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Advances in reliability analysis of the piping failure mechanism of flood defences in the Netherlands

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Piping is one of the main failure mechanisms for flood defences. This paper gives an overview of recent developments in the reliability analysis for this mechanism in the Netherlands. These comprise new approaches in the treatment of heterogeneity of the subsoil with respect to the failure process, the inclusion of information from field observations and monitoring by means of Bayesian Updating. Also, a framework is presented for including the effects of taking emergency flood fighting measures in reliability analysis. In essence, incorporation of each of these aspects in modelling piping reliability can change the probability of failure considerably, depending on the local conditions and amount of information available a-priori.

Key words: internal erosion, piping, reliability analysis, spatial variability, Bayesian Updating, field observations, monitoring, site investigation, emergency measures

1 Introduction

1.1 Background

The safety of flood defences is of great importance for low-lying areas that are threatened by floods. This is particularly the case in the Netherlands, in which almost 60% of the country is at risk from flooding from the coast, rivers and lakes. Given its geography, the Netherlands have a long history of floods. The last major flood was the coastal storm surge of 1953 which led to death and destruction in the Southwest of the country. Most of the failures occurred due to overtopping and consequent erosion of coastal levees. After this disaster major barriers and dams were constructed to reduce the vulnerability of the affected areas. Over the decades that followed also other parts of the flood protection system were upgraded, for example the levee reinforcements and Room for Rivers program along the Rhine River after the 1995 floods. The length of the current flood protection system in the Netherlands is almost 3800 km.

The current safety standards are formulated in terms of the annual probability of exceedance of a design water level which the flood defence should be able to withstand safely. These safety standards range from 1/10,000 for the coastal areas with high potential damages, to 1/1250 or 1/250 for riverine areas.

Since the 1980's research has been on-going on a risk-based evaluation of the flood defences. In this approach, see e.g. [Vrijling, 2001; Vrijling et al., 1998] the various objects in a flood protection system, the different failure mechanisms and the consequences of flooding are explicitly quantified using risk and reliability analysis. Partly due to these studies, it is expected that the metric of the safety standards will change from the current annual probability of exceedance of a design water level to an annual normative or target probability of failure of (a part of) the flood defence system. To be able to use these types of standards for assessment, management and reinforcement of the flood defence system, a broad basis of knowledge is required. In recent years, especially since the flooding of New Orleans in 2005, more attention has been paid to the physical modelling and reliability analysis for so-called geotechnical failure mechanisms of flood defences, such as piping and instability. Evaluations of past flood defence failures such as in New Orleans in 2005 [Seed et al., 2006] and more recently in Germany (2013) show that these mechanisms are often a cause of catastrophic failure and consequent flooding. Also, for the Netherlands, recent large-scale risk analysis studies indicate that failure probabilities are expected to be relatively high (>1/100 per year) due to the piping failure mechanism [ENW, 2010; Jongejan and Maaskant, 2012; Jongejan et al., 2013].

*1.2 **Aim of the paper***

The aim of this paper is to review and present recent developments in reliability analysis for the piping failure mechanism for flood defences in the Netherlands. These developments cover the physics of the mechanism, reliability aspects, field observations as well as (emergency) measures to reduce the risks. Quantitative indications of the impact of these factors on the estimated reliability with respect to piping are presented. The focus of this paper is on the Netherlands, but findings and information are also expected to be relevant for other flood prone delta areas with flood defences. The framework in Figure 1 presents the overall structure of the article. On the left hand side, various elements of the research field are indicated. On the right hand side the most relevant references are shown.

1.3 Outline

The structure of the paper follows the framework outlined in Figure 1. Various models can be used to assess the piping safety in a deterministic way (see section 2). The reliability of a flood defence (system) can be assessed based on the uncertainties in the loads and the resistance. The spatial variation over the flood defence will be a key input in the reliability analysis and this is the topic of section 3. Consequently, piping reliability estimates can be influenced and updated by site and field observations (see section 4). When the failure probability is higher than the target failure probability, both permanent structural and temporary emergency measures can be implemented. The effects of structural measures can be directly incorporated in existing models for piping reliability analysis. However, a risk-based framework for analysing the effects of emergency measures is not yet available, and this is presented in section 5. Eventually, the results of the various types of analysis will be combined and implemented in safety and risk assessments, decision making and risk reduction actions. A closing discussion in this context is presented in section 6.

2 The piping failure mechanism

2.1 Description of the piping failure mechanism

A levee fails due to piping in case the soil particles below the levee are eroded due to excessive seepage. The different stages in the piping failure mechanism are shown in Figure 2 for an earthen levee with a clay blanket on top of a sand layer (aquifer). Five stages can be defined to describe the piping process. In the first stage, water pressures

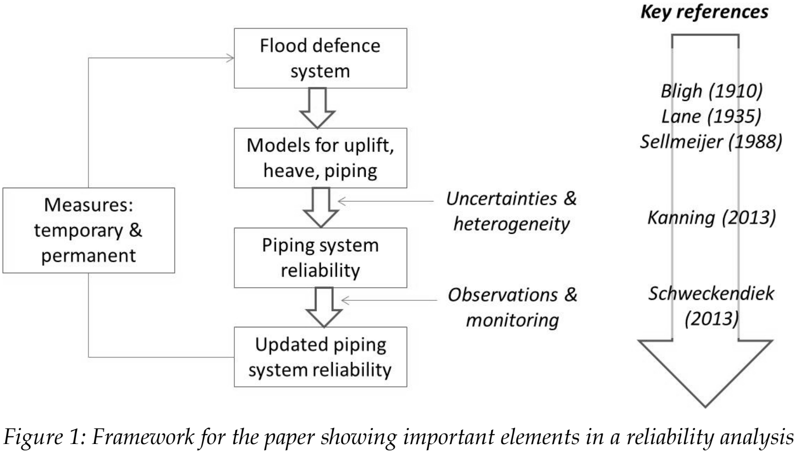
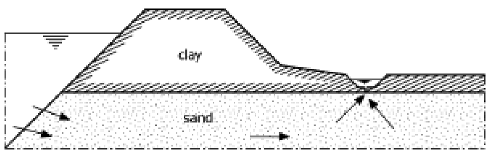
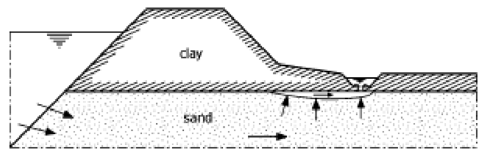


Figure 1: Framework for the paper showing important elements in a reliability analysis for piping (left) and key references (right)

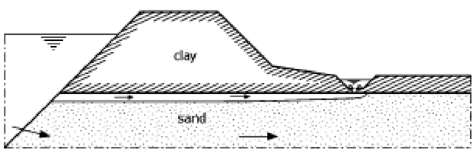
develop below the clay blanket, which is ruptured due to uplift pressures and water starts to flow out. In the second stage, the flow velocities of the out flowing water increase and sand is eroded, a channel starts to form below the levee. In the third phase, the channel develops until an open connection is created between the inner and outer side of the levee. Subsequently, further erosion causes subsidence (stage 4) and finally disintegration of the levee (stage 5).



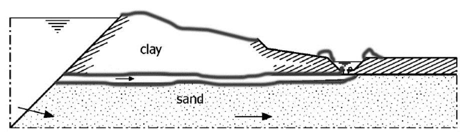
1. Blanket cracks and water starts to flow out.



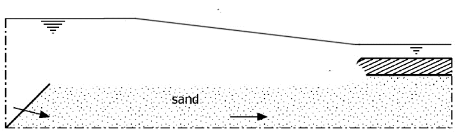
2. Sand starts to wash out.



3. The piping channel forms from inner to outer side.



4. The levee starts to collapse due to the piping channel.



5. The levee is breached.

Figure 2: Conceptual model of the piping process shown in 5 steps, based on [www.enwinfo.nl]

Three (sub-) failure mechanisms can be distinguished which all need to occur in order to have piping failure: uplift, heave and piping. Uplift is defined as the upward water pressure in the sand exceeding the downward pressure of the blanket weight, resulting in rupture of the blanket layer (step 1). Heave is defined as the vertical exit gradient over the blanket at the uplift location exceeding the critical heave gradient, resulting in erosion of sand particles (step 2). Piping is defined as the formation of a continuous erosion channel from the uplift location to the outside (step 3).

There are several documented piping failures. Notably the failures used by Bligh [1915] to derive his empirical rule (see next section). It must be noted though that the cause of a flood defence breach is often not fully unambiguous as there are usually no eye-witness reports. Instead, there must be relied on forensic evidence and hindcast calculations. An example of a historic piping failure is Zalk, the Netherlands, in 1926 [Deltares, 2008].
A more recent piping example is one of the major breaches in New Orleans due to hurricane Katrina in 2005: the London Avenue Canal south breach. [Kanning et al., 2008].
During high water levels in e.g. the Netherlands, often water boils or sand boils are observed. For example, the high river discharge in the river Rhine in the year 2011 had a return period of about 10 years and sand boils were observed at 18 locations along the river [Arcadis, 2011].

2.2 *Developments in piping modelling in the Netherlands*

Piping modelling was historically mainly based on empirical data of survived and failed structures. These led to the design equations of Bligh [1915] and Lane [1935]. Process-based modelling in of the piping mechanism in the second half of the 20th century led to the equation of Sellmeijer [1988]. The combination of lab experiments, observations and process-based modelling recently resulted in a revision of the formula of Sellmeijer in the SBW 2010 research [Sellmeijer et al., 2011]. The developments in piping modelling are shown in Figure 3.

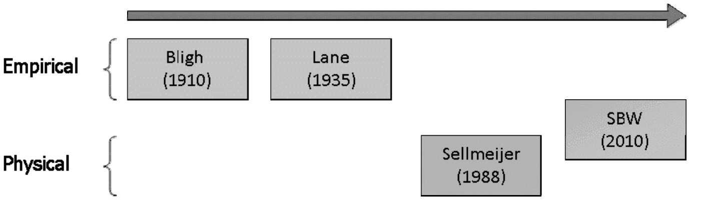


Figure 3: Development of piping modelling in time

2.3 *Modelling piping*

This section describes the updated piping model equations [Sellmeijer et al., 2011], which are based on combination of lab-experiments, observations and process-based modelling. The schematic cross-section in Figure 4 contains the main variables. In the figure, L [m] is the length of the seepage path, h [m] is the outer water level with respect to a reference level (e.g. NAP), h_i is [m] the inner water level, ΔH [m] is the head difference, d [m] is the thickness of the blanket layer and D [m] is the thickness of the sand layer.

The critical head difference ΔH_c is given by:

$$\Delta H_c = L \cdot F_{\text{restance}} \cdot F_{\text{scale}} \cdot F_{\text{geometry}} \tag{1}$$

$$F_{\text{resistance}} = \frac{\gamma_p'}{\gamma_w}\{\eta \tan(\theta)\} \tag{2}$$

$$F_{\text{scale}} = \frac{d_{70\text{m}}}{\sqrt[3]{\kappa L}}\left(\frac{d_{70}}{d_{70\text{m}}}\right)^{0.4} \tag{3}$$

$$F_{\text{geometry}} \overset{\text{MSeep}}{=} F(G) \overset{\text{standard levee}}{=} 0.91 \cdot \left(\frac{D}{L}\right)^{a}, \qquad a = \frac{0.28}{\left(\frac{D}{L}\right)^{2.8} - 1} + 0.04 \tag{4}$$

in which γ_p' [kN/m^3] is the effective soil particle weight, γ_w [kN/m^3] is the volumetric weight of water, θ [deg] is the bedding angle, η is White's constant, d_{70} [m] is the 0.70-fractile of the grain size distribution of the sand, $d_{70\text{m}}$ [m] is a reference value and κ [m^2] is the intrinsic permeability. The three F terms are all dimensionless. F_{geometry} can either be determined by a finite element package such as MSeep or an analytical solution may be used for a standard levee. A structure fails in case ΔH is larger than ΔH_c.

3 Variability and the length-effect

3.1 *Uncertainties affecting piping reliability*

The parameters in the piping model usually exhibit (high) uncertainties. Two groups of uncertainties can be distinguished: inherent uncertainties (uncertainties that stem from natural variability in soils) and modelling uncertainties (uncertainties that arise when translating reality into a model). Measured variability consists of both inherent and

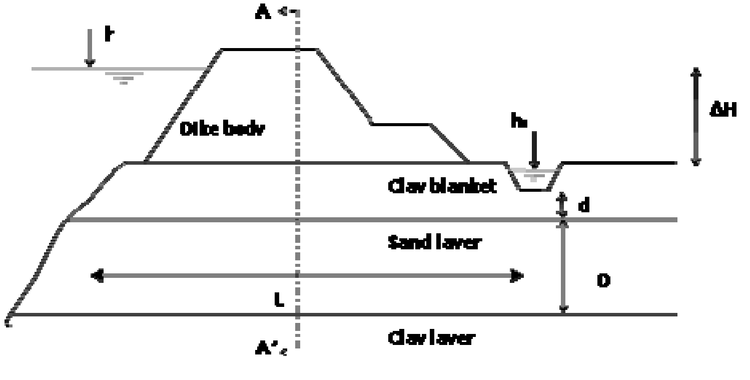


Figure 4: Typical cross-section of a levee that is sensitive to piping

modelling uncertainty. The main uncertainties contributing to uncertainty in structural performance with respect to piping are the water level distribution, the permeability, the grain size (d70) and possible anomalies (e.g. undetected old river beds below the levee). Since inherent (spatial) uncertainties are the main cause of length-effects, these are further elaborated.

The effects of high uncertainties become apparent in reliability analysis. For piping, reliability analysis shows the relative high probabilities of failure for piping [ENW, 2010], causing increased attention in the mechanism.

When performing piping reliability analysis, it should be noted that piping should be modelled as a parallel system since failure only occurs in case uplift and heave and piping occur, see Figure 2 and the text below Figure 2. The limit state functions for uplift and heave are not presented in this paper.

Another important aspect is the difference between cross-section (Figure 4), levee section (statistically homogeneous section) and levee ring (closed system of levees). When calculating the probability of levee section failure or levee ring failure, the length-effect should be taken into account. This is discussed in the subsequent section.

3.2 *The length-effect*

3.2.1 What is the length-effect?

The length-effect refers to the increase of the failure probability with the length of a structure due to partial correlations and/or independence between different cross sections and/or elements; see e.g. Vrouwenvelder [2006]. The length-effect can be explained by Figure 5, which shows the variation in the limit state function Z due to spatial variability in the resistance. The probability of the limit state function Z becoming smaller than 0 (failure) increases with the length of the structure, this is the length-effect.

The underlying reason of the length-effect is a lack of full correlation between the different load and resistance variables as a result of spatial variability. Typically, the load variables are highly correlated over different levee sections; whereas resistance properties of levee sections exhibit little correlation due to the small horizontal correlation distances. This results in a partially correlated limit state function in the length direction and thus an increase of failure probability in the length direction.

As a general rule one may say that the smaller the scale of fluctuation of important random variables, the higher the increase of the probability of failure with the length. Two types of

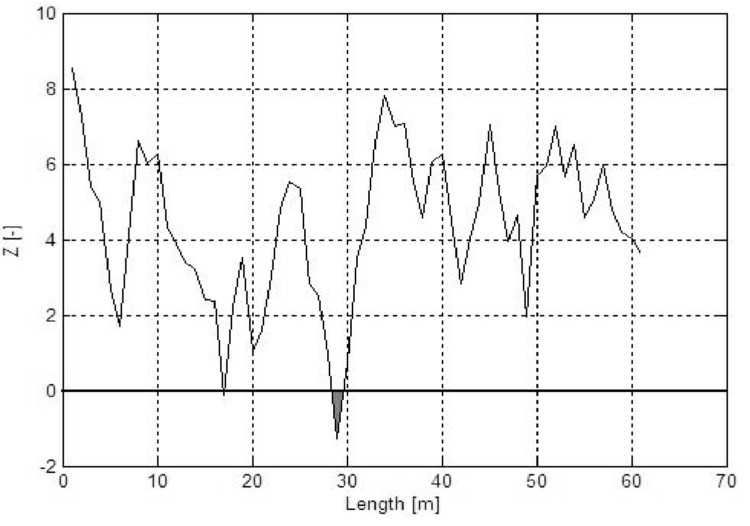


Figure 5: Schematic representation of the length-effect [Kanning, 2012]

spatial variability contribute to the length-effect: continuous fluctuations and discontinuities (e.g. anomalies); this paper mainly focusses on the effect of continuous fluctuations.
Below the length-effect due to continuous fluctuations in soil properties is explained and illustrated.

3.2.2 Modelling the length-effect

Spatial variability can be modelled by random fields, see e.g. [Vanmarcke, 1977]. A Gaussian autocorrelation function can be used to describe the decay of spatial correlation with distance x, using scales of fluctuation of the considered properties. Based on outcrossing approaches, see e.g. [Vanmarcke, 1977], it is possible to derive an 'equivalent independent length' l. This is the representative length of a failure mechanism with a length large enough to make different considered sections independent. See e.g. Vrouwenvelder [2006] for more information about deriving the equivalent independent length. Using this, it is possible to derive a relation between the probability of system failure P_{sys} , which is the probability of failure within a statistically homogeneous levee with length L, and the probability of cross-section failure P_{cs} :

$$P(0,L) = P_{sys} \approx P_{cs}(1+\frac{L}{l}) \tag{5}$$

3.2.3 *Practical implementation of the length-effect*

Figure 6 shows an example of the impact of the length-effect for piping. The different cross-section reliabilities β_{cs} correspond to failure probabilities that equal 10% of the Dutch safety standard. The independent equivalent lengths are based on representative case studies in the Netherlands; they depend on β_{cs} [Calle, 2010] and range between 276 m and 312 m for the different considered β_{cs} 's. The system reliabilities decrease (and corresponding probabilities P_{sys} increase) with increasing contributing levee length. For a β_{cs} of 4.06 and a length of 10 km, the difference between P_{cs} and P_{sys} is a factor 35.

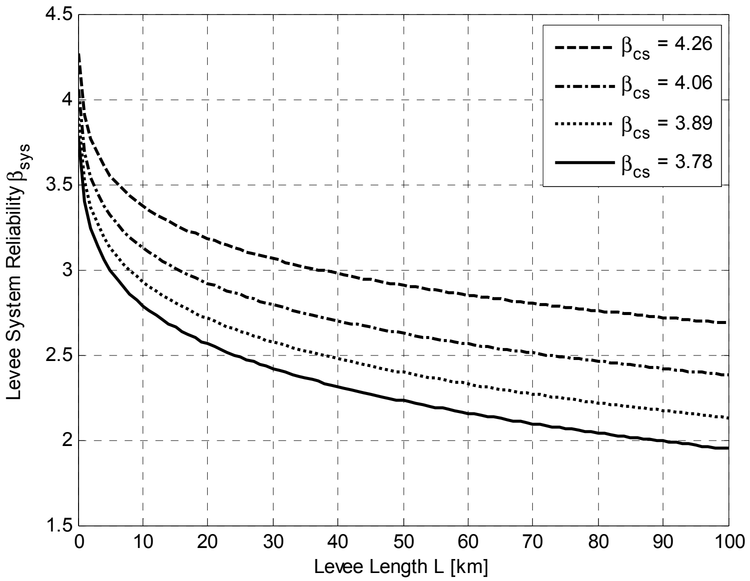


Figure 6: Relation between Target Reliability and Contributing Levee Length L

3.3 ***The width-effect***

Many geotechnical mechanisms need space to develop. This often results in spatial averaging, as not a local weak spot defines the structural resistance but a weak plane or surface. For piping this results in the 'width-effect' as the piping erosion path needs to develop over the full width of the levee. Recently, a new model was developed to model the width-effect [Kanning and Calle, 2013], taking into account spatial variability in the width and length-direction. This model comprises a combined flow and erosion algorithm to find the weakest path below the levee in a random field model to capture spatial variability. The resistance of a levee section is subsequently defined as the strongest point in the erosion path. An example erosion path is show in Figure 7. The main outcome of the width-effect modelling is that small scales of fluctuation in d_{70} result in a higher mean of the representative d_{70}, which results is less required leakage length. On the opposite, larger scales of fluctuation may even result in more required leakage length; see Kanning and Calle [2013]. Interpreting these results, a (maximum) 30% less required leakage length may be obtained, which results in at least a factor 10 lower probability of failure.

3.4 *Conclusions and recommendations*

The piping mechanism is characterized by high uncertainties, mainly in water level, permeability and grain size. When levee systems are considered, as opposed to the current approach of cross-sections, the length-effect should be taken into account. This significantly increases the probability of piping failure. This effect may be compensated by the width-effect which results in averaging of uncertainty in case of small scales of fluctuation. Both length-effect and width-effect require knowledge of scales of fluctuations of the relevant soil parameters. It is recommended to put more effort in finding these scales of fluctuation as relatively little is known.

4 Field Observations, Monitoring and Site Investigation

There are different ways to reduce piping-related uncertainties besides taking structural measures [Schweckendiek, 2013]. Field observations during high flood stages may reveal weak spots but also reinforce our confidence in the reliability of levees [Zhang et al., 2011;

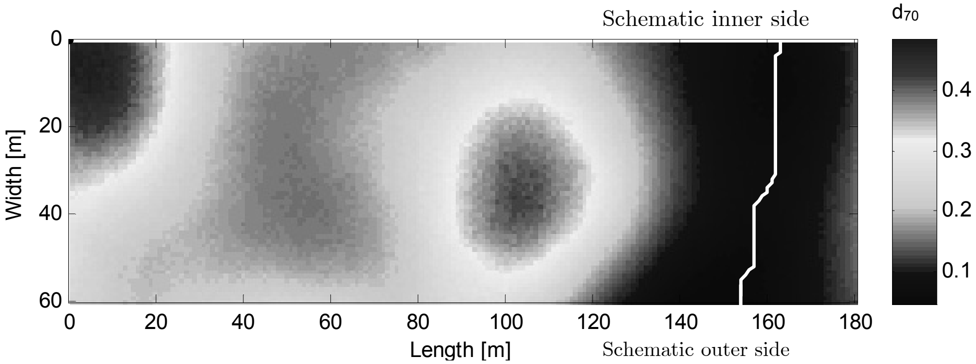


Figure 7: Modelling the width effect in a top view schematisation of a levee with random field modelling of the d70 (figure in colour at www.heronjournal.nl)

Schweckendiek et al., 2013]. Also monitoring a levee's response to (extreme) loading can provide valuable information to reduce uncertainties, for example by measuring the pore pressures in piping-sensitive aquifers [Schweckendiek and Vrouwenvelder, 2013] or by detecting seepage through remote sensing (e.g. infrared imaging). Furthermore, conventional site investigation using soundings (i.e. CPT or borings) or geophysical exploration [Niederleithinger, 2007; Fauchard and Mériaux, 2004] can effectively reduce uncertainties especially in the local stratification.
This section provides three examples illustrating the workings and impact of including information from the sources mentioned above. The examples are summaries of work published earlier providing only the essential information relevant to the context of this paper, detailed information on the underlying theory and case studies can be found in the respective original articles.

4.1 ***Field observations***

During high flood stages, we make observations in the field like seepage in the hinterland or so-called sand boils (Figure 8).

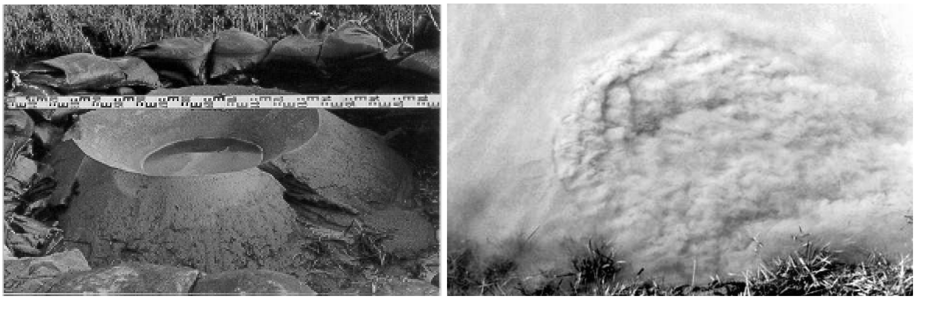


Figure 8: Sand Boils (a) post-flood, left-hand side and (b) active, right-hand side

Bayesian posterior analysis (see e.g. Benjamin and Cornell [1970]) provides a framework for updating both the underlying probability distributions of the basic random variables as well as the probability of failure as long as (a) the observations can be formulated in a mathematical model describing an inequality and (b) this model has random variables in common with or correlated with the failure models described in section 2. In that case, Bayes' rule (here written as the definition of conditional probability) enables us to update the probability of failure by

$$P(F|\varepsilon) = \frac{P(F \cap \varepsilon)}{P(\varepsilon)} = \frac{P(\{Z(x) < 0\} \cap \{h(x) < 0\})}{P(h(x) < 0)} \ , \tag{6}$$

where $F = \{Z(x) < 0\}$ is the failure event, Z being the failure limit state function, and $\varepsilon = \{h(x) < 0\}$ is the event describing the observation, h being the limit state function of the observation. For a discussion on updating the underlying basic random variables and different approaches to reliability updating we refer to [Schweckendiek, 2014].

The prior and posterior fragility curves for uplift, heave and piping in Figure 9 illustrate the effect of including the observation of a sand boil for a 100-year flood event (h_{obs} = 3.5 m) at a location in the Netherlands. Observing a sand boil means in terms of our failure models that at the time of the observation (i.e. at the corresponding water level), the uplift and heave limit state must have been exceeded in order for erosion to take place. Whereas a-priori uplift and heave where rather unlikely, after including the new information they

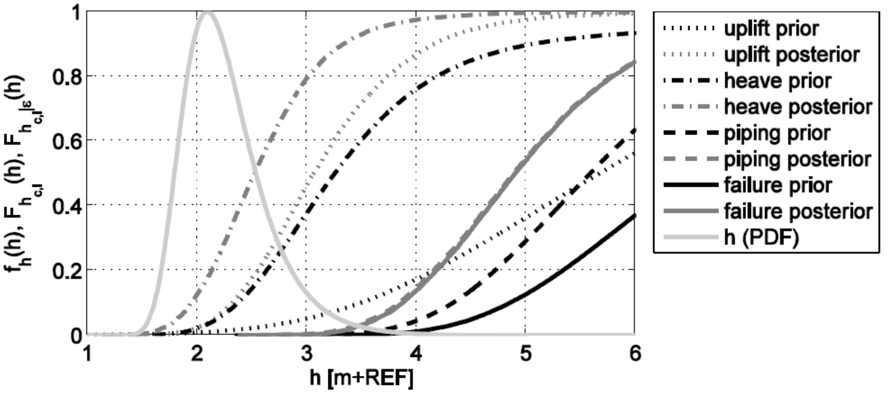


Figure 9: Prior and posterior fragility curves of uplift, heave and piping for an observed sand boil at a case study location in the Netherlands [Schweckendiek et al., 2013]. The continuous light-grey line represents the normalized pdf of the water level.

become much more likely also for lower water levels. And, interestingly, through the common random variables in the different limit state functions (e.g. the permeability of the aquifer); also the probability of piping is affected noticeably.

For the particular example the updated annual probability of failure (i.e. integrated over all water levels), increased by roughly one order of magnitude. At the same time, survival type of information can be used as well, when no signs of (partial) failure are observed. Also for this type of observation changes of one order of magnitude in terms of probability of failure do not seem uncommon. In essence, observing signs of bad performance increase the probability of failure, observing good performance (i.e. no bad performance), decreases it. It is also noteworthy that the major contributions in the changes in probability of failure can often be attributed to uncertainties in the stratification or the presence of potential anomalies rather than ground properties such as the permeability. In other words, the uncertainties about what is in the ground can outweigh the uncertainties on how it behaves.

4.2 *Head monitoring*

Similar to nature itself revealing information on ground-related uncertainties in the form of processes that can be observed visually (see 4.1); we can also actively monitor the levee's response to high flood stages. One possibility is to monitor pore pressures in the aquifer as described in [Schweckendiek and Vrouwenvelder, 2013], where not only the change in probability of failure is quantified for a case, but also the cost-effectiveness of taking such measures is contemplated by means of (pre-posterior) decision analysis.

In contrast to field observations, we would now monitor a system state parameter directly, which means we would obtain the harder to treat equality-type of information (i.e. $h(x) = 0$) [Madsen et al., 1986]. Fortunately, Straub [2011] provides a workable solution. Suppose we install a sensor for measuring the pore pressure in the aquifer at a potential exit point φ_{exit} as illustrated in Figure 10. Just like for field observations, such data can be

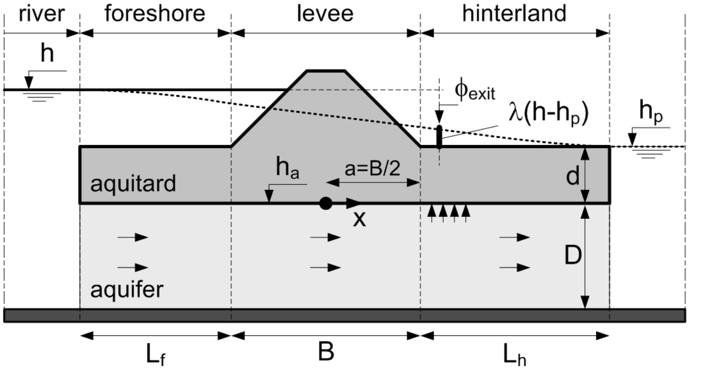


Figure 10: Levee cross section with a low-permeability blanket over-lying an aquifer. The quantity of interest is the piezometric head (i.e. pore pressures) at the exit point (here: levee toe).

used to update the fragility curves for uplift, heave and piping, the annual probability of failure as well as the distributions of the underlying basic random variables. In essence, (conditional) failure probabilities increase, if the observed pore pressure response is higher than expected based on the prior distributions and vice versa. Hence, for a relatively high observed value the updated fragility curves could qualitatively be similar to Figure 9. An example of updated basic random variables is presented in Figure 11.

Clearly the most influential random variable is the permeability *k*, the distribution of which becomes narrower and is shifted to lower values. While further detailed results are omitted here for the sake of brevity, these can be found in Schweckendiek [2013].

Now suppose we would like to know, if installing such a sensor for measuring the pore

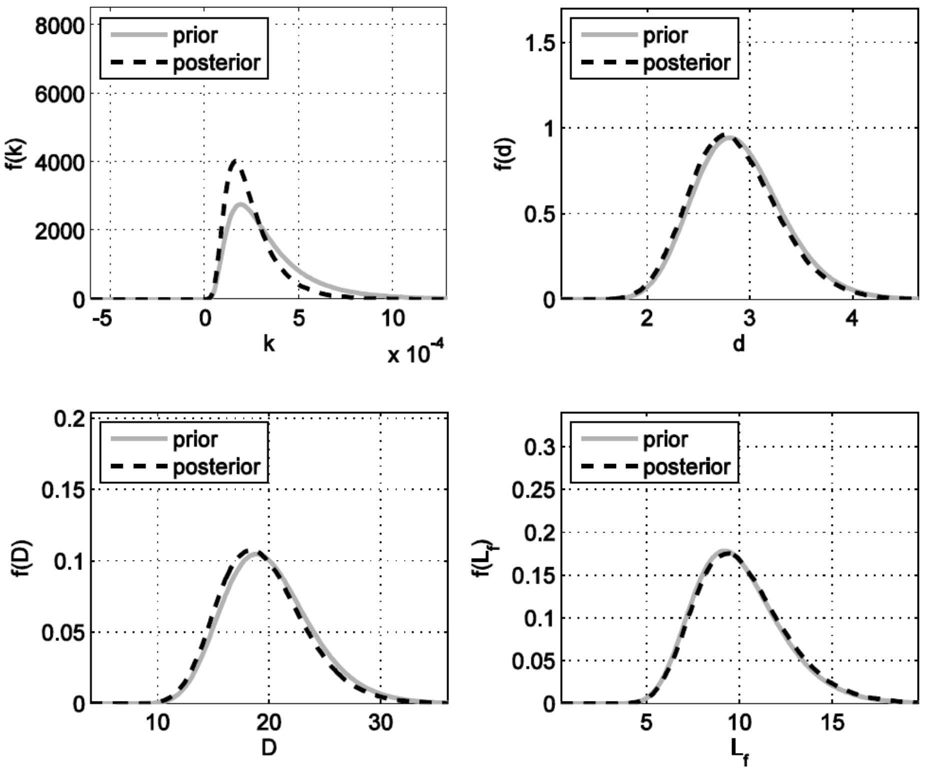


Figure 11: Prior and posterior probability distributions of basic random variables affected by updating based on monitored piezometric head [Schweckendiek, 2013]. In the present example, the measured value was lower than expected a-priori, which results in, e.g., the distribution of the permeability shifting to lower values.

pressure in the aquifer at a potential exit point makes sense economically. In order to do so, we would have to assess the probability distribution of the posterior values of our quantities of interest based on our prior knowledge (i.e. pre-posterior analysis). In essence, we can compare the expected value of the costs with and without monitoring to take risk-informed decision. For example, in a safety assessment setting, we could compare the cost of monitoring to the potential savings in levee reinforcement measures achieved by uncertainty reduction. An essential ingredient herein is the pre-posterior reliability, i.e. the a-priori "expected" distribution of the probability of failure after updating as illustrated in Figure 12 by means of the reliability index (i.e. $\beta = \Phi^{-1}(1 - P_f)$).

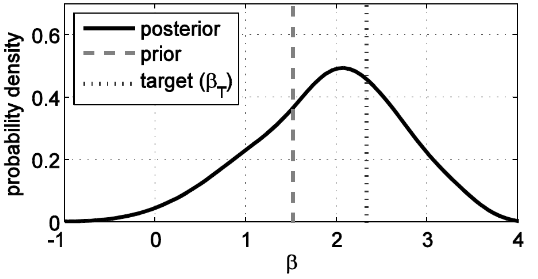


Figure 12: Pre-posterior reliability index illustrating the distribution of the future reliability index after reliability updating('posterior') based on head monitoring data and prior distributions [Schweckendiek and Vrouwenvelder, 2013].

In essence, the example shown in Figure 12 tells us that the reliability index is likely to increase (even though its expected value is equal to the prior, which is inherent to pre-posterior analysis) and that there is a considerable probability of the posterior reliability being greater than the target value (i.e. the probability mass on the right-hand side of the dotted black line).

4.3 Site investigation

It goes without saying that also conventional site investigation can reduce ground-related uncertainties effectively. As with head monitoring (see 4.2), the cost-effectiveness of such measures can be judged by means of decision analysis. Figure 13 shows a decision tree illustrating the decisions, uncertainties and marginal costs typically involved, which are very similar to the monitoring decisions as discussed in the precious section. In essence, the expected savings in retrofitting (or reinforcement) cost have to outweigh the cost for

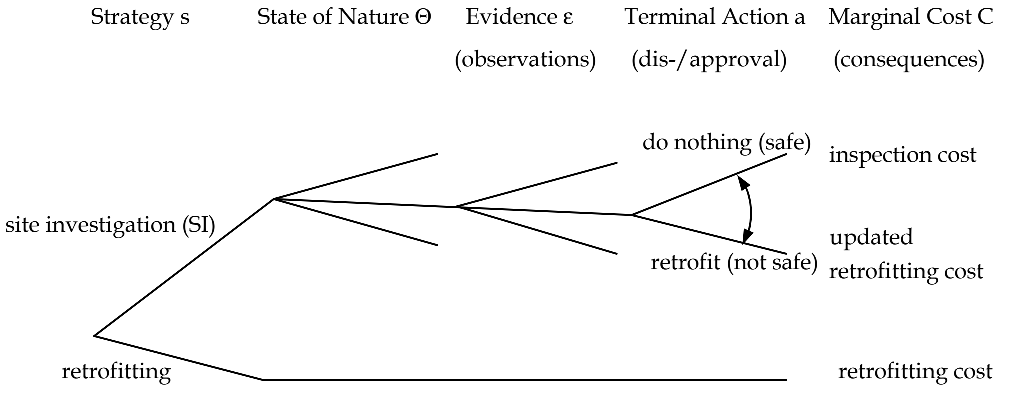


Figure 13: Decision tree for investments in site investigation in a safety assessment setting (Schweckendiek, 2013)

(additional) site investigation. For a detailed discussion on analysing the Value of Information in a Bayesian decision theoretical context it is referred to Straub [2013].
To illustrate the concept we consider the following (simplified) situation (in simplified form, a detailed example with numbers is provided in Schweckendiek et al. [2011]. The probability of piping of a certain levee section is dominated by the potential presence of an adverse geological detail, e.g. a sand lens cutting into the blanket. Now we ask ourselves if searching for such a lens by means of soundings (i.e. CPT or borings) would make sense, and, if so, how dense the grid should be.

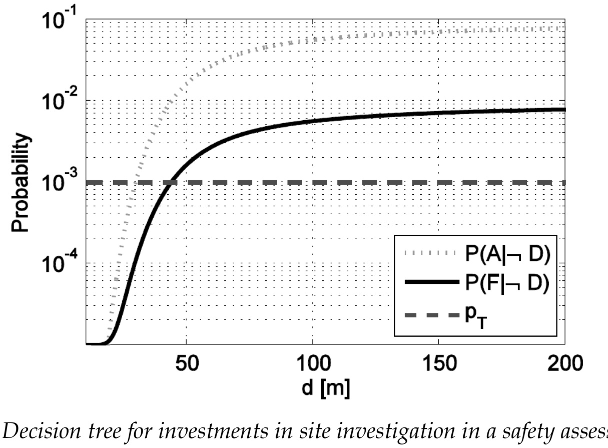


Figure 14: Decision tree for investments in site investigation in a safety assessment setting [Schweckendiek et al., 2011]. (A = presence of an anomaly, F = failure, ⌐D = no detection of an anomaly, p_T = target probability of failure)

To this end, it is important to know what the updated probability of failure would be in case of a negative outcome (i.e. no sand lens found) and for which inter-CPT distance (here *d*) this would result in an acceptable situation, i.e. zero reinforcement cost (or reduced). Figure 14 illustrates this for a simplified example from Schweckendiek et al. [2011], in which case only CPT-distances of less than 50 m would make sense. The same article elaborates on how decision analysis also involving costs can be carried out and that benefit-cost ratios for conducting site investigation can be high (10 to 20 or higher), especially where uncertainty in the stratigraphy is dominant, including anomalies.

4.4 ***Concluding remarks***

We can reduce uncertainties by including additional information from different sources. However, uncertainty reduction is not a panacea for levees with unacceptably low reliability. The new information can go both ways, leading to a higher or a lower probability of failure. On the other hand, even if weak spots are detected, we then know where they are and can take specific and targeted measures. Therefore, it is important to include all those effects in both, the reliability updating but also the cost modelling in a pre-posterior decision analysis, which is a powerful tool for risk-based decision support. Field observations will be usually based on historical data, for waiting for such observations means waiting for extreme high waters and taking your chances (i.e. bearing high risks). The advantage is that the data is obtained with low cost. Monitoring pore pressures on the other hand, requires investments in monitoring equipment and also requires flood stages to be reasonably high to get pore pressure responses which are representative for extreme conditions (think of situations with summer and winter beds in rivers). In this respect, conventional site investigation has advantages because the results can be obtained quickly without the need for high waters. A the same time, we do not observe the levees' responses directly but only obtain local measurements of ground properties, for which the information content with respect to the overall probability of failure is usually lower, except for cases with dominant stratification uncertainties. Roughly speaking, with considerable prior uncertainties all presented types of information can change the probability of failure an order of magnitude in either direction.

5 Reliability of emergency measures for piping

During a critical flood situation several emergency measures are generally implemented by the responsible organizations. Examples are the placement of sandbags, rock or other materials and temporary structures to prevent failure of flood defences. Such emergency measures are generally not taken into account in reliability analysis, and this section presents a framework and examples for the piping failure mechanism, see also (Jonkman et al., 2012) for further background.

*5.1 **General approach***

The performance of emergency measures will depend on the following factors:

- Environmental factors, such as water levels, waves and wind, that will affect the performance of the emergency measures
- Human and organizational factors concerning the effectiveness of operators, organizations and the coordination between these parties, see also [Bea, 2002]
- Logistical factors concerning the transport of materials and equipment (see also de Leeuw et al. [2012])
- Engineering and technical factors: the status and strength of both the existing flood defence and the additional structure that consists of emergency measures.

The above shows that a complex set of factors that concern environmental, organizational, logistical and engineering aspects should be taken into account. For the purposes of reliability analysis we assume the occurrence of some phenomenon that initiates failure of the flood defence if no measures are taken. Examples of such phenomena are critical washing out of sand under a levee or critical overflow. To take into account the effect of emergency measures the following three stages need to be considered:

- Detection of the phenomenon: is the phenomenon detected on time?
- Placement of emergency measures: are the measures positioned in time to stop the levee from breaching?
- Construction: Will the additional "construction", e.g. consisting of sandbags, fail?

The elements are included in an event tree for emergency measures (Figure 15). It becomes clear that this forms a series system. If one of the elements fails (e.g. if detection fails, if placement fails or if the additional construction fails) the emergency measures will not be effective.

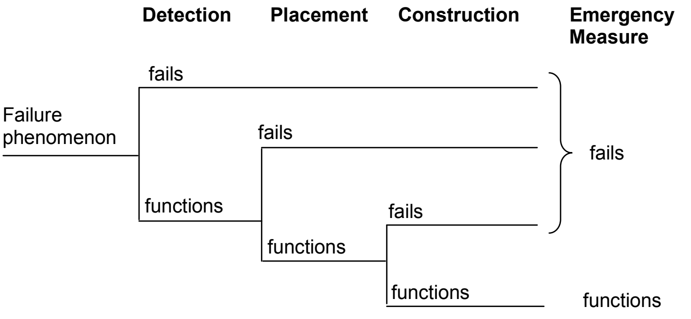


Figure 15: Event tree to assess the reliability of emergency measures

The failure probability of each of these elements needs to be quantified to estimate the effect of the emergency measure. For the failure of the construction an engineering reliability analysis can be applied. For the detection and placement, an analysis of human and organizational task performance will be necessary. For a more simplified and quick analysis (bandwidths for) failure probabilities for various tasks under various circumstances could be used, see e.g. [Bea, 2002].

5.2 Applications to the piping failure mechanism

When the initiation of piping is observed through sand boils forming behind the flood defence, sandbags are often placed as an emergency measure to reduce the hydraulic head difference over the flood defence (Figure 16). A simplified example is elaborated based on the event tree in Figure 15. Based on failure probabilities of human task performance [Bea, 2002] it is assumed that the failure probabilities for detection P_D and placement P_P are estimated at $P_D = P_P = 0.2$ per demand, which is representative for an unfamiliar task. For the failure of the construction P_C a failure probability of $P_C = 0.1$ per demand is assumed. Elaboration of the event tree, while assuming that the elements are independent leads to:

$$P_{ff} = 1-(1-P_D)(1-P_P)(1-P_C) \qquad (7)$$

where P_{ff} is the probability of failure of flood fighting (per demand). With the assumed values $P_{ff} = 0.42$. This simple calculation based on rules of thumb and literature shows that the failure probability of such flood fighting operations is considerable when typical values of human error probabilities are applied.

The emergency measures can now be implemented in the reliability analysis for the piping

Figure 16: Sandbags to prevent piping during the high water in the year 2011 [Source: Waterschap Rivierenland]

failure mechanism. To estimate the total failure probability we have to consider both situations (see also Figure 17): 1) a successful flood fighting, leading to a reduction of the head difference, and; 2) failure of flood fighting with the original head difference. By combination of the two situations we find the total failure probability.

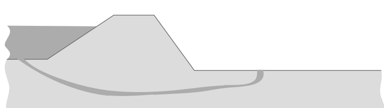
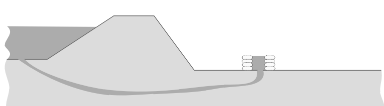
Situation	Head	Piping Probability	Total
Emergency measures not successful 	h	P_0	$P_{ff} P_0$
Emergency measures successful 	h - h_E	P_E	$(1 - P_{ff}) P_E$

Figure 17: Two situations that have to be considered in the reliability analysis including emergency measures. Where: h_E – reduction of hydraulic head due to emergency measures [m]; P_0 – failure probability of the flood defence without emergency measures [1/year]; P_E - failure probability of the flood defence with emergency measures [1/year].

The assumed height of the temporary structure of sandbags determines the reduction of the hydraulic head over the flood defence. Figure 18 shows how the failure probability of a flood defence decreases as a function of the height of the box for an idealized case, in which the failure of emergency measures is not included. If the likelihood of failure of flood fighting is included the effect becomes smaller.

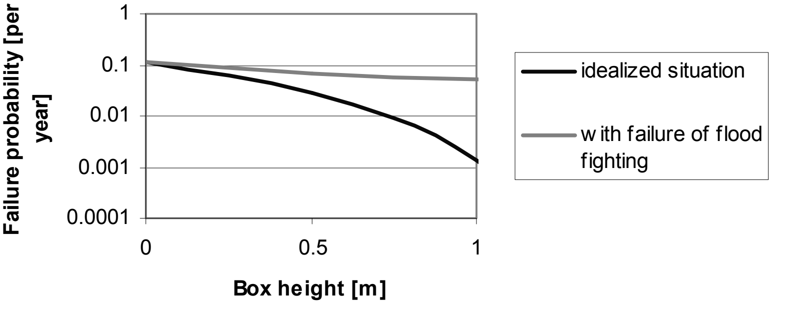


Figure 18: Effect of the height of the box of sandbags on the failure probability (Example from Jonkman et al. [2012], failure probability of flood fighting is assumed P_{ff} = 0.42)

The above concept can be taken into account in a more integrated way in reliability analysis for flood defences. For the case of piping the load and resistance can be expressed in terms of head difference and the related probability density functions (pdf's). The emergency measures increase the strength of the flood defence and the critical head. In the case of successful flood fighting the pdf of resistance would shift to the right side by about 0.5 m (assuming a temporary structure with a height of 0.5 m). However, as indicated above the two situations with and without flood fighting have to be combined to determine the actual pdf of loads with flood fighting and this is shown by means of the dashed line in Figure 19.

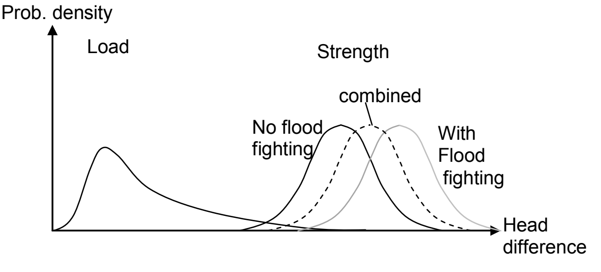


Figure 19: Schematic approach for assessing the effect of emergency measures for the piping mechanism

The above concept has been implemented in combination with a more advanced piping model (the Sellmeijer model) in a reliability analysis for a Dutch river levee [Jonkman et al., 2011]. The initial failure probability was 1/18,000 per year. The probability taking into account the effect of flood fighting, incl. the likelihood of failure of flood fighting P_{ff} is 1/30,000. Thereby the failure probability of the levee due to piping is reduced by 40% which is similar to the values found for more simplified cases.

For other failure mechanisms the same concept can be used. For example, consider placing sandbags on a flood defence to reduce the likelihood of failure due to overtopping or overflow. In that case the value of the pdf of resistance (usually expressed as the height of flood defence) could be shifted to the right to account for the increased elevation achieved with the sandbags.

5.3 Closing remarks

The elaboration and examples in this section have focused on flood fighting for a single location. During a high water event, piping phenomena will likely occur at various locations. This could (negatively) affect the capability to detect and fight all these sand boils. As the flood defence system is a series system (i.e. it fails if one section fails), this may further reduce the effectiveness of flood fighting. The failure probability of the emergency measures will increase if this length effect will be taken into account. In case of a large-scale flood and limited emergency response capacities, decisions may have to be made on how to prioritize the scarce resources and equipment for flood fighting over various areas.

The current calculations are based on simplified estimates of human failure probabilities. It is recommended to perform a further task analysis and a consequent reliability analysis with parties that are responsible for the actual flood fighting (e.g. water boards in the Netherlands). This will lead a) to a more realistic failure probability estimate of emergency actions; b) provide a basis for improving the systems performance and reliability of flood fighting as lessons from the risk analysis could be incorporated in the systems operation. Also, the actual failure mechanisms of the additional "construction" of sandbags could be considered further. It is recommended to perform a more formal analysis of failure mechanisms (height, instability, piping) of the additional temporary construction.

Finally, the management implications of this type of research have to be considered. As indicated above, flood fighting is not expected to result in a drastic decrease of the failure probability of flood defences due to piping. Yet, it could be decided by management organizations that emergency measures are part of the formal flood defence system. In that case the performance of flood fighting should be monitored and periodically assessed as part of the overall inspection and management of the flood defence system.

6 Closing discussion

This paper has given an overview of new insights associated with the piping failure mechanism based on research done in the Netherlands. Considerable efforts in physical and mathematical modelling have led to updated failure models for piping. There are also various new insights related to the inclusion of the piping failure mechanism in reliability analysis that are not yet included in standard practice. The main findings and contributions for the various elements are summarized below:

- Physical model: The transition from older empirical models to more recent mixed process-based and empirical models results in higher computed failure probabilities
- Length effect: high uncertainties in the length-direction of the levee have a very significant effect on the piping failure probability, of up to a factor 100 for very large levee rings. Spatial averaging in the width direction may reduce the failure probability with over a factor 10, but could also increase for certain scales of fluctuation in the subsoil properties.
- Field observations, monitoring and site investigation can all be used to reduce (especially ground-related) uncertainties. One needs to be aware of the fact that additional information can go both ways, to increasing or decreasing the probability of failure; the changes can be an order of magnitude roughly speaking. However, the effect on the overall cost is usually positive, because even if weak spots are revealed, reinforcement measures can be tailor-made and targeted at the locations of interest.
- Emergency measures can reduce the failure probability, but their effectiveness is highly dependent on organization and logistical factors. Based on simplified calculations it is expected that emergency measures can reduce the likelihood of failure by about a factor two for an individual location. This reduction factor will be smaller when the occurrence of multiple piping locations during an emergency and the length effect is considered.

Overall, a probabilistic approach is needed to quantify the effects of various measures in a combined and integrated way. It is recommended to elaborate multiple case studies in which the different factors are combined for various situations and levee sections.

The knowledge of the physical and probabilistic aspects will provide a basis for further interventions to reduce the flood risks associated with piping failures. If there are large uncertainties associated with soil conditions, further soil borings and observations could be recommended. The piping resistance of unsafe sections can be improved by means of interventions aimed at increasing the available seepage length. However, over the last decade there have been considerable changes in the formulation for the required seepage length, leading to continuous large-scale interventions in the field. As another direction it is recommended to pay more attention to interventions that attempt to eliminate one of the sub-mechanisms of piping. This could entail filter constructions on the inner side to reduce the local pressure gradients while preventing the sand particles from eroding (e.g. relief wells).

For these design considerations a thorough understanding of the local situation is required as well as of the factors and uncertainties that have the largest influence on the failure probability. Also for these decisions related to various measures and actions, a risk-based framework will offer guidance to optimize the interventions.

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