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Developments in Levee Reliability and Flood Risk Analysis in the Netherlands

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Abstract. This paper presents and overview of advances in flood risk and levee reliability analysis in the Netherlands. It is described how new safety standards – in the form of a target failure probability – have been derived on the basis of nationwide flood risk assessments which taken into account both economic risk and risk to life. The process for derivation of semi-probabilistic design codes (i.e. factors of safety) for various geotechnical failure mechanisms of flood defences is described and it is shown how these semi-probabilistic requirements are consistent with the target probabilities of failure and ultimately with the underlying flood risk acceptance criteria. The newly introduced approach also raises challenges like the introduction of fully reliability based design and assessment techniques, but it also provides opportunities such as the use of reliability updating and data assimilation, which will be highlighted after discussing the framework and its overall coherence.

Keywords. flood defenses, levees, flood risk, reliability, failure modes, safety standards, acceptable risk, code calibration

1. Introduction

The majority of the global population is located in flood prone coastal deltas, coastal areas and along rivers. Failure of flood defences (also named levees, dikes or embankments) during extreme events can lead to enormous damage and loss of life. This has been shown numerous times, for example during the 1953 storm surges along the North Sea, but more recently when the levees around New Orleans failed during hurricane Katrina in the year 2005. Therefore, an adequate understanding of the risk and reliability of flood defense systems is essential for management and design purposes (Jonkman and Schweckendiek, 2015).

The issue of flood risk management is of particular importance for the Netherlands, since most of the country is prone to flooding and protected by a system of primary flood defenses of a length of almost 3800km. Over the past decades significant progress has been made in developing techniques for risk and reliability analysis for flood defense systems in the Netherlands. Recently, the results of a nationwide flood risk analysis have been published providing detailed insights in failure probabilities, consequences and risk levels for all major flood prone areas (Rijkswaterstaat, 2015; Jongejan and Maaskant, 2015). Also in other countries around the world significant progress has been made in developing methods and tools for assessing risks and reliability of flood defence systems, for example in the UK (Hall et al., 2003), USA (IPET, 2009) and China for the Shanghai region (Xiabi et al., 2013). Overall, it can be observed that the insights from risk and reliability analyses are now at a stage that they can be more directly applied in policy making (e.g. for safety standards), design and management of flood defense systems. This is also illustrated by the recent decision of the Dutch government to propose new safety standards in the form of a tolerable failure probability for a reach of flood defenses (see section 3 for further details). The values of the standards are based on the nationwide flood risk assessment. Consequently, the protection standards can be “translated” into (semi-probabilistic) design codes and rules for various (geotechnical) failure mechanisms – see figure 1.

The objectives of this paper are to give an overview of relevant developments in flood risk and reliability analysis in the Netherlands. The paper will also address how the insights from risk and reliability analysis are incorporated in the design codes for flood defenses. The paper builds on a number of earlier publications on related topics that will be cited throughout this publication. This publication focuses on methods and results from the Netherlands, but the information is expected to be of international relevance, since risk- and reliability-based approaches are developed in several countries.

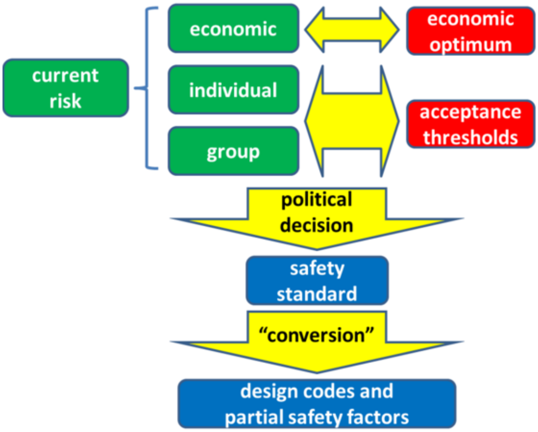

Figure 1: Framework for risk-informed derivation of design values for loads and resistances (LRFD)

The paper is structured according to the framework shown in Figure 1. Section 2 outlines in the approach and outcomes of flood risk assessment. Section 3 will describes the new safety standards and the difference with the existing standards. Section 4 focusses on the derivation of codes and factors of safety for actual levee design. Section 5 addresses how the understanding of the safety and reliability of existing flood defenses can be improved by techniques such as data assimilation, monitoring, sensors etc. The final section contains concluding remarks and resumes some challenges in the field.

2. Flood Risk Assessment

2.1. Flood Risk Analysis : Approach

The aim of a flood risk analysis is to assess the probabilities and consequences of flooding as a basis for risk evaluation and decision-making. In the Netherlands a nationwide flood risk analysis has been performed for all primary flood defenses along the coasts, rivers and lakes in the project VNK (Veiligheid Nederland in Kaart). The approach is typically applied at the level of a flood protection system for a single area and follows the following five steps:

1. **Flood hazard analysis:** the frequencies of hydraulic loads, such as water levels and waves are assessed by means of statistical analysis and hydraulic modelling
2. **Reliability analysis of the flood defense system:** This includes the decomposition of the flood defense system into homogenous sections and the calculation of the failure probabilities per section and failure mechanism; see Jongejan and Maaskant (2015) for further details. Various (geotechnical) failure mechanisms are taken into account, such as instability, piping or overtopping. Ultimately, the probabilities of all system components and failure mechanisms are combined to a (sub-)system probability of failure (i.e. the occurrence of a breach in a dike reach).
3. **Breaching and flood scenarios**: In this step the development breaches in the system is modelled as well as the subsequent flooding of the protected area. The latter is generally achieved by 2-dimensional hydrodynamic models.
4. **Damage and life loss estimation**. Using the results (i.e. flooding parameters) of the previous step, economic damages are determined taking into account the land use in the flooded area and using stage-damage functions. Methods have been developed for life loss estimation that consider the number of people exposed, possibilities for evacuation and so-called mortality functions that are dependent on flood conditions (Jonkman et al., 2008).
5. **Risk quantification and mapping:** the results from the previous steps are combined to display and map the risk using different risk metrics. The economic risk refers to expected economic damages. Risks to life are expressed by means of individual risk (the probability of being killed by a flood at a certain location – including the effects of evacuation) and societal risk (the probability of events with large numbers of fatalities).

2.2. Flood Risk Analysis: Examples of Results

A number of examples of the outcomes of the nationwide flood risk analysis will be presented at the local and national scale.

As an example of results for a local system Figure 2 shows the results for the flood protection system (dike ring) “Land van Heusden / de Maaskant”, in the south-east of the country bordering the river Meuse. The population is about 420,000 inhabitants and the area contains cities such as Oss and ‘s-Hertogenbosch. The total length of flood defenses is about 100km and the area 66,600 ha.

Analysis of the failure probability leads to an estimate of the probability of flooding of more than 1/100 per year. Figure 2 contains the failure probability estimates of the individual dike sections. The main threat is the piping failure mechanism (backward internal erosion), which contributes to 80% of the failure probability. The second largest contribution (15%) stems from hydraulic structures located in the defense line.

By combining the computed failure probabilities to flood scenarios, damage and life loss assessments, risk levels can be determined and expressed in various ways. Societal risk is generally expressed by means of a so-called FN-curve. It shows the probability of exceedance of events with certain numbers of fatalities; see Figure 3 for the investigated area. The potential number of fatalities in case of larger floods of the dike ring can reach more than 100 to 800 fatalities. The expected number of fatalities per year equals 0.3. In addition, an individual risk map was generated (not shown here) and the economic risk was estimated. The mean damage in case of flooding equals € 1.5 billion, and the expected annual risk amounts to €16.6 million. The risks can be decreased substantially by reinforcing a few weak dike sections.

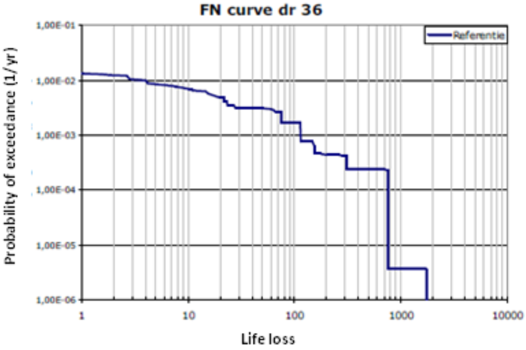

Figure 3: FN curve displaying the societal risk for “Land van Heusden / de Maaskant” (VNK, 2014).

By combing the results of the risk analysis for individual flood protection systems, a national assessment of flood risk can also be created. Figure 4 shows an estimate of the individual risk level with the current state of the flood defenses. It shows that large parts of the country, the areas in orange, are characterized by IR levels higher than 10^{-5} per year. This is mainly due to the fact that the estimated failure probabilities of the defenses along the main rivers are estimated to be rather high (in the order of magnitude of 1/100 per year especially due to the influence of

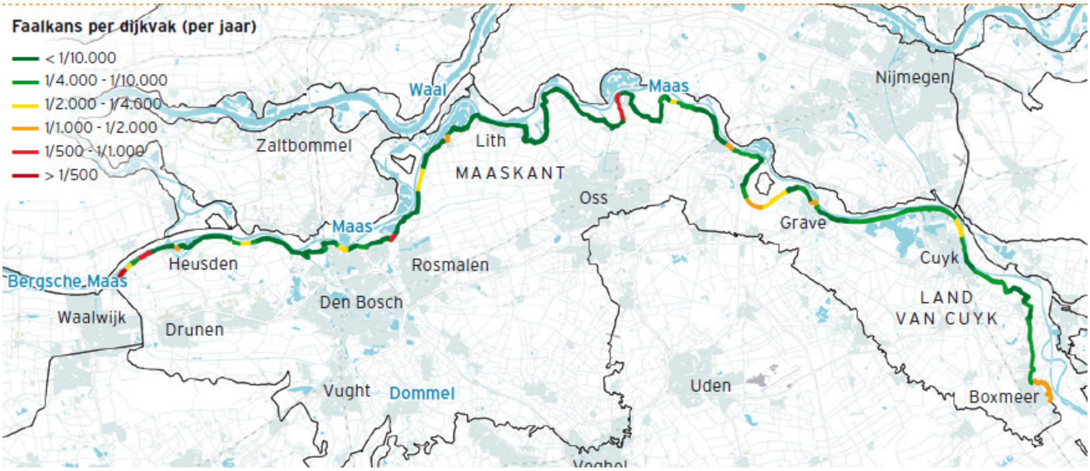

Figure 2: Failure probabilities of dike sections in “Land van Heusden / de Maaskant” (VNK, 2014).

geotechnical failure mechanisms). In addition to the individual risk, the economic and societal risk have also been assessed at a national level. For the societal risk analysis at a national scale, also event scenarios with flooding of multiple systems (dike rings) were considered (Deltares, 2014).

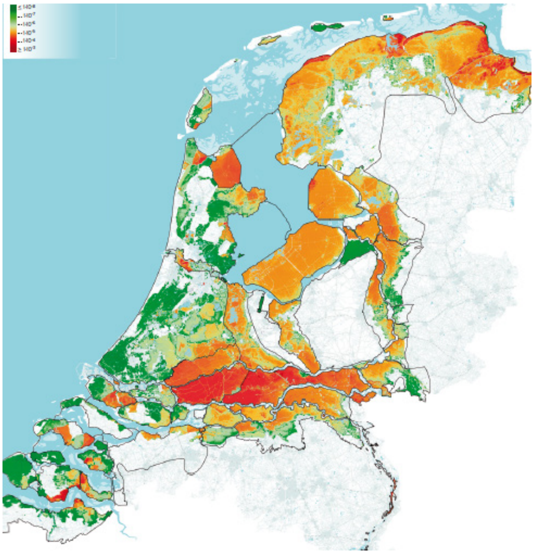

Figure 4: Estimated individual risk for flooding the Netherlands (Rijkswaterstaat, 2015). Colours indicate the following: red: IR>10^{-5} yr^{-1}; orange 10^{-5} yr^{-1} <IR<10^{-5} yr^{-1}; green: IR<10^{-6} yr^{-1}.

3. Derivation of New Safety Standards

3.1. Background: Old vs. New Standards

The results of the nationwide flood risk analyses have been used to derive new safety standards for flood defenses. The old (or existing) standards are formulated in terms of a probability of exceedance of hydraulic load conditions (water levels, waves) that a flood defense should be able to withstand safely. For example, the flood defenses in the densely populated dike ring of South Holland along the Dutch coast have a safety standard of 1/10,000 per year. For other areas with somewhat lower potential damages values hold ranging from 1/250 per year to 1/4000 per year. These standards were derived several decades ago and mostly refer to the frequency of the design load conditions.

The Dutch government has proposed new safety standards in the form of acceptable or target failure probabilities for sections of flood defenses. The change has been motivated by two main reasons. Firstly, the protected values and size of the population in the flood prone areas has grown rapidly. Secondly, new insights in failure mechanisms and failure probabilities of flood defenses have been obtained in the studies on flood risk and levee reliability from the past decades (see previous sections).

3.2. Acceptable Risk

These new standards have been derived in a "risk-informed" way, i.e. outcomes of the nationwide risk studies have been used to determine the new safety standards. . The values of the standards have been chosen such that the risk levels would become acceptable. Three criteria have been considered (see Schweckendiek et al., 2012, Jonkman et al., 2011; and Vrijling et al, 1998):

- Individual risk: the government has proposed that areas of individual risks higher than 10^{-5} per year are insufficiently safe. For these areas dike reinforcements and higher safety standards are required (or other forms of risk reduction)
- Societal risk: no explicit limits (FN limit lines) have been proposed. Alternatively, it was investigated which areas have the highest contribution to the societal risk at the national level. For the systems with the highest contribution to national societal risk, a somewhat higher protection was proposed.
- Economic risk / cost benefit analysis: an economic optimization of costs and risk reduction for various levels of dike reinforcements was performed. For every flood protection system, an optimal level of protection was determined (Deltares, 2014; Eijgenraam, 2006)

In principle, the most stringent of the three criteria is used to derive a proposed safety standard.

3.3. New Safety Standards

Figure 5 shows the new safety standards in proposed by the Dutch Delta Program (2014). A first major change is that these standards refer to the acceptable failure probability (or target failure probability) of a flood defense system, whereas the old standards referred to the probability of exceedance of design loads. This implies that for the new standards multiple failure mechanisms and the length effect need to be incorporated in the design and safety assessment. The second change concerns the protection levels and distribution over the country. In the new safety standards highest protection levels (1/10,000 to 1/100,000 per year) are found along coastal areas and riverine areas. In the previous safety standards the highest protection levels were found in the west of the country (1/10,000 per year for South Holland). One may say that the recent insights from reliability and risk analyses have led to more attention being paid to flood risk originating from the large rivers compared to the last decades where the focus was on coastal flooding after the 1953 coastal flood disaster.

Figure 5: Proposed new safety standards for flood defenses in the Netherlands, in the form of target failure probabilities for a system (Delta program, 2014).

In the coming years, these new safety standards will be incorporated in dike reinforcements and safety assessments. One important question that has received limited attention is how these new standards safety targets can be attained through dike reinforcements and other system interventions. Significant implementation costs and societal implications could affect the discussion on the desired levels of protection. For the purposes of design and safety assessment of levees, it will be necessary to relate the target failure probabilities to design properties of the flood defense (e.g. height, width, etc.), as discussed in the next section.

4. Design and Safety Assessment

Unlike other civil engineering structures, flood defenses in the Netherlands are generally not designed and assessed according to Eurocode requirements. In order to meet the specific safety standard as discussed in the previous section, dikes or other flood defenses can either be designed or assessed in a fully probabilistic fashion, or using specifically derived partial safety factors.

The steps below provide a brief summary of what is described more in detail in Schweckendiek et al. (2012).

4.1. System Reliability and Length-Effect

First of all the design and assessment framework acknowledges the fact that the flood defense for which the safety standard defines a target probability of failure consists of different components (i.e. structures, dike reaches), some of which have a considerable length.

In a risk or system reliability analysis we typically deal with this by organizing the components and their dependencies in a fault tree in order to combine the individual probabilities of failure. For design and assessment purposes we virtually have to do the inverse and assign target reliabilities to each component such that the probabilities of failure combined meet the safety standard (i.e. target probability for the entire reach or system). The most straightforward way to achieve this is by dividing the overall target probability by the number of components. The approach currently being followed is rather based the contributions of the individual types of structures based on the experiences from the nationwide risk analysis (VNK project).

Also within a single dike reach we need to take care of system effects. The so-called "length-effect" is the phenomenon that the probability of failure of a statistically homogeneous dike section grows with its length. The intuitive explanation is that with variable ground conditions, the probability of encountering a weak spot is larger the longer the considered section is. A rather comprehensive treatment of the problem for dikes, focusing on internal erosion (piping) can be found in Kanning (2012), the work in which is based on random field theory as introduced by Vanmarcke (1983) and later applied by many other scholars in the geotechnical domain. Also here we need to follow and inverse approach to determine the target probability of failure for a representative cross section, which then will be stricter (i.e. lower) than the target probability for the entire reach (for examples refer to Schweckendiek et al., 2012).

4.2. Failure Mechanisms

Consequently and similarly, the approach deals with the fact that each component of the flood defense system can fail due to different failure mechanisms, as illustrated in Figure 6. The target probability of failure for an individual failure mechanism is stricter (lower) than the target probability for all failure mechanisms together. Again the most straightforward way to achieve compatibility of the target probabilities is to divide the overall target probability by the number of failure mechanisms considered. Also here the Dutch approach to the problem is slightly more sophisticated. The target probabilities per mechanism are chosen such that their sum does not exceed the overall target and that the contribution or share of each approximately resembles the current contributions found in the VNK-project. This approach has proven to be efficient in the sense that is leads to the least negative outcomes in a safety assessment as compared to other approaches.

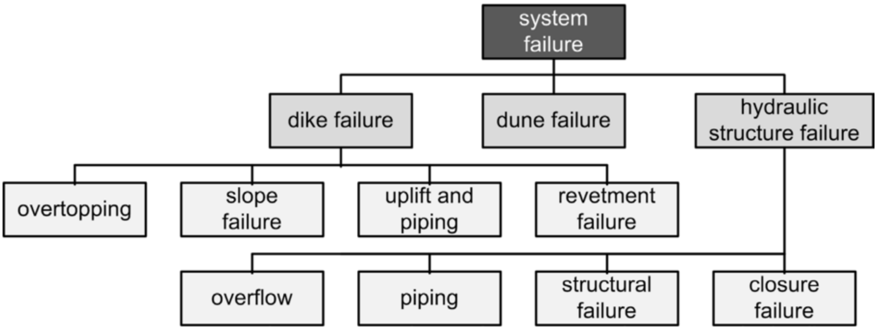

Figure 6: Fault tree of a typical, simplified flood defense system (adopted from Schweckendiek et al., 2012; notice that all connections in the tree are OR-gates)

4.3. Calibration of Partial Factors (LRFD)

With the two elements discussed, the system reliability considerations and the failure modes, we are able to obtain a target probability of failure for each failure mechanism of each component in the flood defense system. At the time of writing, extensive calibration studies are being carried out. The outcome are sets of partial safety factors which need to ensure that a design meeting the semi-probabilistic requirements using these factors is at least as safe as the required target probability.

A novelty in the envisaged Dutch approach is that one of the partial resistance factors will be reliability-dependent for most failure mechanisms. That means that the partial factor increases with the target reliability. The reliability-dependence was deemed necessary due to the large ranges of target reliability to be encountered throughout the domain of application. The approach is similar to the reliability classes used in, for example, Eurocode, with the distinction that the Dutch approach will not use classes but continuous functions.

Details and examples of such calibration studies can be found in Lopez de la Cruz et al. (2011), Schweckendiek et al. (2012) or Jongejan and Calle (2013).

4.4. Summary

To summarize, the Dutch framework under development for full- and semi-probabilistic design and assessment is illustrated in Figure 7 (it is a more detailed version of figure 1). It breaks down the risk-motivated target probabilities of failure for flood defense systems into target probabilities of failure for individual components and failure mechanisms. Together with the partial safety factors calibrated to them they form a coherent set of requirements to ensure that the flood risk becomes acceptable or remains at acceptable levels.

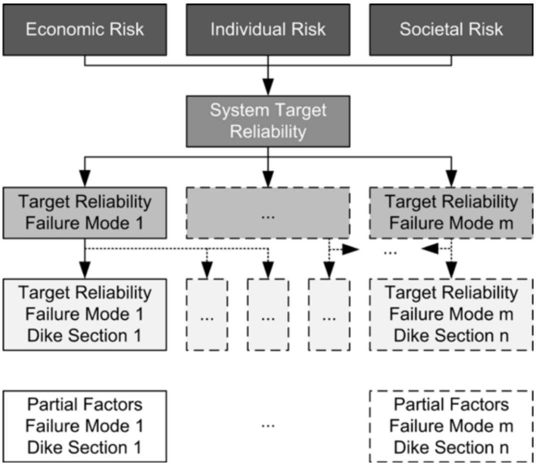

Figure 7: Framework for full- and semi-probabilistic design and assessment based on risk-motivated target reliabilities for flood defense systems (adopted from Schweckendiek et al., 2012)

5. Challenges and Opportunities

The new framework being adopted, using acceptable probabilities of flooding, poses challenges to the (engineering) community, but it also opens up opportunities. In the following, we comment on a few which are of particular relevance to practitioners and researchers in the areas of geotechnical reliability and risk.

5.1. Reliability Updating with Performance Observations

Performance observations and monitoring data of flood defenses are mostly used in a qualitative fashion and usually as indicators for malfunctioning of a structure. A Bayesian probabilistic framework, on the other hand, allows incorporating additional information systematically and quantitatively to update our reliability estimates. Also data from different sources can be combined.

Zhang et al. (2011) demonstrated how site-specific information on survival of loads a dike was subjected to can be used for reliability updating with slope stability. Similarly, Schweckendiek et al. (2014) showed how observations of seepage, sand boils (see Figure 8) or their non-occurrence (i.e. survival) can be incorporated in the reliability estimate for the piping mechanism. We expect that the incorporation of performance observations will also be taken up in Dutch assessment practice, especially where the probability estimates are close to the reliability targets.

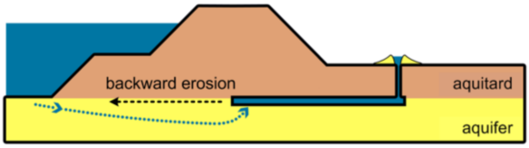

Figure 8: Formation of sand boils due to under-seepage and backward internal erosion

5.2. Monitoring and Site Investigation

Likewise, data from monitoring relevant performance indicators can be incorporated in the reliability estimates by means of Bayesian Updating or data assimilation techniques, preferably using physics-based models to construct the likelihood or observation functions. For example, Kanning et al. (2015) apply reliability updating with structural reliability methods (Straub, 2011) to pore water pressure monitoring data for a levee along the Mississippi river.

Schweckendiek and Vrouwenvelder (2013) used a similar reliability updating approach for a simplified fictitious example, yet extended to decision analysis for monitoring planning. Their proposed method, based on pre-posterior analysis, allows to ponder the investments in monitoring campaigns with the effects on the retrofitting designs and costs to bring a dike up to the required safety standard (see decision tree in Figure 9 for illustration). In other words, dike managers are provided a tool to take decisions on monitoring investments in order to minimize the (expected) total cost of monitoring and retrofitting.

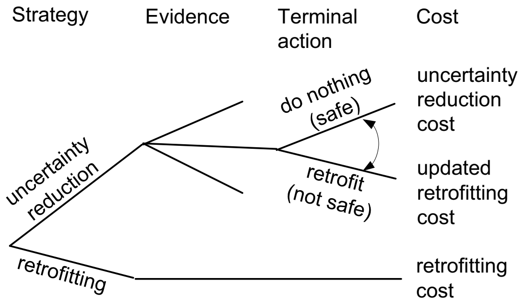

Figure 9: Conceptual decision tree for the decision whether or not to invest in uncertainty reduction by, for example, monitoring or site investigation. It is straightforward to operationalize and extend such a tree to the optimization of the monitoring or site investigation parameters.

The framework fits well into the concept of Value of Information in Structural Health Monitoring as illustrated in Schweckendiek and Vrouwenvelder (2015).

While most available references yet use conventional monitoring and site investigation techniques, there are no conceptual or methodic barriers to apply such reliability updating and decision analysis to innovative sensors or the use of big data, applications we will likely see in the near future.

5.3. Numerical Analysis

While traditionally the largest share of the Dutch flood defense system consistent of earthen dikes, future reinforcement efforts will entail mostly (a) earthen dikes reinforced with structural elements like cut-off walls or seepage screens and (b) hydraulic structures like sluices or locks in the defense line. The reliability assessment tools for the conventional earthen dikes are well developed and frequently used by a relatively wide group of experts and engineering practitioners. Yet, where structural elements need to be considered in conjunction with soil behavior, we typically need to resort to numerical analysis (e.g. FEM). The main challenges here are computation time and (at times strong) non-linearity of the performance functions (i.e. failure mechanisms).

The main specific challenge for dikes is the uncertainty modeling of the pore water pressures, both in terms of initial conditions as well as their response to flood loading. Moellmann (2009) successfully used FORM with response surfaces for numerical analysis of the groundwater flow through and stability of a river dike. His examples considered rather homogeneous embankments and did not, however, include structural elements in the dike body. Challenges remain to solve problems as illustrated in Figure 10, as FORM is typically not applicable for dike with structural elements inside. The key issue here is the system behavior between the different limit states (e.g. failure of the wall or the anchor and overall instability), leading to convergence problems.

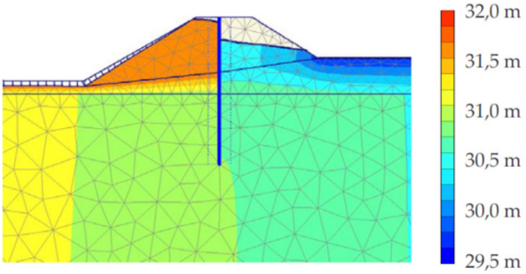

Figure 10: Distribution of hydraulic head in a river dike reinforced with a cut-off wall in the crest. Example of the relevant type of structure presented in Moellmann (2009), which was not analysed probabilistically in the thesis.

Zhang et al. (2015) present promising efforts to enable reliability analysis with FEM using response surfaces, demonstrated by two classical geotechnical problems. Yet, additional developments are required for the application to dike reliability.

Similar challenges arise, as more elements of seepage control enter the designs such as drainage filters or relief wells. Miranda et al. (2015) demonstrate how relief well systems can be designed probabilistically using an analytical model; probabilistic assessment and design of filters, their stability and their effect on other failure mechanisms needs yet to be developed, though much can probably be adopted here from the design and assessment of large dams.

5.4. Back-Analysis of Failures

Most recent dike failures in developing countries occurred by overflow and overtopping, implying that the dikes are not high enough to withstand the water levels (and waves) they were exerted to. Most recent failures in developed countries with engineered flood defense systems are of geotechnical nature, the most common failure mechanisms being internal erosion and instability of the landside slope (Jonkman and Schweckendiek, 2015). Compared to overtopping, where there is reasonable insight in the mechanisms (including guidance on overtopping design, see e.g. EurOtop manual by Pullen et al., 2007), the model uncertainties surrounding geotechnical failure mechanisms are very large and often even dominate the probabilities of failure.

Experimental work in the laboratory can be part of the solution, however, the key to reducing these uncertainties will be exposing our modeling efforts to comparisons will real scale dikes and realistic loading conditions. Besides using full-scale prototypes such as recently the IJdijk facility in the Netherlands (e.g. Zwanenburg et al. 2012, see Figure 11), well-documented historic failures have great potential for back-analysis and improving our understanding of the model error. Also breach models can benefit from back-analysis of historical failures.

5.5. Education and Training

Even though in the Netherlands we have a rather extensive track record in the university education of civil engineers in reliability and risk, further intensification of education and training efforts will be paramount for a successful take-up in practice. We believe that this is an international issue, recognized by many peers.

In doing so, our strong belief is that application-oriented training is essential in order to show the practicability of reliability- and risk-based approaches and their benefits compared to conventional assessment and design. Currently, we observe that incorporation of probabilistic assessment and design exercises in regular courses (i.e. not the ones specialized in the matter) is showing initial success. This is underpinned by many MSc-theses being written in the field and, more importantly, by feedback from young engineers dealing with probabilistic methods in their professional practice.

6. Concluding Remarks

The recent nationwide VNK-studies (VNK, 2014) have led to better insights in the actual risk and reliability levels associated with flood defense systems in the Netherlands, including the geographical distribution of risk over the country and potential hotspots that need to be targeted. Outcomes of these risk studies are now also used for prioritizing dike reinforcements.

Figure 11: Full-scale test embankment failure at the IJkdijk facility in the Netherlands. For more information refer to Zwanenburg et al. (2012). Source: Deltares.

The new safety standards and underlying principles will become part of the formal / legal flood management system, and will be implemented in the coming years. The envisaged starting year for the formal safety assessments of essentially all (primary) flood defenses is 2017. The derivation of concrete engineering requirements from these standards in terms of acceptable probabilities of flooding is challenging and ongoing at the time of writing.

The introduction of the approach poses challenges to practicing engineers, regulators and researchers alike. While semi-probabilistic design and assessment rules will be made available, a fully probabilistic approach can be followed, too, requiring a profound understanding of reliability and risk. We will need to train future and currently practicing engineers to master these concepts in order to fully benefit from their potential. At the same time, tools need to be provided for practitioners allowing them to focus on the engineering aspects and not to have to deal with the mathematical details of computing probabilities of failure. As indicated, this will require more effort where numerical analysis is involved that for analytical or empirical relations.

Besides the challenges posed by the new approach, it also opens up new opportunities, especially in using available data more effectively and in a more rigorous, quantitative manner. Also the acquisition of new data can be planned more systematically using decision analysis.

Eventually, a better understanding of the risks and reliability of flood defenses will contribute to safer and more cost-effective designs, and ultimately to reducing damages and life loss. We hope that the experiences in this domain motivate others to explore similar possibilities in other fields of application. The challenges seem manageable, while we are convinced that the benefits and opportunities will outweigh the initial difficulties to be overcome in the implementation.

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