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Risk based inspection of flood defence dams: an application to grass revetments

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ABSTRACT: In The Netherlands, inspection and maintenance are essential for maintaining stringent flood protection standards. Flood defences are assessed every 12 years to ensure they meet their risk-based safety standards, which are given as legally-binding maximum failure probabilities. Between assessments, flood defence managers are subject to risk-maintenance requirements: they must ensure that the failure probability of the defence does not increase in excess of its safety standard. However, there is no prescribed methodology to meet this requirement. In the study presented here, we developed a method which enables flood defence managers to derive inspection strategies using visual inspection data that will allow them to meet their risk-maintenance requirements. We applied the method to the assessment of grass revetments on the outer slope of the Oesterdam, one of the dams of the Dutch Delta Works. The application illustrates how – using visual inspection data, degradation information, and a failure mechanism model – inspection intervals can be derived that will ensure the risk-maintenance requirements are met.

1 INTRODUCTION

Flood defences in the Netherlands have to meet risk-based safety standards that have been derived using risk analysis for loss-of-life and economic damages (Kind 2014, Jonkman et al. 2018). In order to evaluate these standards, official assessment tools have been developed, consisting of deterministic and (semi-)probabilistic models for calculating the load on and strength of the flood defences (**?**). Flood defence managers are obliged to take all necessary actions to ensure that the flood defence meets its standard (Kok et al. 2017) at all times (called the 'duty-of-care'). In order to ensure this, maintenance and inspection must be related to the risk-based safety standards. Visual inspections on their own are insufficient.

For example, a well-maintained flood defence might still not meet its standard, if the standard is extremely stringent. Similarly, if the standard is relatively low, a poorly-maintained defence might still meet it. Despite this, the most frequently-used type of inspection is visual, based on a database of reference pictures of damages (e.g. holes in a revetment) called the Digigids (Het Waterschapshuis 2016). The classifications given in the Digigids (poor, fair, decent, good) are not related to the risk-based safety standards, making it impossible to ensure that the defence meets its standard. In this paper we present a method to connect visual inspections with the risk-based safety standards, allowing not only for clarity whether the defence meets its safety standard, but also allowing for determining risk-based inspection intervals to ensure the level of safety (i.e. the risk) remains acceptable. First the general methodology is

Figure 1: View of the Oesterdam (Source: Beeldbank Rijkswaterstaat (beeldbank.rws.nl).

presented, after which it is applied to a case study of grass revetments at the Oesterdam, one of the dams that are part of the Dutch Delta Works (see Figure 1).

2 METHODOLOGY

For a flood defence that is thoroughly assessed every 12 years, the philosophy is that via inspections and maintenance interventions we can ensure the defence is sufficiently safe in the years between assessments. In order to determine the required strategy for maintenance and inspection in those interim years, we need to take the following general steps:

1. Determine damage categories following from inspections;
2. Relate damage categories to the (risk-based) safety categories used in the official assessment;
3. Determine the rate and type of degradation for the specific type of damage;
4. Derive inspection strategies that ensure the risk remains acceptably low (i.e. safety standards are adhered to).

These points are further discussed in the following subsections. In the final subsection the model for erosion of grass revetments on the outer slope is described.

2.1 *Visual inspections of flood defences*

For the visual inspections in the Netherlands the Digigids provides a database of reference figures that aid inspectors in classifying (visually) observed damages to revetments, dunes and hydraulic structures. Figure 2 shows example pictures for damage to grass revetments due to small animal burrowing. This is 1 out of 17 different types of damage to a grass revetment that are included in the Digigids. Each of these damage types can be categorized as 'poor', 'fair', 'decent' or 'good'. For a full analysis of inspections all these damage categories would have to be taken into account integrally, but here we focus on burrowing by small animals.

2.2 *Safety standards & safety categories*

Flood defence safety standards are defined per reach in the Dutch network of flood defences, where a reach is a collection of several (statistically-homogeneous) flood defence segments, each of which is represented by a representative cross section for modeling failure. A formalized procedure has been developed (for the legal safety assessment) that enables classification of the safety in 6 safety categories (A through F) both for cross sections and for the reach as a whole. Table 1 gives the 6 categories for grass erosion at the cross section scale. It is important to note that the safety standard for each reach is expressed in two terms: the maximum allowable failure probability (P_{max}), and a lower 'signal' probability (P_{sig}). The latter can be interpreted as a warning sign that large-scale maintenance or reinforcement might be necessary in the foreseeable future. Another important point is that for categories I through III, upper bounds are defined per mechanism at the spatial scale of a cross section. For categories IV through VI these are defined at the spatial scale of a reach. Therefore there is a considerable gap between the bounds of categories III and IV.

Table 1: Upper bounds of the annual failure probabilities ($P_{f,UB}$) corresponding to the safety categories used in the Dutch safety assessments. Presented are both the general expressions and specific values for the Oesterdam case of grass erosion on the outer slope.

Category	$\mathbf{P_{f,UB}}$ *(General)*	$\mathbf{P_{f,UB}}$ *(Oesterdam Case)*
I	$\frac{1}{30}P_{sig,cs}$	2.8e-8
II	$P_{sig,cs}$	8.3e-7
III	$P_{max,cs}$	2.5e-6
IV	P_{max}	1.0e-4
V	$30P_{max}$	3.0e-3
VI	n.a.	n.a.

The safety standards include all possible failure mechanisms. For considering a single failure mechanism, it is necessary to adjust the standard. The safety standard (maximum failure probability) is divided among the many different mechanisms using a failure probability budget (i.e. a distribution of the allowed failure probability over the different mechanisms). This ensures that the total failure probability meets the safety standard and enables assessing for separate mechanisms. For assessing failure mechanisms at the cross sectional scale it is necessary to translate the safety standard to a cross sectional requirement. The safety standard at the reach scale can be translated to the cross sectional scale by accounting for the *length effect* (the increase of failure probability for longer reaches, due to spatial variability (see e.g. Kanning (2012)). Eq. 1 describes the calculation of the safety standard for a single mechanism at the

(a) Poor

(b) Fair

(c) Decent

(d) Good

Figure 2: Examples of reference pictures for different degradation categories for ‘small animal burrowing’ (e.g. mice and moles). Panes indicate different inspection results. Images retrieved from Het Waterschapshuis (2016).

scale of a cross section (P_{cs}):

$$P_{cs} = \frac{\omega * P}{N} \tag{1}$$

In this equation ω is the percentage of the safety standard (P) that is budgeted for the mechanism and N is a length effect factor to account for spatial variability along the reach. Values of ω and N have been derived for all mechanisms and reaches, as part of the national safety assessment guidance. For the Oesterdam these are $\omega = 0.05$ and $N = 2$ for failure of the grass revetment on the outer slope.

2.3 *Relation between damage and safety level*

Inspection results can be translated to safety level estimates. In the absence of failure mechanism models, expert judgement can be used, but in this case we use a grass erosion model from the official Dutch assessment tools (with Dutch acronym WBI-2017). When working with a model, a damage category from visual inspection(e.g. ‘good’) will have to be translated to model input, after which it is possible to assess the safety level of the defence conditional on the damage category.

2.4 *Degradation of flood defences*

The failure probability of a flood defence depends on the strength of the defence and the hydraulic loads upon the defence. Besides the hydraulic loads several other processes can cause damage to the flood defence. For example, soil subsidence has an impact on the dike height, storm surges cause dune erosion and damage to revetments, and soil erosion, wear and corrosion have an adverse effect on the strength of hydraulic structures (see e.g. Buijs et al. (2009) and Speijker et al. (2000)). Without any maintenance the strength of a flood defence decreases over time. The following two types of degradation are distinguished here:

- Gradual degradation due to time-dependent stochastic processes. Often, this type of degradation is induced by natural phenomena, e.g. soil erosion. Many of the damages (see subsection 2.6.2) related to grass revetments fall into this type, e.g. burrowing animals, growing weed and rut formation.
- Randomly occurring shocks that cumulatively damage and weaken the flood defence. For instance dune erosion (and accretion) can accumulate over periods of years as a consequence of se-

quential storms. With respect to grass revetments damage accumulates during a single storm surge (see subsection 2.6.1), but in general this occurs only in very extreme situations and is therefore seldom relevant in day-to-day inspections.

Most degradation types for grass revetments can be considered gradual. Although the failure mechanism itself is cumulative (i.e. damage accumulates during a storm) this is not relevant for day-to-day maintenance. The reason is that transitions to grass revetments are generally very high up the slope, therefore the probability that damage accumulates over sequential storms is very small (i.e. the probability of two damaging storms during a winter is very small). Therefore this cumulative damage due to random shocks is irrelevant for day-to-day maintenance. In subsection 2.6.2 the degradation model for small animal burrowing is introduced.

2.5 *Deriving inspection schemes*

Inspections of flood defences are done for several reasons such as monitoring damage after (major) storms, finding or monitoring weak spots, collecting information to better understand certain random processes and planning or substantiating maintenance decisions. The general underlying objective is to minimize the sum of inspection costs, maintenance costs and flood risk (in terms of flood damage and casualties). For example, in Van Noortwijk and Klatter (1999) the aim is to determine the inspection frequency for which the expected maintenance costs are minimal and the Eastern Scheldt storm surge barrier is safe. This leads to a periodic risk-based inspection scheme.

In the context of grass revetments (see 2.6.2) a periodic inspection (and maintenance) scheme seems obvious. Inspections after storms are useful only for some damage types (such as local grass erosion due to waves and currents), but most types do not depend on the hydraulic loads on the grass revetments. Condition-based inspections might be economically attractive in some situations. In practice, however, periodic inspections are often preferred over non-periodic condition-based inspections, since the necessary manpower and budget can be anticipated and scheduled well beforehand (Van Noortwijk and Klatter 1999).

The risk-based inspection model for grass revetments is specified in subsection 2.6.3.

2.6 *Degrading grass revetments*

2.6.1 *Modeling erosion of grass revetments on the outer slope*

Grass revetments are a preferred revetment type for areas that are not or rarely exposed to wave attack. For the erosion of revetments usually two main mechanisms are considered: erosion of the crest and inner slope due to either wave overtopping or overflow, and erosion of the grass revetment on the outer slope due to wave run-up or direct impact of waves. In this paper we focus on erosion of the outer slope due to wave run-up. Figure 3 shows the general behavior of the mechanism as it is considered in the safety assessment tools in the Netherlands. An important aspect of the model is that it is cumulative, meaning that damage accumulates during a storm. This is modeled using the following equation and limit state function:

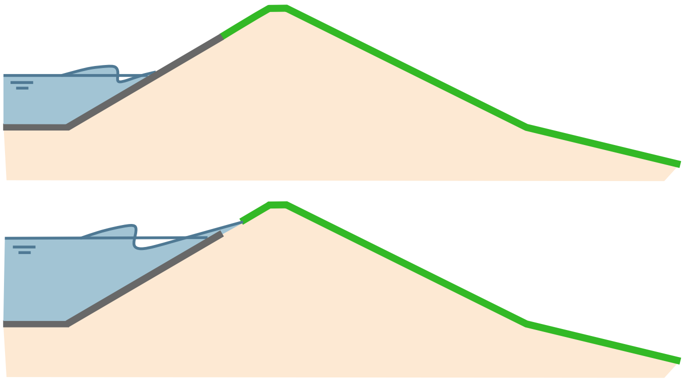

Figure 3: Schematic representation of erosion due to run-up. On the top the initial situation at the beginning of a storm is shown. The bottom pane shows the erosion of the grass revetment (green) due to wave run-up. This erosion initiates at the transition from block/asphalt revetment (in grey) to grass.

$$D(z) = \sum_{i=1}^{N} max(U_i(z)^2 - U_c^2; 0) \tag{2}$$

$$Z = D_{crit} - max(D(z)) \tag{3}$$

where N is the total number of waves in a storm, z is the evaluation point along the outer slope (m + reference level), $U_i(z)$ is the run-up velocity of an individual wave i at the evaluation point z, and U_c is the critical run-up velocity, above which damage occurs (both in m/s). $D(z)$ is total accumulated damage at z and D_{crit} is the critical damage at which failure occurs (both in m^2/s^2).

The run-up velocity (U_i) of an individual wave decreases for evaluation points higher up the outer slope. Therefore the most critical point is typically the point of transition between a hard (block or asphalt) revetment at the lower part of the slope and the grass revetment, as this is the point attacked by the highest number of waves at the highest velocity. In the safety assessments, it is therefore sufficient to only consider the transition point. For inspections it can be useful to also consider points higher up the slope in order to determine at which elevation (if any) the waves no longer pose any threat, regardless of the grass quality. This can help focus the inspections to the most relevant areas.

2.6.2 *Model for degradation of grass*

For grass revetments many different types of damage can occur. Examples are growing weeds or accumulating rut or leaves that might asphyxiate the grass underneath, thus worsening the quality of the sod. Other examples are damage due to traffic (see e.g. Buijs et al. (2009)) causing damage in the grass cover or animal burrowing causing local gaps in the grass and clay cover. The latter is a notorious failure mechanism that many water authorities struggle with. In this case study we consider small animal burrowing, where the grass revetment is damaged by mice and moles.

The damage process of animal burrowing is random by nature. Currently no count data are available and we assume that the number of animal holes follows a homogeneous Poisson process with rate λ. The probability of n animal holes at time t is thus given by

$$P(N(t) = n) = \exp(-\lambda t)\frac{(\lambda t)^n}{n!} \tag{4}$$

Seasonality or other time-dependent behaviour can easily be included in the model by using a non-homogeneous Poisson process but is not considered here.

In order to translate the animal burrowing to the grass sod quality the number of animal holes and the grass sod categories need to be related. The relations are given in Table 2. The score from a visual inspection is related to the number of animal holes that are present. The score is then related to the grass quality which provides a U_c that can be used to calculate the failure probability given a number of animal holes.

Figure 4 illustrates a possible realization of the grass revetment degradation in time. Starting with a closed grass sod the quality gradually decreases to fragmented sod (black star). The grass quality is observed by visual inspection only (yellow dot). The inspection interval is too large as a fragmented sod is unacceptable.

2.6.3 *Inspection model*

The objective is to find an inspection frequency such that the safety level of the flood defence does not exceed the required safety standard with respect to grass erosion. Assuming that a fragmented sod is not acceptable, in the context of Figure 4 this means that it should be guaranteed that the inspections are frequent enough to prevent degradation to a fragmented sod. To achieve that the duration of a period without an observation may not be too long. The probability of failure (grass erosion) depends on the quality of the grass, which in turn depends on the number of animal holes. By conditioning on the random quality of the grass and the number of animal holes the failure probability at any time t can be calculated as follows.

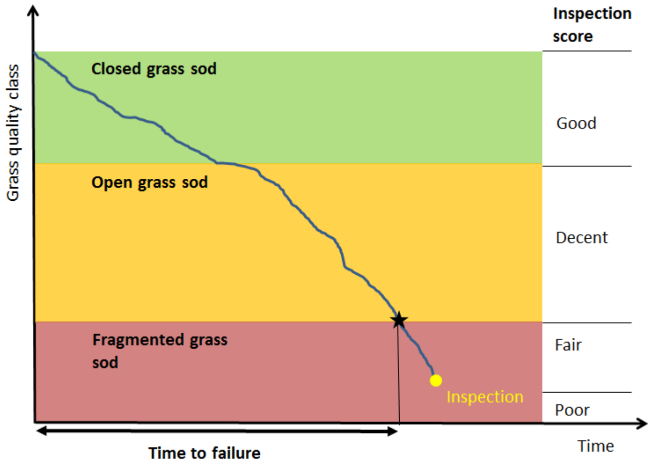

Figure 4: Example of grass degradation and link to inspection scores (from Digigids).

Table 2: Coupling of the visual inspection with the critical run-up velocity U_c

Digigids score	Number of animal holes	Grass quality	U_c [m/s]
Poor	> 16	Fragmented sod	n.a.
Fair	6-15	Fragmented sod	n.a.
Decent	1-5	Open sod	4.3
Good	0	Closed sod	6.6

$$\begin{aligned} P_f(t) \quad = \quad & P_f(Q = \text{closed}) \cdot P(N(t) = 0) + \\ & P_f(Q = \text{open}) \cdot P(N(t) \in [1, 5]) + \\ & P_f(Q = \text{fragm}) \cdot P(N(t) \geq 6) \end{aligned} \tag{5}$$

In this equation $P_f(t)$ is the failure probability of due to wave run-up at time t, Q is the grass quality, $P_f(Q = \ldots)$ is the conditional probability of grass erosion given a specific grass quality, and $N(t)$ is the number of animal holes at time t. Upper bounds of the failure probabilities ($P_f(Q = \ldots)$ for the categories closed, open and fragmented sod follow from calculations with the failure model introduced in subsection 2.6.1.

3 CASE STUDY

We applied the methodology described in Section 2 to the Oesterdam, the longest dam of the Dutch Delta Works, spanning 10.5 km. The dam is located in Zeeland, in the Eastern Scheldt Estuary in the southwest of the Netherlands. For our study, we focused on the physical data (foreshore, slope, etc) relating to one specific location along the dam. For a full implementation of the method, all relevant physical attributes present along the length of the dam would need to be analyzed.

3.1 *Model input*

3.1.1 *Loads*

The load on the dam that is relevant for grass erosion on the outer slope is the wave run-up velocity. This is determined based on: the time series of water levels during a storm, the significant wave height, and the mean wave period. The time series of water levels during a storm is generated using the peak water level, and by making some assumptions about how

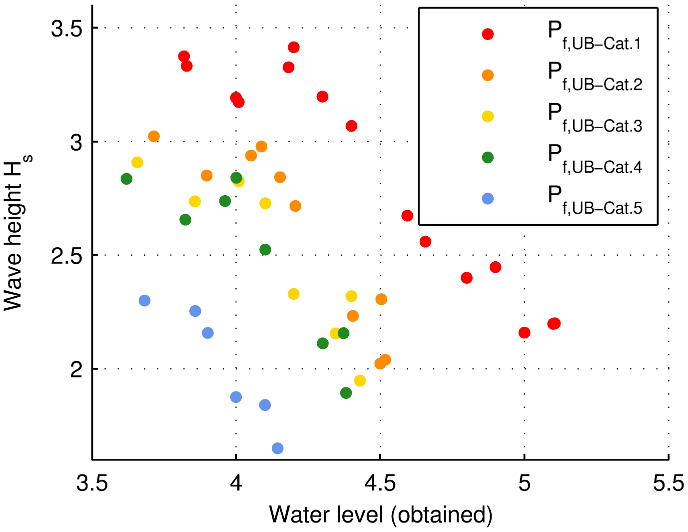

Figure 5: Wave height-water level combinations that lead to the exceedance probabilities of the five safety categories.

the water levels develop throughout a representative storm. We assume that the angle of incoming waves is perpendicular to the revetment. Thus, we need three parameters to characterize a storm:

1. peak water level (h)
2. significant wave height(H_s)
3. peak wave period (T_p)

There are numerous combinations of water level h, significant wave height H_s and peak wave period T_p that lead to the same exceedance probability. By choosing a variety of input water levels, we were able to generate multiple sets of these combinations using of the WBI-2017 module for computing loads for revetments. Figure 5 shows the resulting wave height – water level combinations for the Oesterdam. Figure 5 shows different sets of load combinations for which the exceedance probability equals the upper bound failure probability of the different safety category. Because we do not know which combination will cause the most run-up damage, we analyze all the combinations within a category, and determine the maximum cumulative grass damage over all combinations. As a hydrograph of the storm we assume a standard storm with a base of 35 hours as used in the WBI-2017.

As the range of interesting water levels is very high, here we assume that the Eastern Scheldt Barrier is open: the only way to experience water levels this high at the Oesterdam is if the barrier is open (i.e. it fails to close). In principle, the barrier should never allow water levels higher than 4 m + NAP at the toe of the Oesterdam. However, as the exceedance probabilities are so low, we are in the realm of the probability space that can only be achieved in the unlikely event that the barrier fails.

3.1.2 *Oesterdam profiles*

In addition to the loads, the grass run-up model requires information on the dam profile. We used profiles that were available from Rijkswaterstaat (RWS), the governmental organization responsible for the Oesterdam. This profile could not be directly imported into the grass run-up model; we needed to slightly modify it to meet the model requirements (on minimum slope). Figure 6 shows the original and modified (input) profiles. Also shown is a third profile (shown in red), modified so that the toe of the levee is a bit lower. This turns out to have a noticeable impact on the run-up velocity. We chose to analyze both profiles as a sensitivity analysis. We chose a lower limit of -1.4 m + NAP for the toe because none of the cross sections provided by RWS had a toe lower than this level.

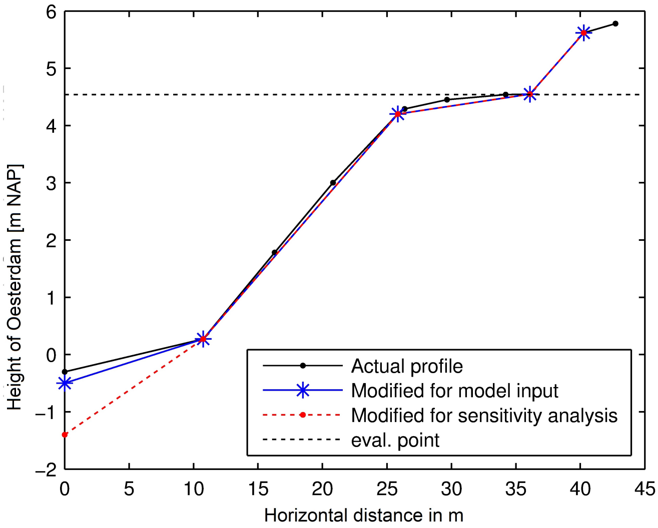

Figure 6: Actual profile of Oesterdam cross section, modified profile for input into the grass run-up model, and a modified profile with a lowered toe to test the sensitivity of the results.

3.1.3 *Foreshore*

In the module for loads on revetments described above, it is required to provide information about any foreshore, if present. This is the case for the Oesterdam, and the foreshore was estimated based on data provided by RWS. There were several options to choose from, depending on the selected location. We chose to analyze one that was not particularly shallow, so that it would be a more conservative choice.

3.1.4 *Evaluation point*

One of the inputs to the grass run-up model is the evaluation point. This is the location along the slope of the levee at which the cumulative damage will be calculated. We chose the transition point, where the block revetment stops and the grass revetment begins. This is a notoriously weak spot, but is also the point with the highest run-up velocities, as it is lowest down on the slope. One of the questions that we want to address in this study is: at what point along the slope is damage to the grass no longer relevant? To answer this question, we also iteratively increased the evaluation point towards the crest level.

3.1.5 *Rate of degradation*

In section 2.6.2 it was already indicated that no long term data regarding observed damages are available, hence a Poisson process with constant failure rate was assumed. In order to show the sensitivity of the derived inspection intervals, different failure rates (i.e. 1, 2 and 4 animal holes per year) were considered.

4 RESULTS & DISCUSSION

Tables 3 and 4 show the maximum grass damages (m^2/s^2) for the two profiles presented in Figure 6. In both cases, the results are fairly binary. We see that for the first profile, both open and closed sod result in maximum damages less than the critical 7000 m^2/s^2, which means the dam survives, even under the stringent failure probability for safety category I. By contrast, fragmented grass leads to an exceedance in the critical grass damage even for the lowest safety category V.

Table 3: Maximum damage (m^2/s^2) per safety category, for profile 1. Red cells indicate the damage is greater than the critical damage (7000 m^2/s^2); green cells indicate the damage is less than the critical damage.

Safety cat.	Closed sod	Open sod	Fragmented
I	11	4456	37828
II	5	3625	40413
III	4	3367	33826
IV	3	3179	34523
V	1	2218	22293

For profile 2, we see that an open sod cannot withstand the loads associated with safety category I. This indicates that if the dam starts with a closed sod quality, then a degradation to open sod will result in a drop from category I to category II. The same results hold for fragmented grass as for profile 1.

Table 4: Maximum damage (m^2/s^2) per safety category, for profile 2. Red cells indicate the damage is greater than the critical damage (7000 m^2/s^2); green cells indicate the damage is less than the critical damage.

Safety cat.	Closed sod	Open sod	Fragmented
I	59	7320	45032
II	36	5947	44649
III	30	5516	36784
IV	26	5200	37481
V	9	3418	24111

For both profiles, we investigated if there was a point along the outer slope where fragmented grass no longer had an impact on the safety category (i.e. the waves would never make it that high), but there was no such point. Therefore, fragmented grass must be avoided over the entire outer slope, as it drops the safety to a level where it does not even adhere to the lowest category.

In order to derive the minimal inspection frequencies we calculated the failure probability of grass erosion in course of time for both profiles using a rate of 2 burrowed holes per year. The resulting probabilities are shown in Figure 7. The only difference is due to the different categorization for safety category I. The time until failure is the same for both profiles. This means that for both sections the same inspection interval can be used. In this case the maximum length of the interval is 14 months. The probability that the grass sod quality is ‘fragmented’ is relatively small after 14 months but the failure probability given a fragmented sod is comparatively large.

As the rate of burrowing is highly uncertain a sensitivity analysis was carried out to determine the influence of the rate on the derived interval. Figure 8 shows the results for this case. It is observed that different rates result in significantly different inspection intervals that seem to increase proportionally to the rate. The maximum length of the interval is 14 months for a rate of 1 hole per year, 7 months for a rate of 2 holes per year and 4 months for a rate of 4 holes per year. This shows the importance of the rate and whether the degradation rate has temporal variations throughout the year (e.g. higher rate in spring). The latter would also mean that the inspections have to be condensed around a certain period in the year.

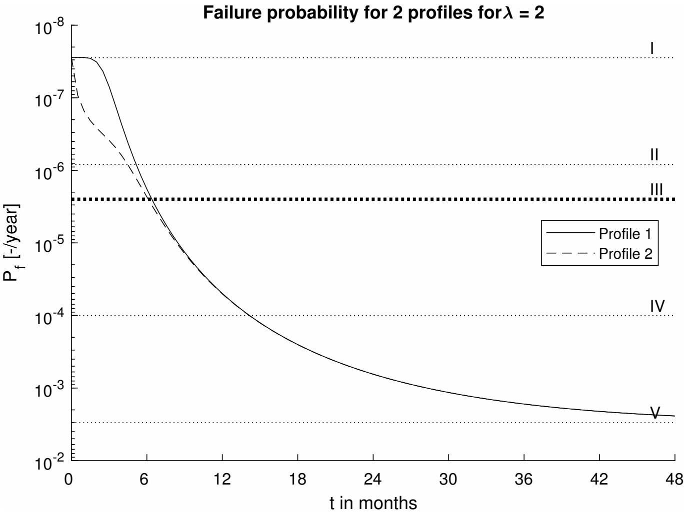

Figure 7: Failure probability in time for an average rate of 2 burrowed holes per year.

The case study focused on damage to grass revetments due to small animal burrowing. It has to be noted that in the actual inspection many other damage types and mechanisms have to be considered as well, which will have consequences for the inspection intervals. It might be the case that other damage types dictate the inspection frequency. For animal burrowing the lack of knowledge on the degradation rate is the largest unknown for deriving inspection frequencies that ensure sufficient safety. Without a properly underpinned rate it is not possible to efficiently derive a risk-based inspection strategy as the uncertainty on the rate will determine the strategy. Therefore the asset manager can best start with a conservative inspection strategy and in the meantime gather data on occurred damage and past inspections. Based on the observed rates and the corresponding risk he or she

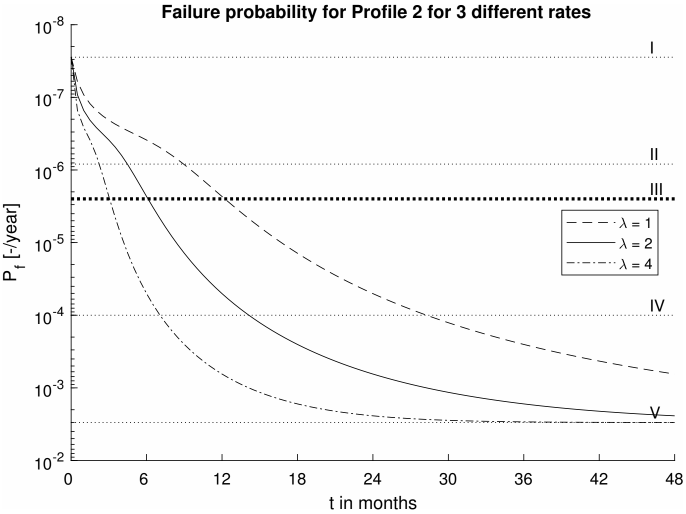

Figure 8: Failure probability in time for profile 2, for rates of 1, 2 and 4 burrowed holes per year.

can revise the inspection/maintenance strategy.

This approach will lead to a tailored risk-based inspection approach, where spatial variability along the reach can also be included in inspection strategies (e.g. more frequent inspections on areas with a history of burrowing), but also temporal patterns (e.g. more frequent burrowing in spring) can be taken into account. It has to be noted that this is currently often done implicitly (i.e. in the inspector's mind). However, as many inspections are outsourced by water authorities this knowledge is easily lost. In order to meet the official requirements with respect to the 'duty-of-care' (i.e. continuously being able to show the flood defence is up to standard), a more explicit consideration would be required. The illustrated approach is a concrete example of how this can be done.

5 CONCLUSIONS & RECOMMENDATIONS

In this study we presented a method for deriving inspection strategies for flood defences using different available building blocks (i.e. inspection tools (Digigids) and assessment tools (WBI-2017)). In general this works quite well: the method relates visual inspection scores to the statutory assessment of flood defences and yields a risk-based inspection scheme for grass revetments.

The method has been applied to a case for one type of damage to grass revetments. In this case inspection strategies have been derived successfully, but these were found to be rather sensitive to the rate of degradation. In general, information on degradation rates is not available and it is necessary to obtain this in order to efficiently derive risk-based inspection strategies. Therefore it is proposed to start with a conservative strategy and gather data on degradation to gradually improve the risk-based inspection strategy. In principle it is also necessary to consider the costs of inspection, but as these are very low compared to the flood risk these have not been considered. Adding other types of degradation (i.e. damage types) of grass revetments would be valuable for the asset manager, as the effect of combining inspections for different types of damage/degradation can then be taken into account.

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