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Risk-based maintenance and inspection of riverine flood defence systems

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ABSTRACT

The condition of flood defence revetments is influenced by many different degradation processes such as animal burrowing, rutting and growth of weeds. Many of these processes are shock-based rather than progressive continuous. As shocks can cause a drop in performance, this means that the condition of a revetment can suddenly decrease, meaning that revetments can have significant initial damage at the beginning of a storm. Combined with the limited detection probability of common visual inspections of flood defences, this can have a significant influence on the reliability of flood defence systems, something typically not considered in reliability analysis. In this paper we study the reliability of a flood defence system subject to shock-based degradation. Various maintenance concepts are compared for a case study of a riverine flood defence of 20 kilometres length. This demonstrates that the current maintenance concept is insufficient to satisfy the reliability requirements for failure of the revetment. Overall, the joint influence of degradation and the existing maintenance concept leads to a 20 times higher failure probability estimate compared to a typical assessment without these aspects. Next, we demonstrate that both additional inspections, and targeted interventions to reduce the impact of for instance animal burrowing, can significantly reduce total cost and improve robustness of the considered flood defence system.

1. Introduction

Systems of flood defences protect many delta regions in the world from catastrophic flooding [1,2]. These systems consist of sandy coasts, earthen flood defences and hydraulic structures, that together keep the many inhabitants of these regions safe. Earthen flood defences (levees) along rivers form a major part of these flood defence systems, and can fail through a variety of failure modes. The International Levee Handbook distinguishes three main failure modes for flood defences: external erosion, internal erosion and instability [3]. To cope with long term degradation processes, changes in performance requirements [4] and changes in hydraulic loads, such flood defences require regular interventions in order to ensure sufficient reliability for each of these failure modes. In this paper we focus on external erosion, of which the risk is mostly mitigated by revetments (e.g. block revetments or clay covers with grass vegetation).

The accumulation of damage to structures is modelled through degradation models. The processes underlying such damage accumulation are typically considered as continuous-progressive or shock-based degradation processes [5]. Continuous-progressive degradation is typically a slow process, settlement of the crest is a common example for flood defences [6,7]. Shock-based degradation is caused by randomly occurring shocks of varying size. As such, a single or many different shocks might lead to a (sudden) reduction of structural capacity, which leads to structural failure or insufficient strength to counter design loads. For external erosion of flood defence structures, this is of particular importance. Revetments can be damaged by amongst others animal burrowing, damage due to storms, and bare spots or cracks due to drought events [8]. These can all cause a sudden or at least rapid reduction of the structural capacity. Regular inspections are required to mitigate the consequences of these damages [9]. In practice, inspection of flood defences typically focuses on identifying when degradation leads to an insufficient condition, after which this is mitigated through repair of (parts of) the structure.

Optimal inspection frequency and intervention levels for shock-based degradation depend on the inter-arrival time and size of shocks [10]. In modelling shock-based degradation, Phase-type (PH) distributions can be used as a means of obtaining the mean time to failure [10]. A PH-distribution represents the time for a Markov process to reach an absorption state (in this context structural failure). This is however mainly useful if shocks are cumulative. While there is some cumulative effect, most damages to revetments are caused by different and often independent processes. Other authors use Markov processes [11], often

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in the context of Dynamic Bayesian Networks [12–14] to characterize degradation. In that case a transition matrix is used to model the development of the condition of a structure in time. Using state space augmentation both time-variant and time-invariant aspects of degradation can be taken into account [14]. As Dynamic Bayesian Networks also include the option to consider inspections and maintenance interventions, this is a versatile tool for the problem at hand.

Past time-dependent reliability analyses of flood defences typically only consider degradation as a slow, continuous process that takes several decades. For instance, settlement of the crest is considered by Speijker et al. [7], Buijs et al. [6] and Klerk et al. [15]. Buijs et al. [6] considered rutting damage to grass revetments over a period of 50 years and Chen and Mehrabani [16] related the condition grades of flood defences used by the Environment Agency in the UK [17] to the time-dependent reliability over a period of 50–80 years. These analysis ignore the influence of sudden shocks: e.g., animal burrowing can lead to a sudden decrease in structural performance and reliability [18]. Also, the influence of inspections and maintenance on reliability is seldom accounted for explicitly.

Klerk and Adhi [19] found that most damages encountered in condition inspections are caused by such shock-based processes, in particular for grass revetments. Such damages can result in a very rapid degradation of the flood defence condition. The most often encountered damages are animal burrows, bare spots and rutting, which are typically caused by shock-based drivers rather than continuous-progressive degradation, and are often independent of the main hydraulic loads. This means that the state of a revetment might abruptly degrade from a good to bad condition. Therefore it is pivotal that this is detected timely by inspections. As Klerk et al. [9] demonstrated that visual condition inspections have limited accuracy, such damage processes can be a major contributor to the failure probability of flood defences.

Aside from the shock-based character of damage, there are two other aspects that make inspection and repair of damage to flood defences different from other infrastructure. First of all, many flood defences are ‘inactive’ most of the time in the sense that they are not loaded at all. This means that damages and anomalies can remain unnoticed for several years without causing any failures or other problems. This distinguishes (a major part of) the maintenance of flood defences from for instance fatigue-sensitive structures, where cyclic loading can cause behaviour that increasingly deviates from the original behaviour [e.g. [20,21]]. Secondly, flood defences are primarily loaded during specific seasons, such as when most rainfall, snow melt or storms occur. As many damages can be repaired before an extreme load occurs, even the most detrimental damages do not necessarily have immediate structural consequences in terms of failure or flooding.

The core aim of this paper is to quantify the influence of shock-based degradation on the reliability of a flood defence system. To that end we develop a Dynamic Bayesian Network that can be used to determine the reliability of the system, while including different degradation processes and the influence of different maintenance concepts and structural interventions. We focus on external erosion for a riverine earthen flood defence with a length of 20 km, but the general approach is extendible towards other failure modes and system types and configurations.

Section 2 presents the general setup of the model, after which Section 3 evaluates a typical maintenance concept, and Section 4 evaluates how other concepts, combined with structural interventions might influence structural robustness and reliability of flood defence systems. Section 5 presents discussion and conclusions.

2. Methodology

2.1. Description of the considered flood defence system

In this section we translate the key aspects identified in the previous sections to a model with which maintenance concepts for flood defence segments can be evaluated. Fig. 1 shows a flood defence segment that consists of $n \in N$ sections with independent strength — each section n might or might not contain damaged spots, and might also have different geometrical and/or soil properties. Typically such a segment consists of approximately 20 sections of 1 km length. Each section n is divided into $z \in Z$ (perpendicular) zones along the slope, where each zone z denotes the part between the vertical coordinates $[y_i, y_j]$. At each of these zones damage to the revetment can occur, resulting in a change of the failure probability of that specific zone z at section n. Different types of damage are represented by different states $s \in S$, which each result in a different failure probability for the slope part, given that state ($P(F|n, z, s)$). As external erosion can occur at both the inner and outer slope, in our case study we apply this principle to both the inner and outer slope.

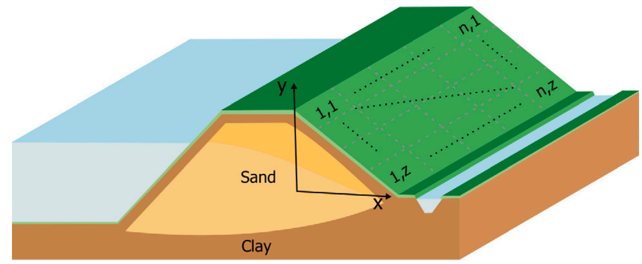


Fig. 1. Schematized flood defence segment consisting of n sections (1 km length). The slope of each section is divided into z zones at which occurrence and consequences of damages are considered. The flood defence consists of a clay cover layer with grass revetment and a sandy core.

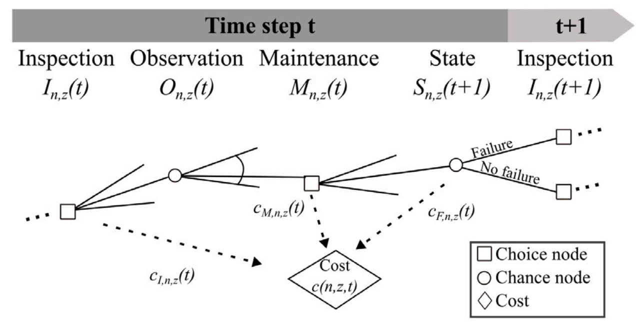


Fig. 2. Generic decision tree for the sequential actions of inspection, observation, maintenance and state development of dike section n and slope zone z.

2.2. Modelling degradation and interventions through a dynamic Bayesian network

Decisions on maintenance and inspection for each element n and each slope part z for a period of $t \in T$ time steps can be structured using the decision tree in Fig. 2. At time t, there is the option to do an inspection $i_{n,z}(t) \in I_{n,z}(t)$ at section n at slope part z. Next, an observation $o_{n,z}(t) \in O_{n,z}(t)$ is obtained which can be used to update the belief about the state of part z at section n ($s_{n,z}(t) \in S_{n,z}(t)$). In order to improve $s_{n,z}(t)$, maintenance actions ($m_{n,z}(t) \in M_{n,z}(t)$) can be taken such as repair works, overhaul, or more intensive monitoring of the section and zone. Jointly with the degradation, these actions influence the state $s_{n,z}(t+1) \in S_{n,z}(t+1)$ after which the sequence of decisions repeats itself. Both the cost of inspection and maintenance actions ($c_{\mathrm{I,n,z}}(t)$ and $c_{\mathrm{M,n,z}}(t)$), as well as cost of potential failures given the state $s_{n,z}(t)$ ($c_{\mathrm{F,n,z}}(t)$) contribute to the cost $c(n, z, t)$. Note that this cost contribution should be considered at the level of system failures (i.e., flooding of the hinterland) which will be outlined further in Section 2.4.

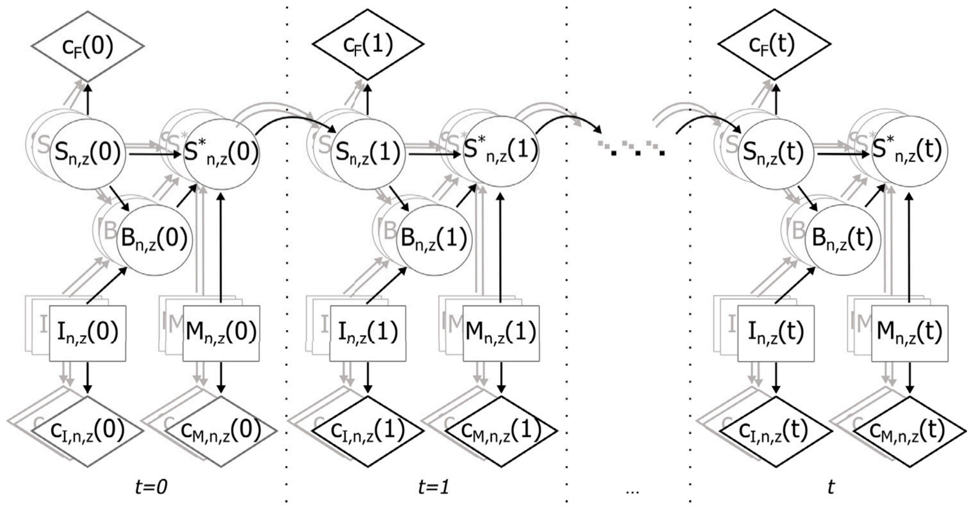


Fig. 3. Influence diagram for inspections, maintenance and state development of dike section n and slope zone z including different utilities at every time step. Note that shaded nodes and edges represent different sections n and slope zones z, which together determine the $c_F(t)$ (i.e., the cost of failure of the system).

For systems with many elements and sequential choices influence diagrams are more convenient than decision trees [12]. Influence diagrams are an extension of Bayesian Networks, and also include decision and utility nodes [22]. Fig. 3 shows the influence diagram for inspection and maintenance for a flood defence segment of $n \in N$ sections with $z \in Z$ slope parts for a period of $t \in T$ time steps. Note that the observation ($o_{n,z}(t)$) is not present in the influence diagram but replaced by a belief node $B_{n,z}(t)$, which represents the belief on the state $S_{n,z}$ conditional on the actual state of the slope part and the inspection that has been done. Additionally we add a node $S^*_{n,z}(t)$ that represents the state after maintenance $M_{n,z}(t)$ of the observed damages (represented by $B_{n,z}(t)$). Subsequently, the degradation model yields $S_{n,z}(t+1)$.

Provided that the transition matrix does not vary in time, the Dynamic Bayesian Network for each section n and zone z is in fact a Partially Observable Markov Decision Process (POMDP) [23]. However, as we look at a system scale this is no longer the case, as the utility (in particular the cost of failure $c_F(t)$) depends on the state of the flood defence segment rather than that of an individual section and zone. Note that this could be resolved by reformulating the different nodes to include all relevant combinations of states and actions for each section and zone, but this is a non-generic step as this differs per flood defence segment, and solving such a problem is computationally challenging due to the extremely large number of possible combinations.

2.2.1. State of the revetment

Within a Dynamic Bayesian Network the condition can be represented by time-variant and time-invariant parameters. The state of the revetment at section n in zone z is represented by 4 states, which are related to the sod quality of the grass revetment [24,25]:

- S_1: the pristine state of the revetment. The sod quality of the grass is 'closed' (maximum erosion resistance).
- S_2: some damage to the grass sod due to for instance weeds. The sod quality of the grass is 'open' (reduced erosion resistance).
- S_3: major damage to the grass sod due to presence of bare spots or rutting. The sod quality of the grass is 'fragmented' (no erosion resistance).
- S_4: major damage to the grass sod and clay layer due to animal burrowing. The clay layer thickness is reduced, the sod quality of the grass is 'fragmented' and provides no erosion resistance. Note that we do not consider burrows that cause large voids in the sandy core of the flood defence.

The state S of the revetment is modelled as a Markov process where the state of zone z at section n is represented by the 4 previously introduced states (S_1 to S_4), for which changes are evaluated through a transition matrix representing $P(S_{n,z}(t+1)|S^*_{n,z}(t))$. As each state is caused by a different type of shock and shocks are not cumulative, the Markov process is assumed to be progressive. In our case we assume that the transition probability only depends on the current state. There are ample examples in literature where continuous degradation (combined with shock-based degradation) has been considered using transition matrices [13,26,27], and this extension could also be made here (e.g., by using a sequential Markov process). Additionally, for simplicity we assume that every section and zone degrades independently from other sections and zones, and all zones degrade with the same rate. Dependence of degradation between sections and zones could be modelled by for instance a Markov random field, but in such cases one would also have to distinguish between the different causes of damage (e.g., burrowing by different animals, rutting, weeds), which each have a different spatial variability structure. Assumptions on this cannot be substantiated with the available data.

Obviously, there are factors which can increase the probability of animal burrowing or rutting at a specific location, as was illustrated in Klerk and Adhi [19] for the influence of neighbouring urban areas. Another example is that species such as beavers and nutria start burrowing below the waterline [28], such that flood defences that are not directly adjacent to water bodies are much less susceptible to their burrows. Buijs et al. [6] framed such factors on a more general level through the distinction between excitation (i.e.., flood defence properties that initiate some kind of degradation), ancillary (i.e., properties that transform the process) and affected features (i.e., properties in the reliability model that are influenced). Unfortunately, this has not yet been translated to quantitative insight into the relation between features and occurrence frequency of different types of damage. If such insights would be available, specific transition matrices for different zones/section can be used to account for local variations, and hyperparameters such as in Luque and Straub [12] can be used to account for common causes in damage of slopes, e.g., in case of droughts.

2.2.2. Possible interventions

Nearly all inspections of flood defences are done visually: other methods are only used occasionally [e.g. 29–31] but are not common practice. Here we only consider visual inspections characterized by a Probability of Detection (PoD). We only consider failure to detect damage, although it was demonstrated in Klerk et al. [9] that also incorrect classifications can lead to incorrect beliefs about the state of a flood defence. The PoD can vary, depending on the type of inspection and the state (i.e., not all damages are detected with the same accuracy). Klerk et al. [9] also found variation between inspectors, but as we focus on expected average cost per year we do not need to consider this variation.

In the influence diagram in Fig. 3, inspections are implemented by a conditional probability $P(B|S, I)$ which relates the belief $b \in B$ to the actual state $s \in S$ and the inspection action $i \in I$. The probability that the belief is equal to the actual state is equal to the PoD (which can differ per type of inspection and per state), and if no damage is observed it is assumed that the state is S_1 (pristine state).

Based upon the belief, maintenance actions can be taken in order to obtain the state after interventions $P(S^*|B, M, S)$. We consider 3 interventions: small-scale repair (M_1), complete overhaul (M_2), and monitoring (M_3) of the revetment. Maintenance actions can be planned both as condition and time-based maintenance, where condition-based maintenance is carried out automatically after an inspection, and time-based at a fixed point in time [32]. If maintenance is executed in the model, all zones with a state equal or worse than the threshold S_c are repaired. We assume perfect repair, such that all zones with detected damage are restored to their pristine state.

In practice, some slightly damaged parts might not be repaired immediately but are monitored. This ensures that any further degradation is detected, and that these spots can be dealt with through emergency measures in case of high water. Lendering et al. [33] demonstrated that the reliability of such measures mostly depends on errors in detection, followed by placement errors. As monitored spots are already detected and their characteristics are known, we assume that the failure probability of a slope with a monitored spot is equal to that of the intact state $P(F|S_1)$ (i.e. we assume that deployment of emergency measures is successful). Based on this assumption we can accommodate this by adding an additional state S_m to the matrices of S and S^*. At these monitored zones new damage spots might occur with the same probability as for non-monitored slope parts, as the slope parts are large in comparison to the typical scale of damage. With the probabilities $P(S^*(t))$ for each zone z and section n we can determine the probability for each zone being in a certain state, at each time step. In the next section we discuss how this is translated to the system reliability.

2.3. Estimating system reliability

2.3.1. Failure due to external erosion

Next to the occurrence of damage, the key question is to what extent it influences the overall reliability of a flood defence. The International Levee Handbook (ILH) [3] distinguishes 3 main failure modes for flood defences: external erosion, internal erosion and instability. In this paper we will focus on external erosion and its relation to the condition of revetments.

External erosion can be caused by inner slope erosion through overflow or overtopping waves, and erosion due to wave impact on the outer slope. With regards to the influence of the revetment condition, most of the research in experimental settings has focused on quantifying the strength of for instance rubble mound, grass revetments or block revetments in a good state. The resistance of a damaged revetment to withstand external erosion has not been considered but for some exceptions.

For overtopping erosion on grass revetments, van Bergeijk et al. [34] investigated the influence of damage on overtopping erosion failure probabilities and found this to increase the failure probability by (several) orders of magnitude. Similarly, Aguilar-López et al. [35] demonstrated, using a computational fluid dynamics (CFD) model, that transitions between a road and grass slope result in larger erosion rates due to more turbulent flow. Similar behaviour is found for some of the types of damage encountered on grass slopes and this thus indicates that damage can significantly increase the failure probability. For external erosion on grass-covered outer slopes, not much is known about the influence of damaged spots, but some research has been done on the influence of transitions and initial damage using a wave impact simulator [36,37]. Again it is found that initial damage can lead to a significant reduction of the strength of the revetment. An important point is that it is found that also the underlying clay layers provide additional resistance [38], but experience from tests is that once the sandy core is exposed to wave loads, erosion can proceed very quickly.

For failure due to slope stability and internal erosion Taccari and Van Der Meij [39] and Palladino et al. [18] investigated the influence of animal burrows. They mostly considered very large burrows, and found these to be of relevance for both slope stability and internal erosion. However, modelling the effects is difficult as the influence depends strongly on their shape, location and size. For internal erosion especially burrows at the lower part of the inner slope, and burrows with entrances at both sides of a flood defence are of relevance. For slope instability the largest influence is found for burrows that increase the hydraulic gradient in the dike body [39].

An important factor which reduces the likelihood of large animal burrowing for riverine flood defences, is the presence of large foreshores that are dry under normal conditions. At such locations, large burrows are unlikely, while there are many records of smaller burrows in field inspection data [19]. For such smaller burrows the main question is whether these extend through the typically present clay cover layer. In such cases, internal erosion might occur due to a.o. concentrated leak erosion or suffusion [40]. From field data it is found that whether this occurs depends on the animal species: rabbits typically penetrate the cover layer, while burrows by dogs are much more superficial. On a more general level, there is a lot of uncertainty regarding the failure processes related to internal erosion and their quantitative risk analysis, such that assessment depends almost exclusively on engineering judgment [41].

In this paper we look at the failure mode of external erosion at both the inner and outer slope, and how this is influenced by shock-based degradation. Along rivers extreme water levels and waves are typically uncorrelated. As such, most failures of the outer slope are caused by events with large waves and moderate water levels, and most failures of the inner slope by events with high water levels and less extreme waves. Therefore, in line with the safety assessment in the Netherlands, we assume the failure of both slopes to be independent.

Figs. 4(a) and 4(b) show failure paths (a form of event trees) that show how the flood defence can fail due to external erosion of the outer and inner slope, given different initial states S caused by previous damage due to degradation. For outer slope erosion we assume failure occurs when the remaining width at the water level is lower than the original crest width. For inner slope erosion we assume failure if the clay cover layer has been eroded and the sandy core is exposed, for which experiments show that erosion proceeds extremely quickly. Additionally we assume that the flood defence fails due to overflow if the water level exceeds the crest which is not influenced by the state S. Further details on the physical models used for evaluating the failure process for both mechanisms and states are given in the supplementary files.

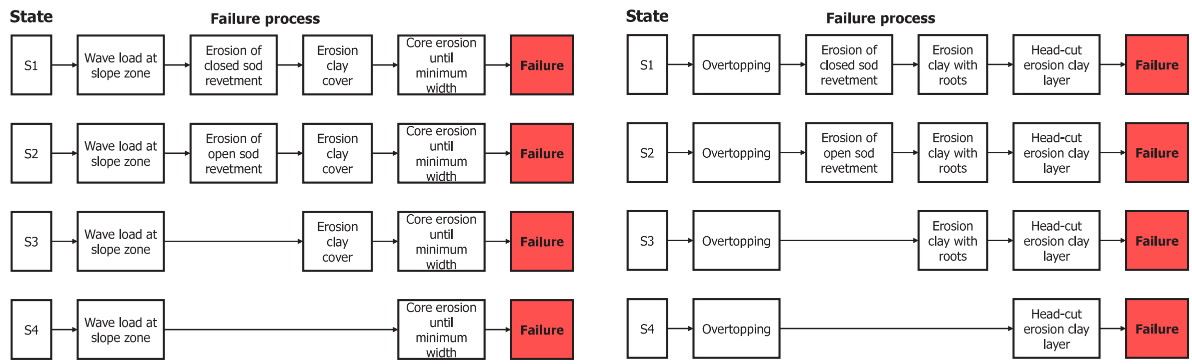
2.3.2. Reliability on system level

The failure probability of a flood defence section n susceptible to $e \in E$ failure modes at $z \in Z$ slope zones is given by:

$$P_{\mathrm{f}}(n) = P(\min_{e \in E,\ z \in Z} g_{n,m,z}(\mathbf{X}) < 0), \tag{1}$$

where $g(\mathbf{X})$ is the limit state function for failure mode e with uncertain inputs $\mathbf{X}$. The influence of damage is included by modifying specific parameters in $\mathbf{X}$ (in particular the erosion resistance of the grass and clay layer thickness).

If failure modes e are (partially) dependent this can be solved by for instance an integrated Monte Carlo analysis of Eq. (1), or by combining failure modes using the Equivalent Planes method [42], such that a failure probability is derived for each combination of z and e at section n. Subsequently, the failure probability can be upscaled to a flood defence segment in a similar way.



(a) Erosion due to wave impact at the outer slope. (b) Erosion due to wave overtopping at the inner slope.

Fig. 4. Failure processes for both failure modes for different states of the revetment.

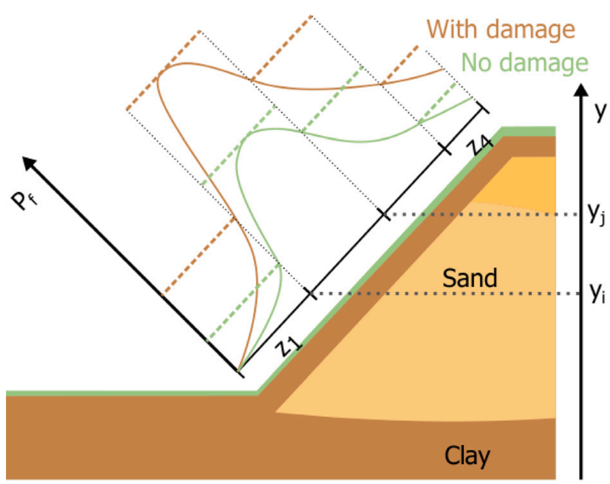


Fig. 5. Indicative failure probability along the slope for 2 states s with (brown) and without (green) damage. Solid lines indicate $P_f(y|s)$, dashed lines indicate the probability of failure for a slope part $P_f(z|s)$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In practice, despite influence from the same load variables, failure modes are often considered to be independent for two main reasons [15,43]: typically one failure mode dominates, or the design point values of shared random variables are different. In both cases assuming independence does not lead to significantly different failure probability estimates. This does reduce the computational burden, which is an issue especially for integrated Monte Carlo analysis.

When considering damages at different slope zones z, damage will result in an increase of the failure probability, such that it is typically dominated by the damaged zone. Consider the slope in Fig. 5 : here the failure probability along the outer slope of a section n is shown with (brown) and without damage (green) (we only consider erosion of the outer slope here). The failure probability of the section is defined by Eq. (1), and determined by the part of the slope with the highest failure probability. If we discretize the slope into 4 zones as shown in the figure, this means that the most unfavourable case is when the second zone z_2 is damaged. Thus, given Eq. (1), all zones where $P_f(z_i,s) < P_f(z_2,S_1)$ will not contribute to the failure probability. We can then determine the failure probability of the section n with $z \in Z$ zones and $s \in S$ states using the following equation:

$$P_f(n) = 1 - \prod_{z,s}^{Z,S} (1 - P_f(z,s) \cdot P(z,s) \cdot P(P_f(z,s) > P_f(z^*,s^*))) \quad (2)$$

where $P(P_f(z,s) > P_f(z^*,s^*))$ is the probability that zone z in state s is the weakest along the slope (i.e., $P_f(z^*,s^*)$ is the failure probability of the weakest zone at the section). We assume that for each zone z between coordinates y_i and y_j it holds that the failure probability for state s at section n is given by:

$$P_f(n,z,s) = \max P_f(y|n,s) \text{ for } y_i < y < y_j. \quad (3)$$

As was displayed in Fig. 1, we have multiple sections $n \in N$ along the flood defence segment. In order to determine the failure probability of failure mode m at a segment level we look at the probability that zone z at section n is the weakest zone along the entire segment with $n \in N$ sections, such that:

$$P_f(m) = 1 - \prod_{n,z,s}^{N,Z,S} 1 - P_f(n,z,s) \cdot P(n,z,s) \cdot P(P_f(n,z,s) > P_f(n^*,z^*,s^*)) \quad (4)$$

where $P(P_f(n,z,s) > P_f(n^*,z^*,s^*))$ is the probability that the zone z at section n is the weakest along the dike segment.

Next, as we have multiple independent failure modes $m \in M$ we can combine them and obtain the failure probability of the flood defence segment:

$$P_{\mathrm{f,segment}} = 1 - \prod_{m \in M} (1 - P_f(m)) \quad (5)$$

Note that as the probability of an extreme load is very close to 0 in the summer we assume failures only occur in winter (see also Section 1.1 in the supplemental file).

2.4. Evaluation of intervention strategies

The cost of inspection and maintenance have to be accounted for in the evaluation of Total Cost, jointly with the risk costs. The cost at time t can be computed as follows:

$$C(t) = P_{\mathrm{f,segment}}(t) \cdot D + \sum_{n \in N} \sum_{z \in Z} C_{\mathrm{I,n,z}}(t) + \sum_{n \in N} \sum_{z \in Z} C_{\mathrm{M,n,z}}(t) \quad (6)$$

where D is the damage due to a flood. By summing all costs for time steps t in a certain year we can obtain the annual cost C_{annual}.

Subsequently, we can also include investments for a longer investment using the Equivalent Annual Cost (EAC)[32]. The EAC is the annual cost of an asset. In our case this consists of the C_{annual} of flood risk, inspection and maintenance, and of the annualized costs of investments with a lifespan longer than a year. For investment C_A in a structural upgrade with lifespan t_{life} we can compute the equivalent cost of the investment (EAI) [44]:

$$EAI = \frac{C_A \cdot r}{1-(1+r)^{-t_{\mathrm{life}}}}, \quad (7)$$

such that

$$EAC = C_{\mathrm{annual}} + EAI, \quad (8)$$

where r is the discount rate ($r = 1.6\%$ [45]). The implementation of the cost computation is further discussed in Section 3.1.2.

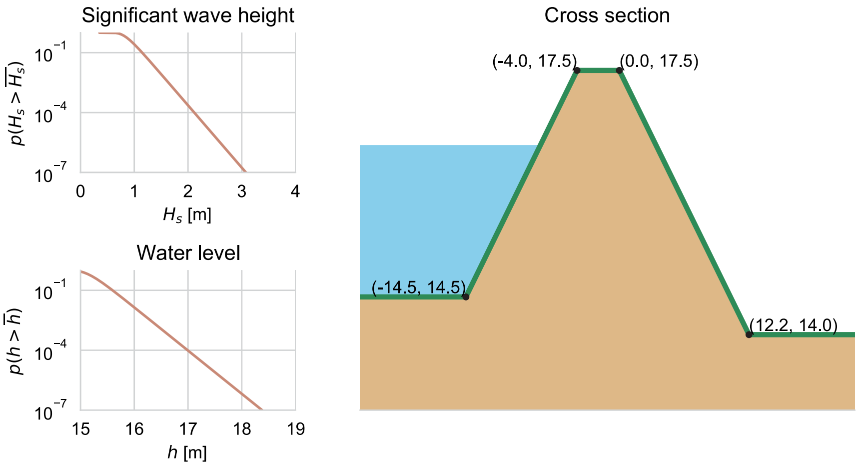


Fig. 6. Left: distributions of significant wave height and water level for the case study. Right: geometry of the flood defence section.

3. Influence of damage on flood defence segment reliability

3.1. Description of case study

For our case study we consider a flood defence segment consisting of 20 identical sections of 1 kilometre length. If the segment fails, the flood damage is 3.5 billion€. We assume the failure probability requirement ($P_{\mathrm{f,req}}$) for the segment is 1/10000 per year, and 1/35000 per year for external erosion in line with Jongejan et al. [43]. The right pane in Fig. 6 shows the geometry of the considered cross section. We assume the sandy core is completely covered by a grass revetment and a clay layer of 50 centimetres thick. The left panes show the marginal distributions for the significant wave height H_s and water level h. Both h and H_s are represented by Gumbel distributions fitted to values for a location along the Rhine, as obtained from the hydraulic models used for the Dutch statutory safety assessment [46]. For wave loads we use a simplified criterion for depth-induced breaking on the foreshore: $H_s < 0.5(h - h_{\mathrm{foreshore}})$. For erosion at the inner slope we consider the entire slope from inner crest to inner toe. For erosion at the outer slope we consider the slope from the outer toe until 0.5 meters below the outer crest line — if the top part of the slope is loaded by waves of any relevance the overtopping volume will be so large that this will lead to failure of the inner slope. Input values and distributions for the different failure modes are given in the supplementary files.

3.1.1. Degradation

To determine the probability of damage at a section, we analyse 6 years of inspection data of 470 km of primary flood defences along the Dutch Rhine. During the spring inspections in these years, inspectors registered all observed damages using the Digigids system [9] which is a classification system used for flood defence inspections in the Netherlands. Inspectors register the damage parameter (e.g., burrowing or rutting) and severity (good, reasonable, mediocre or bad) and take pictures of damaged spots. Additionally they can indicate the urgency of repair (e.g., emergency repair or medium urgency). We use these parameters to couple damage spots to estimates of the state of flood defence sections of 1 km length. We split the 470 km into sections of 1000 m, and couple damage registrations for each year to the nearest section. Based on the worst reported damage, we determine the sod quality of the revetment in a given year, for both slopes. S_4 is assigned if there is a burrowing damage with severity bad, and the urgency indicates that it is to be repaired before the next winter season. S_3 consists of all other damages with severity bad, S_2 of all damages with severity mediocre, and S_1 is assigned to all other sections.

There are a few remarks towards the data used. First of all, as these are field observations, the data not only represents the influence of degradation but also maintenance interventions influence the transition of the state between subsequent years. Secondly, as the inspections are approximately 1 year apart, there might be other recovery and degradation processes on a shorter time scale, e.g. due to seasonal influences, that do not emerge clearly from the data. Thirdly, it was demonstrated in Klerk et al. [9] that the registrations in spring inspections are inconsistent in two ways: not all damages are detected, and the severity of damaged spots is often misclassified. As such, deriving transition probabilities between specific states based on yearly observations of a visual inspection is not possible based on this data.

However, we do have an estimate of how many sections are in a certain state S_i at the time of the inspection, and that this is typically repaired quite soon afterwards. As such we can derive the probability that, after a year, a section is in state S_i.[1] Fig. 7 shows the $P(S_i)$ for the inner and outer slope at a random section, including Kernel Density Estimations obtained from 10000 bootstrap samples of the dataset. It can be observed that $P(S_i)$ differs slightly per slope, in particular for S_4, but for S_4 the (relative) variation from the bootstrap samples is also larger than for the other states. For the analysis we use the same transition probabilities for each slope. Based on the mean $P(S_i)$ of both slopes we use the following transition matrix for degradation of both slopes:

$$P(S_{n,z}(t)|S_{n,z}(t-1)) = \begin{bmatrix} 0.773 & 0.123 & 0.096 & 0.008 \\ 0 & 0.912 & 0.096 & 0.008 \\ 0 & 0 & 0.992 & 0.008 \\ 0 & 0 & 0 & 1.0 \end{bmatrix} \tag{9}$$

Note that this is the transition matrix for a year and for the entire slope, the transition matrix for an individual time step and zone is obtained by rescaling under the assumption that the probability of degradation is constant over a year and equal along the different slope zones z. It should be noted that in practice the rate of degradation might vary along the slope. For instance, damage caused by debris will mostly occur along the water line. Similarly, weeds mostly grow in spring. The available data does not provide information on the exact location on the slope, and as it has only 1 inspection per year seasonal variation can also not be derived from the data. This was investigated by altering degradation rates in different seasons, but this has very little influence on overall results. Maintenance and monitoring is accounted for as described in Section 2.2.2.

3.1.2. Baseline inspection and maintenance

We assume that inspection and maintenance actions are always carried out for the entire flood defence segment of 20 kilometres. For

[1] It should be noted that there are still false negatives due to inaccurate inspections.

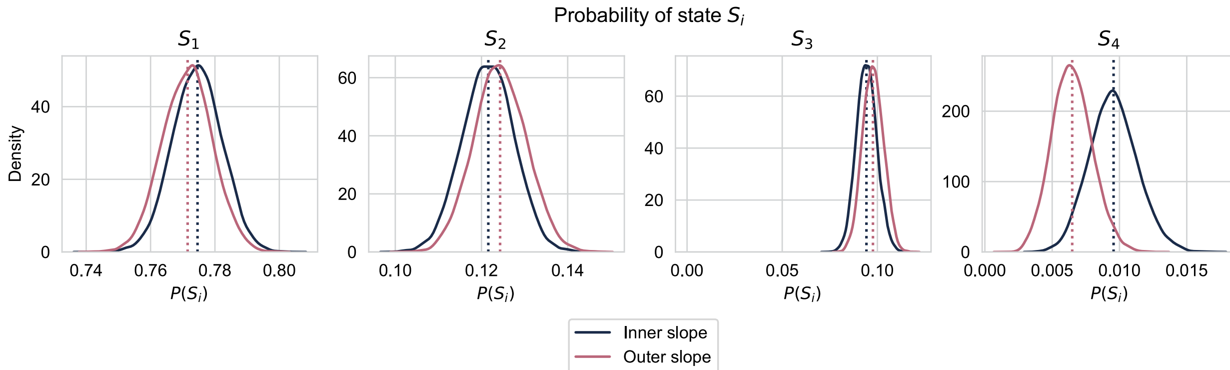


Fig. 7. $P(S_i)$ for a flood defence section of 1000 m for both inner and outer slope. Kernel Density Estimates obtained from 10000 bootstrap samples of the original dataset (dotted line).

Table 1
Overview of all inspection and maintenance actions considered in this study, including the baseline maintenance concept. Note that the baseline parameters indicate the first time an action is taken (T_0) and the interval (ΔT), both in weeks. Costs are per kilometre per slope. Note that monitoring costs are assumed to be included in the general inspection by car.

Action	Description	Kind	Threshold	PoD			Cost	Baseline	
			S_c	S_2	S_3	S_4	€/km/slope	T_0	ΔT
I_1	General inspection by car	Periodic		0	0	0.05	30	0	2
I_2	Condition inspection by foot	Periodic		0.6	0.6	0.6	120	13	52
I_3	Specific burrowing inspection	Periodic		0	0	0.8	120	–	–
M_1	Repair of damaged spot	Condition-based	S_4				680		
M_2	Overhaul of all damaged spots	Time-based	S_2				1920	15	52
M_3	Monitoring of a damaged spot	Condition-based	S_2				0		

our case we consider a baseline maintenance concept that consists of 2 inspection actions (I_1 and I_2) with different accuracy and frequency. I_1 is an inspection by car that is typically done biweekly and not specifically aimed at thorough condition inspection. Due to the general character of this inspection only major damages (S_4) will be discovered with a relatively low PoD. Note that as inspections are considered independent and carried out biweekly, the PoD of a given damaged spot is still relatively high (e.g., for a damaged spot with biweekly inspections the probability of the spot being detected after 26 weeks is ≈50%). I_2 is a condition inspection by foot as considered in Klerk et al. [9], and is aimed at detecting all meaningful damages. Additionally we consider 3 types of maintenance actions: M_1 is aimed at repairing a single damage spot, M_2 at overhauling all slightly damaged spots at a slope. Repair actions are carried out if it is detected that the state of a section $S_i \leq S_c$, where S_c is the critical threshold. M_3 is a specific action that ensures damages are continuously monitored, such that their further development or degradation is known. Such spots can then be repaired later during time-based maintenance actions such as M_2. Monitoring has no additional cost as in practice this will be done as part of the general inspection (I_1). Table 1 displays costs and other parameters for the different actions, further details are given in the supplementary files.

3.2. Results for baseline inspection and maintenance

Fig. 8 shows $P_f(y|s)$ for external erosion at the inner and outer slope for the different states $s \in S$ for a section n. For the outer slope it can be observed that there is a zone around approximately $15.7\,\mathrm{m}+\mathrm{ref}$ where P_f is highest, such that even if there is damage at other parts of the slope (e.g., at $14.5\,\mathrm{m}+\mathrm{ref}$) the overall failure probability will typically not be impacted. This is primarily caused by the fact that the slope is loaded most severely at this level. For the inner slope there is a strong influence of S_3 and S_4 on the reliability. A notable difference is also visible for S_1 and S_2: $P_f(y|S_2)$ varies along the slope as the speed of the overtopping wave front increases further down the slope. For $P_f(y|S_1)$ this is not visible as failure is dominated by overflow failure. It should be noted that $P_f(y|S_3)$ is also dominated by wave overtopping, but the critical erosion velocity U_c of clay is very low, such that the failure probability does not significantly depend on y.

Without accounting for damage, the requirement of 1/35000 for the overall failure probability is met both for S_1 and S_2. However, other damages at both slopes might result in a failure probability that is unacceptable. The question is whether the currently implemented maintenance concept is sufficient to ensure that the failure probability requirement is met. To assess that we evaluate the Dynamic Bayesian Network with the baseline maintenance concept.

Next we use Eq. (4) and (5) to obtain the failure probability for the entire flood defence segment including damage and inspection and maintenance. This is shown in Fig. 9, and compared with the failure probability without any damage $P(F|S_1)$. Without damage, this segment meets the requirement (1/35000) for external erosion, provided that the slopes are in state S_1 or S_2. It is clearly observed that damages to both the inner and outer slope cause a significant increase in failure probability, and when accounting for damage and the baseline maintenance concept the requirement is no longer met: the maximum failure probability is approximately 20 times higher when accounting for damage, inspection and maintenance. Note that we evaluate a period of 20 years, but after approximately 3 years an equilibrium situation is reached. As such, we can evaluate the costs for both cases by looking at the average costs per year (C_{annual}) obtained through Eq. (6).

Table 2 shows the average costs per year for the period of 10 to 20 years in the simulation. Here we observe that the base risk costs without damage are similar to the expenditure on inspection and maintenance. However, accounting for damage to the flood defence gives a large increase in flood risk costs. As such, additional measures are required, and likely cost-efficient.

4. Improving robustness and reliability of flood defence segments

In the preceding section we demonstrated that revetment damage can contribute significantly to flood risk, and is much higher than

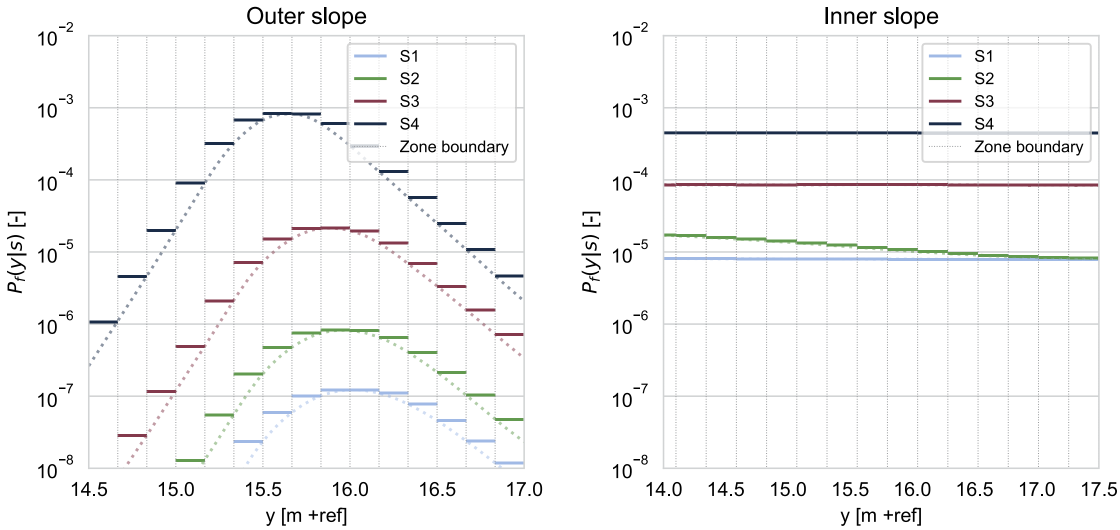


Fig. 8. Failure probability $P_f(y|s)$ for external erosion at the outer (left) and inner (right) slope (with $s \in S$). Dotted coloured lines indicate $P_f(y|s)$, solid lines indicate the discrete values per zone z along the slope. Values are for a single flood defence section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

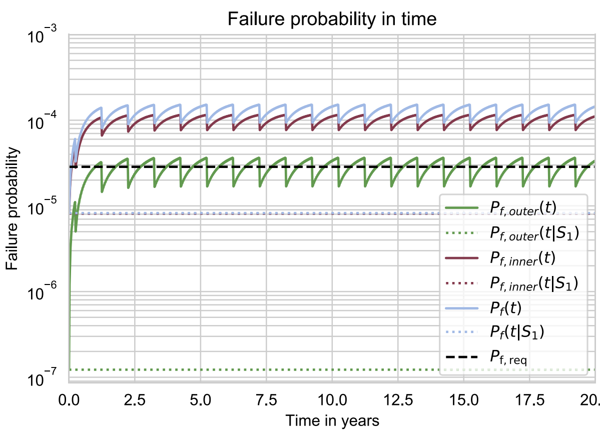


Fig. 9. Annual failure probability in time $P_f(t)$, for inner and outer slope and overall. Dotted coloured lines indicate the failure probability without damage $P_f(t|S_1)$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Annual cost of inspection, maintenance and flood risk. Flood risk costs are split into the base risk (without damage) and the risk increase due to damage.

Cost component	€/yr
Maintenance	13 385
Inspection	18 000
Base risk	28 848
Risk increase	4.74e5
C_{annual}	5.34e5

the expenditure on inspection and maintenance for the considered case. This indicates that the current maintenance concept is insufficient for this flood defence segment. In this section we evaluate several interventions that could improve the overall performance, which we evaluate through total cost and structural robustness to damage. We consider changes to the maintenance concept as well as investments in structural upgrades of the flood defence.

4.1. Approach

Structural robustness is typically defined as that 'the consequences of structural failure should not be disproportional to the effect causing the failure' [47], and is mostly used in the context of designing structures to prevent progressive collapse [48]. For structures with large potential consequences of failure, the Eurocode [47] specifically advises to include a risk-based analysis of the capability to withstand accidental loads caused by for instance explosions or human error. For flood defence systems, robustness can be particularly useful as a performance measure for estimating the relative contribution of accidental damage and human error by inspectors, and its consequences for system reliability. Baker et al. [49] proposed a quantitative indicator for structural robustness that relates direct and indirect risk due to a specific exposure causing damage (e.g. a terrorist attack). We use a similar approach here, but rather than looking at a specific exposure causing damage, we look at the contribution of all damages to flood risk. As such we formulate a robustness indicator I_R:

$$I_R = \frac{R_{\text{base}}}{R_{\text{base}} + \Delta R} \tag{10}$$

Where R_{base} is the flood risk without accounting for damage (so $R_{\text{base}} = P(F|S_1) \cdot D$, where D is the economic damage due to a flood in €) and ΔR the increase in annual flood risk due to damage to the flood defence (both in €/yr). The latter follows from the difference between $P(F|S_1)$ and $P_f(t)$ and is computed as $\Delta R(t) = (P_f(t) - P(F|S_1)) \cdot D$. Similar to the previous section we use the average $\Delta R(t)$ from year 10 onward. With this formulation, flood defence systems where damage has a large contribution to the overall flood risk will have a low value for I_R, and vice versa.

As Baker et al. [49] state, robustness might decrease if the (relative) direct consequences of a failure increase (in our context the failure probability of the pristine flood defence). Therefore we both look at the robustness indicator I_R and the costs in a multi-objective setting. It should be stressed that the relevance of solely looking at I_R is limited, as it is a relative indicator. As an indicator for cost we use Equivalent Annual Cost (EAC), using Eq. (8).

In our analysis we consider (combinations of) two types of measures: structural upgrades of the flood defence, and changes to the maintenance concept. Table 3 shows the different maintenance concepts considered. In a separate analysis it was evaluated whether changing the threshold S_c for repair (M_1) to a lower value would yield benefits — as this was not the case this is not included in the analysis

Table 3
Different inspection schedules evaluated as part of the analysis of different maintenance concepts. PoD and cost of inspection actions are listed in Table 1. All units are in weeks.

Policy name	I1		I2		I3		I4		M3	
	T_0	ΔT	T_0	ΔT	T_0	ΔT	T_0	ΔT	T_0	ΔT
Base	0	2	13	52					15	52
Autumn inspection	0	2	39	52					41	52
Base & autumn inspection	0	2	13	26					15	52
Base & burrowing inspection	0	2	13	52	45	52			15	52

Table 4
Considered interventions and their equivalent cost of investment (EAI).

	Intervention	EAI €/km/yr
Maintenance concepts	Base	900
	Autumn inspection	900
	Base & autumn inspection	1020
	Base & burrowing inspection	1020
Structural interventions	Increase of inner slope clay cover to 1 meter	12 067
	Decrease inner slope to 1:4.5	10 056
	Burrow-preventive measures at outer slope	4223
	Burrow-preventive measures at inner slope	4223
	Crest heightening 0.5 m	28 157
	Crest heightening 1.0 m	36 202

and the only difference between the different concepts considered is the inspection schedule. We also evaluate several (combinations of) structural upgrades for the different slopes. We consider 4 types of such interventions:

1. Burrow protection: construction of a protective layer (e.g. grid or geotextile) such that burrowing animals cannot penetrate the top layer. It is assumed that for this solution $P(F|S_4) = P(F|S_1)$. This is applicable at both inner and outer slope.
2. Increase clay layer thickness: reinforcement by increasing the clay layer thickness at the inner slope to 1 meter in order to increase the erosion resistance of the slope.
3. Reduction of inner slope angle: reinforcement by decreasing the inner slope from 1:3.5 to 1:4.5, such that overtopping waves have a lower flow velocity and cause less erosion. Additionally this slightly increases the allowed erosion volume for wave impact at the outer slope as the width of the flood defence is increased.
4. Crest heightening: increase of the crest height by 0.5 or 1 meter. Reduces the probability of overtopping and increases the allowed erosion volume for wave impact at the outer slope.

Table 4 shows the equivalent cost of investment for each considered intervention. Details on the computation of these values are given in the supplementary files. Fig. 10 shows the failure probability for the different structural upgrades considered. Note that burrow-preventive measures are not included in the figure, but can be combined with the displayed measures such that $P(F|S_4) = P(F|S_1)$. Worthwhile to note is that for instance a clay cover of 1 meter has a relatively large impact on $P(F|S_3)$ and $P(F|S_4)$ for inner slope erosion, while increasing the crest height impacts the failure probability for all states.

4.2. Comparison of interventions

Next we compare the effectiveness of (combinations of) different maintenance concepts and structural interventions. Fig. 11 shows the result of all considered combinations, where different maintenance concepts are distinguished by coloured dots. Axis represent the robustness indicator I_R and the EAC consisting of flood risk cost, and costs of structural upgrade and/or the maintenance concept as determined using Eq. (8). Stars indicate different maintenance concepts without any structural upgrade. The Pareto front is indicated by the black line and dots, for which the underlying structural upgrades are shown in the table. With regards to the maintenance concept it can be seen that especially an inspection in autumn can both increase robustness and reduce EAC: each Pareto optimal solution has a maintenance concept with condition inspections both in spring and autumn.

A structural intervention that greatly improves robustness is to increase the thickness of the clay cover at the inner slope. Installing additional protection against burrowing at either or both slopes can further increase robustness, albeit at the expense of a slightly higher EAC.

Increasing the crest level was also considered in the analysis: while this decreases the overall failure probability, the high costs of this intervention result in an increase in EAC and a decrease in I_R. In other cases this might be different for costs, but it is expected that a decrease in robustness will also be encountered in other cases due to the lower R_{base}. With the definition of structural robustness that we use here, a safer flood defence is thus not necessarily more robust.

5. Discussion & conclusions

5.1. Discussion

In this paper we considered the influence of damage on the failure probability of a flood defence segment subject to external erosion. The developed model can be used to estimate the effect of different interventions on the failure probability at a segment level: both structural upgrades and changes to the maintenance concept.

Based on the available inspection data for similar riverine flood defences, degradation was modelled as a random process using a progressive Markov process. This is different from previous studies [e.g.6, 16], but aligns well with both data and field experience. It should be noted that degradation rates for specific locations are difficult to obtain due to a lack of complete inspection datasets that span a considerable time range. Main reasons are the limitations of existing inspection techniques (i.e., not all damages are detected), and the fact that inspection records have not been recorded consistently over longer periods of time. From practical experience it is qualitatively known that certain types of damage occur in specific seasons (e.g., weeds in spring and summer). However, there is no data available to substantiate such seasonal patterns. As it was found to have limited influence on overall outcomes, degradation rates were assumed to be constant over the year. Provided that estimates are available, this can be accounted for using the presented method and might lead to further optimization of timing of inspections throughout the year, or focussing inspections in certain months at specific types of damage.

In our analysis we considered a flood defence segment consisting of 20 identical sections but the approach is also applicable for segments with sections of different lengths and properties. This is of relevance, as some types of damage might occur more frequently in specific locations: Klerk and Adhi [19], for instance, found that animal burrowing occurs more frequently in rural areas, and such areas might justify use of a transition matrix based on local rather than regional data (e.g., by determining the transition matrix based on sections with similar features). In such cases redefining the states to better distinguish the causes of damage (e.g., burrowing or drought) is recommended. A result might be that it is preferable to consider specific inspection

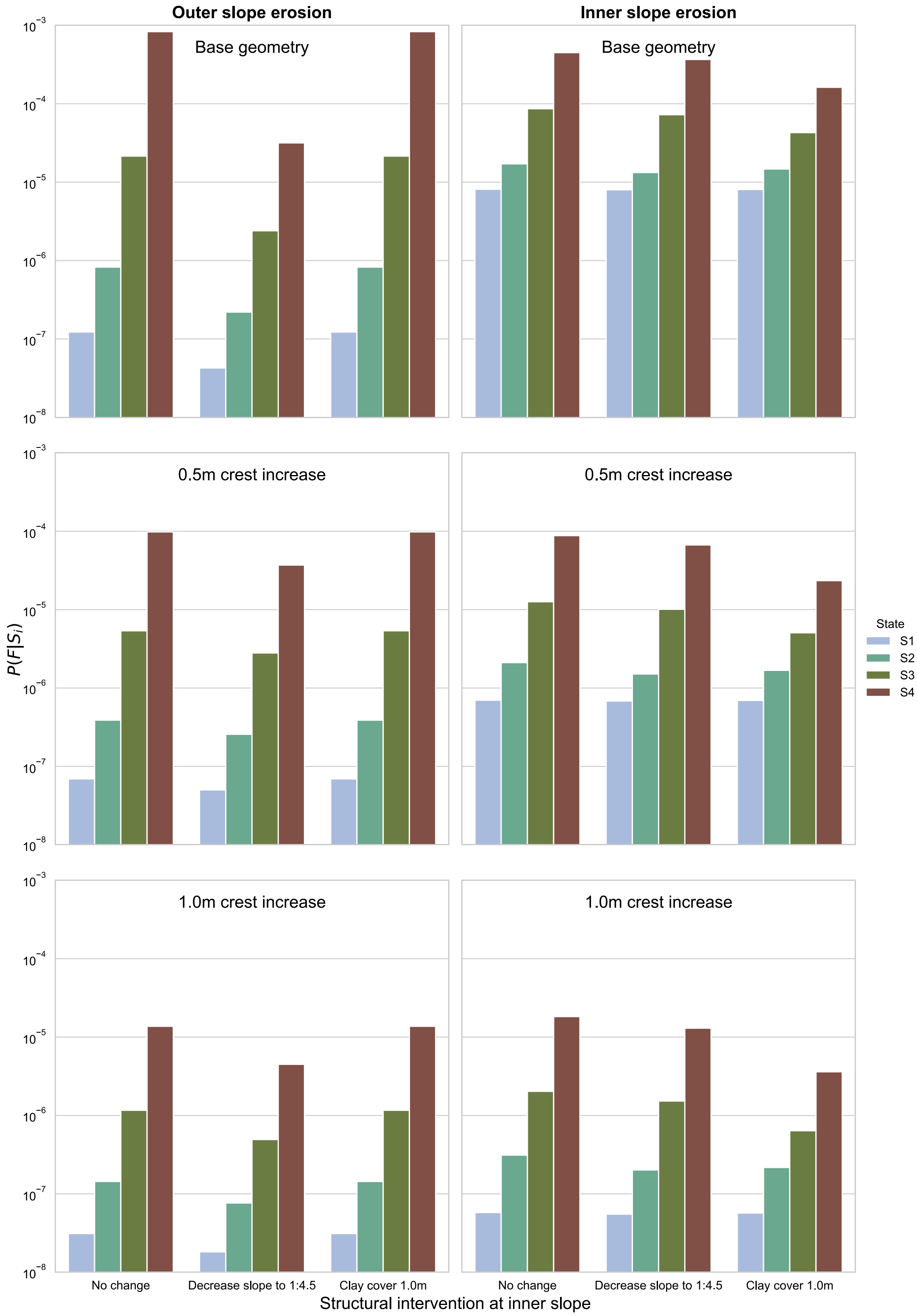


Fig. 10. $P(F|S_i)$ for different combinations of crest increase and changes to the inner slope for the different states.

policies for such sections [6]. It should also be considered whether dependence between the state of different zones and sections should be considered, something which could be modelled using a Markov random field. Given that such an approach would require high-quality data on (spatial distribution of) damage, this was not deemed feasible in this study.

While we only considered external erosion in this analysis, it is found from literature that also other failure modes can be affected by the types of damage considered here, most notably inner slope instability and internal erosion [e.g.18,39]. However, due to the large variation in effects of different (especially larger) burrows and the uncertainties in modelling for instance internal erosion [e.g.41] it was

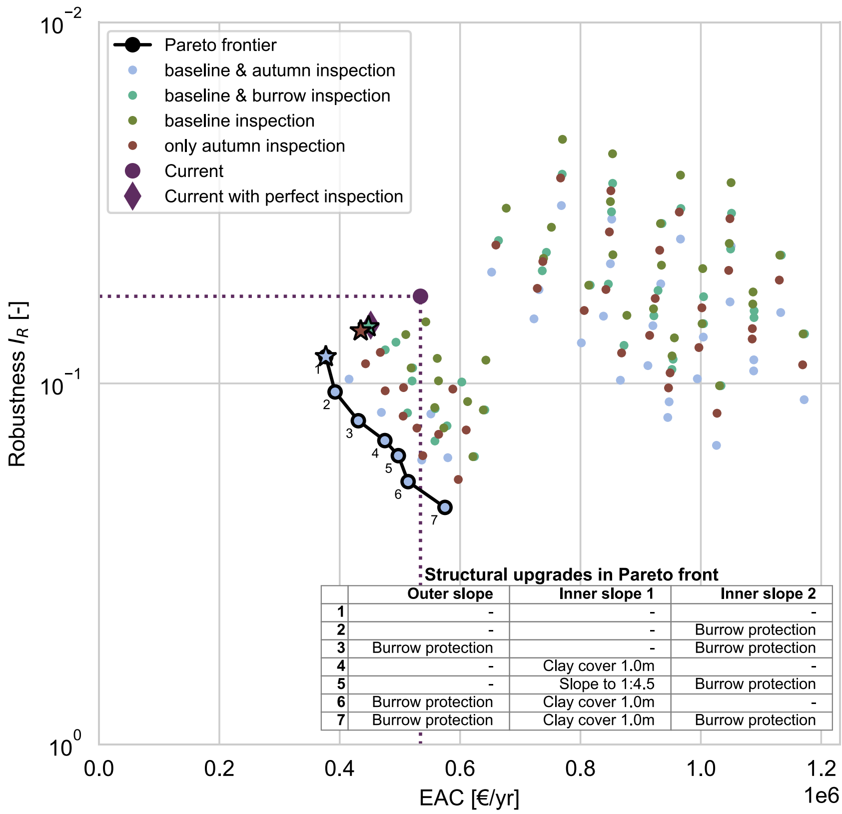


Fig. 11. Pareto front for robustness index I_R and Equivalent Annual Cost (EAC) (annual cost of flood risk, inspection, maintenance and structural interventions). Pink diamond and dot indicate current situation with/without perfect inspection. Colours indicate different maintenance concepts, with stars indicating combinations without any structural upgrades. Structural interventions of the Pareto optimal solutions (black line) are given in the table at the bottom left. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

decided to not consider these in this study, despite their practical relevance.

Based on the findings in Klerk et al. [9] we set the PoD of visual condition inspection to 0.6, but it should be noted that in practice the PoD can vary greatly for different situations, per inspection type, and also per inspector. The PoD of inspection by car and specific inspections for animal burrowing were based on expert estimates, but to better estimate the effectiveness of different types of inspections further investigations are required.

In the analysis of different interventions we combined both structural interventions and changes to the inspection policy. The influence on both the structural robustness and costs was assessed. To that end we formulated a robustness index that represents the contribution of flood defence damage to system flood risk. From this it was found that both inspections and several targeted structural interventions can lead to lower costs and higher robustness of flood defence segments compared to the baseline situation.

The use of structural robustness in this study differs from robustness indicators used for flood defences in the past. An example is the Dutch robustness allowance proposed in ENW [50], where the flood defence height was increased to make flood defences more robust to potential uncertainty in water level estimates. As all uncertainties in hydraulic loads are now explicitly taken into account this allowance is no longer used. Yet, robustness is often associated with increasing dimensions of a flood defence. The findings from this study with regards to increasing flood defence height show that this is not always correct, and that a broader interpretation of flood defence robustness may be required. It should be noted that relative robustness indicators as used here should always be considered jointly with an absolute indicator related to reliability (i.e., EAC or segment reliability) [49].

A limitation of this study is that it only considers regular inspections, but emergency inspections during high water situations are also an important part of flood defence asset management in general. In our analysis it is found that inspections in autumn are more effective than inspections in spring, as autumn inspections are closer to the high water season. This is even more so for emergency inspections as these are done right before or during a high water situation. As such, improvements of emergency inspections can likely significantly reduce costs and increase robustness of flood defence segments [33], and could be an important extension of the model.

5.2. Conclusions

In this study we presented a model that can account for the influence of degradation and Inspection & Maintenance (I&M) on the reliability of flood defence segments subject to external erosion. Based on a large dataset from inspections it was found that degradation of flood defences is mostly random in time. Using a Dynamic Bayesian Network, a riverine flood defence segment subject to relatively large waves was evaluated using a baseline inspection policy commonly applied in the Netherlands. From this it was found that without accounting for the influence of damage the segment is assessed to satisfy the requirements. However, when accounting for damage, the implemented I&M policy is insufficient to mitigate the consequences of damage to the revetment. For the case study, damage increases the failure probability by approximately a factor 20. On a more general level this means that flood defence designs that do not account for the occurrence of damage can lead to insufficiently safe flood defences.

Next, several changes to the maintenance concept, as well as structural upgrades were considered. Combinations of measures were evaluated based on structural robustness and Equivalent Annual Cost (EAC). It was found that especially increasing the clay cover layer thickness, and doing additional inspections in autumn are effective measures that both reduce EAC and increase structural robustness.

While the degradation rates of different flood defence segments can vary, the developed approach can both aid in assessing the impact of damage, and identifying efficient strategies for dealing with damage in flood defence segments. Potential extensions of the analysis are the inclusion of different sections with differentiated inspection policies and including emergency inspections in the model. A more fundamental improvement required for better assessment of the effectiveness of I&M is a better understanding of degradation patterns of flood defences. Focus could for instance be on the relation of degradation to structural properties and seasonal variation in degradation. Additionally a better understanding of the impact of damage on other failure modes such as inner slope instability and internal erosion is required to fully assess the impact of damage on flood defence system reliability.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Wouter Jan Klerk reports financial support was provided by Dutch Research Council. Vera van Bergeijk reports financial support was provided by Dutch Research Council. Wim Kanning reports financial support was provided by Dutch Research Council. Matthijs Kok reports financial support was provided by Dutch Research Council.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.strusafe.2023.102406.

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