# Value of Information in Retrofitting of Flood Defenses

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ABSTRACT: Dikes and levees play a crucial role in flood protection. The main causes of levee failures are of geotechnical nature; geotechnical failure modes are also the main contributors to the probability of failure of flood defences due to the typically large uncertainties in ground conditions. Hence, information on ground conditions and soil properties is crucial in safety assessments and retrofitting designs of levees. The present paper demonstrates how we can reduce these uncertainties and how we can provide input for rational decision making on investments in monitoring and site investigation. If working in a framework with an explicit target reliability, the value of such information can be expressed in terms of the savings that can be achieved in retrofitting costs. The key ingredients of the approach are Bayesian posterior analysis for reliability updating by incorporating the information from various sources and Bayesian (pre-posterior) decision analysis for estimating the uncertainty and expected values of the consequences and costs of the considered decision options. The optimal strategy is the one with the least expected cost to meet the pre-set reliability target (e.g. by a safety standard). Several examples and case studies addressing different sources of information, such as field observations and piezometer monitoring during floods or site investigation by Cone Penetration Tests (CPT), illustrate the impact of reliability updating and suggest that investments in inspection and monitoring are often worthwhile, especially when the prior uncertainties are large.

## 1. INTRODUCTION

What is a sensible investment in site investigation and monitoring for flood defences which have been assessed to be unsafe and, consequently, need to be retrofitted? Practitioners as well as researchers have been struggling with this question for a long time. Though we know that acquiring additional information, especially on geotechnical properties, helps us to reduce uncertainties and, hence, to come up with more appropriate safety assessments and design, it is hard to quantify the value of information or the return on investment with the deterministic or semi-probabilistic codes of practice currently applied in most places. On the other hand, Eurocode or the envisaged revision of Dutch safety standards for flood defences (Deltaprogramma, 2014) provide openings to work with target reliabilities, enabling us to work in a fully probabilistic fashion.

### 1.1. *Objectives*

The main objective of present paper is to demonstrate how the value of information of site investigation and monitoring of flood defences can be quantified in order to support decision making in safety assessment and retrofitting situations where the safety requirement is formulated as target reliability (i.e. an acceptable annual probability of failure).

As there are several sources of information to be employed, we also aim to provide an overview of the types of information and the way they can be used to update the reliability and how their value of information can be quantified.

Ultimately, application of the presented approach in levee retrofitting projects should lead to optimized retrofitting designs and to a reduction of the costs to keep flood defense systems safe (i.e. meet their reliability targets).

### 1.2. Scope

As the field of flood defences is wide in terms of hazards (e.g. coast, rivers, lakes), structures and failure mechanisms, we will focus on one specific application after discussing the general framework for the sake of illustration, namely the failure mode backward internal erosion for river levees (in the remainder called "piping"). In the Dutch flood risk analysis project VNK2 (Jongejan et al., 2013), piping was identified as the main contributing mechanism to the probability of breaching of river levees and to the associated flood risk. Hence, it is of particular practical relevance.

The starting point for the approach is a levee which does not meet its target reliability for the failure mode piping. The decision options considered are essentially (a) to reduce uncertainty by acquiring and/or incorporating additional information, (b) to take physical reinforcement measures (e.g. piping berms or seepage screens) or (c) a combination of both.

### 1.3. Outline

The application of Bayesian posterior and decision analysis to the problem at hand is discussed in section 2, as well as how the envisaged application relates to applications reported earlier in the literature. Section 3 briefly recaps two sources of information related to observations during flood loading, namely (visual) field observations and monitored pore water pressures, and demonstrates the impact of such observations of the probability of failure. Section 4 elaborates on a novel application of posterior and decision analysis on the mapping of the blanket layer on the landside of the levee by means of Cone Penetration Testing (CPT), where the thickness of the blanket is treated as a two-dimensional random field.

## 2. BAYESIAN DECISION ANALYSIS FOR LEVEE RETROFITTING

Many structures world-wide approach their design life time and there is a growing demand for assessment of existing structures. Hence, it is surprising that also in the literature we increasingly see contributions on structural (re-)assessment, data assimilation and reliability updating, both in terms of method development as well as in applications. This section provides a concise overview of recent developments in geotechnical engineering and, more specifically, with respect to flood defences.

### 2.1. Bayesian posterior analysis

The basis for incorporating additional information in a reliability analysis is Bayesian posterior analysis (or Bayesian Updating), which is based on Bayes' rule (Bayes, 1763):

$$P(F|\varepsilon) = \frac{P(F \cap \varepsilon)}{P(\varepsilon)} = \frac{P(\varepsilon|F)P(F)}{P(\varepsilon)} \qquad (1)$$

where $P(F|\varepsilon)$ is the posterior or updated probability of failure $F$, conditional on the observation $\varepsilon$. In structural reliability problems, typically the failure set is defined in terms of the performance function $g$ through $F \equiv \{g(\mathbf{x}) < 0\}$, in which $\mathbf{x}$ represents the vector of random variables.

Recent examples of Bayesian reliability updating in the literature are Ching and Hsieh (2006) who describe a way of using Monte-Carlo simulation for updating the reliability of monitored geotechnical systems, Zhang et al. (2011) who update the probability of an embankment by incorporating site-specific performance information (e.g. survival of a load) and Schweckendiek et al. (2014) as well as Schweckendiek and Vrouwenvelder (2013), both considering reliability updating for levees with respect to internal backward erosion (piping).

Besides direct reliability updating there are numerous reports of applications of Bayesian updating to reduce uncertainties in soil properties, most notably due to its pioneering nature Tang (1971) and more recently Zhang et al. (2004) as well as Ching and Phoon (2012).

Furthermore, Straub (2014) describes how Bayesian Updating (and value of information analysis) can be done in a computationally efficient manner using standard techniques from structural reliability analysis.

### 2.2. *Target reliability constraints*

Most commonly in real-life designs or decisions on the scope of site investigation and monitoring for assessment and design purposes, we do not have the opportunity to apply full-fledged risk analyses and risk acceptance criteria directly. However, modern codes of practice such as Eurocode or the envisaged Dutch safety standards for flood defences (Schweckendiek et al., 2012) provide us with risk-motivated target reliability levels, which allows us to apply probabilistic approaches at least. As will be shown in the remainder, a probabilistic approach enables us to express the value of information through expected costs, which would be virtually impossible or largely arbitrary in a semi-probabilistic setting.

Working with target reliabilities means that the probability of failure of the structure in question needs to comply with the target probability of failure $p_T$, $P(F) \leq p_T$, or for the posterior probability of failure:

$$P(F|\varepsilon) \leq p_T \tag{2}$$

Notice that different codes of practice may works with different reference periods. Whereas Eurocode uses the design life time, the Dutch safety standards for flood defences are based on annual probabilities.

### 2.3. *Bayesian decision analysis*

Bayesian decision analysis enables us to compare different decision options in terms of their expected utility. For risk-neutral decision makers the optimal decision boils down to be the one with the minimum expected cost.

For flood defenses that have to comply with a target reliability as defined in the previous section that means that the total cost of the decision options usually consists of investments in uncertainty reduction (e.g. site investigation, monitoring) and the cost of retrofitting to bring the structure up to the reliability target. If we opt for measures to reduce uncertainty first, the retrofitting is based on the posterior knowledge (i.e. probabilities), as illustrated in Figure 1.

More formally, the optimal pre-posterior (i.e. expected future) retrofitting cost $C_r$ are obtained by:

$$E[C_r^{''}(\Psi)] = \int \min_{\Omega} C_r(\Omega, f(x|\varepsilon)) f(\varepsilon|\Psi) d\varepsilon \tag{3}$$

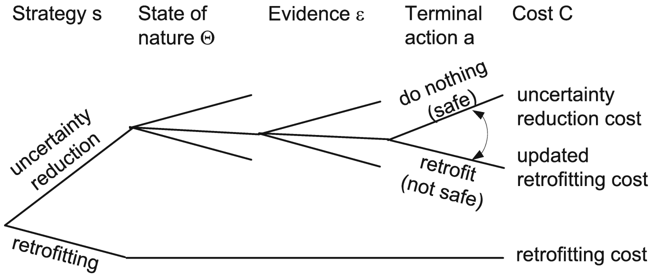


*Figure 1: Decision tree for safety assessment and retrofitting of flood defenses.*

$$s.t. \quad P(F|\varepsilon) \leq p_T$$

where $\Omega$ is the set of retrofitting design variables, $f(x|\varepsilon)$ is the posterior distribution of the random variables and $f(\varepsilon|\Psi) = \int f(\varepsilon|\Psi, x) f(x) dx$ is the prior distribution of the evidence conditional on the investigation parameters $\Psi$. For a more thourough elaboration refer to Schweckendiek (2014).

### 2.4. *Value of Information*

Using the definition of minimum pre-posterior cost from the previous section (Eq. 3), we can express the value of information in different ways. Following the commonly used concepts (Straub, 2014), the value of information of inspection and monitoring can, in the contemplated assessment and re-design situation, be expressed in terms of the difference in (expected) cost of the assessed decision option and the retrofitting cost with prior knowledge (i.e. without acquiring and incorporating more data):

$$VoI(\Psi) = C_r^{'} - E[C_r^{''}(\Psi)] \tag{4}$$

where $C_r^{'}$ is the retrofitting cost for the cost-optimal design based on prior knowledge:

$$C_r^{'} = \int \min_{\Omega} C_r(\Omega, f(x)) f(x) dx \tag{5}$$

$$s.t. \quad P(F) \leq p_T$$

Consequently, a (pre-posterior) benefit-cost ratio (BCR) can be defined as the ratio of the $VoI$ and the investment cost $C_s$ in reducing uncertainty:

$$BCR(\Psi) = \frac{VoI(\Psi)}{C_s} = \frac{C_r^{'} - E[C_r^{''}(\Psi)]}{C_s} \tag{6}$$

Recent examples of applications of VoI concepts from related disciplines are described in Faber et al. (2000), Straub and Faber (2004), Corotis et al. (2005), Thoens and Faber (2013) or Garre and Friis-Hansen (2013).

The following sections will provide examples of new observations can be incorporated in the reliability of a levee with respect to internal backward erosion, including considerations of cost-effectiveness using the definitions above.

## 3. SURVIVED FLOODS

A valuable source of information for geotechnical failure mechanisms of levees are survived load events, i.e. extreme floods.

### *3.1. Field observations*

Field observations during heavy loading like seepage or sand boils are signs of bad performance, because they indicate the initiation of (partial) failure mechanisms such as uplift or heave. Schweckendiek et al. (2014) describe how reliability updating for this type of observations can be done in a Bayesian framework using the same performance functions as for the (prior) reliability analysis itself, considering the observation as if the flood were a load test. Figure 2 illustrates the impact such observations can have on the fragility curves (probability of failure conditional on the river water level) for an observed sand boil.

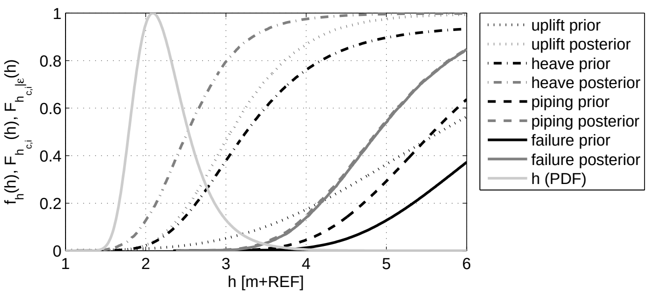


*Figure 2: Prior and posterior fragility curves of a levee with respect to uplift, heave and piping as function of the river water level according to a case study from the Netherlands (Schweckendiek, 2014)*

Not only observing partial failure can be used for reliability updating purposes, also (partial) survival similarly contains valuable information, resulting in an increase of reliability. Schweckendiek (2014) concludes that changes in probability of failure of one order of magnitude are not uncommon, depending on the magnitude of (reducible) prior uncertainty.

Apart from the effort that goes into the reliability updating analysis itself, there is virtually no cost involved in this type of observation. Hence, the value of information can hardly be expressed here in practical terms. On the other hand, it is obvious that the information should be used, if available.

### *3.2. Monitored pore water pressures*

Similar to the visual observations, we can use monitoring of the pore pressure response to flood loading (ideally at potential exit points for piping, see Fig. 3) for reliability updating and, hence, influencing the investment cost in retrofitting measures.

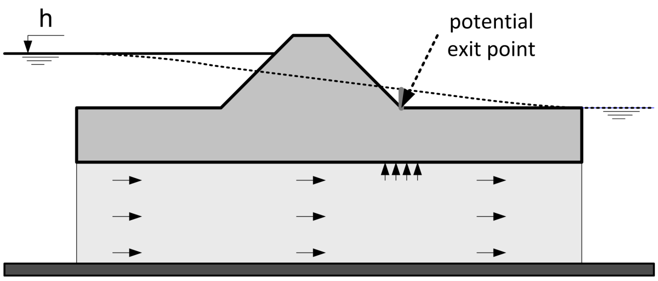


*Figure 3: Illustration of the uplift (partial) failure mechanism and the potential exit point where installation of piezometers to monitor the pore pressure response to flood loading is most effective.*

Compared to the inequality type of information provided by observations partial failure or survival, the challenge here is the treatment of equality type of information. Straub (2011) provides and elegant solution for this problem using standard structural reliability analysis methods, as also illustrated by Papaioannou et al. (2014). Schweckendiek (2014) discusses the application to uplift, heave and piping (backward erosion). The impact of incorporating the monitoring information is similar to field observation and can bring about changes of a factor 10 both ways.

Schweckendiek and Vrouwenvelder (2013) demonstrate pre-posterior analysis for a simplified example, investigating the cost-effectiveness of such installing piezometers for monitoring the pore pressure response to flood loading. Our conclusion was that the VoI (i.e. difference in expected cost) was considerable and that due to the fact that monitoring costs are typically orders of magnitude lower than retrofitting costs, even small savings the the retrofitting design lead to rather high benefit-cost ratios (in the example the BCR was roughly 30).

Similar conclusions are drawn in Schweckendiek (2014) for a case study in the Netherlands, in which not only uncertainties in ground properties are considered, but also the uncertainty in the stratification though so-called subsoil scenarios. Figure 4 illustrates that the pre-posterior distribution of the reliability index (for the combined failure mechanism of uplift, heave and piping; black continuous line) can be quite wide due to the large prior uncertainties in the relevant ground properties and the stratification. The red vertical line in Figure 4 is the

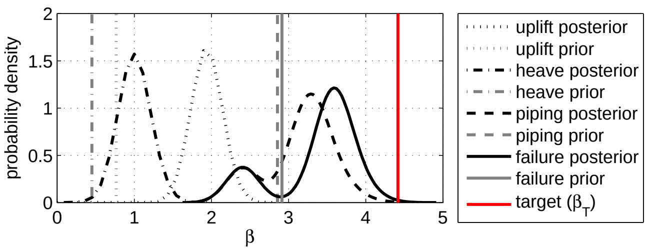


*Figure 4: Density plots of pre-posterior realisations of posterior reliability indices for four subsoil scenarios with a random future water level and measurement error (1 year of monitoring), from Schweckendiek (2014).*

reliability target in the case study. The probability of exceeding the target reliability after incorporating the next year's flood's response was 5% in the case study. That meant a potential saving of millions of Euro investment in retrofitting with a 5% probability (because retrofitting wouldn't be necessary at all), implying expected savings in the order of $10^5$ Euro versus investments in the order of $10^4$ Euro. That in turn, according to the definitions in section 2.4, implies a VoI in the order of $10^5$ Euro and a BCR of roughly 10.

It needs to be mentioned that the fact that there may be a waiting time until the next significant flood was neglected here. It can be easily incorporated in the decision analysis by accounting for the probability of a relevant observation in the considered monitoring period. Depending on the local conditions, taking this effect into account can significantly reduce the cost-effectiveness.

## 4. SITE INVESTIGATION

Several approaches to support decisions in geotechnical site investigation planning have been reported in the literature (Baecher, 1979; Halim and Tang, 1990; Elkateb et al., 2003; Meriaux and Royet, 2007; Goldsworthy et al., 2007), but none of them actually quantifies the value of information in monetary terms.

### *4.1. Anomaly detection*

Schweckendiek et al. (2011) do provide a framework similar to the concepts presented in the present paper and illustrates the value of information of soundings (e.g. CPT) to detect adverse geological details under a levee, at the same time optimizing the site investigation parameters (i.e. the sounding distance).

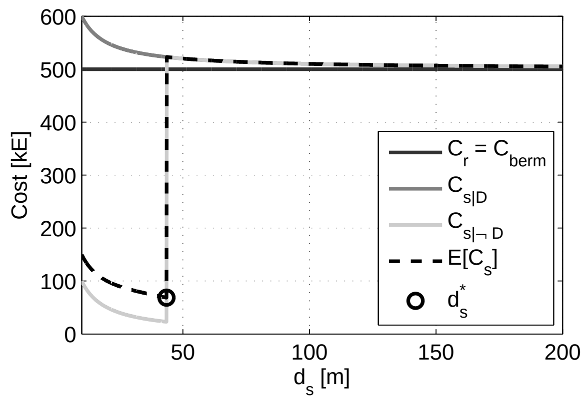


*Figure 5: Anomaly detection example from Schweckendiek (2014) - costs as a function of the sounding interval. The light-grey line shows the total cost of retrofitting and site investigation, provided no anomaly is detected. The dashed black line is the expected cost including the probability of detection.*

The black dashed line in Figure 5 shows the expected total cost (site investigation plus retrofitting) as function of the sounding distance, where the soundings are targeted at finding an adverse geological detail of uncertain width (mean 50 m, standard deviation 15 m). The optimum is found at the lowest expected cost (black circle). The example again

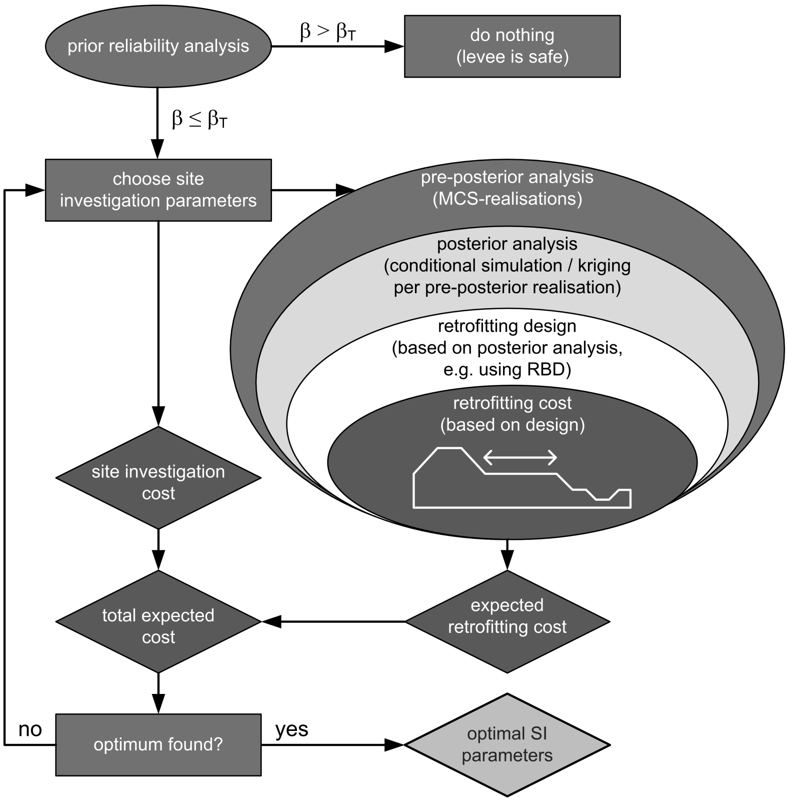


*Figure 6: Computational framework for the optimisation of site investigation (SI) parameters for a levee involving modelling the spatial variability of properties by means of random fields. After Schweckendiek (2014). Notice that $\beta$ is the prior reliability and $\beta_T$ is the reliability target.*

shows a high VoI (i.e. difference between the black circle and the continuous black line) and BCR and at the same time it illustrates the existence of a minimum amount of site investigation in a framework with a target reliability (at the jump of the expected cost).

### *4.2. Example: Blanket thickness*

Similar to anomaly detection, VoI-concepts, optimization of site investigation parameters and decision analysis can also be applied to more sophisticated problems. Schweckendiek (2014) applied pre-posterior analysis to a problem of levee reliability with respect to piping, particularly to the investigation of the blanket thickness on the landside of the levee, which was modelled as a two-dimensional random field. As illustrated in Figure 6 The regular sounding grid was optimized by simulating the inspection outcome based on prior knowledge, the results of which where then used to determine the posterior reliability using conditioned random fields and, subsequently the width of the landside berm was designed for the levee to meet the target reliability using posterior properties.

Figure 7 shows the expected total cost (site investigation and retrofitting) for different configurations of the search grid. From the results could be concluded that in the particular case study, one row of soundings in the levee with a sounding distance of roughly 300 m would be optimal (which was roughly the horizontal auto-correlation distance of the blanket thickness). Also in this example, the VoI of site investigation exceeded the cost of the soundings, implying a positive benefit-cost ratio. For details refer to Schweckendiek (2014).

## 5. CONCLUSIONS

The proposed framework for assessing the cost-effectiveness of investments to reduce uncertainties works with a target reliability. The optimal strategy is defined as the one with the least expected costs to reach a pre-set reliability target. The (costs of) con-

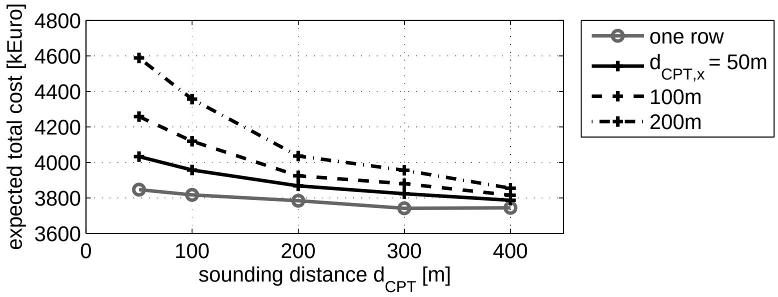


*Figure 7: Expected total cost (site investigation plus retrofitting) according to case study from Schweckendiek (2014). The horizontal axis depicts the sounding distance in the landside blanket in longitudinal direction of the levee and the different lines represent different transversal distances of a second row of soundings from the levee toe line (see legend).*

sequences are only treated implicitly through the safety standard (i.e. reliability target). Such an approach has the advantage that it is more accessible to practitioners than a fully risk-based approach, as considering the consequences of failure explicitly is usually cumbersome and beyond the experience of the designing engineers. Furthermore, safety standards are often motivated not only economically but also through loss-of-life considerations, which are even more difficult to assess explicitly.

On the other hand, the proposed framework has a significant drawback compared to a fully risk-based approach. As demonstrated in several of the referenced examples and case studies, the incentives in the approach can lead to sub-optimal decisions. The reason is that there is no award for incorporating "unfavourable observations" (i.e. leading to a decrease in reliability), because they lead to no decrease or even an increase in retrofitting cost. From a risk point of view, even buying unfavourable evidence can pay off, as the increased risk can then be reduced by measures. In the presented framework that is not the case.

Despite this drawback, the approach can be a useful tool for practitioners for optimizing investments in site investigation and monitoring for geotechnical problems and for comparing different strategies. Overall, the referenced examples and cases show that the value of information can be very high, if the prior uncertainties are large, as is very typical in geotechnical engineering.

Future work should focus on the combination of multiple sources of information and on the analysis of staged strategies. Furthermore, little is known about which portion of the uncertainties faced in the assessments is reducible and which is not, especially when it comes to model uncertainty.

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