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Influence of Monitoring on Investment Planning of Flood Defence Systems

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Abstract: Many flood defences in the Netherlands will have to be reinforced in the coming decades. Many dikes do not fulfill the safety standard due to geotechnical failure modes, largely due to epistemic, reducible uncertainties. . The Value of Information is a measure to indicate beforehand whether an investment towards reducing epistemic uncertainty is economically attractive. This paper investigates how reduction of the epistemic uncertainty in aquifer permeability might influence the Total Cost of a dike reinforcement, and the choice of reinforcement method. From the case study it is shown that the Value of Information from measurements strongly depends on firstly, whether the overall prioritization of investment for a larger dike segment is influenced, and secondly, whether the local reinforcement decision is sensitive to the parameter for which uncertainty is reduced.

Keywords: Value of Information; flood defence; dike reinforcement; investment planning.

1 Introduction

In the Netherlands, major flood defence (e.g., dikes) renovations are ongoing and are scheduled for the future, as many dikes do not comply with the legal safety requirements. These requirements are defined as acceptable target probabilities of failure for a dike segment (typically 5-25 km long); this segment typically consists of multiple dike sections of about 500 – 1500 m. This is translated into a set of probabilistic and semi-probabilistic methods for the relevant failure modes to comply with per dike section. The general goal is for all segments to comply with the safety standards by 2050. However, there are restrictions on available annual budgets and construction capacity is limited. A prioritization of investments is needed in order to reduce dike segment failure probabilities in an efficient way. Hence, in this paper we are looking when (when in time), where (which dike section), what (which measure) and how much to invest in order to comply with the safety standards in 2050. The investments are optimized in such a way that the Total Cost (combination of investment cost and risk, using discounting in time) are minimized. Typically in the Netherlands, the assessment of flood defence reliability is based on a relatively rough analysis based on limited data. Measures to increase the assessed reliability of a flood defence thus not only consist of structural measures/reinforcements, but can also be aimed at reducing epistemic uncertainties by monitoring (Klerk et al. 2015).

The goal of this paper is to determine optimal investment decisions for a dike segment, and specifically under which conditions monitoring will improve the investment decision. We look at head monitoring for the failure mode piping. As a case we look at a dike segment where sections are assessed for the failure modes overtopping, piping and slope instability.

2 Method

2.1 Computation of dike segment reliability over time

Investments in flood defences typically have lifetimes of several decades to 100 years, depending on the type of reinforcement. In this paper, the life-cycle reliability (Biondini and Frangopol 2016) over a course of 50 years is considered, including deterioration due to settlement and increasing loads due to climate change. Three failure modes are considered: overflow/overtopping, inner slope instability and piping erosion, but this could easily be extended or changed to include different failure modes.

For overflow/overtopping, failure probabilities are computed for various levels of the crest, using the Dutch safety assessment software Hydra-Ring (Slomp et al. 2016). The underlying models are described in van Balen (2017). For inner slope instability, data is available from the statutory safety assessment, for the years 2025 and 2075. Thus the reliability over time is computed by linearly interpolating between the factors of safety in those years, such that a factor of safety for each year is obtained. The factor of safety can be translated to an estimated reliability index β ($=\Phi^{-1}(P_f)$), where P_f is the annual failure probability of a cross section using:

$$\beta = \frac{FS/\,m - 0.41}{0.15}, \tag{1}$$

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where *FS* is the factor of safety, and *m* is the model factor for the applied LiftVan stability model. This relation was obtained from a code calibration for the Dutch safety assessment (Jongejan 2017). For piping we use the Sellmeijer rule as described by Sellmeijer et al. (2011) and a comparable relation between FS and reliability as Eq. (1). This is combined with separate limit states for heave and uplift (see Jongejan 2017). Of particular importance here is the derivation of the hydraulic head in the conductive sand layer for the piping mode. We determine this using the standard Dutch flood defence safety assessment guidelines. These standard guidelines are typically conservative in case limited data is available, hence the potential of head monitoring is large.

In general it is important to note that both for inner slope instability and piping semi-probabilistic assessments are used. As semi-probabilistic assessments are conservative compared to probabilistic assessments a worthwhile first step in an actual case would be to use probabilistic rather than semi-probabilistic assessments. However the aim of the paper is merely to illustrate the relevance of reducing uncertainty towards reinforcement decisions, and this can be done both with semi-probabilistic and probabilistic assessments as a basis.

As all safety assessments are at the level of a cross section (cs), they have to be scaled first to dike section (≈1 km) and then to the segment level (≈5-25 km) to determine the actual flood risk and properly account for spatial variability. As a riverine area is considered, for overflow/overtopping there is hardly any spatial variability along the segment, so $P_{f,segment,over} = \min(P_{f,cs,over})$ is used to translate cross sectional failure probability assessments to an assessment on a segment scale. To compute the segment failure probability for inner slope instability and piping, spatial variability has to be taken into account. First it is upscaled from cross section to section, and next from section to segment for all sections *i* using:

$$P_{\text{f,segment}} = \sum_i P_{\text{f,section}} = \sum_i P_{\text{f,cs}} * \frac{L_i}{\Delta L}, \qquad (2)$$

where the subscripts “cs”, “section”, and “segment” denote the scale to which the failure probability P_f applies; ΔL is the length of a statistically equivalent independent section, for inner slope instability a default value 50 meters is used, for piping 300 meters (Jongejan 2017); L_i is the section length of section *i*.

2.2 Flood defence investment planning

In a risk-based approach, the required reliability of flood defence segments can be based on several risk indicators. While in the Netherlands, several indicators are used, in this paper only economic value is used. In Jongejan and Maaskant (2013) it has been shown that this gives a sensible prioritization, also for other risk indicators such as loss of life.

The economic value can be expressed by the Total Cost (*TC*), which consists of the investment costs and risk costs over a certain time horizon:

$$TC = \sum_i P_{\text{f,reach}} * \frac{D}{(1+r)^i} + \frac{C}{(1+r)^i} = LCR + LCC, \qquad (3)$$

where *D* is the damage in case of a flood; $P_{\text{f,segment}}$ is the failure probability of a dike segment; *C* are the investment costs; *r* is the discount rate, for which *r*=3% is prescribed for government investments in the Netherlands. Summed over years *i,* this yields the Total Cost that can be split in a risk (LCR) and cost (LCC) component. Highest economic value is found where the Total Cost is minimal.

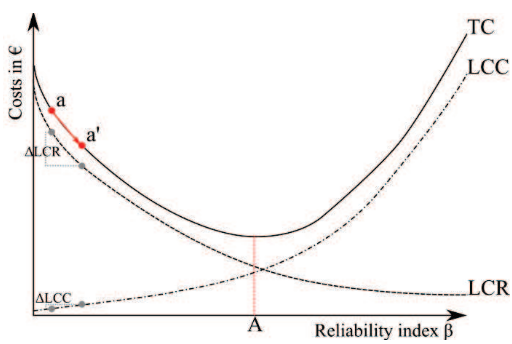

Figure 1. Relation of the Total Cost (TC) and β. I are the total (discounted) investment costs, R is the total risk.

From a practical perspective it is rarely possible to improve all segments at the same time to obtain the optimal level, for instance due to budget and capacity constraints, so measures have to be prioritized. This is illustrated in

Figure **1** for a single section. Starting at point *a* the most efficient investment of a limited amount of money is that with the largest slope which is governed by the benefit-cost ratio (i.e., *BC=ΔLCR/LCC*). Hence we invest until the point a' is reached, for the measure with the largest BC. If a case with multiple of such sections is considered, an optimal order of investments can be achieved by ensuring that each time BC is maximal and larger than 1, and higher than for other alternative investments. Internationally various stopping criteria are used. For instance in the United Kingdom a benefit-cost ratio of 5 for investments in flood protection with small failure probabilities (Penning-Rowsell et al. 2014). In the Netherlands the stopping criterion would be when the statutory safety standard is reached.

2.3 Assessing the influence of monitoring on investment planning

Given a certain initial situation and a set of available measures it is possible to derive an optimal prioritization of interventions. However, many of the assumptions in the initial situation are uncertain, and changes might result in different prioritization sequences or different optimal measures for sections. For instance, the reduction of the uncertainty in some parameter might have as result that sufficient safety can be obtained with a cheaper alternative.

A common measure to assess whether it is sensible to reduce the uncertainty of a certain input parameter is the Value of Information (*VoI*) (Raiffa and Schlaifer 1961), which can be calculated using:

$$VoI = TC_0 - TC_{\mathrm{I}}, \tag{4}$$

where TC_0 and TC_{I} are the total costs for the initial situation and the situation where information has been obtained. TC_{I} can be obtained by for instance a pre-posterior analysis of the decisions taken given the a priori estimate of possible outcomes. The VoI can also be considered conditional upon a certain observed parameter, rather than an integrated prior distribution. The conditional Value of Information (*cVoI*) given that the observed value for parameter θ is x can be computed by:

$$cVoI(\theta = x) = TC_0 - TC(\theta = x). \tag{5}$$

3 Case Study

3.1 Current safety

We consider a case study that consists of 5 dike sections located along the river Lek, the Netherlands. These sections are part of a larger reinforcement project of which the input data originates. The reinforcement will be carried out in 2025, and it is assumed that up until then there is the opportunity to execute a head monitoring campaign to reduce the uncertainty in aquifer permeability for the piping assessment. Table 1 shows the most important input parameters for the safety assessment piping and inner slope instability. All input values are representative values in accordance with the semi-probabilistic safety format (see Jongejan 2017).

Table 1. Overview of most relevant input parameters for inner slope instability and piping for all sections.

Parameters	Description	Section	1	2	3	4	5
Inner slope instability		Unit					
FS_{2025}	Factor of safety in 2025	-	1.14	1.07	1.09	1.3	0.88
FS_{2075}	Factor of safety in 2025	-	1.09	1.03	1.04	1.18	0.8
Piping							
k	Permeability of conductive layer	10^{-4} m/s	3.47	1.74	1.74	3.47	1.74
d_{cover}	Thickness of cover layer	m	8.36	0.40	0.50	0.12	2.68
h_{exit}	Phreatic surface in cover layer	m	1.16	2.10	2.50	1.82	1.33
r_{exit}	Damping factor of phreatic surface	-	0.93	0.73	0.82	0.69	0.85
$L_{\mathrm{fore+base}}$	Seepage length water side & base of flood defence	m	85.0	54.3	36	57.8	75.3
L_{back}	Seepage length of base and at back of flood defence	m	0	10.9	5.7	0	0

With these input values, reliability indices can be derived for each section per mode, as well as a reliability for the segment as a whole using method from section 2.1. The calculated reliability indices per section are shown in Figure 2 for the year 2025. The same computations are made for all years up until the year 2075. It can be observed that none of the sections has overflow issues, whereas some of the sections have issues with inner slope instability, some with piping and some with both. It has to be noted that reliability indices are quite low, which is partly due to the conservatism in the semi-probabilistic approach, and partly due to the quite conservative method used for upscaling the cross-sectional reliability for piping and inner slope instability to section level (see Eq. (2)).

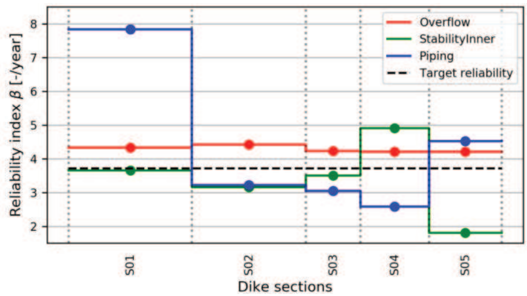

Figure 2. Reliability indices β for each section per mode. These values have been upscaled to the length of the section. The dashed black line denotes the target reliability for the segment as a whole.

3.2 Possible measures

We consider 3 possible methods for reinforcing the flood defence, next to the monitoring:

- Reinforcement with soil consisting of either or both berm widening and an increase in crest level.
- A self-retaining structure that eliminates both piping and inner slope instability, such as a diaphragm wall (Reliability index $\beta > 6$).
- A Piping elimination measure, specifically a Vertical Sandtight Geotextile (VSG) (Koelewijn et al. 2014) that largely eliminates the probability of piping failures. This measure is only available at Section 4.

A soil reinforcement is parameterized by a crest level increase and berm widening. These are then translated to the respective input parameters per mode. Piping elimination and self-retaining structures are taken into account for piping and/or inner slope instability using the following formula:

$$P_f = P(F \mid M) \cdot P(M) + P(F \mid \overline{M}) \cdot P(\overline{M}), \tag{6}$$

where F denotes failure of the flood defence; M denotes functioning of the measure; $\overline{M}$ denotes failure of the measure. Probabilities for all measures are given in Table 2 as well as the parameters for the costs.

Table 2. Overview of costs for each measure. For piping elimination and self-retaining structure also the applicable failure probabilities are given.

Parameter	Unit	Description	Soil Reinforcement	Piping elimination	Self-retaining structure
C_{start}	€	Initial cost	200,000	-	-
$C_{unit,1}$	€/m^3	Cost volume of soil	40	-	-
$C_{unit,2}$	€/m^1	Cost per meter	-	700	20,000
C_{house}	€/house	Cost per removed house	500,000	-	-
$P(\overline{M})$	-	Failure prob. of measure	-	10^{-3}	10^{-8}
$P(F \mid M)$	-/year	Failure prob. if measure functions	-	10^{-8}	10^{-8}

All methods are available for all sections, except for the Vertical Sandtight Geotextile which is only available for section 4. The following cost function is used:

$$C = C_{\text{start}} + C_{\text{unit},1} \cdot V + C_{\text{house}} \cdot h + C_{\text{unit},2} \cdot L, \tag{7}$$

where V is the soil volume in m^3; h is the number of houses removed; L is the length of a Vertical Geotextile or Self-retaining structure. Other input parameters for the measures are shown in Table 2. Both the piping elimination and self-retaining structure are based on the length of the measure. For the soil reinforcement the costs consist of initial cost, costs depending on de soil volume added and the houses removed. The soil volume is determined by upscaling the representative cross-section over the entire section, the number of houses is based on a GIS analysis where for equidistant steps of 10 meters the number of large (area > 50 m^2) houses was determined. For soil reinforcement the incremental increase in crest height is 0.5 meters, and berm widening is discretized in steps of 10 meters.

3.3 Prior and posterior estimates for permeability

The monitoring is included in the analysis by first determining the prior distribution of k and subsequently determining the influence of possible monitoring outcomes on the posterior distribution of k, after monitoring. The prior distribution is a lognormal distribution of which the 95% representative value (k_{repr}) is known, and a coefficient of variation (CoV) of 50% is assumed (default value in the Netherlands). The posterior distribution is governed by a monitored mean k_i and a CoV of 10%, caused by measurement inaccuracy of the monitoring method. This can then be translated to a posterior value for k_{repr}. Possible values for k_i are discretized into 8 scenarios, weighted by their a priori probability.

Figure **3** shows the prior and posterior distribution of the representative value of k, including the discretization into 8 scenarios of representative values. The left pane shows the results for a prior k_{repr} of $1.74 \cdot 10^{-4}$ m/s (sections 2,3 and 5), the right pane for a k_{repr} of $3.47 \cdot 10^{-4}$ m/s (sections 1 and 4). It has to be noted that these k-values also translate to different values for damping factor r_{exit}.

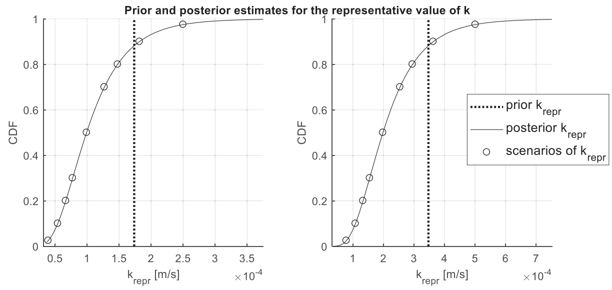

Figure 3. A priori estimate of the representative k (dotted vertical line) versus the posteriori distribution of k, after monitoring. o indicates a combination of a scenario considered in the calculations. Left and right pane show results for different a priori values for k_{repr}.

4 Results

We consider whether reducing the permeability uncertainty by monitoring is useful at sections 2, 3 and 4, where there is insufficient reliability for piping erosion. Figure 4 shows the resulting conditional VoI for the target reliability of the segment. It is observed that the expected VoI (*E(VoI)*) is positive for sections 2 and 3, and 0.0 for section 4. In line with expectation it is observed that more favorable monitoring outcomes (smaller non-exceedence probability of the posterior k_{repr} $P(k_{repr})$) result in a higher VoI. An exception is section 4, where there are no direct benefits of monitoring: due to the availability of the relatively cheap Vertical Geotextile for reinforcement, there is no cost reduction by monitoring and in any case the section will be reinforced using the same method. A peculiar thing is that for monitoring at section 2 there is a negative VoI around $P(k_{repr})=0.8$, caused by the relatively large discrete steps that are used for the available measures (e.g. berm widening in steps of 10 meters).

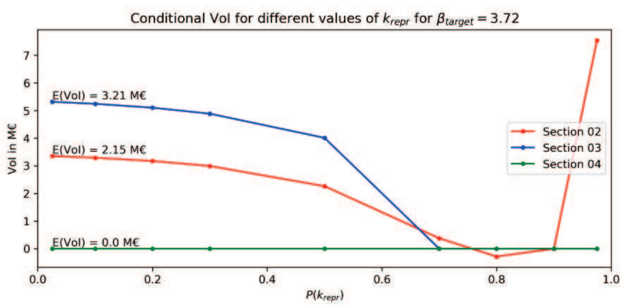

Figure 4. Conditional Value of Information for various values of k_{repr} for monitoring at different sections. $P(k_{repr})$ denotes the non-exceedance probability of k_{repr} after monitoring. A small $P(k_{repr})$ denotes a very favorable monitoring outcome. E(VoI) denotes the VoI weighted by the scenario probabilities. The VoI is here the difference in investment cost to segment a certain target reliability β_{target} compared to the investment cost without monitoring.

Each of the possible scenarios in Figure 4 has an underlying investment pattern that consists of a prioritized sequence of measures based on the optimal BC ratio of investment steps (see section 2.2). Figure 5 shows such a sequence for monitoring at section 2 with a favorable monitoring outcome ($P(k_{repr})=0.025$). This shows that that the measures taken at section 2 in the case without monitoring (red dashed line), do not increase the reliability β, whereas in the case with monitoring (blue line), these measures are deemed unnecessary and not taken at all. This shows that monitoring improves the efficiency of investments, although it strongly depends on a variety of factors, such as the available reinforcement measures and the relative strength of a section, compared to other sections in a segment.

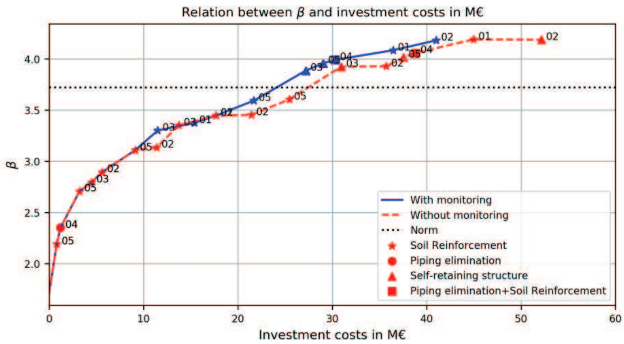

Figure 5. Total investment costs (*LCC*) versus the reliability for the entire segment for prioritized investments with and without monitoring. Symbols indicate different measures, numbers indicate the section. Where lines overlap identical measures are taken in both strategies.

5 Conclusions

In this paper the potential value of monitoring information for the specific application of head monitoring to reduce permeability has been evaluated. It is shown that it is not necessary to use full probabilistic safety assessments to identify valuable locations for monitoring. It is also shown that monitoring is not effective in all cases: the findings at section 4 clearly show that a decision to monitor should relate to a decision that can be improved, meaning that the decision without information is expected to be different from the decision with information. For section 4 this was not the case. Thus, if a dike reinforcement has as goal to reach a certain target reliability it should be evaluated whether the monitoring outcomes will change the measures that are taken. If that is the case, monitoring is economically beneficial if the costs of the monitoring outweigh the investment.

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