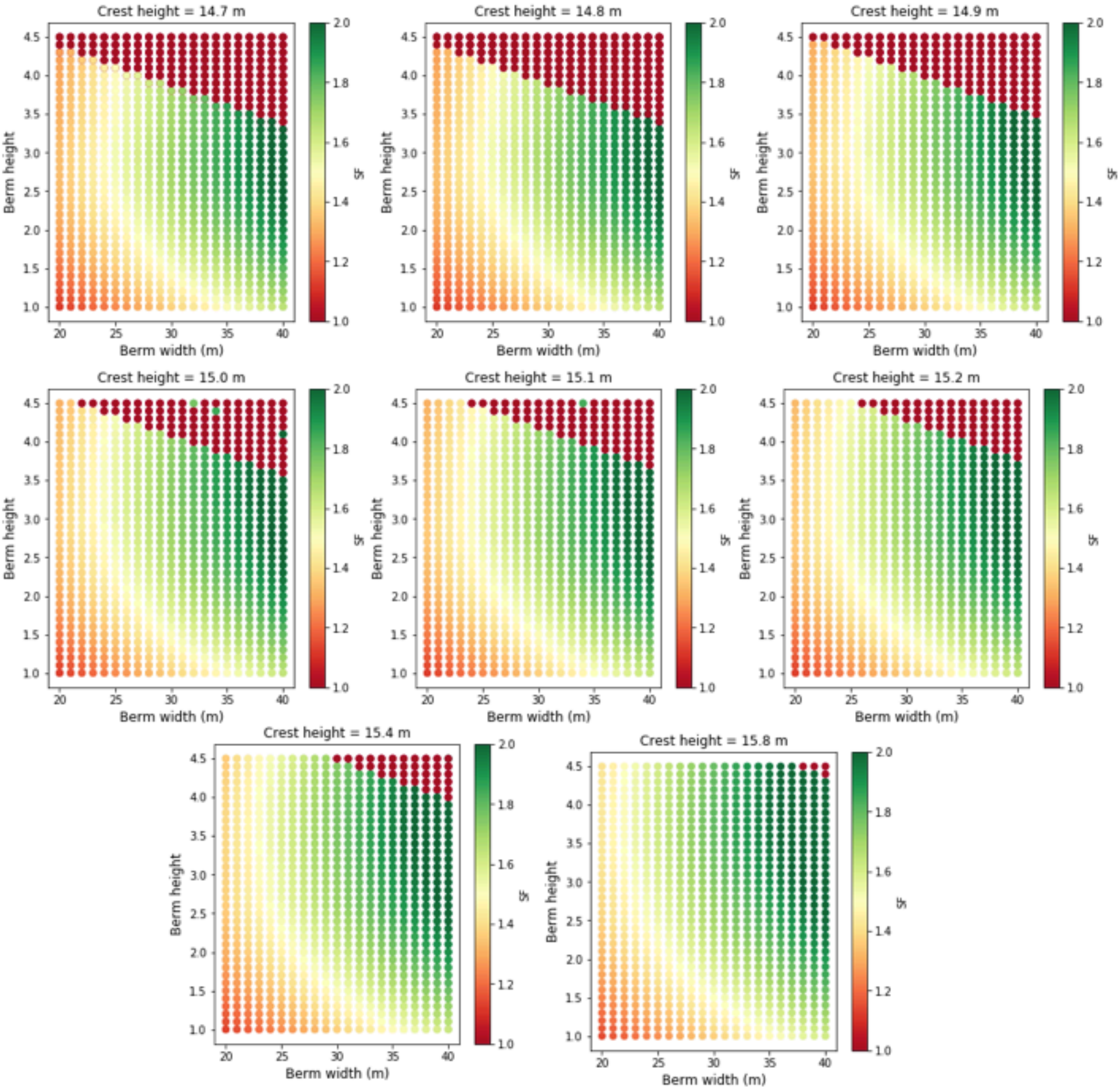


Figure 117: Section 13 inner slope 1:4

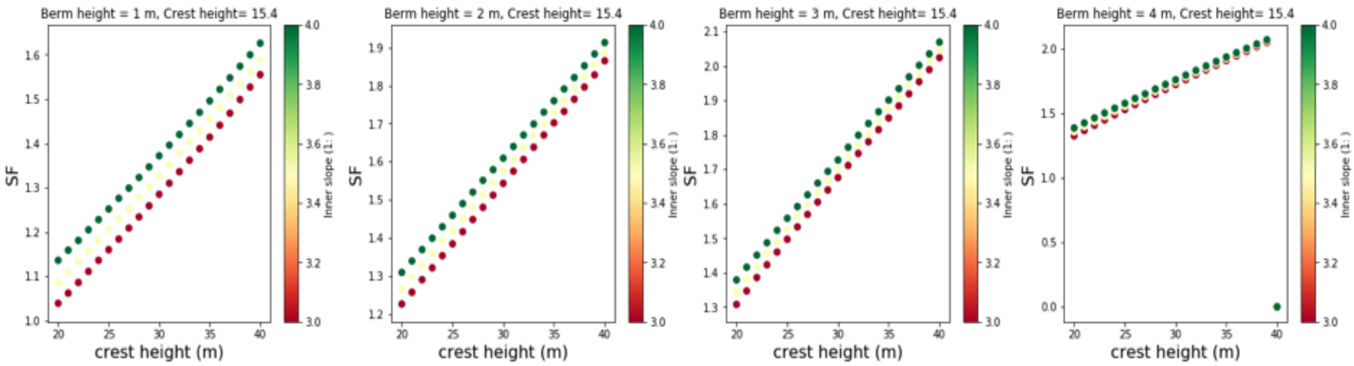


Figure 118: Effect of inner slope on safety factor Section 13

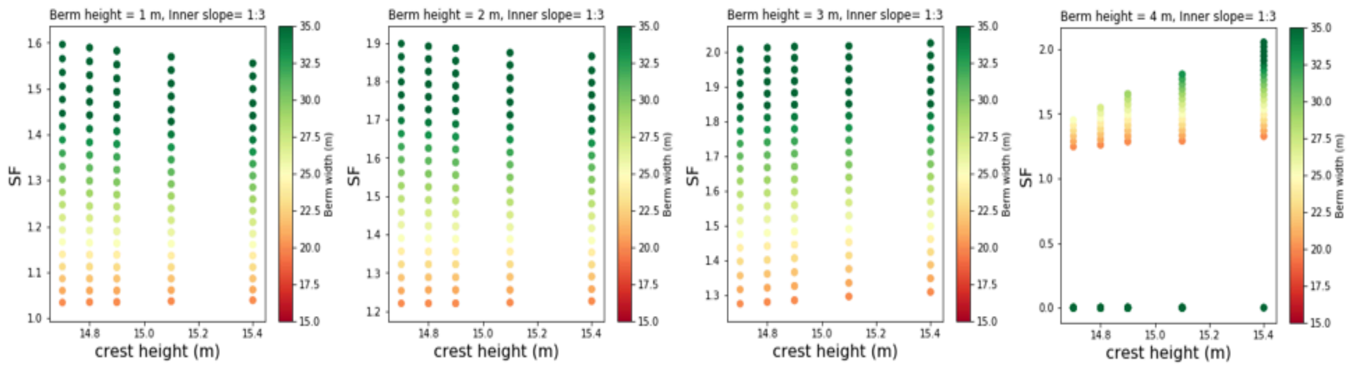


Figure 119: Effect crest height on safety factor Section 13

The effect on the safety factor of changing the inner slope angles, is visualized in Figure 118 for a crest height of 15.4 m and a fluctuating berm height. It is observed that the safety factor increases slightly when the angle of the slope decreases; this is the expected effect of changing the slope. Similar as in section 14, it is found that the difference between the effect induced by angle of the inner slope decreases for higher berm widths. In Section D.6.1, it is explained what the cause of the effect is. Figure 119, illustrates the effect of the height of the dike. Again, it is observed that the crest height does not influence the safety factor largely.

D.6.3. Section 12

The verification of the calculations obtained to review the technical assignment of section 12 is presented in Figure 120, Figure 121, Figure 122, and Figure 123. As the exact same observations are made for section 12, as for section 13, and section 14, no separate explanation will be provided on the presented figures. This is the expected result, as the hydrodynamic, and geotechnical conditions of these sections are well comparable. For explanation on the results, it is referred to Section D.6.1 and Section D.6.2. Overall the same conclusion holds for section 12; the provided outcomes of the safety assignment supply a realistic representation of the required dimensions to reinforce the normative dike as provided for section 12.

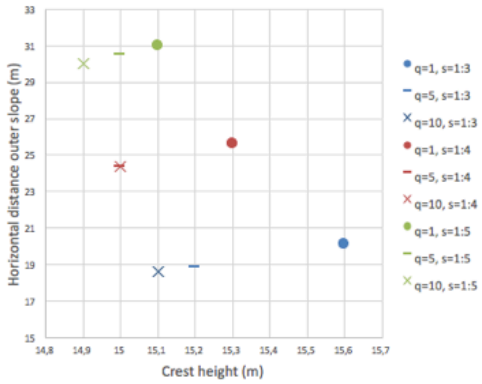
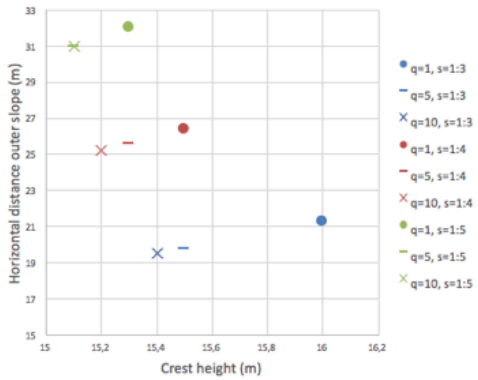


Figure 120a: outer slope scenarios (standard)



120b: outer slope scenarios (failure budget = 0.04)

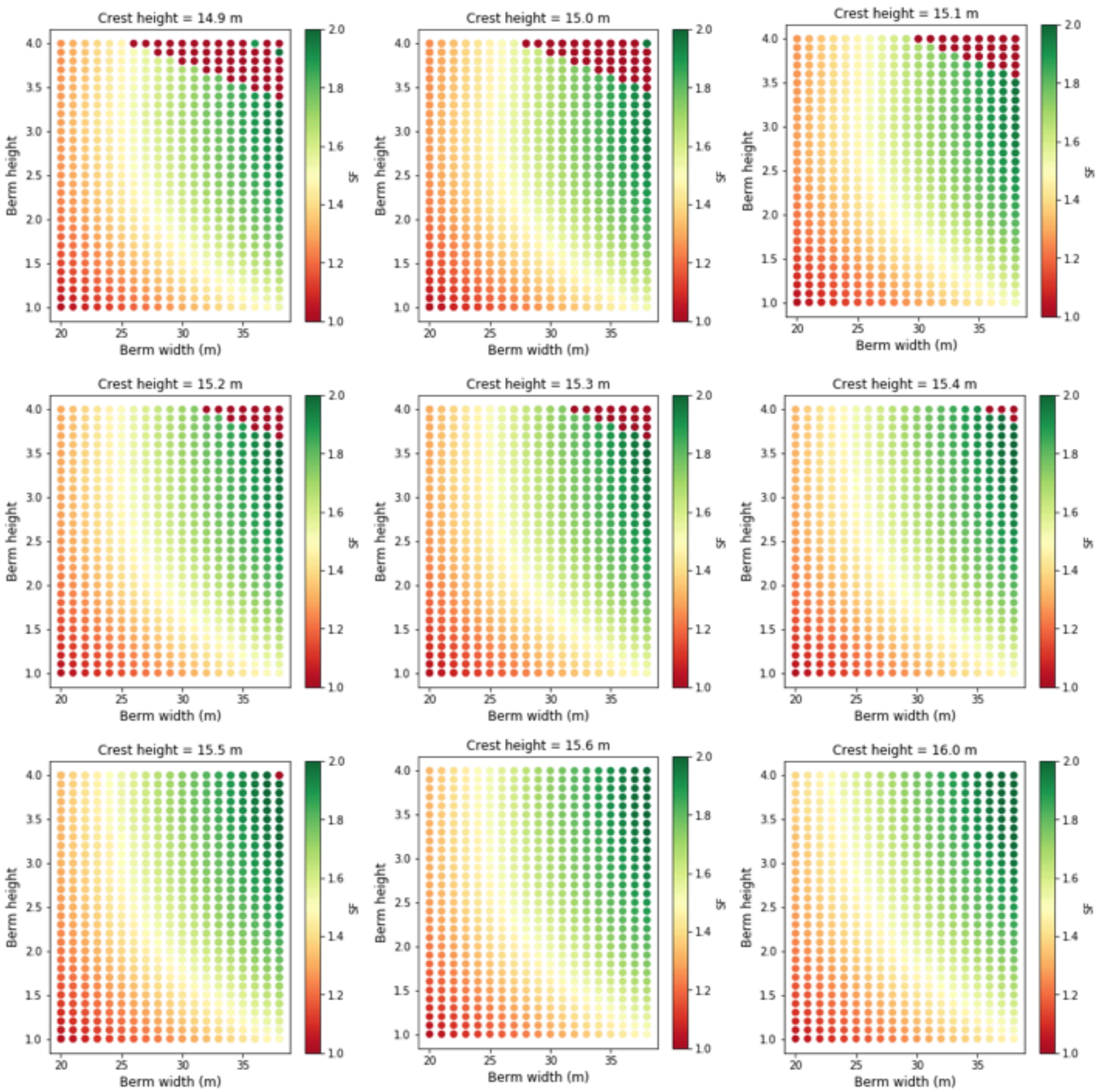


Figure 121: Section 12, inner slope 1:3

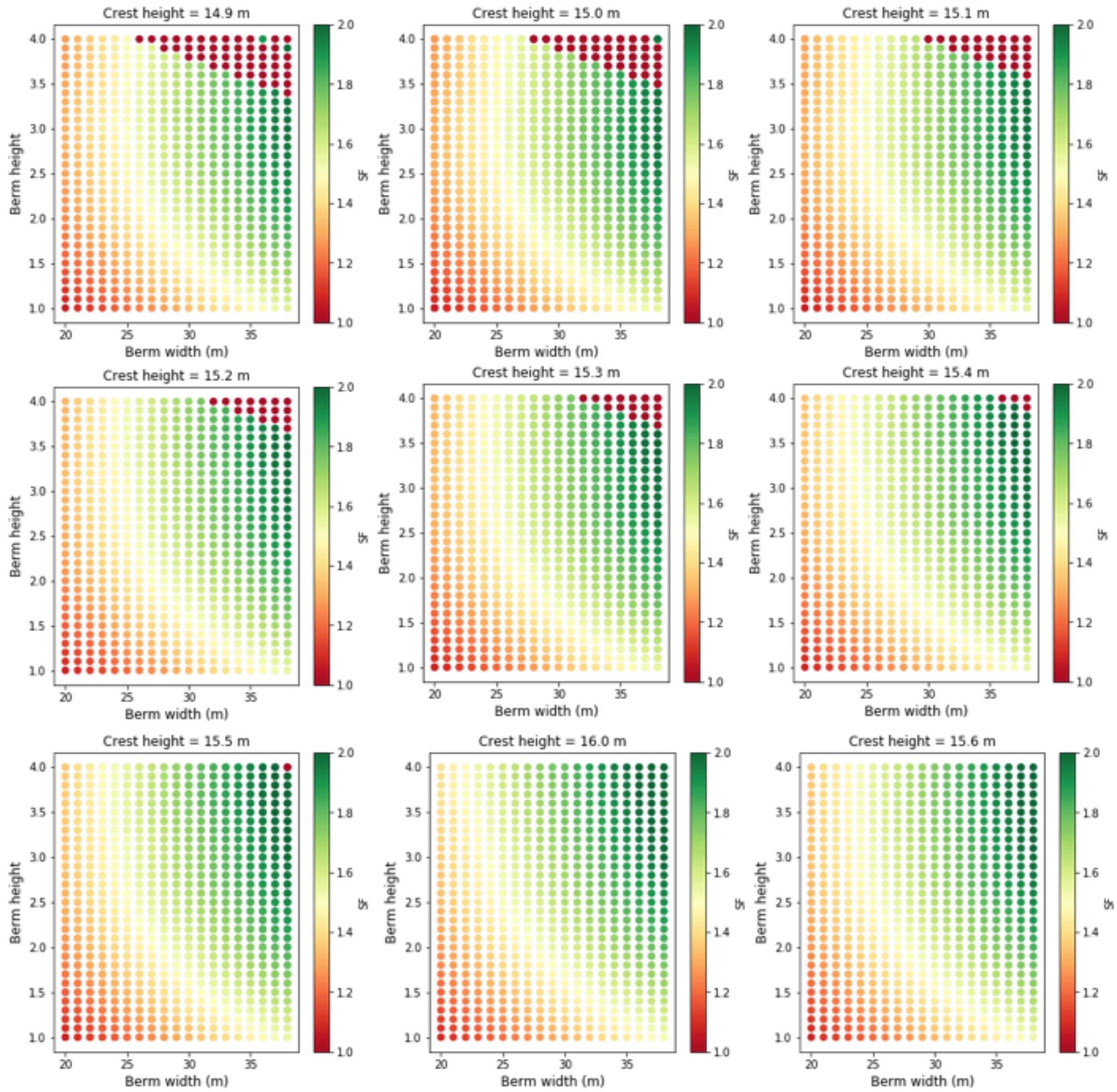


Figure 122: Section 12, slope 1:3.5

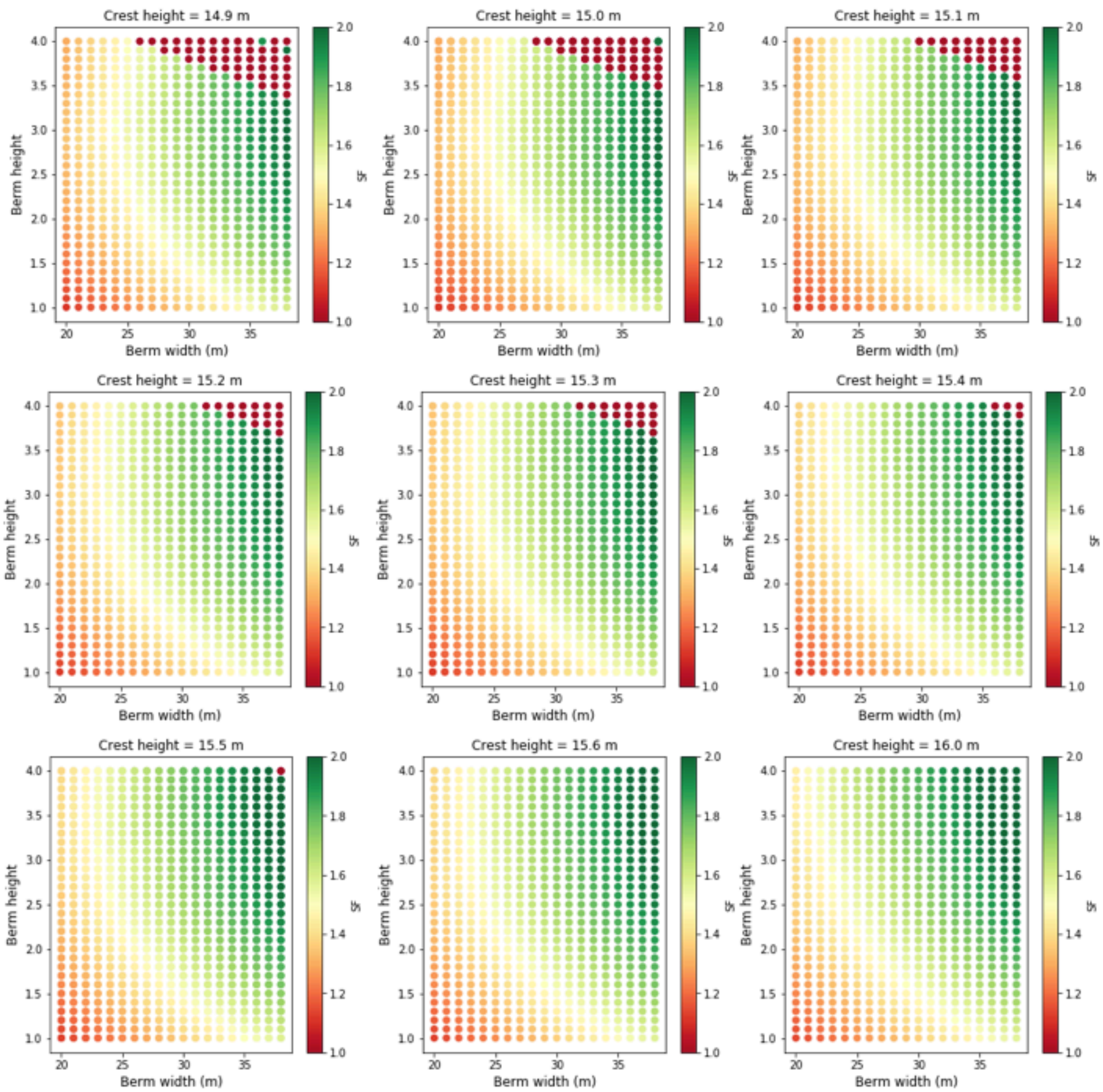


Figure 123: Section 12, slope 1:4

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