Response to reviewers' comments to the manuscript "Re-evaluating safety risks of multifunctional dikes with a probabilistic risk framework" by Richard Marijnissen et al.

We thank reviewer 1 for his constructive and helpful comments and suggestions. We hope he/she is satisfied with the changes of the manuscript.

Reviewer 1:

General comments:

Comment 1:

The paper is extremely relevant in the context of the design of flood protection under consideration of multifunctionality. In general it is well structured and contains all necessary information to follow the discussion

Response:
We thank the reviewer for this nice comment.

Comment 2:

The paper could be improved by explaining more clearly what was actually calculated to allow a better understanding of results and findings.

Response:
We agree that further explanations on the methods and findings are needed. The section describing how multifunctionality is implemented in the case-study has been revised entirely with explanations on the reinforcement strategies. Furthermore additional analyses of the results are provided in the revised manuscript with an additional figure (Fig. 6). Finally the abstract has been revised entirely based on suggestions from reviewer 2 as well to make it clearer what was calculated. Please see the marked-up document for details of the changes.

Comments 3:

The word function is used regarding multifunctionality as well as mathematical function. Because this word is used very often in the text, the authors should revise the text if the context for the word function is always clear.

Response:
This is a good point. The word "function" in the context of multifunctionality will be changed to "multifunctional use" or "multifunctional elements" where possible. Function in the context of mathematical functions are usually part of a larger definition like Probability Density Function (PDF) which require no further context. As can be seen in the marked-up manuscript many instances of the word "function" have been replaced.

Specific comments:

Comment 4:

Page 1: L11ff: (While a traditional ...) please define more precisely. As for now it does not become clear what the difference really is.

Response:
This was indeed not clear from the abstract. Based on the suggestion of reviewer 2 as well the abstract has been revised entirely.

Comment 5:

Page 3: L18: "... to exclude flood defences with an insignificantly low failure probability ... " If the probability to fail is insignificantly low, this would be a positive result. Why should such flood defences be excluded?

Response:
The goal of an assessment is to check whether it meets the safety standards. If the dike passes the basic assessment in can be excluded from further detailed and tailored assessments for that failure mechanism as it is already considered to be safe. To reflect this the word "exclude" has been replaced by "approve".

Comment 6:

Page 5: L11ff: The referral to table 1 gives the impression that either the set of analysed MFFDs or the respective calculations can be found in table 1. Neither is correct. Table 1 only shows (very generally) the differences of the approaches.

Response:
Table 1 is meant to introduce the reader to the different approaches as you correctly identified. The sentence has been reformulated to: "a set of MFFDs is assessed with the new probabilistic approach and the traditional conservative approach (see Table 1 for the approaches)."

Comment 7:

Table 1: Please rethink: If the probability of occurrence in scenario 1 (additional function present) is x%, is then the probability for scenario 2 (additional function absent) really 100-x %? This seems to be a mistake. Otherwise this needs explanation in the text.

Response:
x has been changed into P (from probability) in scenario 1 and 1-P in scenario 2. Since only 2 scenarios are considered the probability of scenario 1 + the probability of scenario 2 must equal 1 or 100%. The % sign may have led to confusion and has therefore been removed.

Comment 8:

Page 7: L28: is there really a hole presenting the profile or is there an empty space, the outer shape of the area of the additional function or something like this?

Response:
In principle all space occupied by the additional function becomes empty. This was referred to as a hole because the outer edge is no longer grass, but rather loose soil. In the revised version the word hole has not been used as it may convey a different message. This section has been revised entirely (also based on a comment by reviewer 2).

Comment 9:

L31f: Why is the probability of the absent structure chosen to be 1%? And why is this a conservative approach?

Response:
This number has been subject to some discussion. Initially the reliability requirement for housing structures in the Netherlands was taken (P_absent = 1E-5), but that would only reflect the

structural reliability. Another approach was to look at the designed lifespan of houses which is 50 years (P_absent = 0.02) but this neglects the fact many structures are renovated rather than destroyed. According to van der Flier and Thomsen (2006) 0.13 and 0.23% of houses are demolished annually in the Netherlands. Based on this 1% was chosen as an conservative order of magnitude estimation of the house being demolished during a high water event. This explanation has been added in the revised manuscript as:

"*The probability the structure is absent during a high water event is estimated to be 1%. This probability is based on the percentage of houses demolished in the Netherlands annually which has varied between 0.13 and 0.23% per year (van der Flier and Thomsen, 2006) rather than the probability of structural failure of the house*."

Comment 10:

Page 8: L3: ... when the structure remains just outside of the profile (0,1,2)... Please explain: why does this not also apply to profiles 3 and 5?

Response:
Thank you for pointing this out. This sentence should have referred to 0,1 and 5 not 0,1 and 2. It does not apply to 2 and 3 because here soil is replaced by additional weight of the structure leading to a net positive effect on stability. Because the explanation of the findings were confusing to the reader, this section has been rewritten for the revised manuscript.

Technical corrections

Comment 11:

Page 1: L22: ..., a better understanding... L26: "This is true..."please reformulate. Page 3: L4ff: please do not use the personal pronoun "we". Page 5: L12: ...and the traditional... Table 1: ...a given failure mechanism ... probability of occurrence Page 7: L10: ... by weighing... L25: please reformulate... L27: ...2 two...?; ...present in which CASE the load... Page 8: L1: ... berm [] both... L6: for better readability: ...along the full length, the inclusion of uncertainty... L7f: reformulate: TRUE L34: reformulate: "risk of functions" Page 9: L1: personal pronoun "we"... see above L2f: Please revise the sentence for better understanding. Figure 3: Please reformulate the caption: ...for calculation the probability"...

Response:
We thank the reviewer for pointing out these corrections. These have been implemented in the revision.

References:

van der Flier, C., and Thomsen, A.: Life cycle of dwellings: Analysis and assessment of demolition by Dutch housing associations, International Conference ENHR, Ljubljana, Slovenia, 2-5 July 2006; Workshop 7, Physical Aspects of Design and Regeneration, 2006,

Reviewer 2:

We would like to thank the reviewer for his thorough feedback on the paper. This feedback was of great help during the revision and hope the reviewer is satisfied with the changes.

General comments:

Comment 1:

> ... The manuscript is well-structured, presents a novel advancement of the methodology and reaches substantial conclusions. It is mostly well-written, though some sections need to be made clearer (see comments below). However, I believe the authors can further strongly improve the manuscript with regards to two aspects.

Response:
We thank the reviewer for this comment. Indeed we think that by following the suggestions the paper has improved.

Comment 2:

> (1) The section P7-L18-32 describes the effect of two additional functions (vegetation and build-structure) on dike stability. I found this description rather cryptic and unclear. It should be significantly improved. It is not clear, how either of the functions affects each breach mechanism. *[1]* Does the build structure affects only macro-instability due to additional weight? *[2]* Is there effect on piping, e.g. due to longer pipe length needed to induce a dike failure? *[3]* What do you mean by the insignificant amount of overtopping q<0.1 is acceptable? *[4]* What does this have to do with the structure or absence of a structure? *[5]* How one should imagine a scenario (with the annual probability of 1%), where a house disappears creating a hole at its location with the dike being intact (!). This is not clear to me.

Response:
We agree that this section can be made clearer and revised it based on this suggestion. The entire section has been revised to make it clearer. As the changes are extensive, please see the revised manuscript for the changes. The individual points are addressed here:

[1] The built structure is schematised by 2 effects in the model: 1) its additional weight and 2) a decrease in the maximum allowable overtopping rate.

[2] No, in our cases the structure does not extend into the aquifer and thus has little effect on piping. Furthermore one could argue the presence of a structure inhibits the well from emerging at the structure's location but a pipe could emerge just beside the structure instead along its outer wall.

[3] & [4] During overtopping the outer layer on the landward side of the dike should not erode during design conditions. When a structure is present it is effectively a discontinuity in the outer cover where water can more easily erode soil. This is reflected in a lower critical overtopping rate (q). When the structure is absent (see Table 1) there is presumed to be no grass cover but instead loose bare soil that will almost immediately start eroding. Since it is statistically impossible to rule out any overtopping (q=0 l/m/s) it is practise in the Netherlands to use q=0.1 l/m/s as a threshold value if effectively no erosion resistance can be expected and thus practically no overtopping is allowed during design conditions.

[5] The situation considered is not necessarily a collapse of the structure, but can also be when the structure is removed temporarily (e.g. a renovation or demolished intentionally to construct another). See also my response to reviewer 1. We will make sure to clarify this distinction in the revision.

Comment 3:

The second aspect is related to the first one and concerns the results of failure probability calculations (Fig. 5) and in particular the influence of different breach mechanisms. As the role of functions for various breach mechanisms was not clarified in details, it is very difficult to understand the effect of considering these functions on the distribution and changes of breach mechanisms presented in pie charts in Fig. 5. Unfortunately, the authors only scratch the surface and leave much of the presented results undiscussed and not analysed in-depth. I would appreciate a much more detailed analysis and discussion of the effects of (a) function failure and (b) reinforcement scenarios onto the role of breach mechanisms.

Response:
We agree with reviewer 2 and have explained this more in-depth by elaborating further on the reinforcements in section 3.4. Furthermore we expanded the results section to analyse the role of function failure for each of the reinforcement strategies as well as with an additional figure.

Comment 4

Finally, the authors mention in the text that uncertainties where somehow considered by considering scenario 7 "Robust dike". I did not understand this and do not see that uncertainties (of whatever nature) are considered here. Actually, the study is self-contained and there is no need to assess uncertainties as the probabilistic analysis already incorporates the uncertainties of various model parameters.

Response:
Indeed this sentence and its message were unclear. It was shown in the calculations that as the reliability of the dike increases, the influence of the uncertainty introduced by the functions has less influence on the failure probability. As the robust dike has the highest reliability, this effect was most clearly visible through this dike. The sentence has been revised to: "*The observation that the dike's own reliability influences the degree to which multifunctional use can affect the probability of failure of the dike was also found in this study*."

Comment 5:

Abstract is poorly written and is not self-explaining. L11-14 are unclear for someone who has not read the paper and comes with general, though profound knowledge on flood risk.

Response:
Based on your and reviewer 1's comment the abstract has been rewritten. Please see revised manuscript.

Comment 6:
In overall, I rate this study as very solid and believe that after addressing the two major issues and a few minor comments below it can make an interesting and significant contribution to the research on probabilistic assessment of dike failures and flood risk assessment.

Response:
We are happy with the comments and have addressed the issues you have pointed out as best as we could.

Minor issues

Comment 7:
Introduction: The text is somewhat doggerel and needs a careful revision. (e,g, P1-L26-35 and comments below)

Response:

The section between P1-L26-35has been substantially shortened. Specifically by removing the section on the history of flood risk management in the Netherlands.

Comment 8:

P1-L19: risk of floods is not increasing everywhere. One should differentiate. "these cataastrophes" – you are talking of risk in general and not about some specific catastrophes.

Response:

While flood risks are in general increasing due to a combination of climate change (sea-level rise and extreme rainfall) and economic developments in deltas, I can imagine that in specific regions this is not the case. The sentence was revised to: *"many regions in the world are faced with increasing flood-risk."*

Comment 9:

P1-L21: "Risk based approaches have been" used not "performed". L22: remove "the" before "understanding".

Response:

Thank you for pointing out these corrections. They have been addressed.

Comment 10:

P1-L36-37: revise the sentence**.**

Response:

Upon more careful reading we concluded the sentence did not convey new relevant information and was therefore removed.

Comment 11:

P2-L1: Is this really true? The nation-wide risk assessment for England and Wales (Hall et al., 2003, 2005) also used probabilistic approach to assessment of protection level/failure probability.

Response:

While a probabilistic approach was certainly used there, by our knowledge it was not legally required to do so.

Comment 12:

P2-L35: Reference Hinkel et al. is missing in the reference list.

Response:

Hinkel et al. will be added to the reference list. We also manually checked each of the references and corrected other references where information was missing or incorrectly formatted.

Comment 13:

P3-L1: what is a 'cohesive' framework?

Response:

The word should have been coherent, not cohesive. This has been corrected.

Comment 14:

P3-L40 – P4-L1: as you mention, a conservative approach is usually taken assuming the NWO to be in the most critical state. Make clear that the actual probability of failure of the NWO is thus not considered.

Response:

The word "actual" has been inserted to make this clear*: "... because the actual probability of multifunctional elements being in a critical state is not considered***".**

Comment 15:

P4-L9ff: in general, it seems that the vast majority of literature sources used in the manuscript is of Dutch origin. Nevertheless, there is also some relevant literature outside. E.g. the use of limit state functions and fault trees for flood defence assessment and hazard/risk assessment was performed by Kortenhaus (2003), Apel et al. (2004), Dawson & Hall (2006), Vorogushyn et al. (2009, 2010).

Response:

Indeed we could have used more international sources. The majority of references are of Dutch origin as the starting point of the research was the Dutch guidelines and sources/studies to support them. We have added Apel et al. (2004) and Vorogushyn et al. (2009) as references.

Comment 16:

P4-L28: what is WBI2017?

Response:

WBI2017 is the official abbreviation of the current Dutch assessment tools. References to WBI2017 were changed to "*the official Dutch assessment framework for flood defences"* . This particular sentence was removed as it repeated information presented in the introduction and aim.

Comment 17:

P5-L19: also Vorogushyn et al. (2009) compiled the statistics on dike failures from a few previous studies

Response:

Thank you again for the suggested literature. We have incorporated the suggestion in the manuscript.

Comment 18:

Eq.3.6: Use h=0 as the lower limit of the integral. –Inf dies not make sense for water levels.

Response:

If h would refer to water depth the lower limit would indeed make more sense to be 0. However since h can be negative in some reference systems (e.g. -1m +MSL which would be 1m below Mean Sea Level), h=-Inf is appropriate here. No change was made.

Comment 19:

P8-L3: Is this correct that the effect of the function is limited in the scenario 2? The yellow bar is significantly lower than for the monofunctional assessment! At P7-L40 you mentioned that in the scenario 2 there is a significant positive effect of the structure. Please, check.

Response:

As also pointed out by reviewer 1, this sentence should have referred to profiles 0,1 and **5** not 0,1 and **2**. It does not apply to 2 and 3 because here soil is replaced by additional weight of the structure leading to a net positive effect on stability. We have rewritten this section of the results in a clearer manner. Please see the revised manuscript.

Comment 20:

P9-L29-30: The sentence and the message is unclear to me.

Response:

The message was that before the new Water Act probabilistic assessments could be used but there was no obligation to do so. Now a probabilistic assessment is required and naturally more probabilistic assessments are being used. The sentence was revised to: "*Although probabilistic assessments have been used before, the new regulations of the Water Act in the Netherlands necessitate a full probabilistic assessment of flood defences.*"

Comment 21:

The list of references is not carefully formatted. Temmermann et al., journal missing.

Response:

The journal was added. Thank you for spotting this. We also manually checked each of the references and corrected other references where information was missing or incorrectly formatted.

Comment 21:

Move the equation for the Iribaren number from Table B1 into the B-section prior or after Eq. B10.

Response:

The equation was moved after Eq. B7.

Changes made during revision

Page	From line	to line	Reason for revision	Change made
1	8	18	Both reviewers found the original abstract to be unclear and not self-explanatory. The abstract has therefore been entirely rewritten to better convey the message and concepts of the paper.	*See the submitted revision for the new abstract*
1	21	22	As pointed out by reviewer 2 the risk of floods is not increasing everywhere.	*From: "*With sea-level rising globally and an expected rise in extreme rainfall events due to climate change the risk of floods is increasing (Bouwer et al., 2010;Hirabayashi et al., 2013)." *To: "*With sea-level rising and an expected rise in extreme rainfall events due to climate change many regions in the world are faced with increasing flood-risk (Bouwer et al., 2010; Hirabayashi et al., 2013)"
1	22		To make the introduction more concise as requested by reviewer 2, the introduction was shortened. This line did not convey new information and could therefore be omitted.	*Removed:* In order to develop sufficiently strong infrastructure to prevent flooding a framework is needed to assess the safety the infrastructure provides.
1	23		Correction suggested by reviewer 2	*Replaced:* "used" by the word "applied"
1	24		Corrected an error	*Corrected:* "a better the understanding" to "a better understanding"
1	27		To make the introduction more concise as requested by reviewer 2, the introduction was shortened by removing this section on the history of Dutch flood risk management	Removed:"Flood protection has always been a priority yet standards ... a full probabilistic approach (Delta Committee, 2008) and the change was made in 2017."
1	28	37	This section of the manuscript has been partially rewritten based on the suggestion of reviewer 2: "Introduction: The text is somewhat doggerel and needs a careful revision"	*See revised manuscript*
2	2		Added the word "engineered" to clarify MFFDs are man-made structures	"Multifunctional flood defences (MFFDs) are engineered structures ..."
2	5		Better word used	From: "... multiple additional ..." to: "... more ..."

2	7		Reviewer 1 suggested: “the authors should revise the text if the context for the word function is always clear.” We feel the use of the word is clear in this section. Still here this replacement is used to avoid repeating the word function too often.	From: “Other functions ...” to: “Multifunctional use of the flood defence ...”
2	8		Simplified the sentence	From: “do not need to be a detriment to safety” to: “...does not need to decrease safety”.
2	9		The term “nature” was in this context	From: “nature” to: “green foreshores”
2	14		“Because they” fits better in the sentence	From: “... which ...” to: “... because they ...”
2	16		No emphasis by the word especially was needed	Removed: “Especially”
2	21		Shortened the sentence	From: “...to rules of thumb on the one hand and in-depth studies on the other.” To:”... to rules of thumb and in-depth tailor-made studies.”
2	21	23	Simplified and shortened this complex sentence	From: “Unless the multifunctional aspect is perceived to be of sufficient importance to justify a tailor-made study, assessments are often limited to showing other functions do not significantly diminish the safety of the flood defence while ignoring potential positive contributions to safety.” To: ”Unless the multifunctionality is a key feature assessments are often limited to proving multifunctional use does not significantly diminish the safety of the flood defence ignoring potential positive contributions to safety.”
2	23	24	Simplified and shortened this complex sentence	From: “Using a conservative approach for dike assessments where multifunctional elements can only negatively influence flood risk does ensure safe dikes from a flood risk perspective but may hamper the implementation of efficient multifunctional dikes by requiring larger or more expensive dikes.” To: “Using such a conservative approach for dike assessments does ensure safe dikes from a flood risk perspective but may result in requiring larger and more expensive multifunctional dikes.”

2	31	32	Avoiding the term “functions” here as suggested by reviewer 1	From: “to combine multiple functions with dikes” To: “for multifunctional use of the flood defence”
2	34		Avoiding the term “functions” here as suggested by reviewer 1	From: “functions” To: “multifunctional elements”
2	37		Changed misused word as pointed out by reviewer 2	From: “cohesive” To: “coherent”
2-3	41	6	Changed the sentences with an active structure using the word “we” into passive sentences.	*See revised manuscript*
3	5		Monofunctional dikes were meant here as some traditional dikes were already multifunctional	From: “traditional dikes” to :” monofunctional dikes”
3	9		Using a better word for the context	From: “communicated” to “documented”
3	11		Using a better word for the context as pointed out by reviewer 1. See also the response to reviewer 1 comment 5	From: “exclude” to “approve”
3	20		Avoiding the term “function” here as suggested by reviewer 1	From: “the function” to: “multifunctional use of the dike”
3	24		Avoiding the term “functions” here as suggested by reviewer 1	From: “functions” to: “multifunctional elements”
3	34		Present tense fits better	From: “assessing” to “assess”
3	35		Avoiding the term “functions” here as suggested by reviewer 1	From: “functions” to: “multifunctional elements”
3	35		Clarified the actual probability is calculated as suggested by reviewer 2	From: “... the probability...” to: “... the actual probability ...”
3	40		Added the word “mathematical” to avoid confusion with multifunctional use as suggested by reviewer 1	“... mathematical limit state function ...”
4	4	5	Added 2 non-Dutch references as suggested by reviewer 2.	(Apel et al., 2004; ...; Vorogushyn et al., 2010)
4	13		Avoiding the term “function” here as suggested by reviewer 1	Changed: “function” To: “multifunctional element”
4	18		This was later clarified by (Knoeff, 2017). This sentence can therefore be removed	Removed: “but it was left unclear how these failure probabilities can be implemented in the overall framework (Witteveen+Bos, 2013).”
4	20		Introduce the approach earlier in the manuscript for clarity	Added: “This approach will be explored further in the study.”
4	23		Avoiding the term “functions” here as suggested by reviewer 1	Changed: “functions” into: “multifunctional elements”
4	23		Repeated information	Removed: “While in scientific ... evaluate multifunctional elements.”
4	23		Avoiding the term “functions” here as suggested by reviewer 1	Changed: “functions” into: “multifunctional elements”
4	23	24	Simplified this sentence	From: “Through scenarios the inclusion of unspecified functions can be evaluated in different states through simple or complex models ...”

				To: “Multifunctional elements can be evaluated in different scenarios with simple or complex models ...”
4	25		Avoiding the term “functions” here as suggested by reviewer 1	Changed: “function” into: “multifunctional element”
4	25		Avoiding the term “functions” here as suggested by reviewer 1	Changed: “function” into: “element”
4	28		Avoiding the term “functions” here as suggested by reviewer 1	Changed: “function” into: “multifunctional element”
4	28	29	Avoid using the word “we” as suggested by reviewer 1	From: “We therefore synthesize the methods for MFFD assessments in the Netherlands in Fig. 2” To: “Therefore the steps for MFFD assessments in the Netherlands are synthesized as follows (also see Fig. 2):”
4	39		Replaced the word “approach” to “assessment” for consistency throughout the paper	From: “... difference between a basic approach and the risk-based approach ...” To: “... difference between a basic assessment and a probabilistic one ...”
4	39		Replaced the word “approach” to “assessment” for consistency within the paper	From: “In a basic approach ...” To: “In a basic assessment ...”
4	41		Typo corrected	From: “... found in steps 1 to 4 ...” To: “... found in steps 1 to 5 ...”
4	42		Replaced the word “risk approach” to “probabilistic assessment” for consistency within the paper	From: “... risk approach ...” To: “... risk-based probabilistic assessment ...”
4	42		Corrected with the proper tense	From: “... should be ...” To: “.. are ..”
5	2		Replaced the word “approach” to “assessment” for consistency throughout the paper	From: “Comparing the basic framework with the expanded risk-based framework” To: “Comparing the basic assessment with the expanded probabilistic assessment”
5	3		Removed an unnecessary word	Removed: “more”
5	4		Used a passive tense to avoid using the word “we” as suggested by reviewer 1	From: “... we assess a set of MFFDs ...” To: “...a set of MFFDs is assessed ...”
5	4		Error corrected	From: “and a the traditional conservative approach” To: “and a traditional conservative approach”
5	5		Clarified table1 shows the approaches as suggested by reviewer 1.	From: “(see Table 1).” To: “(see Table 1 for the approaches).”

5	6		The concept of limit states has not yet been introduced in the paper.	From: “the limit state functions” To: “the models describing failure”
5	7	8	The concept of fragility curves has not yet been introduced in the paper.	From: “To combine the different failure probabilities the fragility curves of the mechanisms can be used (Bachmann et al., 2013) to arrive at the probability of failure.” To: “The failure probabilities per scenario and failure mechanism are combined to arrive at the probability of failure.”
5	12		A low number can be better expressed with words	From: “3” to: “three”
5	13		Added a reference as suggested by reviewer 2.	Added: Vorogushyn et al., 2009 as refference.
5	16		Clarified a limit state function is a mathematical concept and not a form of multifunctional use as suggested by reviewer 1.	Added: “an equation called”
5	23		Reference changed to the report detailing the experimental version of D-Stability used instead of the official release	From: “(Deltares, 2016)” To: “(Brinkman and Nuttall, 2018)”
5	27	30	The variables in the text have been rewritten with equation-tool to get the same formatting as in the equations.	*See revised manuscript*
6	1		Year of publication was missing in the reference	Corrected to: (Hasofer and Lind, 1974).
6	2		Better words used for the context	From: “find the low” to: “assess the small”
6	10		Minor correction	Added the word relevant to: “all relevant water levels”
6	22	23	The sentence was better suited as an introduction to the section with some minor modifications	Moved and adapted sentence: From: “The dike is situated in ... a structure respectively” To: “The multifunctional dike for the case-study is situated in a riverine area, with nature on the floodplain side and a building on the landward side.”
6	24	25	Made a list within the sentence for better readability	“with three methods: ..., ... and a ... .”
6	27	32	Section added explaining the effects of each reinforcement on the failure mechanisms as suggested by reviewer 2	*See revised manuscript*
7	1		Avoiding the term “function” here as suggested by reviewer 1	From: “function” To: “multifunctional element”
7	1		Clarification that only damage that results in dike failure needs to be considered.	From: “... can potentially damage part of the dike section.” To: “... can compromise a section of the dike resulting in failure.”

7	2		Avoiding the term “function” here as suggested by reviewer 1	From: “functions” To: “multifunctional elements”
7	3	5	Revised the sentence and made a link to the appropriate profiles in Fig. 4.	From: “In alternatives 1 and 5 the use of the hinterland remains separate from the dike itself, while in the other alternatives the structure becomes an integral part of the flood defence.” To: “When broadening the dike on the flood plain or making a shallow outer slope (see profiles 1 and 5 in Fig. 4) the hinterland remains unaffected by the dike itself, while in the other alternatives the building becomes part of the flood defence”
7	5		Making the sentence clearer	From: “...how the safety after the reinforcements is evaluated.” To: “ ... the effect of the multifunctional elements on safety is evaluated.”
7	7		Avoiding the term “functions” here as suggested by reviewer 1	From: “functions” To: “multifunctional elements”
7	8		Revised this sentence to be clearer	From: “The schematisation of functions in this study has been based on the fact-sheet by Knoeff (2017) ....” To: “Effects of multifunctional elements on dike failure are incorporated through scenarios based on the fact-sheet by Knoeff (2017) ....”
7	8		This is explained in the next sentences already	Removed: “for incorporating indirect failure mechanisms in assessments.”
7	9		The word element is more consistently used in the paper while it has the same meaning in this context.	From: “object” to: “element”
7	13	36	This section was entirely rewritten as suggested by reviewer 2. It was improved by including an explanation of how each function affects the different failure mechanisms, added a reference on the demolition of houses and a clarification on the “failed” state of a structure.	*See revised manuscript*
7	25		Corrected the sentence by adding the word “the”.	From: “... profile ...” to: “... the profile ...”
7	29		Using the proper preposition	From: “... of the case study ...” to: “... in the case study ...”
7	38		Textual error corrected	Removed: “... summarry ...”
7	39	40	Sentence was revised	From: “The probabilistic assessment of the functions and the monofunctional assessment yield a lower probability of failure.”

				To: "Both the probabilistic assessment of the additional multifunctional elements and the monofunctional assessment yield a lower probability of failure for each dike profile (Fig. 5)."
7	40		Sentence contains no new information.	Removed: "Whether a function has a net positive or negative influence on the safety of the dike becomes only apparent by comparing these."
8	1	31	The entire section has been rewritten based on the suggestions of reviewer 2. Changes include: • Headers for each failure mechanism • Addition of Fig. 6 with fragility curves of each mechanism and profile in different states of the multifunctional components • deeper analysis of the effects of the structure and its different states on the failure mechanisms • the effect of the trees on the (piping) assessments	*See revised manuscript*
9	5	6	The meaning of this sentence was unclear	From: "... holds true for a conservative approach that only assesses the parts of the dike unaffected by other functions." To: "... holds true for a conservative approach that omits multifunctional elements from the assessment."
9	6		Avoiding the term "function" here as suggested by reviewer 1	From: "... additional functions the ..." To: " ... multifunctional elements their ..."
9	7	8	Avoiding the term "functions" here as suggested by reviewer 1	Changed "functions" into "multifunctional elements"
9	11		Avoiding the term "functions" here as suggested by reviewer 1	Changed "functions" into "multifunctional elements"
9	11		The word "failures" is clearer in this context	Changed : "risks" int "failures"
9	16	17	The exact meaning of "risks of functions" was not clear	From: "... new information on the risks of functions ..." To: "...new information on the interaction between multifunctional uses and failure mechanisms ..."
9	20		Avoiding the term "functions" here as suggested by reviewer 1	Changed "functions" into "multifunctional elements"
9	24		Avoiding the term "functions" here as suggested by reviewer 1	Changed "functions" into "multifunctional elements"
9	24	25	Avoiding the term "functions" here as suggested by reviewer 1	Changed "other functions" into "multifunctional use of the flood defence"

9	25	27	Sentence revised as suggested by the reviewers	From: “For piping Aguilar-López et al. (2015) demonstrated that reducing the uncertainty in the seepage of the soil of a multifunctional dike by correlating grain-size and hydraulic conductivity the probability of a piping failure is already reduced.” To: “For piping Aguilar-López et al. (2015) demonstrated that reducing the uncertainty in the seepage properties of the soil of a multifunctional dike the probability of a piping failure is already significantly reduced.”
9	28		Replaced “ground” with “soil” for consistency with previous sentence	From: “ground” to “soil”
9	29	31	The sentence suggested uncertainties were only addressed by the robust dike (as pointed out by reviewer 2).	From: “The influence of uncertainties was also observed within this study through the case of a robust dike.” To: “The observation that the dike’s own reliability influences the degree to which multifunctional use can affect the probability of failure of the dike was also found in this study.”
9	31	37	Avoiding the term “function(s)” here as suggested by reviewer 1	Changed “function(s)” into “multifunctional element(s)” or “multifunctional use of the flood defence”
9	37		Minor correction	Added “of” before “multifunctional use”
9	39		Avoiding the term “function” here as suggested by reviewer 1	Changed “function” into “multifunctional use”
9	39		Revised the sentence	From: “...can have their own ...” To: “...comes with its own ...”
9	40		Minor correction	Changed: “should” into “must”
9	41		Minor correction	Changed: “is” into “can be”
9	42		Added the word measures for clarity	From: “... flood protection” to “flood protection measures ...”
9	43		Minor correction	Changed: “should” into “need to”
10	1	2	Shortened the sentence to make it clearer	From: “While the current study looked at assessments for an existing situation, relating and managing uncertainties of functions to uncertainties in future climate conditions will be crucial for a probabilistic application of additional functions in designs.” To: “This study investigated the assessments of multifunctional flood defences for the current situation. In the design of these defences, however, future conditions, like for example

				climate change or societal trends, need to be taken into account.”
10	2		Changed word to better fit the context	Changed: “Predictions” into “Scenarios”
10	8		Changed “we” into “this study” as suggested by reviewer 1	Changed “we” into “this study
10	7	19	Avoiding the term “function(s)” here as suggested by reviewer 1	Changed “function(s)” into “multifunctional element(s)”, “multifunctional use(s)” or “multifunctional use of the flood defence”
10	10	11	Revised this sentence as suggested by the reviewers	From: “Although a probabilistic assessment was not forbidden, new regulations and insights of the Water Act in the Netherlands stimulate a probabilistic assessment of flood protection.” To: “Although probabilistic assessments have been used before, the new regulations of the Water Act in the Netherlands necessitate a full probabilistic assessment of flood defences”
10	11	12	Specify that the framework is probabilistic	From: “a framework ... was synthesized” To: “a probabilistic framework ... was developped”
10	14		Specify that probabilistic assessment only always return lower assessed risks compared to conservative assessments	Added: “compared to conservative assessments”
10	17	18	Replaced the less clear term “protection level” with “reliability”	Replaced “protection levels” with “reliability”
10	21	26	Avoiding the term “function(s)” here as suggested by reviewer 1	Changed “function(s)” into “multifunctional element(s)”, “multifunctional use(s)” or “multifunctional use of the flood defence”
10	24	25	Added how scenarios are determined	Added: “These scenarios and associated probabilities will need to rely on expert judgment.”
10	25		Minor change	Changed: “Furthermore,” into: “However,”
10	26		Combined the 2 paragraphs into 1	-
10	27		Not necessarily monitoring schemes need to be used to guide the scenarios of probabilistic assessments.	Removed “into monitoring schemes”
10	27		Specified scenarios and their probabilities need further research	Added: “... on the proper scenarios and their associated probabilities ...”
12	15		Reference to Bretschneider removed as the equations are	Removed (1957)

			taken from another source based on Bretschneider.	
12	21		Moved equation and updated the equation numbers accordingly	Moved equation $$\xi_0 = \frac{\tan(\alpha_{\mathrm{out}})}{\sqrt{\frac{2\pi H_{\mathrm{s}}}{gT_{\mathrm{s}}^2}}}$$ out of table B1
13	5		Section on the ground water model has been omitted as this was only relevant for the heave and uplift sub-failure mechanisms of piping erosion. Because the internal erosion sub-mechanism of piping was dominant for all situations of this case-study, the uplift an heave sub-failures were eventually discared. Therefore the formulas and accosiated equations were obselete. The original Eq. (C3) stated the considered head difference for piping to be h*(1-r) which is wrong for the Sellmeijer formula. This equation only applies to the initiation of the heave and uplift sub-failure mechanisms where head differences under the blanket layer before resulting in an exit point are considered, not for the final internal erosion piping process described by Sellmeijer ultimately used in this study.	*Removed:* "Piping is evaluated with the ground water schematisation ... H=h*(1-r) (C3)"
13	11	12	WBI was not explained in the manuscript	From: "estimates provided for WBI assessments" To: "estimates used in Dutch dike assessments"
13	15		WBI was not explained in the manuscript	From: "WBI 2017" To: "official Dutch guidelines"
15	7		Revised the sentence to be clearer	From: "with the highest probability of occurring but rather converges to a local minimum" To: "with the highest probability but rather converges to a local design point"
16-20	-	-	References have been updated and missing information was added. Some references were removed or replaced (see below*)	*See further below**
22	Fig. 3		Caption corrected	From: "The probabilistic procedure for calculation the probability of failure of a dike cross-section in this study"

				To: “The probabilistic procedure for calculating the probability of failure of a dike cross-section in this study”
23	Fig. 5		The piecharts for the probabilistic assessment and monofunctional assessment had been switched-up, this has been corrected. Colors altered to work better when printing in grey-scale	*Figure has been updated*
24	Fig. 6		New figure to show the influence of the multifunctional elements on failure for every mechanism and profile	*Figure added*
26	Table 1		Avoiding the term “function(s)” here as suggested by reviewer 1	Replaced the word “functions” with “multifunctional elements “
26	Table 1		Grammatical error corrected	Corrected: “... for a given failure mechanisms” To: “...for a given failure mechanism”
26	Table 1		The words “of occurring” are not necessary	From: “a probability of occurring” To: “a probability”
26	Table 1		Figure in the row probabilistic: X% changed to P for clarity based on reviewer 1’s comment	*See manuscript*
28	Table B1		Formula for ξ_0 moved out of the table	*See manuscript*

* Additional changes to references

Original reference	**New reference**	**Reason**
Kok, M., Jongejan, R., Nieuwjaar, M., and Tanczos, I.: Grondslagen voor hoogwaterbescherming, Ministerie van Infrastructuur en Milieu and Expertise Netwerk Waterveiligheid, Utrecht, the Netherlands, 2016.	Kok, M., Jongejan, R., Nieuwjaar, M., and Tanczos, I.: Fundamentals of Flood Protection, Ministery of Infrastructure and the Environment and Expertise Network for Flood Protection (ENW), Breda, the Netherlands, 2016.	Changed reference to the international version instead of the Dutch version
Slomp, R.: Flood risk and water management in the Netherlands : a 2012 update, Ministerie van Infrastructuur en Milieu and Rijkswaterstaat, Waterdienst, Utrecht, the Netherlands, WD0712RE205, 2012.	-	Omitted as the same information is present in the more easily accessible English book: “Fundamentals of flood protection”
Ministerie van Infrastructuur en Milieu: Wijziging van de Waterwet en enkele andere wetten (nieuwe normering	-	This has been removed as Ministerie van Infrastructuur en Milieu (2016b) contains the same information

primaire waterkeringen). In: Kamerstuk 34 436 2016a.		
Witteveen+Bos: Review notitie DHV/BomenwachtDT392-2, 2013.	-	Section with the reference was omitted
Delta Committee: Rapport Deltacommissie. Deel 1. Eindverslag en interimadviezen, 1960	Maris, A.G., De Blocq van Kuffeler, V.J.P., Harmsen, W.J.H., Jansen, P.P., Nijhoff, G.P., Thijsse, J.T., Verloren van Themaat, R., de Vries, J.W., Van der Wal, L.T.: Rapport Deltacommissie. Deel 1. Eindverslag en interimadviezen, Delta Committee, Delft, the Netherlands, http://resolver.tudelft.nl/uuid:0e28dfd8-4e67-4267-a443-54b74a062bcb (last access: 21 february 2019), 1961.	Using the members of the Delta Committee as authors and added necessary information
Deltares: D-GEO STABILITY; Slope stability software for soft soil engineering, User manual, Deltares, The Netherlands, 2016.	Brinkman, R., and Nuttall, J. D.: Failure mechanisms – Macro Stability kernel; Scientific Background, Deltares, Delft, The Netherlands, 11201523-001-HYE-001, 2018.	Changed the reference from the manual of the official 2016 release to the 2018 report with the unofficial release used in the study

Re-evaluating safety risks of multifunctional dikes with a probabilistic risk framework

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Abstract. ~~Multifunctional use of~~ It is not uncommon for a flood ~~defences is often seen~~defence to be combined with other societal uses as a ~~disadvantage for flood protection. Safety assessments of~~ multifunctional ~~dikes only require functions do not negatively affect safety but leave potential synergies untapped.~~flood defence, from housing in urban areas to nature conservation in rural areas. The assessment of the safety of multifunctional flood defences is often done using conservative estimates. This study ~~synthesizes the~~synthesises new probabilistic approaches to evaluate the safety of multifunctional flood defences employed in the Netherlands ~~after the introduction of the new Water Act~~ and explores ~~how~~ the results of these approaches. In this ~~affects the~~ paper a case representing a typical Dutch river dike combining a flood safety function with a nature and housing function is assessed ~~risk of flooding. While a traditional conservative approach does~~ by its probability of failure for multiple reinforcement strategies considering multiple relevant failure mechanisms. Results show how the conservative estimates of multifunctional flood defences lead to ~~safe assessments,~~a systematic underestimation of the reliability of these dikes. Furthermore, in a probabilistic ~~approach assesses a~~ assessment uncertainties introduced by multifunctional elements affect the level of safety of the dike proportional to the reliability of the dike itself. Hence, dikes with higher protection ~~level of the dike. Positive contributions of functions to safety can be included in a probabilistic approach even when in a critical state there is a negative contribution to safety. In a probabilistic approach the probability of such scenarios is made explicit. Multifunctional flood defences thereby~~levels are more ~~safe than is expected from conservative assessments only.~~ suitable to be combined with potentially harmful uses for safety whereas dikes with low protection levels can benefit most from uses that contribute to safety.

1 Introduction

1.1 Evolution of the flood risk approach

With sea-level rising ~~globally~~ and an expected rise in extreme rainfall events due to climate change ~~the risk of floods is~~ many regions in the world are faced with increasing ~~(Bouwer et al., 2010;Hirabayashi et al., 2013). In order to develop sufficiently strong infrastructure to prevent these catastrophes a framework is needed to assess the safety the infrastructure provides.~~flood-risk (Bouwer et al., 2010; Hirabayashi et al., 2013). Risk based approaches towards flood protection have been ~~performed~~applied all over the world to inform decision makers on effective flood risk measures in spite of the large uncertainties ~~(Jonkman et al., 2009;Kheradmand et al., 2018;Hall et al., 2003).~~(Jonkman et al., 2009; Kheradmand et al., 2018; Hall et al., 2003). Nevertheless, a better ~~the~~ understanding of the fragility of flood protection measures, including innovative ones like natural flood defences ~~(Temmerman et al., 2013),~~(Temmerman et al., 2013), is instrumental to properly evaluate the flood risk in the future.

~~This is true for the Netherlands especially where about 60% of its area is already prone to flooding from the sea or rivers (Slomp, 2012). Flood protection has always been a priority yet standards were only formalised in the past century. The first Delta committee, established to advise the government on flood risk after the large flood of 1953, advised to set a design water level with an acceptably small exceedance probability that flood defences need to retain. The acceptable exceedance probability followed from an economic optimisation between investment costs and obtained risk reduction (Delta Committee, 1960). This approach was the basis of the Water Act which sets the required protection level of all dikes in the Netherlands. As of January 2017 a new probabilistic approach has been adopted in the Water Act to which flood defences need to comply by 2050 (Ministerie van Infrastructuur en Milieu, 2016a). Because of the shortcomings of the old approach, economic developments and growing concerns over climate change the second Delta Committee advised to revise the water-level exceedance based risk approach into a full probabilistic approach (Delta Committee, 2008) and the change was made in 2017.~~

~~The metric for the protection level of flood defences used to be the most extreme event with a specified exceedance probability it is still able to retain (Van der Most et al., 2014).~~The Netherlands in particular is vulnerable to rising flood risks as about 60% of its area is prone to flooding from the sea or rivers (Kok et al., 2016). After the large flood of 1953 a design water level with an acceptably small exceedance probability was set based on an economic optimisation between investment costs and obtained risk reduction (Maris et al., 1961). Many studies have argued for a comprehensive probabilistic approach towards assessing the protection level provided by flood defences ~~before (Apel et al., 2006;Vrijling, 2001;Hall et al., 2003). The Dutch Water Act is the first to put these principles into practise~~(Apel et al., 2006; Vrijling, 2001; Hall et al., 2003). As of January 2017 the water-level exceedance based national risk standards were replaced by a more complex full probabilistic approach to more effectively adapt to social and economic developments, and climate change (Kok et al., 2016). The Dutch Water Act is the first to require the implementation of these principles on a nation-wide scale. While these approaches were developed for dikes that serve flood protection only, in practise many dikes have features serving other functions than flood protection. It is yet unclear how such ~~functions~~multifunctional aspects of a flood defence must be included in probabilistic safety assessments.

1.2 Multifunctional flood defences

Multifunctional flood defences (MFFDs) are engineered structures designed for the purpose of flood protection while simultaneously enabling other uses ~~(Voorendt, 2017).~~(Voorendt, 2017). Combining dikes with other functions is fairly common. Dikes can have roads on top, cables and/or pipelines running through them, structures on them, or are part of a historic landscape. In the Netherlands alone a majority of dike reinforcement projects already face the presence of one or ~~multiple additional~~more functions. Usually, enabling multiple functions requires strengthening of the dike beyond the minimal requirements for a traditional dike to account for uncertainties related to ~~the~~those functions ~~(van Loon-Steensma and Vellinga, 2014). Other functions do~~(van Loon-Steensma and Vellinga, 2014). Multifunctional use of the flood defence does not need to ~~be a detriment to~~decrease safety. For example, the development of ~~nature~~ green foreshores for flood protection services is an attractive option for future climate adaption ~~(van Loon-Steensma et al., 2014)~~(van Loon-Steensma et al., 2014) as such flood defences with green foreshores can reduce the risk of flooding by natural processes ~~(van Loon-Steensma and Kok, 2016;van Loon-Steensma et al., 2016).~~(van Loon-Steensma and Kok, 2016; van Loon-Steensma et al., 2016).

Flood defences can strengthen other values when functions are properly integrated ~~(Lenders et al., 1999;van Loon-Steensma et al., 2014).~~ (Lenders et al., 1999;van Loon-Steensma et al., 2014). In urban areas where space is limited there is continuous pressure to build on or integrate structures with the flood defence ~~(Stalenberg, 2013). In rural areas nature-based solutions have gained interest, which~~(Stalenberg, 2013). In rural areas nature-based solutions have gained interest, because they combine beneficial properties of natural systems for flood protection (e.g. wave attenuation by vegetation on foreshores) with conserving or developing important natural values ~~(Temmerman et al., 2013;Pontee et al., 2016). Especially in~~(Temmerman et al., 2013; Pontee et al., 2016). In the Netherlands these developments favour the implementation of a multifunctional flood defence due to the limited space and government policy to consider other uses (e.g. the natural, historical, economical, etc.) ~~(van Loon-Steensma and Vellinga, 2014).~~(van Loon-Steensma and Vellinga, 2014).

Despite the large number of multifunctional dikes and incentives the tools to assess the safety of MFFDs have still been limited to rules of thumb ~~on the one hand~~ and in-depth tailor-made studies ~~on the other.~~. Unless the ~~multifunctional aspect~~multifunctionality is ~~perceived to be of sufficient importance to justify~~ a ~~tailor-made study,~~key feature assessments are often limited to ~~showing other functions do~~ proving multifunctional use does not significantly diminish the safety of the flood defence ~~while~~ ignoring potential positive contributions to safety. Using such a conservative approach for dike assessments ~~where functions can only negatively influence flood risk~~ does ensure safe dikes from a flood risk perspective but may ~~hamper the implementation of efficient multifunctional dikes by~~result in requiring larger ~~or~~and more expensive dikes.

1.3 Aim

There is a need for improved flood defences due to climate change (rising sea-levels, higher river discharges) and socio-economic developments. The number of people exposed to a high risk of flooding is expected to increase from 271 million in 2010 to 345 million in 2050 due to socio-economic growth alone (Jongman, Ward, & Aerts, 2012). By 2100, 168 million people per year will experience floods due to sea-level rise. By reinforcing dikes this number can already be reduced by a factor of 461 (Hinkel~~, van Vuuren, Nicholls, & Klein,~~ et al., 2013). While reinforcing dike systems, there is plenty of opportunity to ~~combine multiple functions with dikes.~~ enable multifunctional use of the flood defence.

However, the means to determine the safety provided by multifunctional flood defences remain limited to conservative approaches where ~~functions~~multifunctional elements can only be shown to have no significant negative influence. Spurred by the threat of increasing flood risks by climate change and the revised legislation on flood standards in the Netherlands a new probabilistic framework to assess multifunctional flood defences is emerging that can be used for a wider context. The aim of this paper is to synthesize the new approaches to evaluate the safety of MFFDs employed in the Netherlands into a single ~~cohesive~~coherent framework and evaluate how this new probabilistic approach towards MFFDs can change the assessed safety compared to the commonly applied conservative approach towards MFFDs .

To this end, ~~we~~ first ~~analyse~~ the existing official framework for assessing multifunctional dikes in the Netherlands is analysed and ~~explore~~ alternative frameworks in both scientific and grey literature for a probabilistic risk-based approach towards assessing MFFDs as required by the new Water Act~~.~~ are explored. These are synthesized in an adapted framework (section.2). Secondly ~~we explain~~ the methods used to calculate the probability of failure of several dikes are explained using the synthesized probabilistic approach and the traditional conservative approach (section 3) to show the differences in assessed safety level (section 4). Finally ~~we discuss~~ the implications and results are discussed (sections 5 and 6). By illustrating how a probabilistic approach towards multifunctional use can affect the assessed level of safety, new types of integrated solutions can be more fairly compared to ~~traditional~~monofunctional dikes both in the Netherlands and outside.

2. Formulating a framework for MFFD assessment

2.1 Official Dutch guidelines for MFFD dike assessments and design

The methods to assess flood defences in compliance with the official Dutch safety standard are ~~communicated in official guidelines (Ministerie van Infrastructuur en Milieu, 2016b;Ministry of Traffic and Water Management, 2007;Rijkswaterstaat, 2017).~~documented in official guidelines (Ministerie van Infrastructuur en Milieu, 2016; Ministerie van Verkeer en Waterstaat, 2007). The assessment can be performed on different levels: basic, detailed, and tailored. Basic assessments are a quick-scan with simple rules to ~~exclude~~approve flood defences with an insignificantly low failure probability. Detailed assessments consist of design formulas and models taken or adapted from Dutch design manuals and are commonly applied for (initial) designs and assessments. These are suitable for predicting the failure of dikes where general descriptions of dike failures can be applied. Such generalisations are not always suitable for MFFDs. Tailored assessments allow for the use of advanced models and experiments outside the guidelines to assess the probability of failure as accurately as possible. These assessments require a large amount of information for a specific location and are generally expensive to perform. The dike needs to pass at least one of these assessments to be considered safe and a proper design ensures the dike will pass the assessments for its entire designed lifespan.

In the official Dutch framework, multifunctional use of the dike is considered either directly as objects on the dike, by the materials used, or indirectly by the geometry of the dike. When only the geometry of the dike is affected or a different material is used (e.g. to integrate with the surrounding landscape) ~~the official framework can still be applied (Slomp et al., 2016). However, if the function~~the official framework can still be applied (Slomp et al., 2016). However, if multifunctional use of the dike is facilitated by a Non-Water retaining Object (NWO), e.g. a house or pipeline, an additional assessment must be made for the NWO. For a few ~~functions~~multifunctional elements a basic safety assessment is described in guidelines (structures, vegetation and traffic) ~~(Deltares, 2012;STOWA, 2000;TAW, 1994, 1985;STOWA, 2010;Rijkswaterstaat, 2017).~~(van Houwelingen, 2012; STOWA, 2000; TAW, 1994, 1985; STOWA, 2010; Ministerie van Infrastructuur en Milieu, 2016). Only for pipelines a more detailed assessment is available following the Eurocode ~~(NEN, 2012)~~(NEN, 2012) which ensures the pipeline itself has an acceptably small probability of failure. If a dike cannot be approved by a basic assessment and no suitable detailed assessment is available, a tailored assessment for that specific dike section with NWOs must be made.

The philosophy of a basic assessment is to rule out the possibility of the NWO affecting the dike significantly. Hence, the dike is considered safe only if the dike is dimensioned such that the zone of influence of the NWO does not extend into the minimum dike profile needed to meet the safety standard (see Fig. 1). As a result, in basic assessments the NWO is always assumed to be in its most critical state during design conditions (e.g. uprooting of a tree). This is the conservative approach to ~~assessing~~assess the influence of ~~functions~~multifunctional elements on the safety because the actual probability of multifunctional elements being in a critical state is not considered. The ambition of the Dutch Water Act is to consider the actual probability of flooding which necessitates a risk-based approach to these elements.

2.2 Synthesizing a risk-based approach to MFFD design

The scientific basis for the risk-based framework adopted in the Netherlands was presented by ~~Vrijling (2001).~~Vrijling (2001). The risk of a flood is decomposed into a fault tree of failure mechanisms, each of which can be described with a mathematical limit state function and evaluated probabilistically. Limit states are common for designing structures in Civil Engineering and define when a structure collapses resulting in damages and casualties (ultimate limit state) or can no longer perform its intended use (serviceability limit state) ~~(Gulvanessian, 2009).~~(Gulvanessian, 2009). Vrijling's approach of structuring the ultimate limit states of flood defences into a fault tree for risk analyses has been incorporated in many frameworks of flood defences, e.g. ~~(Steenbergen et al., 2004;van Gelder et al., 2008;Slomp et al., 2016), and has already been applied on a large scale to evaluate the Dutch flood defences (Jongejan et al., 2013).~~(Apel et al., 2004; van Gelder et al., 2009; Steenbergen et al., 2004; Vorogushyn et al., 2010), and has already been applied on a large scale to evaluate the Dutch flood defences (Jongejan & Maaskant, 2013). However, the framework was developed for monofunctional flood defences.

Studies on MFFDs specifically are available. However, the developed frameworks address different aspects like: to identify the degree of spatial and structural integration ~~(Ellen et al., 2011b;Voorendt, 2017;Van Veelen et al., 2015), to identify costs and benefits (Anvarifar et al., 2013), to identify the threats and opportunities of functions (Anvarifar et al., 2017), and to identify and evaluate flexibility for MFFDs (Anvarifar et al., 2016). Other studies on MFFDs tend to only focus on the effects of a specific function or failure mechanism (Chen et al., 2017;Bomers et al., 2018;Zanetti et al., 2011). Only recently an assessment framework specifically for hybrid nature-based flood defences was put forward accounting for multiple failures by putting vegetation-specific equations directly into the assessment procedure (Vuik et al., 2018).~~ (Ellen et al., 2011b; Voorendt, 2017; Van Veelen et al., 2015), to identify costs and benefits (Anvarifar et al., 2013), to identify the threats and opportunities (Anvarifar et al., 2017), and to identify and evaluate flexibility for MFFDs (Anvarifar et al., 2016). Other studies on MFFDs tend to only focus on the effects of a specific multifunctional element or failure mechanism (Chen et al., 2017; Bomers et al., 2018; Zanetti et al., 2011). Only recently an assessment framework specifically for hybrid nature-based flood defences was put forward accounting for multiple failures by putting vegetation-specific equations directly into the assessment procedure (Vuik et al., 2018).

~~Pending an official framework practitioners in the Netherlands have used approaches to integrate multifunctional dike elements. One such approach was put forward for trees through the use of scenarios such as uprooting (Deltares, 2012) but it was left unclear how these failure probabilities can be implemented in the overall framework (Witteveen+Bos, 2013). An approach for assessing NWOs as indirect failure mechanisms with scenarios is being suggested in these cases (Knoeff, 2017).~~

Pending an official framework practitioners in the Netherlands have used approaches to integrate multifunctional dike elements. One such approach was put forward for trees through the use of scenarios such as uprooting (van Houwelingen, 2012). An approach for assessing NWOs as indirect failure mechanisms with scenarios is being suggested in these cases (Knoeff, 2017). This approach will be explored further in the study.

Formulating a practical framework for the assessments of MFFDs is challenging due to the large variety of possible configurations and range of ~~functions. While in scientific literature decision frameworks and the knowledge gaps of specific functions and failures are addressed, the assessment framework of the WBI2017 addresses how to evaluate the overall safety of the dike system but lacks the means to evaluate the additional functions. Through scenarios the inclusion of unspecified functions can be evaluated in different states through~~multifunctional elements. Multifunctional elements can be evaluated in different scenarios with simple or complex models in literature while preserving the established structure of the existing Dutch framework. Scenarios in this context are different possible states of a ~~function~~multifunctional element with a probability of occurrence in which the ~~function~~element affects the flood defence. By assessing each scenario and weighing the probability of failure in each scenario by the probability of the scenario, the probability of failure of the flood defence is calculated accounting for the uncertainty in the state of the ~~function. We therefore synthesize~~multifunctional element. Therefore the ~~methods~~steps for MFFD assessments in the Netherlands ~~in~~are synthesized as follows (also see Fig. 2~~.~~):

- Step 1: Establish the required safety level of the dike segment
- Step 2: Assign a portion of the required safety level to unknown/unquantifiable risks
- Step 3: Distribute the remaining failure budget across the known failure mechanisms
- Step 4: Divide the dike in (close to) homogeneous sections
- Step 5: Determine a representative cross section and safety level taking variations along the dike section into account (length effect)
- Step 6 (Addition): Determine the scenarios, i.e. states in which the NWO affects the flood defence differently, assess the probability of these scenarios, and combine them based on their probability of occurrence.

The difference between a basic ~~approach~~assessment and ~~the risk-based approach~~a probabilistic one is the addition of step 6. In a basic ~~approach~~assessment, i.e. a detailed assessment without NWOs followed by a basic NWO assessment to exclude significant potential negative influences, first a dike cross-section would be designed with the criteria found in steps 1 to ~~4~~5 and then adapted such that the influence of the intended NWO is outside the designed profile. ~~-~~In the risk~~-approach-~~based probabilistic assessment the effects of NWOs ~~should be~~are calculated directly with the scenarios in step 6 and combined with their probability of occurrence to arrive at a safe cross-section.

3 Application of the risk frameworks

3.1 Comparing the basic ~~framework~~assessment with the expanded ~~risk-based framework~~probabilistic assessment

To answer how a ~~more~~ probabilistic approach towards multifunctional dikes can affect the evaluated safety compared to a monofunctional dike, ~~we assess~~ a set of MFFDs is assessed with the new probabilistic approach and ~~a~~ the traditional conservative approach (see Table 1 for the approaches). The calculations are performed on a cross-sectional level. The reliability of a cross-section is calculated for the most common dike failure mechanisms by probabilistically evaluating the ~~limit state functions for the different scenarios. To combine the different failure probabilities the fragility curves of the mechanisms can be used (Bachmann et al., 2013) to arrive at the probability of failure.~~ models describing failure for the different scenarios. The failure probabilities per scenario and failure mechanism are combined to arrive at the probability of failure.

3.2 Failure mechanisms

To assess the risk of a flood it is important to know the mechanisms by which the flood defence could fail. Though many failure mechanisms are possible ~~(Kok et al., 2016), the vast majority of documented dike failures worldwide (Danka and Zhang, 2015) are the result of 3~~(Kok et al., 2016), the vast majority of documented dike failures worldwide are the result of three dominant mechanisms: overtopping (resulting in erosion of the inner slope), internal erosion (also referred to as piping), and inner slope stability~~.~~ (Danka and Zhang, 2015; Vorogushyn et al., 2009) .Within the Netherlands predominantly overtopping and slope instability have been the cause of dike breaches in the past ~~(Van Baars and Van Kempen, 2009).~~(van Baars and van Kempen, 2009). For this study the probability of a flood is calculated by considering the failure mechanisms overtopping, piping, and macro stability (see Table 2). Whether the flood defence fails by a failure mechanism is expressed in an equation called a limit state function:

$$Z = R - S \tag{3.1}$$

where $Z<0$ denotes failure, R is the resistance to failure, and S is the soliciting load.

~~For overtopping and overflow the load (S) is the amount water flowing over the dike while the resistance (R) is the capacity of the crest and inner slope to resist the flow of water without eroding. For piping the method of Sellmeijer et al. (2011) is used to calculate the stability of the sand particles in the subsoil under a pore water pressure gradient. It is expressed as a critical head difference (R) that cannot be exceeded by the head difference across the dike (S). Macro stability is calculated within the program D-Geo Stability (Deltares, 2016) with the stability method by Van (2001) and ground water model by TAW (2004). The method by Van (2001), like the Bishop (1955) method, calculates the sum of the driving moments (S) and the total resisting moment (R) along the slip plane. However, it also accounts for uplift forces on the interface of aquifers present beneath most dikes. The resulting limit states are:~~

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$$Z_{\text{overflow \& overtopping}} = q_{\text{c}} - q \qquad (3.2)$$

$$Z_{\text{piping}} = H_{\text{c}} - H \qquad (3.3)$$

$$Z_{\text{macro stability}} = \Sigma M_{\text{R}} - \Sigma M_{\text{S}} \qquad (3.4)$$

~~Here q_c is the empirically determined critical overtopping discharge, q is the overtopping discharge calculated according the methods of van der Meer et al. (2016) and TAW (2002), H_c is the critical hydraulic head according to Sellmeijer et al. (2011), H is the difference in water level in front and behind the dike, ΣM_S is the sum of the active moments in the critical slip plane, and ΣM_R is the sum of resisting moment in the critical slip plane.~~

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3.3 Probabilistic procedure

Multiple procedures are available for calculating the reliability of a flood defence. ~~-~~A fully probabilistic procedure like Monte Carlo relies on evaluating the limit state function for many variations of the random variables and determines the failure probability as the number of failures over the total number of samples. Meanwhile, a semi-probabilistic approach evaluates the limit state function once and captures uncertainties with (partial) safety factors to determine (non)failure. A probabilistic procedure like the first order reliability method (FORM) iteratively converges to an approximation of the probability of failure ~~(Hasofer and Lind).~~(Hasofer and Lind, 1974). This option was chosen as it does not require millions of evaluations of the limit state function to ~~find~~assess the ~~low~~small failure probabilities required for dikes while still retaining the probabilistic distribution of the variables otherwise lost in a semi-probabilistic approach.

While the FORM procedure can approximate the failure probability of a single limit state function of a single failure mechanism, a combination of failure mechanisms is more complex to evaluate. When the only dependence between failure mechanisms is assumed to be the water level, each failure mechanism becomes an independent event for each discrete water level such that the probability of failure of the system is:

$$P_{f,sys|h} = P_{sys}(f|h) = 1 - \prod_{i=1}^{n} \left(1 - P_{f,i|h}\right) \tag{3.5}$$

Where $P_{f,i|h}$ is the probability of failure given water level h for the ith failure mechanism and $P_{f,sys|h}$ is the probability of failure given water level h. ~~Repeating this calculation across all water levels results in the fragility curve of the system to the water level (Bachmann et al., 2013).~~Repeating this calculation across all relevant water levels results in the fragility curve of the system to the water level (Bachmann et al., 2013). The failure probability of the system is computed by integrating the fragility curve of the system ($F_R(h)$) over the probability density function (PDF) of the water level ($f_h(h)$):

$$P_{f,sys} = \int_{h=-\infty}^{h=\infty} f_h(h) * F_R(h)\, dh \tag{3.6}$$

Eq. 3.6 is discretised to:

$$P_{f,sys} = \sum_{j=1}^{m} P(h_j) * P_{sys}(f|h_j) \tag{3.7}$$

Low failure probabilities can more easily be expressed in terms of the reliability index which is defined as:

$$\beta = -\Phi^{-1}(P_f) \tag{3.8}$$

Where Φ^{-1} is the inverse standard normal cumulative distribution function.

~~The probabilistic procedure described above has been utilised before successfully by Lendering et al. (2018) and Bischiniotis et al. (2018) to compute the reliability of canal levees and a cost-optimal river dike respectively. An overview of the entire process as applied in this study is schematised in Fig. 3.~~

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3.4 Case-study

3.4.1 Setting and cross sections

The multifunctional dike for the case-study is situated in a riverine area, with nature on the floodplain side and a building on the landward side. To test how a risk approach can affect the calculated level of safety 8 cross-sections of multifunctional dike profiles (Fig. 4) are evaluated with three methods: a conservative, a probabilistic and a monofunctional approach (see Sect. 3.1). ~~Each profile represents a common reinforcement strategy. The dike is situated in a riverine area where both the flood plain and hinterland are occupied by a function, nature and a structure respectively.~~

~~Each function can potentially damage part of the dike section. For the purpose of this study the functions~~If a dike does not meet the set safety standards a reinforcement by adapting the profile, among other options, is explored. Each profile in this study represents a common reinforcement strategy. Broadening the dike by widening the crest or expanding the slope reduces the risk of a piping failure by increasing the piping length by a few meters. Furthermore broadening inwards and making the inner slope shallower makes the inner slope more stable. A berm also improves the stability of the inner slope. Finally heightening the dike decreases the risk of overtopping waves and overflow during high water. The final reinforcement strategy is a combination of heightening and decreasing the steepness of the inner slope.

Each multifunctional element can compromise a section of the dike resulting in failure. For the purpose of this study the multifunctional elements have been simplified so these can be incorporated directly in variables of the limit state functions or dike geometry (see Sect. 3.4.2). ~~In alternatives~~When broadening the dike on the flood plain or making a shallow outer slope (see profiles 1 and 5 in Fig. 4) the hinterland ~~function~~ remains ~~separate from~~unaffected by the dike itself, while in the other alternatives the ~~structure~~building becomes ~~an integral~~ part of the flood defence. By reviewing the options ~~we explore how~~the effect of the multifunctional elements on the safety after the reinforcements is evaluated in each framework.

3.4.2 Schematisation of ~~the functions~~ multifunctional elements

~~The schematisation of functions in this study has been based on the fact-sheet by Knoeff (2017) for incorporating indirect failure mechanisms in assessments. For each mechanism scenarios are defined in which the object (e.g.~~Effects of multifunctional elements on dike failure are incorporated through scenarios based on the fact-sheet by Knoeff (2017). For each mechanism scenarios are defined in which the element (e.g. tree, structure, pipeline, etc.) affects the failure mechanisms. The probability of failure can then be calculated for each scenario. The total probability of failure for the specific mechanism ~~can be~~is computed ~~be~~by weighing the probability of failure of each scenario with the probability of the scenario.

~~A natural flood plain can add ecological, landscape and recreational values to the flood protection system. However it comes with implications for safety. Woody vegetation can penetrate the clay top soil resulting in cavities within the clay (Zanetti et al., 2011). This will allow water to seep into the aquifer closer to the dike increasing the risk of piping. In greater densities woody vegetation like willows can be beneficial to safety by damping incoming waves (de Oude et al., 2010).~~

~~For the examples in this study it is assumed woody vegetation develops somewhere in the representative cross-section. Following the conservative estimation by TAW (1994) it has a 2% annual probability of failure evenly distributed along the foreshore of the dike. As the density of trees is too small for significant wave damping this effect is ignored. If the vegetation has disturbed the top soil the effective length for piping was reduced to the distance between the dike outer toe and the location of the disturbance.~~

~~Within the base profile there is a structure~~A natural flood plain can add ecological, landscape and recreational values to the flood protection system. However, elements like trees can penetrate the clay top soil resulting in cavities within the clay when the tree dies (Zanetti et al., 2011). Following a conservative estimation for the uprooting of trees by TAW (1994) a 2% annual probability of a cavity within the flood plain is assumed. If a cavity is present the effective length for piping is reduced to the distance between the dike's inner toe and the location of the disturbance. The trees on the flood plain do not affect the inner slope stability nor is the tree density in the case-study high enough to expect an influence on overtopping by wave dampening properties of trees.

A building on or close to the dike affects multiple failure mechanisms. The weight of the structure is transferred to the underlying soil where the load increases both friction with the subsoil, increasing slope stability, and lateral stress on the soil, decreasing slope stability. On the slope itself the structure affects the overtopping mechanism through the inner slope cover that prevents erosion. When a structure is present it acts as a discontinuity in the outer grass cover such that water can more easily erode soil during overtopping and is reflected in a lower critical overtopping rate. When the structure is absent the space occupied by it in the profile is assumed to be empty. Furthermore there is no grass cover but instead loose bare soil with practically no overtopping resistance (see Table 3). In the case-study the effect of the structure on piping is insignificant as it: does not penetrate the aquifer, and pipes can still develop along the outside of the structure rather than directly beneath it.

The structure in the case-study is located 3 m behind the inner dike toe. The structure is taken to be 15 m wide, exerts a weight of 17 kN/m and is embedded 1 m into the soil ~~with~~ on a shallow foundation without additional geotechnical measures like piles or sheet pile walls~~.~~. The horizontal position of the structure remains fixed for each reinforcement strategy ~~except for the robust dike where the structure is raised onto the slope. The structure is only considered in two 2 states: present in which the load is exerted, or absent in which case the load of the structure is absent and a hole is present in the profile at its location. When the structure is present an 'open' grass cover is assumed as along the edges of the structure the grass will not be present. When the structure is absent the large stretch of bare soil will be vulnerable. It is assumed that in this situation only an insignificant amount of overtopping (q<0.1 l/m/s) is acceptable (see Table 3). The probability of the structure being absent is taken to be 1% as a conservative estimate~~while vertically the landward end of the structure is always embedded only 1 m in the soil when the dike is expanded inwards. The probability the structure is absent during a high water event is estimated to be 1%. This probability is based on the percentage of houses demolished in the Netherlands annually which has varied between 0.13 and 0.23% per year (van der Flier and Thomsen, 2006) rather than the probability of structural failure of the house. The structure in its demolished state leaves a discontinuity in the dike profile, exerts no weight on the dike and exposes bare clay on the dike slope while leaving the remaining dike intact.

4. Results

The ~~summary~~ results are presented in Fig. 5. As expected the conservative approach consistently yields the highest probabilities of failure for the assessed dikes. ~~The~~Both the probabilistic assessment of the ~~functions~~additional multifunctional uses and the monofunctional assessment yield a lower probability of failure~~. Whether a function has a net positive or negative influence on the safety of the~~ for each dike ~~becomes only apparent by comparing these.~~ profile (Fig. 5).

~~The weight of the structure has a noticeable net positive influence on the reliability when it is included as part of a reinforcement (see profiles 2, 3 and 5) which is lost in a conservative assessment. Meanwhile it is also clear that the weight of the structure is less beneficial in a different configuration (profile 4). With a berm as both the structure and berm add weight, but the structure introduces a risk of the berm being lost when the structure fails. The effect is also limited when the structure remains just outside of the profile (profiles 0, 1, 2) or stability as a failure mechanism is not significantly contributing to the probability of failure (profile 7).~~

~~While in the calculations with a structure the clay cover on the flood plain is assumed to be intact along the full length, including~~4.1 Slope stability

The weight of the structure can improve the slope stability of the dike in the probabilistic assessment as shown in the assessment of profile 1 with the structure only. The changes in annual failure probabilities are solely due to the presence/absence of weight increasing friction in the passive zone of the slip circle. In the conservative approach the weight of structure is always ignored leading to a noticeably higher failure probability. This effect is most noticeable in profile 2 with only a structure. The reliability increases by a factor 10 in the probabilistic assessment compared to a monofunctional dike due to a favourable position of the structure in the critical slip circle (see Fig. 6). In contrast to profile 2, in profile 4 the position of the structure is detrimental to stability where a monofunctional dike has a three times larger reliability ($1.6*10^{-8}$ versus $5.02*10^{-8}$) for the probabilistically assessed dike with a structure. Both the structure and berm add weight, but the structure has a risk of being absent while the risk of a monofunctional berm being absent is negligible. This makes the berm a safer option. Nevertheless this effect on the reliability of profile 4 was insignificant compared to the overall failure probability which was dominated by piping and overtopping.

4.2 Overtopping

The presence/absence of the structure had a minor impact on overtopping as can be seen in Fig. 6. This is mainly the result of the relatively high predictability of the mechanism itself (reflected by the steepness of the fragility curve) rather than the direct influence of the structure on the mechanism (reflected by the shift of the fragility curve) or additional uncertainty introduced by the structure (reflected by a decreasing steepness of the fragility curve). Because overtopping has a steep fragility curve, the influence of the structure only affects a limited range of water levels and thus the net effect of the structure on the safety of the dike is limited.

4.3 Piping

Including uncertainty because of unmanaged ~~activity~~vegetation on the flood plain ~~(nature, recreation)~~ has a large effect on piping failure~~. This~~ which was ignored in the assessments with the structure. Because the flood plain in the case-study is wide, a scenario with a cavity close to the dike results in a major reduction of the piping length in the probabilistic assessment. Fig. 6 shows where large difference between the fragility curves of critical state and the ordinary state. The presence of trees on the floodplain on piping is ~~especially true~~even more pronounced in the conservative approach ~~where~~because the entire ~~length~~width of the flood plain is ~~not taken into account~~automatically excluded in the assessment~~ where it~~. This leads to a different ~~perception~~assessment in the need for piping specific reinforcement measures~~. There~~ in, particular for the conservative assessment. Due to the dominance of the piping failure mechanism in a conservative schematisation there is an increasing discrepancy between the conservative assessment and the other assessments~~ mainly due to very different assessments of the risk of piping. ~~.

4.4 Assessments

Finally the difference in probability of failure between a monofunctional dike and a multifunctional dike depends on the reliability of the monofunctional dike itself. Unless there are large differences in the schematisation of a failure mechanism (as was discussed for piping), differences in failure probabilities between assessments scale roughly by the same order of magnitude as the decrease in failure probability after a reinforcement (Fig. 5 note the log-scale for the probability of failure). However, the relative differences become more pronounced leading to proportionally higher failure probabilities in a conservative assessment compared to a probabilistic assessment.

5. Discussion

The results show a large difference between the reliability assessed between the conservative approach and the probabilistic approach. ~~-~~A prevailing view against multifunctional use of flood defences is that these require larger dimensions to meet the same safety standard as a traditional dike ~~(Ellen et al., 2011a;van Loon-Steensma and Vellinga, 2014).~~(Ellen et al., 2011a; van Loon-Steensma and Vellinga, 2014). However, as the case-study above illustrated this perception only holds true for a conservative approach that ~~only assesses~~omits multifunctional elements from the ~~parts of the dike unaffected by other functions.~~assessment. With a more probabilistic approach towards ~~additional functions the~~multifunctional elements their perceived negative influence~~ of the functions~~ was significantly smaller or could even result in a net positive influence. Positive contributions of ~~the function~~multifunctional elements under likely conditions can be included as well as the likelihood of the ~~function~~multifunctional elements affecting the flood defence negatively.

A drawback of the probabilistic approach is that it needs specific information about the ~~risks~~failures and states of ~~the functions~~multifunctional elements before an assessment can be conducted. For example, erosion around or over discontinuities during overtopping (possibly due the presence of ~~multi-functional~~multifunctional elements like a road) is highly variable and hard to capture in a generic limit-state function even with well-calibrated models ~~(Hoffmans et al., 2009;Bomers et al., 2018).~~(Hoffmans et al., 2009; Bomers et al., 2018). Depending on the sensitivity of the failure probability to these processes assumptions on effects and statistical distributions would need to be increasingly conservative to guarantee the safety level is met. However, new information on the ~~risks of functions is becoming increasingly available through ongoing research (Aguilar-López et al., 2018;Vuik et al., 2018). Furthermore, new techniques are being employed to continuously monitor the dikes in detail (Hanssen and Van Leijen, 2008;Herle et al., 2016) while advances in remote sensing allow for closer monitoring of the state of foreshores (Niedermeier et al., 2005;Friess et al., 2012). As a result, a probabilistic approach towards functions~~interaction between multifunctional uses and failure mechanisms is becoming increasingly available through ongoing research (Aguilar-López et al., 2018; Vuik et al., 2018). Furthermore, new techniques are being employed to continuously monitor the dikes in detail (Hanssen and van Leijen, 2008; Herle et al., 2016) while advances in remote sensing allow for closer monitoring of the state of foreshores (Niedermeier et al., 2005; Friess et al., 2012). As a result, a probabilistic approach towards multifunctional elements can capitalise on these advances by updating the previously assumed risks in assessments with observations of the actual performance of MFFDs over time.

~~Aside from the effects of functions themselves, other uncertainties influence how much other functions can affect the level of safety. For piping Aguilar-López et al. (2015) demonstrated that reducing the uncertainty in the seepage of the soil of a multifunctional dike by correlating grain-size and hydraulic conductivity the probability of a piping failure is already reduced. Lanzafame (2017)~~Aside from the effects of multifunctional elements themselves, other uncertainties influence how much multifunctional use of the flood defence can affect the level of safety. For piping Aguilar-López et al. (2015) demonstrated that reducing the uncertainty in the seepage properties of the soil of a multifunctional dike the probability of a piping failure is already significantly reduced. Lanzafame (2017) concluded variability introduced by vegetation has only a small effect on the probability of a slope failure due to larger uncertainties in strength and seepage of the ~~ground~~soil. In contrast a relatively small disturbance by burrowing animals in a fragile dike has resulted in a breach under conditions it had previously survived ~~(Orlandini et al., 2015). The influence of uncertainties was also observed within this study through the case of a robust dike. As the reliability of the dike itself increases, the influence of a function on the level of safety decreases as the added variability of the function~~(Orlandini et al., 2015). The observation that the dike's own reliability influences the degree to which multifunctional use can affect the probability of failure of the dike was also found in this study. As the reliability of the dike itself increases, the influence of a multifunctional element on the level of safety decreases as the added variability of the multifunctional element becomes smaller compared to the uncertainties in other parameters the dike was already designed for. This effect of dike reliability on the influence of ~~functions~~multifunctional element has implications. An increase in failure probability due to ~~functions~~multifunctional element is likely to be over-estimated in a traditional assessment for dikes with a high protection level while similarly for these dikes also only a limited decrease in failure probability can be expected from beneficial ~~functions.~~multifunctional elements. Conversely, dikes with a low protection level are influenced more by both beneficial and detrimental effects of ~~additional functions.~~ multifunctional use of the flood defence.

This study only looked at the effects of ~~functions~~multifunctional use on flood protection. However, ~~these functions can have their~~multifunctional use comes with its own set of requirements that ~~should~~must be taken into account. For example structures need to comply with building codes, flood protection measures in nature reserves ~~is~~can be subject to environmental protection regulations while to preserve landscape values substantial dike heightening ~~-~~may be unacceptable. How much such additional non-flood protection requirements influence the design of dikes ~~should~~need to be researched for a successful implementation of MFFDs.

~~While the current~~ This study ~~looked at~~ investigated the assessments of multifunctional flood defences for ~~an existing~~the current situation~~, relating and managing uncertainties of functions to uncertainties in~~. In the design of these defences, however, future ~~climate~~ conditions ~~will be crucial~~ , like for ~~a probabilistic application of additional functions in designs. Predictions~~example climate change or societal trends, need to be taken into account. Scenarios for future sea-level rise in the coming century vary between 0.23 and 0.98 m ~~(IPCC, 2013).~~(IPCC, 2013). Incorporating beneficial ~~multi-functional~~multifunctional uses of flood defences, either natural like marshes or man-made like structures, can become an asset to achieve the levels of flood protection needed in the future.

6. Conclusion

~~We~~This study analysed how a full probabilistic approach towards multifunctional flood defences can change the assessed safety compared to the commonly applied conservative approach where ~~additional functions~~multifunctional use of the flood defence can only be shown to have no significant negative influence. Although ~~a~~ probabilistic ~~assessment was not forbidden,~~ assessments have been used before, the new regulations ~~and insights~~ of the Water Act in the Netherlands ~~stimulate~~necessitate a full probabilistic assessment of flood ~~protection~~defences. Therefore a probabilistic framework incorporating multifunctional elements probabilistically was ~~synthesized~~developed. The overall conclusion is that application of a probabilistic approach towards ~~additional functions~~multifunctional use of the flood defence will lead to a lower assessed risk of flooding compared to conservative assessments because: 1) positive contributions of ~~functions~~multifunctional elements to safety can be included, even when in a critical state there is a negative contribution to safety and 2) the risk of ~~a functions~~multifunctional elements being in such a critical state is made explicit. Another important aspect is that effects of ~~functions~~multifunctional use on safety become smaller as the reliability of the dike increases. Therefore monofunctional dikes with already a high ~~protection levels~~reliability are more suitable to be combined with ~~functions~~multifunctional uses detrimental to safety whereas dikes with a low ~~protection levels~~reliability can benefit more from ~~functions~~multifunctional uses that contribute to safety.

Based on the results we recommend that a probabilistic framework is further developed and implemented for including multifunctional elements into dike assessments. While many knowledge gaps are still present in quantifying the effects of ~~functions~~multifunctional use of flood defences, incorporating scenarios in which a ~~function~~multifunctional element can harm or help flood protection can already provide insights in synergies that can be exploited or dangers that can be mitigated. ~~Furthermore~~These scenarios and associated probabilities will need to rely on expert judgment. However, it is expected that with the growing number of methods to monitor dike performance and ongoing studies in dike failures these gaps can be filled in the future.

To this end further research is required ~~into monitoring schemes~~on the proper scenarios and their associated probabilities that can be used to improve future assessments of ~~the functions on the dike~~multifunctional dikes. Additionally, more research is needed to assess how multifunctional elements influence the safety of dikes over longer periods especially in relation to the large uncertainties involved in climate change. A real-world case-study for design should be used to explore how these aspects can be incorporated in practise.

7. Author contributions

The study and methodology were conceived by RM, JvL and MK. RM carried out the analyses, produced the results and wrote the manuscript under the supervision of JvL, MK and CK. The results were discussed and reviewed among all authors.

8. Competing interests

The authors declare that they have no conflict of interest.

9. Acknowledgements

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Appendix

A: Case-study parameters

The dike geometry of the base case is captured by the variables in Table A1.

The soil was divided into 3 layers: the dike core, the blanket layer and the aquifer. Representative values for the soil layers were taken from known soil types in the Dutch riverine area (Table A2, Table A3 and Table A4).

Hydraulic load parameters are given in Table A5. Representative water and wind characteristics were estimated from the hydraulic loads database of the upper Rhine area in the Netherlands which is available as part of the WBI software. For simplification the wind direction is only considered in the direction perpendicular to the dike.

B: Overflow and overtopping limit state function

Overflow is calculated directly from the water level (h) and crest height (z_{crest}) by the formula for a broad crested weir:

$$q_{\text{overflow}} = \sqrt{2g} * \frac{2\sqrt{3}}{9}(h - z_{\text{crest}})^{\frac{3}{2}} \tag{B1}$$

~~To calculate the overtopping discharge first the significant wave height (H_s) and period (T_s) perpendicular to the dike are estimated from the water depth (h), fetch length (F), and wind speed (u_{wind}) with the equations of Bretschneider (1957) as presented by Holthuijsen (1980):~~

To calculate the overtopping discharge first the significant wave height (H_s) and period (T_s) perpendicular to the dike are estimated from the water depth (h), fetch length (F), and wind speed (u_{wind}) with the equations of Bretschneider as presented by Holthuijsen (1980):

$$\mathrm{F_x} = \frac{gF}{u_{\text{wind}}^2} \tag{B2}$$

$$h_{\text{x}} = \frac{gh}{u_{wind}^2} \tag{B3}$$

$$p_1 = \tanh(0.53 * h_{\text{x}}^{0.75}) \tag{B4}$$

$$p_2 = \tanh(0.833 * h_{\text{x}}^{0.375}) \tag{B5}$$

$$H_{\text{s}} = 0.283 * \frac{u_{wind}^2}{g} * p_1 * \tanh\left(0.0125 * \frac{F_{\text{x}}^{0.42}}{p_1}\right) * m_{\text{Bret,H}} \tag{B6}$$

$$T_{\text{s}} = 7.54 * \frac{u_{\text{wind}}}{g} * p_2 * \tanh\left(0.077 * \frac{F_x^{0.25}}{p_2}\right) * m_{\text{Bret,T}} \tag{B7}$$

~~With the wave characteristics the average overtopping discharge is calculated following the formulas by TAW (2002) and van der Meer et al. (2016). Since no berm is present on the dike of the case-study and waves are assumed perpendicular factors related to these aspects are omitted.~~

With the wave characteristics the average overtopping discharge is calculated following the formulas by TAW (2002) and van der Meer et al. (2016). Since no berm is present on the dike of the case-study and waves are assumed perpendicular factors related to these aspects are omitted.

$$\xi_0 = \frac{\tan(\alpha_{\mathrm{out}})}{\sqrt{\frac{2\pi H_s}{gT_s^2}}} \qquad \text{(B8)}$$

$$\cancel{q_1 = \min\left(\frac{\frac{0.067}{\sqrt{\tan\alpha_{out}}} * \xi_0 * \exp\left(c_1 * \frac{z_{crest} - h}{H_s} * \frac{1}{\xi_0 * \gamma_f}\right)}{0.2 * \exp\left(-2.6 * \frac{z_{crest} - h}{H_s} * \frac{1}{\gamma_f}\right)}\right) * \sqrt{g * H_s^3}}\, q_1 = \min\left(\begin{matrix}\frac{0.067}{\sqrt{\tan\alpha_{\mathrm{out}}}} * \xi_0 * \exp\left(c_1 * \frac{z_{\mathrm{crest}} - h}{H_s} * \frac{1}{\xi_0 * \gamma_f}\right) \\ 0.2 * \exp\left(-2.6 * \frac{z_{\mathrm{crest}} - h}{H_s} * \frac{1}{\gamma_f}\right)\end{matrix}\right) * \sqrt{g * H_s^3} \qquad \text{(~~B8~~B9)}$$

$$q_2 = 10^{c_2} * \exp\left(-\frac{z_{\mathrm{crest}} - h}{\gamma_{\mathrm{f}} * H_s * (0.33 + 0.022 * \xi_0)}\right) * \sqrt{g * H_s^3} \qquad \text{(~~B9~~B10)}$$

$$q_{\mathrm{overtopping}} = \begin{cases} q_1 & \xi_0 < 5 \\ 10^{\frac{\log(q_1)+\log(q_2)}{2}} & 5 \geq \xi_0 \geq 7 \\ q_2 & \xi_0 > 7 \end{cases} \qquad \text{(~~B10~~B11)}$$

A description and values for the variables are presented in Table B1.

The limit state function is then evaluated as:

$$Z_{\text{overflow and overtopping}} = q_{\mathrm{c}} - q_{\mathrm{overflow}} - q_{\mathrm{overtop}} \qquad \text{(~~B11~~B12)}$$

C: Piping limit state function

~~Piping is evaluated with the ground water schematisation of TAW (2004) and piping erosion formulae of Sellmeijer et al. (2011). To simplify the calculation these assumptions are made: a finite foreshore blanket is considered of a significant thickness (d > 1 m) and impermeable (k <1*10^-7 m/s), the hinterland blanket is significant and continuous in, there is no flow of water through the aquifer from other sources than the river, and finally the blanket layer has the same properties at the foreshore and hinterland. Following these assumptions the response in water head just behind the dike during high water is determined by the leakage length (λ) and response factor (r) at the end of the leakage path with length L which is the distance from the entree point to the dike (L_entree) plus the width of the dike (L_dike).~~
Piping is evaluated with the piping erosion formulae of Sellmeijer et al. (2011). The critical head difference (H_c) is calculated as:

$$\cancel{\lambda = \sqrt{k_{aquifer} * d_{aquifer} * \frac{d_{blanket}}{k_{blanket}}}}\, F_{\mathrm{R}} = \frac{\gamma_p - \gamma_{\mathrm{w}}}{\gamma_{\mathrm{w}}} * \eta * \tan\theta * \left(\frac{RD}{RD_{\mathrm{m}}}\right)^{0.35} \qquad \text{(C1)}$$

$$\cancel{r = \frac{\lambda}{L + \lambda} * \exp\left(\frac{-\left(\frac{L_{dike}}{2} + L_{entree}\right)}{\lambda}\right)}\, F_S = \frac{d_{70}}{\sqrt[3]{\kappa L}} * \left(\frac{d_{70\mathrm{m}}}{d_{70}}\right)^{0.6} \qquad \text{(C2)}$$

$$F_{\mathrm{G}} = 0.91 * \left(\frac{d_{\mathrm{aquifer}}}{L}\right)^{\frac{0.28}{\left(\frac{d_{\mathrm{aquifer}}}{L}\right)^{2.8} - 1} + 0.04} \qquad \text{(C3)}$$

$$H_{\mathrm{c}} = F_{\mathrm{R}} * F_S * F_{\mathrm{G}} * L \qquad \text{(C4)}$$

Failure occurs when the critical~~The hydraulic~~ head level (H_c) is exceeded by the head difference ~~within~~(H) and the ~~aquifer~~resistance of the blanket layer ~~across the dike and foreshore (H) is calculated as~~:

$$\cancel{H = h * (1 - r)} Z_{\mathrm{piping}} = m_{\mathrm{p}} * H_{\mathrm{c}} - (H - 0.3 * d_{\mathrm{blanket}}) \qquad (\cancel{C3}C5)$$

~~The critical head difference (H_c) is calculated with the piping erosion formulae of Sellmeijer et al. (2011):~~

$$\cancel{F_{\mathrm{R}} = \frac{\gamma_{\mathrm{p}} - \gamma_{\mathrm{w}}}{\gamma_{\mathrm{w}}} * \eta * \tan\theta * \left(\frac{RD}{RD_{\mathrm{m}}}\right)^{0.35}} \qquad \cancel{(C4)}$$

$$\cancel{F_{\mathrm{S}} = \frac{d_{70}}{\sqrt[3]{\kappa L}} * \left(\frac{d_{70\mathrm{m}}}{d_{70}}\right)^{0.6}} \qquad \cancel{(C5)}$$

$$\cancel{F_{\mathrm{G}} = 0.91 * \left(\frac{d_{\mathrm{aquifer}}}{L}\right)^{\frac{0.28}{\left(\frac{d_{\mathrm{aquifer}}}{L}\right)^{2.8} - 1} + 0.04}} \qquad \cancel{(C6)}$$

$$\cancel{H_{\mathrm{c}} = F_{\mathrm{R}} * F_{\mathrm{S}} * F_{\mathrm{G}} * L} \qquad \cancel{(C7)}$$

~~Failure occurs when the critical head level is exceeded by the head difference and the resistance of the blanket layer:~~

$$\cancel{Z_{\mathrm{piping}} = m_{\mathrm{p}} * H_{\mathrm{c}} - (H - 0.3 * d_{\mathrm{blanket}})} \qquad \cancel{(C8)}$$

The variables introduced by Eq. (~~C4~~C1) to Eq. (~~C8~~C5) are given in Table C1. and are based on estimates ~~provided for WBI~~used in Dutch dike assessments~~, expect for the~~. The intrinsic permeability (κ) which is directly converted from the permeability of the aquifer (k_{aquifer}).

D: Macro stability limit state function

The macro stability of the dike is evaluated using the schematisation of the phreatic surface of a clay dike from the ~~TAW (2004)~~TAW (2004) following the ~~WBI 2017~~official Dutch guidelines (see Fig. D1). The ~~TAW (2004)~~TAW (2004) schematisation assumes a drop in the phreatic surface on the interface of the dike with the outside water (1 m as by default) and a linear drop towards the inner toe. The water head in the aquifer was calculated using the equations by TAW (2004) as ~~for piping (see appendix C).~~ implemented in the D-stability software (Brinkman and Nuttall, 2018).

~~The stability of the slope is calculated with the method by Van (2001) for the slip plane and works on the same principle as the method by Bishop (1955).~~The stability of the slope is calculated with the method by Van (2001) for the slip plane and works on the same principle as the method by Bishop (1955). The main difference between the methods is the separation of the slip plane in an active circle connected by a straight section followed by a passive circle. The centres of these circles of the critical slip plane (R_A and R_P) are found iteratively using the D-stability software ~~(Deltares, 2016).~~(Brinkman and Nuttall, 2018).

The slip plane is divided into slices and the net force induced by each slice is calculated. If the moment induced by the active slices (ΣM_S) is greater than the combination of friction forces and moments induced by the passive slices (ΣM_R) the slope is unstable. This is both expressed in a factor of safety (F_S) and Z~~-~~function.

$$F_{\mathrm{S}} = \frac{\Sigma \mathrm{M}_{\mathrm{R}}}{\Sigma \mathrm{M}_{\mathrm{S}}} \qquad (D1)$$

$$Z_{\mathrm{macrostability}} = F_{\mathrm{S}} - 1 \qquad (D2)$$

To calculate the probability of failure with FORM the factor of safety needs to be evaluated during each iteration with D-stability. An experimental version of D-stability with an additional piece of software from the same developers called the probabilistic toolkit (PTK) was utilised to automatically execute D-stability with updated parameters calculated by the FORM algorithm in the PTK.

The iterative procedure of finding the critical slip plane is both computationally demanding and complicates conversion in the probabilistic FORM algorithm. To speed up the procedure in the computation first a test run is performed using average soil strength parameters at a fixed critical slip plane with a water level halfway at the crest . With the results of the first indicative run~~-~~, stochastic variables with little to no influence ($|\alpha|<0.001$) are set as constants. Then the entire model was run for each discretised water level.

After the run the fragility curve was checked for points where no convergence was achieved with FORM or a non-critical slip circle must have been evaluated. To this end points where the maximum number of iterations was reached or the probability of failure decreased with ascending water level were removed to obtain a monotonically increasing fragility curve.

E: FORM algorithm

The first order reliability method (FORM) is a method to iteratively calculate the probability of a limit state function ($Z(\mathbf{X}) \leq 0$) being exceeded given a set of independent random variables ($\mathbf{X}$) ~~(Hasofer and Lind, 1974).~~(Hasofer and Lind, 1974). The starting point for the iteration is arbitrary, but usually the mean of the variables is taken as the first point to evaluate ($\mathbf{x}^*$). The problem is first simplified by converting the random variables before each iteration into realisations of equivalent normally distributed variables ($\mathbf{x}'$) with an equivalent normal transformation ~~(Rackwitz and Flessler, 1978).~~(Rackwitz and Flessler, 1978).

$$\mu'_{X_i} = x_i^* - \sigma'_{X_i} * \Phi^{-1}[F(x_i^*)] \tag{E1}$$

$$\sigma'_{X_i} = \frac{\varphi\{\Phi^{-1}[F(x_i^*)]\}}{f(x_i^*)} \tag{E2}$$

Where μ'_{X_i} and σ'_{X_i} are the mean and standard deviation of the equivalent normal distribution of variable x_i in the point $\mathbf{x}^*$. Also f and F are the probability density function (PDF) and cumulative distribution function (CDF) of variable x_i while φ and Φ are the standard normal PDF and CDF.

The mean and standard deviation of the limit state function are evaluated by:

$$\mu_Z = Z(\mathbf{x}^*) + \sum_{i=1}^{n} \frac{\partial Z}{\partial X_i}(\mu'_{X_i} - x_i^*) \tag{E3}$$

$$\sigma_Z = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial Z}{\partial X_i}\right)^2 {\sigma'_{X_i}}^2} \tag{E4}$$

With the mean and standard deviation calculated from the design point ($\mathbf{x}^*$) the reliability index (β) and influence factor of each variable (α_{X_i}) are calculated.

$$\beta = \frac{\mu_Z}{\sigma_Z} \tag{E5}$$

$$\alpha_{X_i} = \frac{\partial Z}{\partial X_i} * \frac{\sigma'_{X_i}}{\sigma_Z} \tag{E6}$$

The point is updated by adjusting each variable based on the overall safety level (β) and the sensitivity of the limit state to the variable (α_{X_i}):

$$x_i^* = \mu'_{X_i} - \alpha_{X_i}\beta\sigma'_{X_i} \tag{E7}$$

The process is repeated until the reliability index has converged and no longer changes significantly after an iteration.

While the method is effective there are limitations. It is not guaranteed FORM finds the design point with the highest probability ~~of occurring~~ but rather converges to a local ~~minimum~~design point. Furthermore for FORM to converge the limit state function should be smooth without jumps or discontinuities. This complicated the implementation of for example macro stability as when a different slip circle becomes critical there can be a sudden jump in the evaluation of the limit state function.

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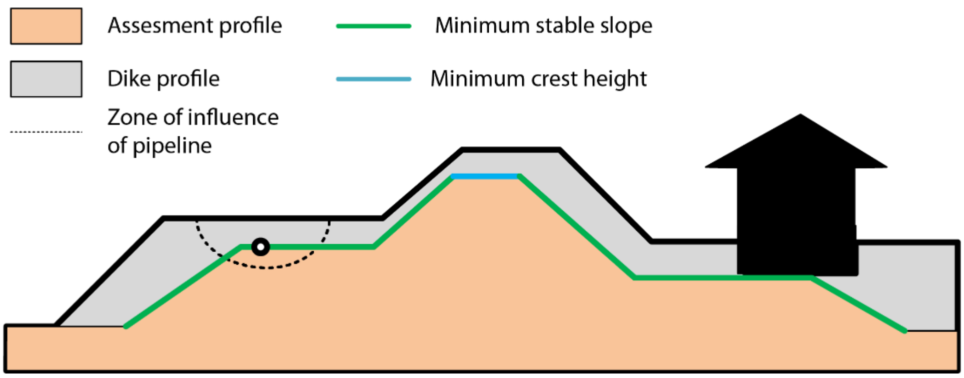
~~**Figures**~~



~~**Fig. 1 Assessment profile for a dike with NWOs (pipeline and house with basement). Adapted from figure A.4 of the current Dutch guidelines (Rijkswaterstaat, 2016)**~~

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Figures

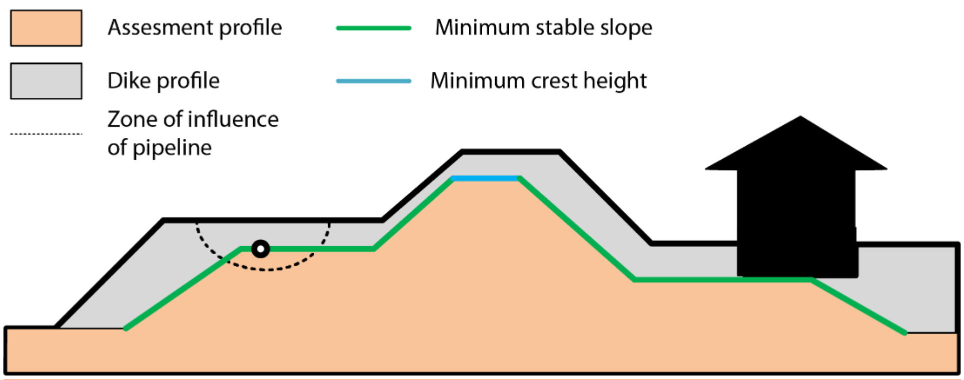


Fig. 1 Assessment profile for a dike with NWOs (pipeline and house with basement). Adapted from figure A.4 of the current Dutch guidelines (Rijkswaterstaat, 2016)

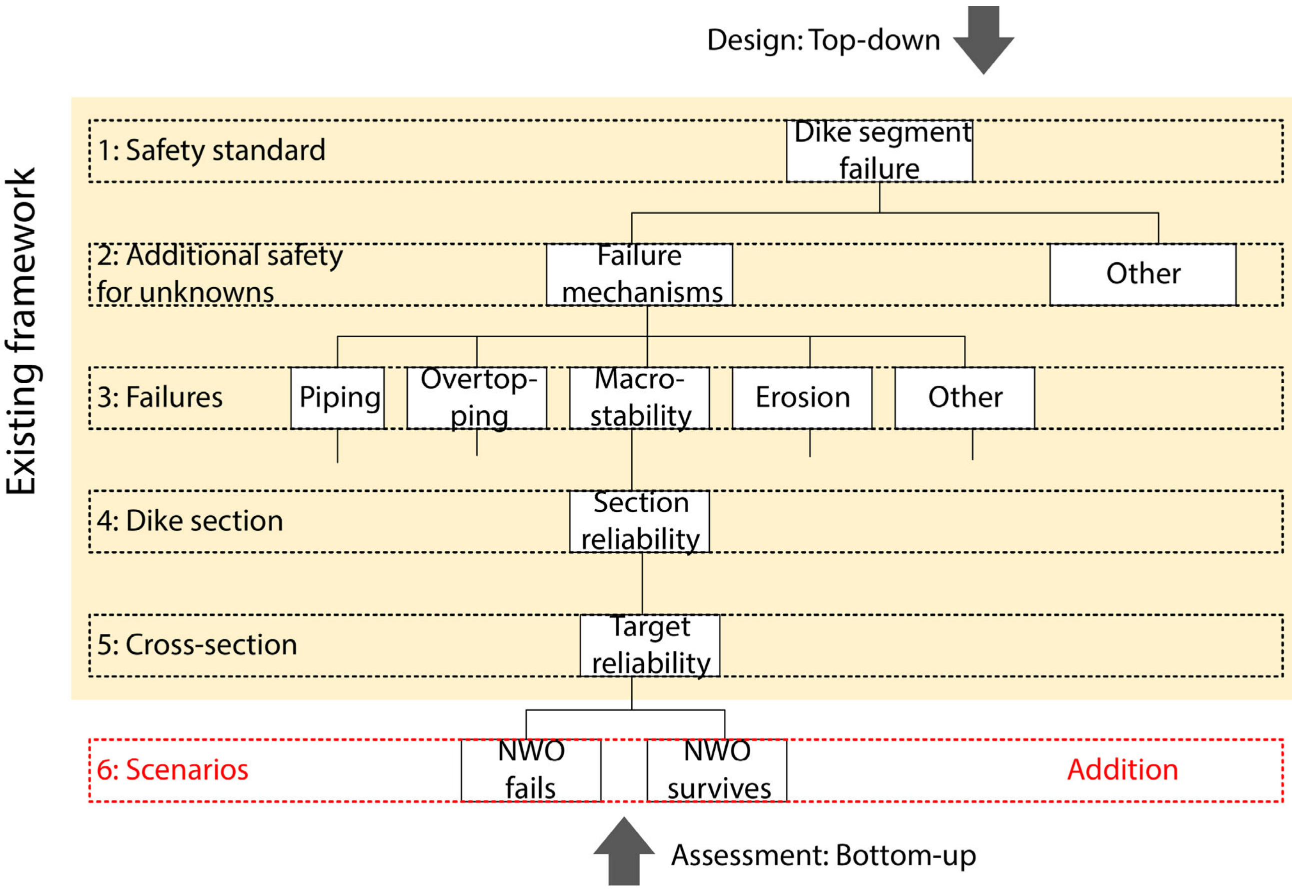


Fig. 2 A framework for a detailed assessment and design of a dike with multifunctional elements. The yellow section is the existing framework while the last step in *red* denotes the addition of scenarios (e.g. a failed NWO and functioning NWO) to conform to a risk-based approach.

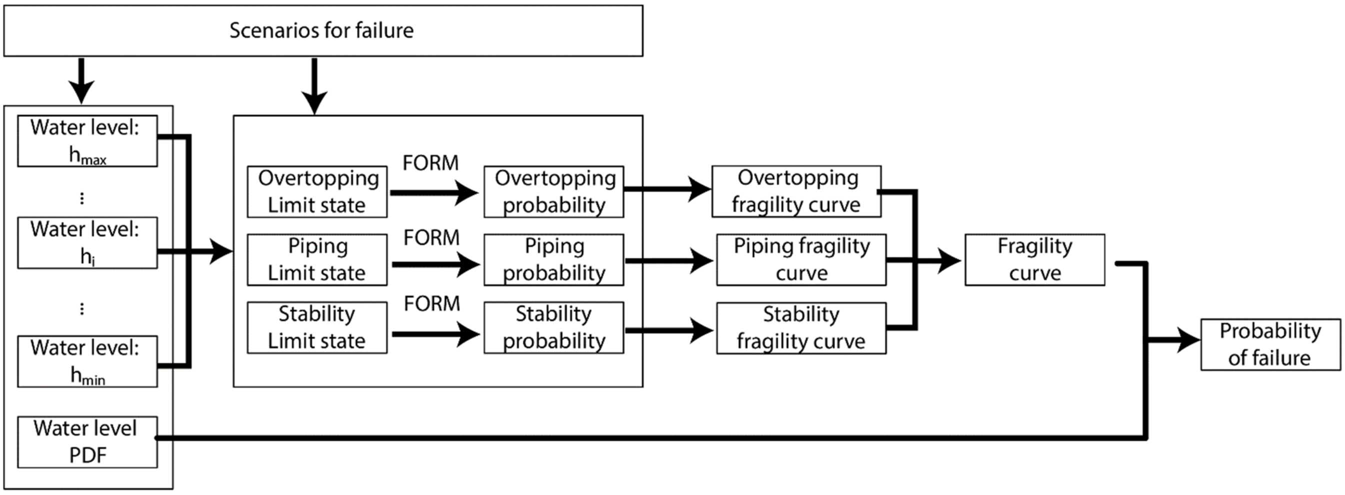


Fig. 3 The probabilistic procedure for ~~calculation~~calculating the probability of failure of a dike cross-section in this study

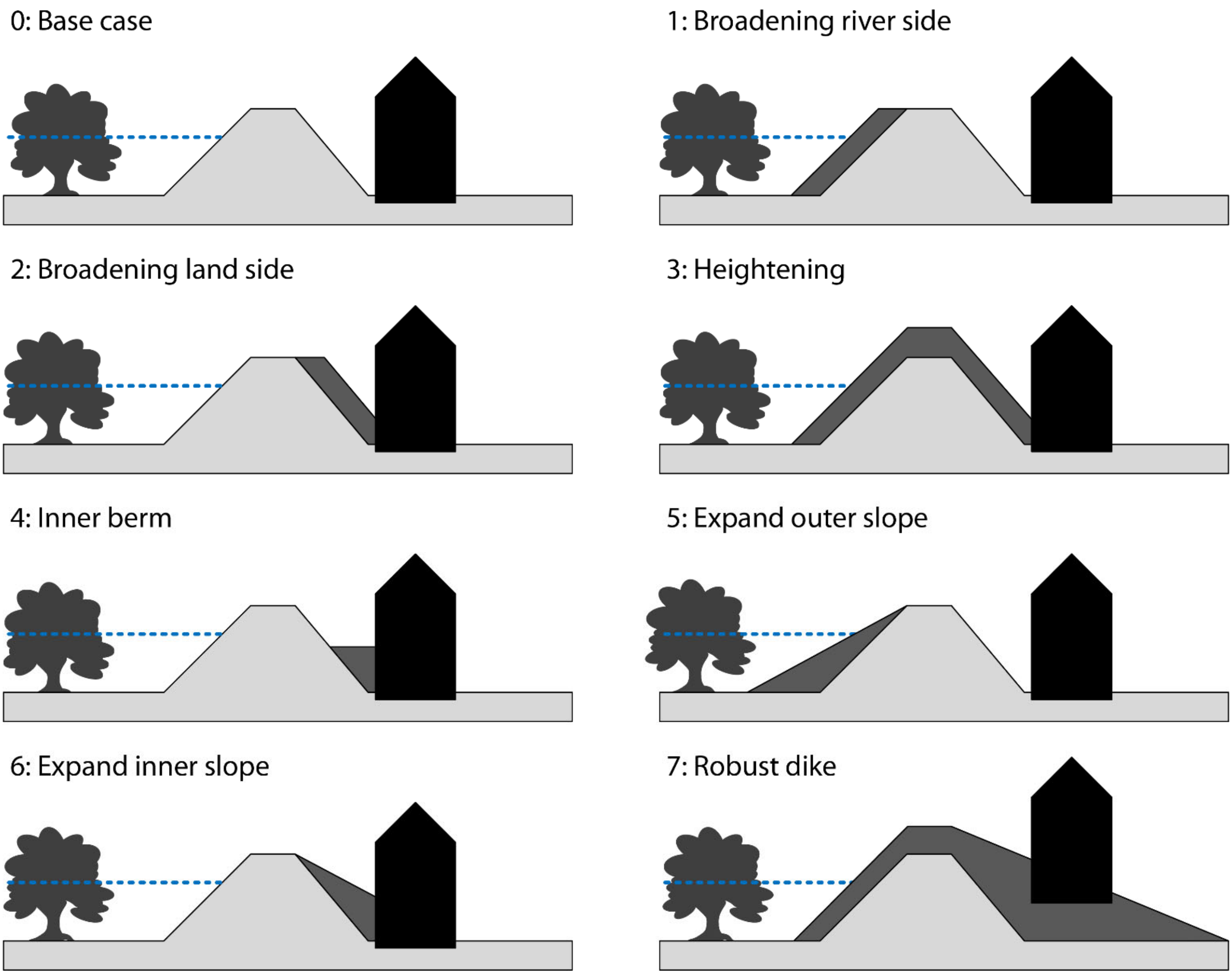
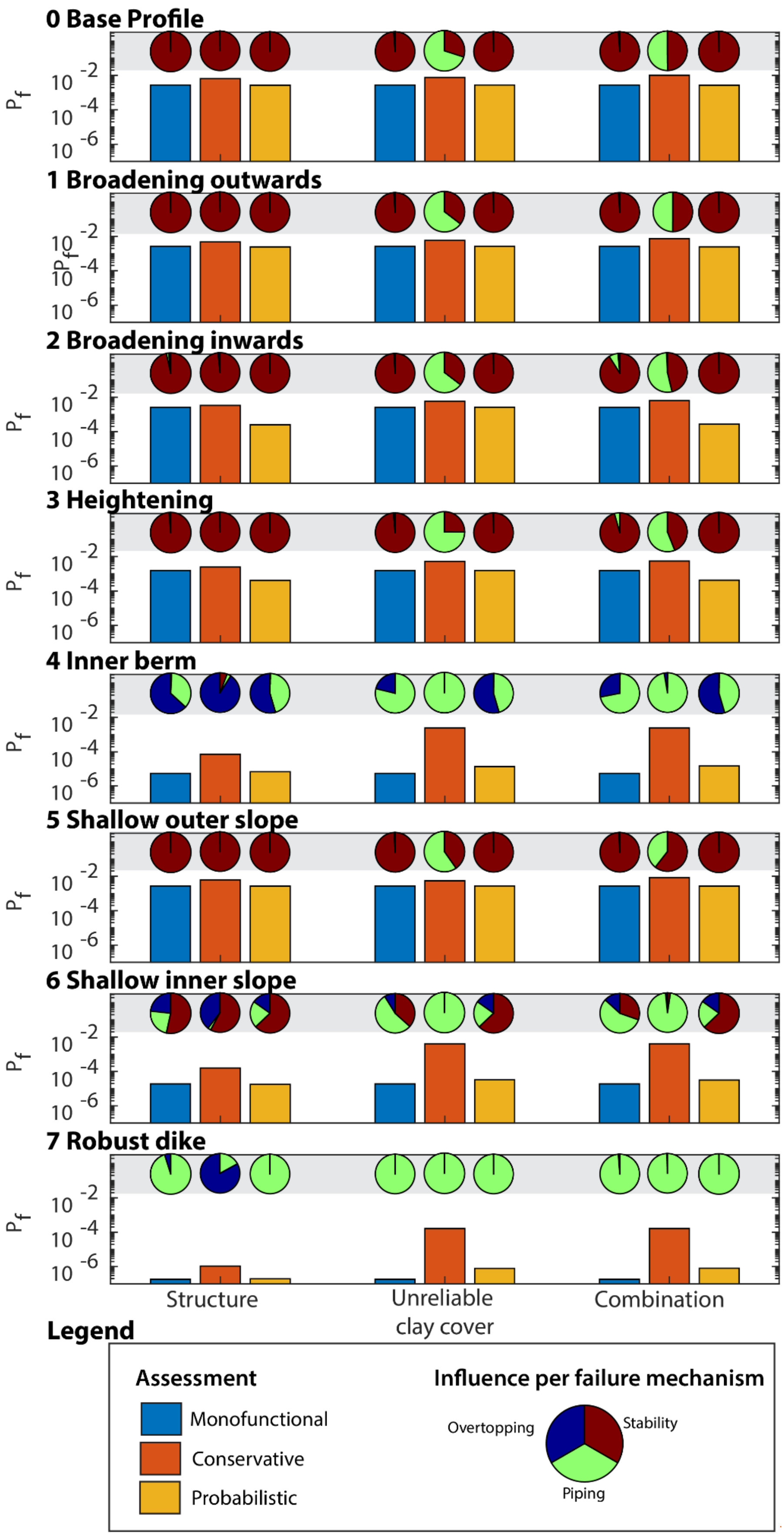


Fig. 4 Case studies for comparing the conservative and the new probabilistic approach in this study


0 Base Profile
1 Broadening outwards
2 Broadening inwards
3 Heightening
4 Inner berm
5 Shallow outer slope
6 Shallow inner slope
7 Robust dike
P_f
10^{-2}
10^{-4}
10^{-6}
Structure
Unreliable clay cover
Combination
Legend
Assessment
Monofunctional
Conservative
Probabilistic
Influence per failure mechanism
Overtopping
Stability
Piping

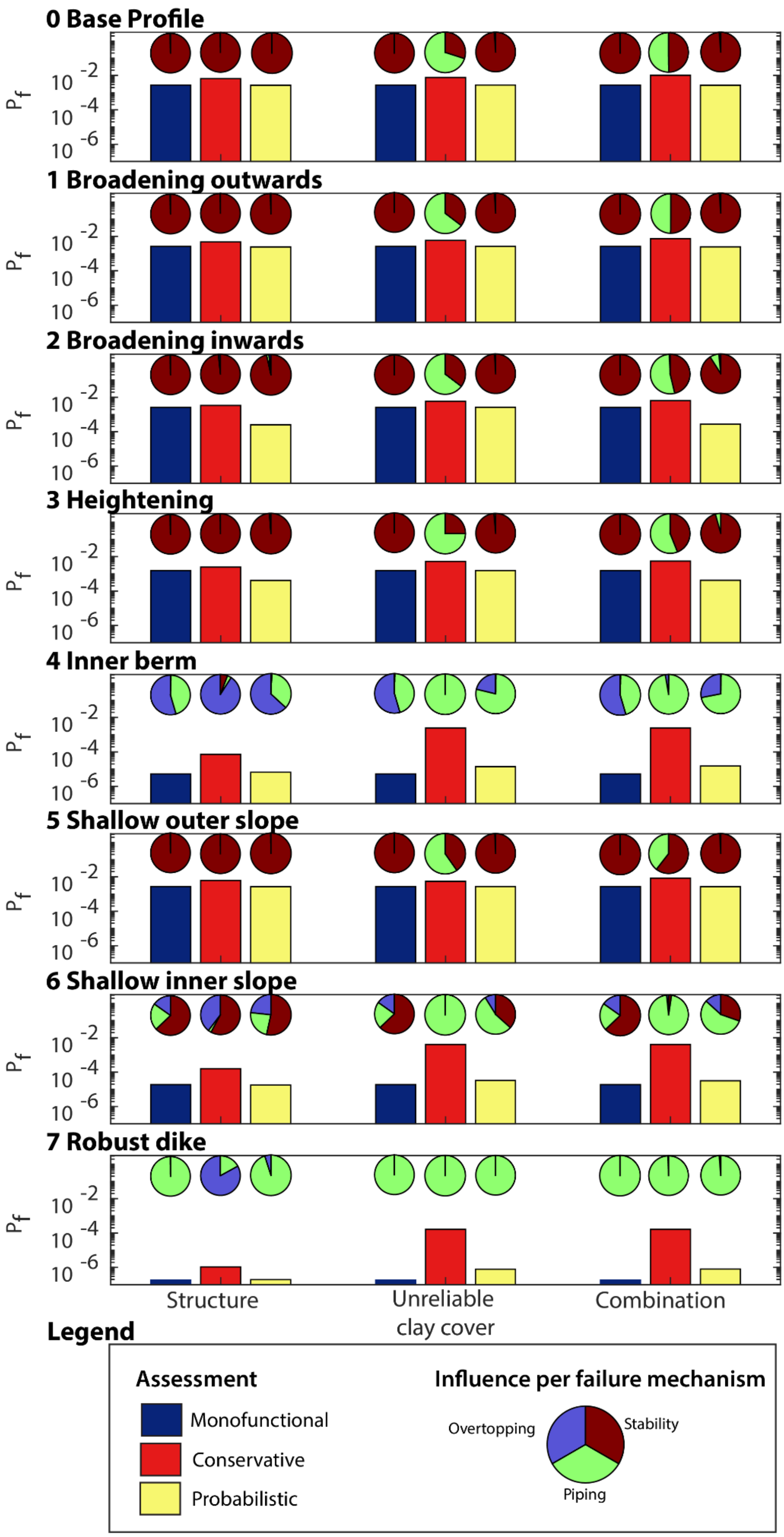


Fig. 5 The probability of failure (P_f) for every dike profile (0 to 7) assessed as a monofunctional dike (blue bar), a multifunctional dike with a conservative approach (~~orange~~red bar) and a multifunctional dike using a probabilistic approach (yellow bar) in the situation where a structure is present (left), an impaired clay cover on the flood plain could be present (middle) and both a structure

and unreliable clay cover are present (right). The influence of the three failure mechanisms overtopping (blue), piping (green) and stability (red) is given per bar with a pie chart.

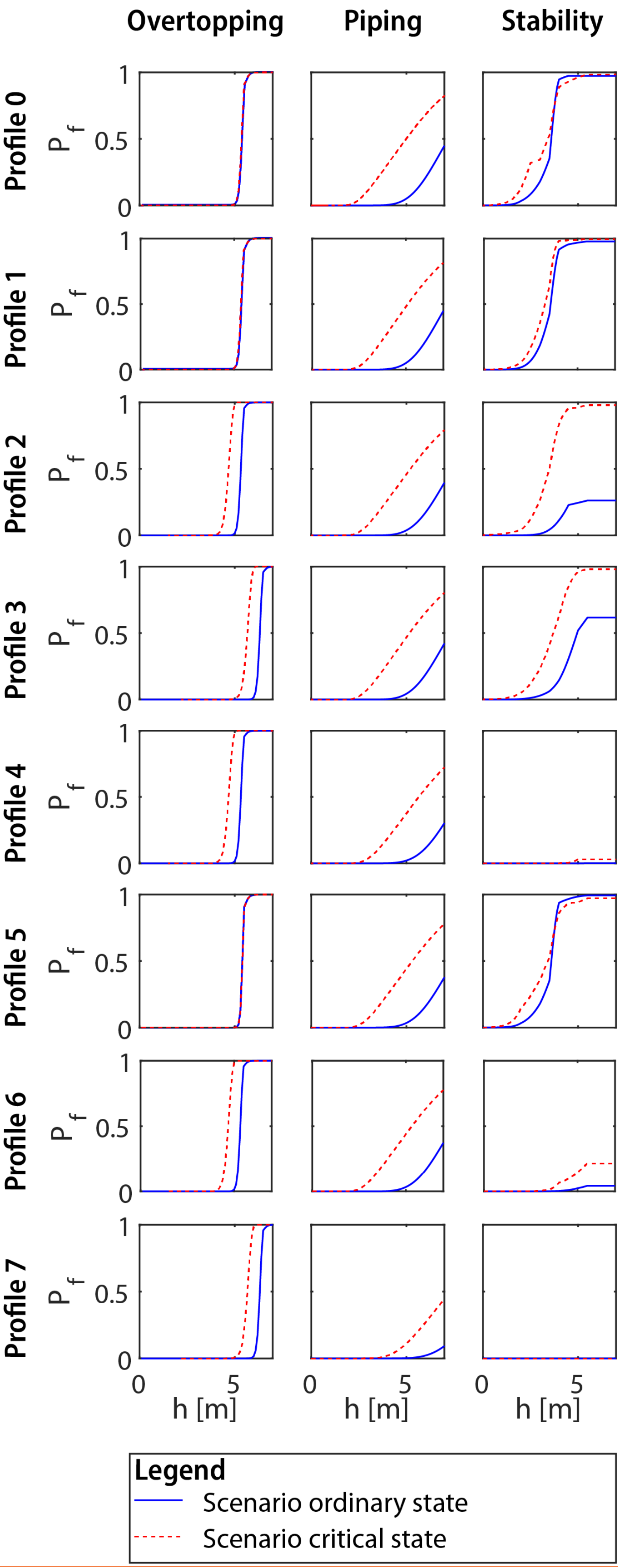


Fig. 6 The difference between the fragility curves of the 3 failure mechanisms and each profile with both multifunctional elements intact in blue and both multifunctional elements in a critical state in red.

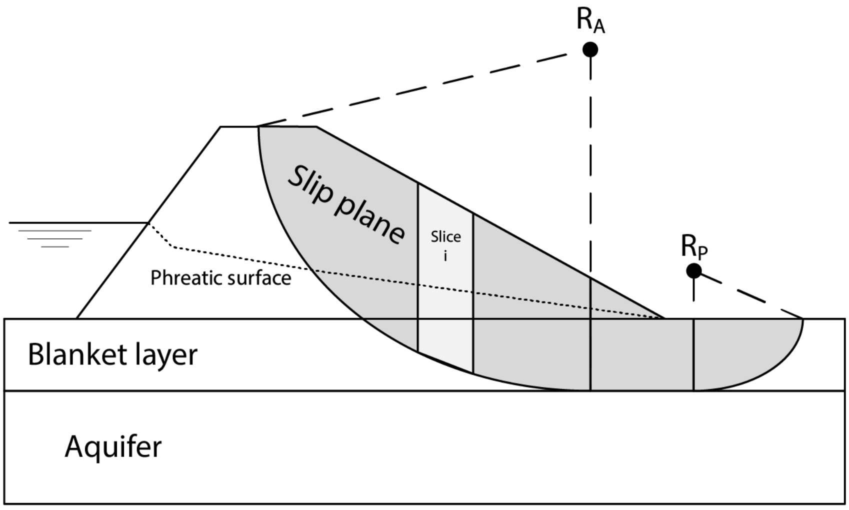


Fig. D1 Schematisation of the slip plane and phreatic surface used for the macro stability calculation

Tables

Table 1 The different approaches for assessing the cross-section of a multifunctional dike in this study

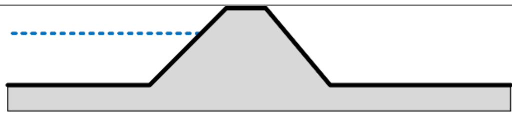
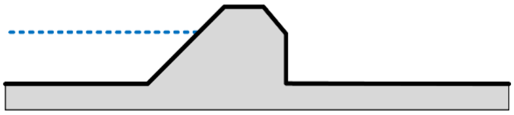
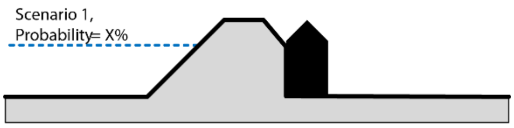
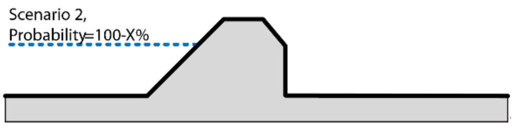
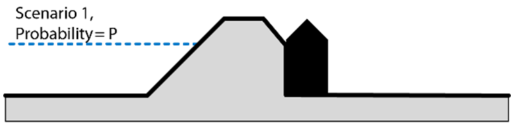
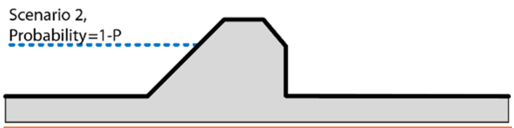
Approach		Assumptions	Example
Mono-functional		• No ~~functions~~multifunctional elements present	
Multi-functional	Conservative	• Functions are always in the critical state for a given failure ~~mechanisms~~mechanism • Dike zones affected by the ~~functions~~multifunctional elements are omitted from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

Table 2 Overview of failure mechanisms and corresponding methods

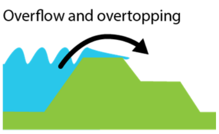
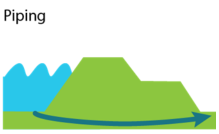
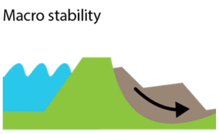
Failure mechanism	Description	Limit state function	Method
	Excessive flow of water over the dike with severe inundation of the hinterland as a result, possibly by erosion of the revetment and soil on the crest and inner slope leading to a dike breach	$q_c - q$	~~Overtopping: van der Meer et al. (2016), TAW (2002), Waal (1999)~~Overtopping: van der Meer et al. (2016), TAW (2002), de Waal (1999)
	Erosion of soil particles under the dike as a result of seepage. This in turn leads to collapse of the dike and failure by inundation of the hinterland.	$H_c - H$	~~Ground water: TAW (2004) Erosion: Sellmeijer et al. (2011)~~Ground water: TAW (2004) Erosion: Sellmeijer et al. (2011)
	Loss of slope stability as the dike becomes saturated. The collapse of the dike results in inundation of the hinterland	$\Sigma M_R - \Sigma M_S$	~~Ground water: TAW (2004)~~ ~~Slope stability: Van (2001)~~ Ground water: TAW (2004) Slope stability: Van (2001)

Table 3 Variation in parameters between reinforcement strategies

	Inner slope	Outer slope	Crest width	Max. overtopping rate (μ, σ)* [l/m/s]

Profile nr.	[-]	[-]	Crest height [m+REF]	Berm width [m]	[m]	Flood plain length [m]	House ~~intact~~present		House ~~collapsed~~ absent		No house	
0	1:2.5	1:3	5.5	0	5	100	-	-	-	-	100	120
1	1:2.5	1:3	5.5	0	10	95	-	-	-	-	100	120
2	1:2.5	1:3	5.5	0	10	100	70	80	0.1	0	100	120
3	1:2.5	1:3	6.5	0	5	97	70	80	0.1	0	100	120
4	1:2.5	1:3	5.5	15	5	100	70	80	0.1	0	100	120
5	1:2.5	1:4.5	5.5	0	5	91.75	-	-	-	-	100	120
6	1:4	1:3	5.5	0	5	100	70	80	0.1	0	100	120
7	1:10	1:3	6.5	0	5	97	70	80	0.1	0	100	120

~~*parameters of the lognormal distribution based on (van Hoven, 2015)~~

*parameters of the lognormal distribution based on (van Hoven, 2015)

Table A1 The standard geometry parameters for the dikes in the hypothetical case-study

Symbol	Description	Distribution	Parameters	
			μ	σ
z_{hinter}	elevation of the hinterland [m] above REF	Deterministic	0	-
z_{crest}	elevation of the crest [m] above REF	Deterministic	5.5	-
z_{fore}	elevation of the foreshore (at the dike toe) [m] above REF	Deterministic	0	-
z_{deep}	the average bed level, [m] above NAP along the fetch of the wind	Deterministic	-0.8	-
$\tan(\alpha_{in})$	inner slope angle [-]	Deterministic	1/2.5	-
$\tan(\alpha_{out})$	outer slope angle [-]	Deterministic	1/3	-
B_{crest}	crest width [m]	Deterministic	5	-
L_f	length of the foreshore	Lognormal	100	10

Table A2 Standard parameters of the blanket layer for the dikes in the hypothetical case-study

Symbol	Description	Distribution	Parameters	
			μ	σ
$d_{blanket}$	blanket layer thickness [m]	Lognormal	2	0.6
$\gamma_{sat,blanket}$	saturated volumetric weight of the blanket layer [kN/m^3]	Normal	18.8	0.1
$k_{blanket}$	specific conductivity of the blanket layer [m/s]	Lognormal	2.00E-08	2.00E-08
$ch_{blanket}$	cohesion of blanket material [kN/m^2]	Deterministic	0	0
$\phi_{blanket}$	Friction angle of blanket material [deg]	Normal	28	4.5

Table A3 Standard parameters of the aquifer layer for the dikes in the hypothetical case-study

Symbol	Description	Distribution	Parameters	
			μ	σ
$d_{aquifer}$	Aquifer layer thickness [m]	Deterministic	30	
$\gamma_{sat,aquifer}$	saturated volumetric weight of the aquifer layer [kN/m^3]	Normal	18	0.1
η	drag factor/White's coefficient [-]	Deterministic	0.25	
θ	bedding angle [rad]	Deterministic	0.61	

d_{70}	70%-percentile of the grain size distribution [m]	Lognormal	3.07E-04	4.61E-05
$k_{aquifer}$	specific conductivity aquifer [m/s]	Lognormal	4.86E-04	2.82E-04
$ch_{aquifer}$	cohesion of aquifer material [kN/m^2]	Deterministic	0	0
$\phi_{aquifer}$	Friction angle of aquifer material [deg]	Deterministic	31.3	4.5

Table A4 Standard parameters for the dike soil material for the dikes in the hypothetical case-study

Symbol	Description	Distribution	Parameters	
			μ	σ
$\gamma_{sat,core}$	saturated volumetric weight of the dike core [kN/m^3]	Normal	18.2	0.1
$\gamma_{dry,core}$	dry volumetric weight of the core[kN/m^3]	Normal	13.1	0.1
ch_{core}	cohesion of core material [kN/m^2]	Deterministic	0	0
ϕ_{core}	Friction angle of core material [deg]	Normal	33	4.5

Table A5 Standard hydraulic load and resistance parameters for the dikes in the hypothetical case-study

Symbol	Description	Distribution	Parameters		Source
			μ	σ	
ρ_w	density of water [kg/m^3]	Normal	1000	1	Known constant
h	water level [m] above REF	Generalized extreme value	-2.5	σ =1.5, ξ= -0.17	Assumed
γ_{break}	breaker index of waves [-]	Normal	0.425	0.075	Estimated ~~(EurOtop, 2016;TAW, 2002)~~(van der Meer et al., 2016;TAW, 2002)
γ_f	roughness factor for an outer slope with grass [-]	Deterministic	1	-	~~(EurOtop, 2016;TAW, 2002)~~(van der Meer et al., 2016;TAW, 2002)
u_v	hourly wind speed at 10 m above the surface [m/s]	Gumbel	16.8	1.6	Assumed
F_{max}	fetch [m]	Deterministic	1800		Assumed
q_c	critical overtopping discharge [l/m/s]				~~(van Hoven, 2015)~~(van Hoven, 2015)
	- No house (closed grass cover)	Lognormal	100	120	
	- Intact house (open grass cover)	Lognormal	70	80	
	- Collapsed house (no major overtopping allowed)	Lognormal	0.1	-	

Table B1 Description and values of variables in the overtopping and overflow limit state function

Variable	Description	Note
~~α_{out}~~α_{out}	Outer slope angle [-]	-
~~γ_f~~γ_f	Friction factor for the outer slope [-]	1 (TAW, 2002)
~~H_s~~H_s	Significant wave height [m]	*See Eq. (B6)*
~~ξ_0~~ξ_0	Iribaren number [-]	~~$\xi_0 = \frac{\tan(\alpha_{out})}{\sqrt{\frac{2\pi H_s}{g T_s^2}}}$~~*See Eq. (B8)*
~~c_1~~c_1	Factor for overtopping [-]	Normally distributed with μ=4.75 and σ=0.5 (TAW, 2002)
~~c_2~~c_2	Factor for overtopping [-]	Normally distributed with μ=-0.92 and σ=0.24 (TAW, 2002)

$\cancel{m_{\mathrm{Bret,H}}}\boldsymbol{m}_{\mathbf{Bret,H}}$	Model factor for Bretschneider equation	~~Lognormally distributed with μ=1 and σ=0.27 (Diermanse, 2016)~~Lognormally distributed with μ=1 and σ=0.27 (Diermanse, 2016)
$\cancel{m_{\mathrm{Bret,T}}}\boldsymbol{m}_{\mathbf{Bret,T}}$	Model factor for Bretschneider equation	~~Lognormally distributed with μ=1 and σ=0.13 (Diermanse, 2016)~~Lognormally distributed with μ=1 and σ=0.13 (Diermanse, 2016)

Table C1 Description and values of variables in the piping limit state function

Variable	Description	Destribution	Parameters	Unit
$\cancel{\gamma_{\mathrm{p}}}\boldsymbol{\gamma}_{\mathbf{p}}$	specific weight of sand particles	Deterministic	26	$\frac{kN}{m^3}$
$\cancel{\gamma_{\mathrm{w}}}\boldsymbol{\gamma}_{\mathbf{w}}$	specific weight of water	Deterministic	10	$\frac{kN}{m^3}$
$\cancel{\eta}\boldsymbol{\eta}$	drag factor	Deterministic	0.25	-
$\cancel{\theta}\boldsymbol{\theta}$	bedding angle [°]	Deterministic	35	-
$\cancel{\frac{RD}{RD_m}}\boldsymbol{\frac{RD}{RD_m}}$	Relative density of the material compared to small-scale piping experiments	Determinsistic	1	-
$\cancel{d_{\mathrm{70m}}}\boldsymbol{d}_{\mathbf{70m}}$	Reference d_{70} of the material used in small-scale piping experiments	Determinsistic	$2 * 10^{-4}$	m
$\cancel{m_{\mathrm{p}}}\boldsymbol{m}_{\mathbf{p}}$	Model factor for piping	Lognormal	$\mu = 1, \sigma = 0.12$	-