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41. Dresdner Wasserbaukolloquium 2018
„Wasserbauwerke im Bestand – Sanierung, Umbau, Ersatzneubau und Rückbau“

Risk-based safety standards and safety assessment tools in the Netherlands

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The Netherlands has established new safety standards for flood defences since 2017. This paper describes the definition and format of the new standards, as well as the tools that have been developed to carry out the assessments in practice. The assessment itself is a layered approach from coarse to fine, including the possibility to work with a conventional semi-probabilistic approach (with partial safety factors), or to opt for full probabilistic analysis. After describing the main features of the assessment, two examples are given for the failure modes of wave overtopping and slope stability. We conclude by pointing out the main differences between the old and the new assessment, and the advantages and opportunities of the new approach.

Keywords: flood risk, dikes, assessment of flood defenses, semi-probabilistic

1 Introduction

Large parts of the Netherlands are flood-prone. Potential damages are extremely high especially in the along the Dutch coast and along the major rivers Rhine, Meuse and IJssel; the threat from floods is existential. The project VNK2 (‘Veiligheid Nederland in Kaart’; *Vergouwe, 2014*) has provided an extensive analysis of the flood risk in the entire country, using a combination of flood defense reliability analysis and consequence estimation through flood simulations (i.e. risk = probability x consequence). Risk was analyzed in economic terms as well as in terms of risk to life in the reference year 2015. Simultaneously *Kind (2010)* compared investments in flood defenses with the risk reduction achieved in terms of a cost-benefit analysis, using the Optimalisering model as described in *Brekelmans et al, (2014)*. The objective was to determine economically optimal protection levels for the year 2050, taking into account estimates for climate change and economic growth until that date. Kind’s study was part of a larger policy study called WV21 (Dutch acronym for Flood Protection in the 21st century), the objective of which was to provide input for policy decisions related to long term flood risk management (e.g. *Deltares* 2011). Ultimately, new safety standards for flood defenses were derived standards in terms of ‘acceptable probabilities of flooding’ based on the results of both VNK2 and WV21. Ultimately, they were embedded in law and are in force since 2017.

Figure 1: Proposed new safety standards for flood defences in the Netherlands, in the form of target failure probabilities for a system (*Delta Program*, 2014)

The current challenge with the new safety standards is to develop and bring into practice assessment and design codes, which are consistent with the acceptable probabilities of failure (flooding) the standards demand. The main difference with the former codes is that instead of considering a load event (e.g. storm, river flood or a combination) with a certain return period, we now need to consider a wide range of possible load events with their respective probabilities. Also uncertainties on the resistance side need to be considered explicitly.

While the responsibility for assessing and managing flood defenses lies with the regional and national water authorities, the National government is responsible for providing the assessment and design guidelines and tools to meet the new standards. In order to do so, the WBI-2017 project has been preparing guidelines and tools since 2012, *Slomp (2016)*. The assessment can be done semi-probabilistically (i.e. with partial safety factors) or fully probabilistically; the partial factors for the semi-probabilistic assessment were calibrated ensure that the required probabilities of failure are met.

The outcome of an assessment, which is planned to take place in 12-year cycles, is whether or not a dike reach meets the safety standard. In case of noncompliance, the dike (or other flood defense structure) needs to be reinforced. To that end, a national reinforcement program HWBP *Jorissen et al (2016)* has been established with the task to meet the safety standards by 2050 in the entire Netherlands.

Section 2 will provide an overview of the assessment and design instruments currently being developed and brought into practice. Section 3 provides an example of the assessment for the failure modes wave overtopping and slope instability respectively. A reflection of the advantages and challenges of the new approach is discussed in the concluding section 4.

2 Flood defense assessment tools (WBI-2017)

2.1 Overview of instruments

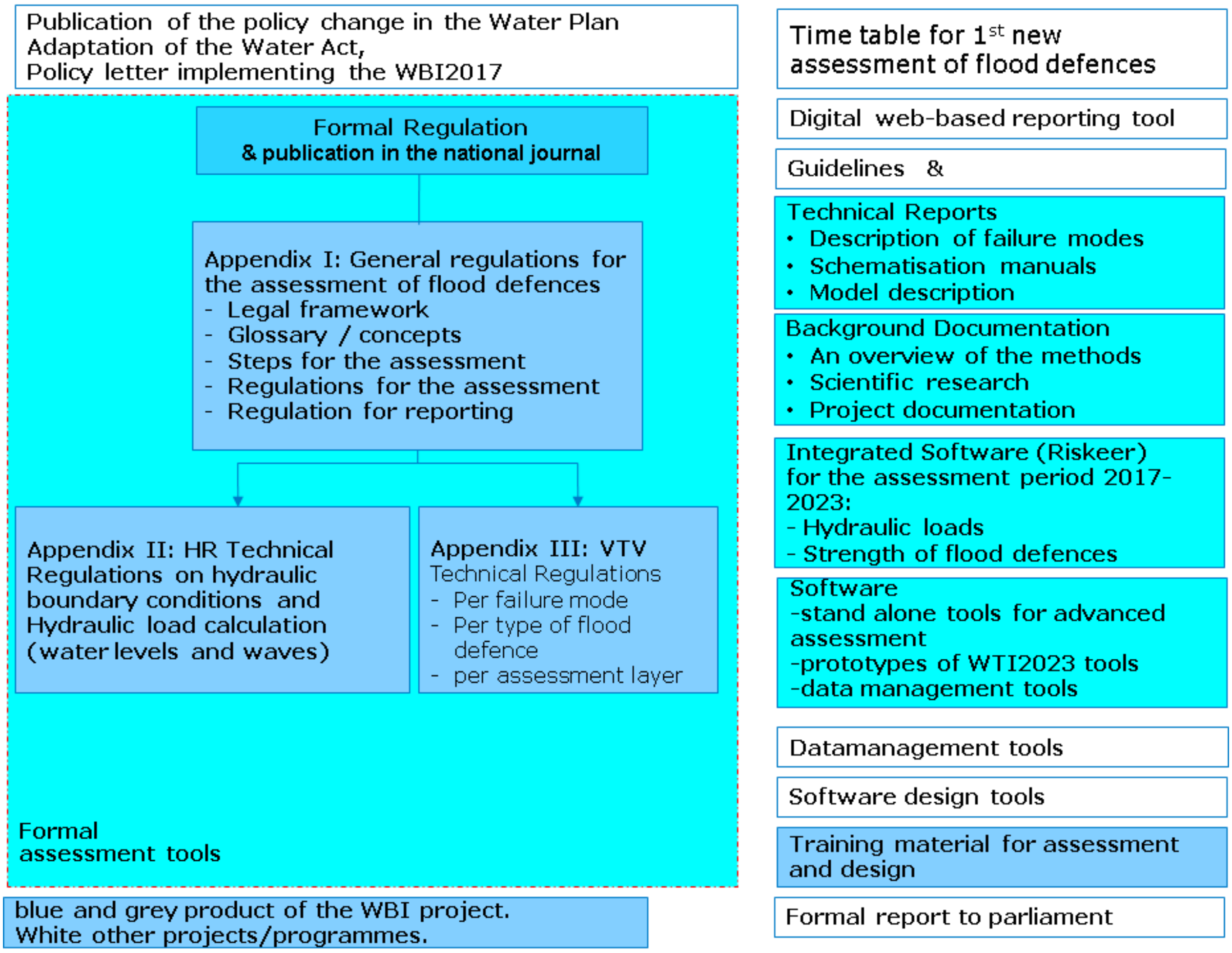

Figure 2: Overview of the instruments and documents for implementing the new flood risk management policy, *Slomp (2016)*

The change of definition of the safety standard to an acceptable probability of flooding (or failure) implies introducing a new safety concept in the assessment and design of flood defenses. Consequently, all documents, software and legislation needed to be amended accordingly. Figure 1 contains an overview of all the instruments provided by the national authorities to this end. The main distinctions are between the legally binding formal assessment rules on the left hand side and the supporting guidelines, technical reports and software on the right hand side of the scheme.

2.2 Assessment levels (coarse to fine)

The assessment of existing flood defenses (carried out in 12-year cycles) is a layered approach with essentially three assessment levels, working 'from coarse to fine' (see Figure 3). The motivation for the different levels is to use the appropriate amount of resources in data acquisition and modelling depending on the complexity of the conditions. Evidently safe or unsafe conditions can be filtered out immediately in the simple assessment (level 1) based on simple and conservative criteria (e.g. there can be no backward erosion piping without a cohesive 'roof'). If a simple assessment is not possible, a detailed assessment is carried out using physics-based models or criteria per failure mode. The novelty here is this level 2 assessment can be done conventionally with partial factors (i.e. semi-probabilistically) or in a fully probabilistic fashion. If no satisfactory assessment can be obtained with the level 2 provisions, there is the option to carry out an advanced assessment (level 3), essentially allowing the use of any state-of-the art models and methods enabling to show that the acceptable probability of failure requirement is met.

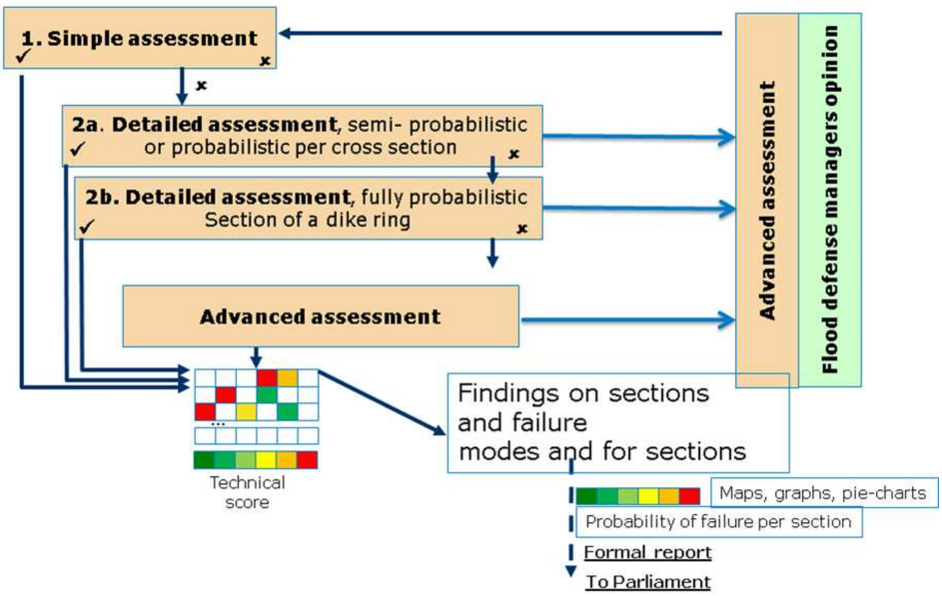

Figure 3: A layered approach for flood defence assessment (*Slomp, 2016*)

2.3 Operational requirements (failure modes and length effect)

The operational safety requirement for a full probabilistic analysis of a flood defense system is directly given by the legally required 'acceptable probability of flooding' (see section 1), which is defined for segments of typically tens of kilometers of flood defense with similar consequences in case of a breach. In order to enable (semi-probabilistic) assessments of individual dike sections and per failure mode, there are essentially three steps to establish operational requirements:

A - Acceptable probability of failure per failure mode:

Flood defenses can fail due to various failure modes, as illustrated in the fault tree in Figure 4, which contains all failure modes considered in a detailed (level 2 assessment). The presence of a multitude of failure causes implies that the reliability target for each failure mode individually needs to be stricter than the system reliability target. The reason is that the system probability of failure is a combination of the individual failure mode probabilities (e.g. the sum if they are independent).

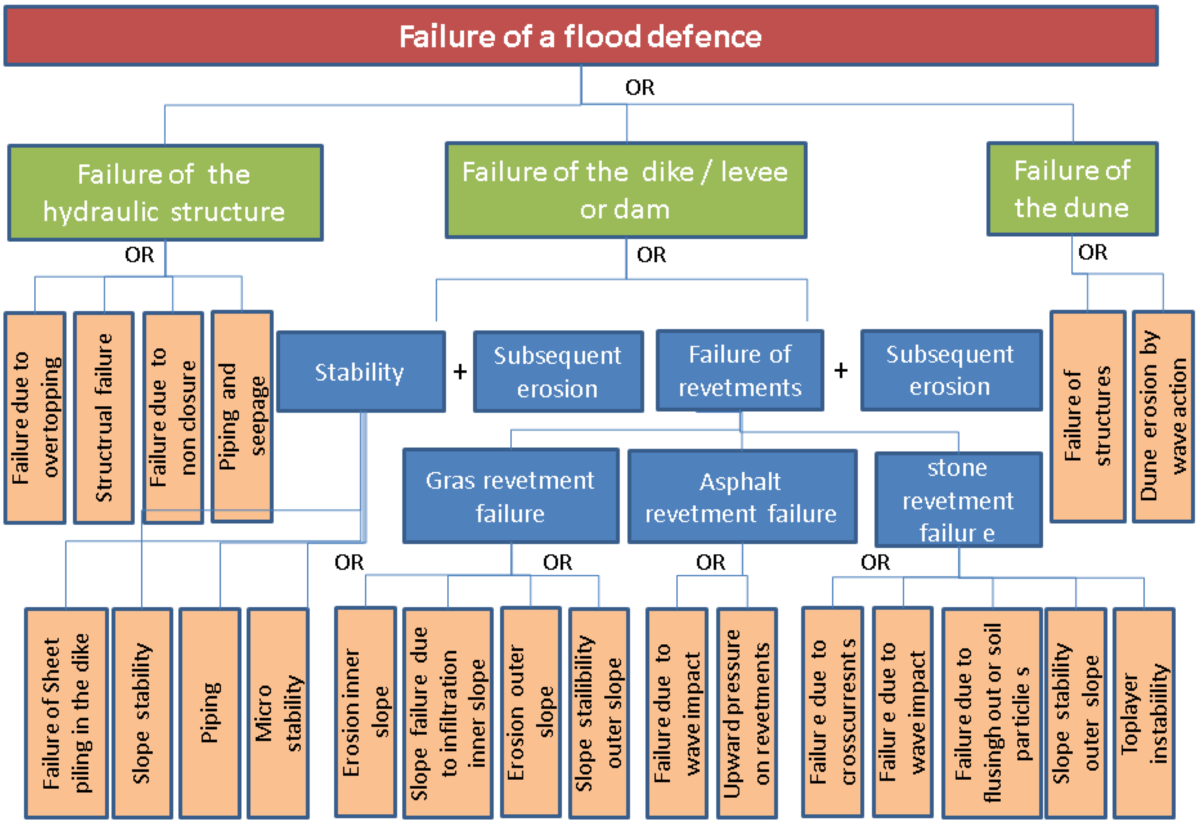

Figure 4: Fault tree for flood defences in the Netherlands (*Slomp, 2016*)

B - Acceptable probability per dike section:

Likewise, the target reliability for an individual structure needs to be stricter that the system target. Besides accounting for the different structures of sections in the flood defense system, also the length-effect needs to be taken into account, i.e. the fact that the probability of failure of a homogenous section increases with its length.

C - Partial load and resistance factors:

In case of full probabilistic assessments the target reliabilities per section and failure mode can be used directly. To enable conventional semi-probabilistic assessments, the partial load and resistance factors are to be chosen such that they correspond to the required reliability or acceptable probability of failure. As the available partial factors in, for example, Eurocode do not always reflect well the characteristics of flood defenses and the corresponding failure modes, dedicated studies to calibrate partial factors have been carried out in the WBI-2017 project.

For details on deriving the target reliability levels refer to *Schweckendiek et al. (2012);* examples of partial factor calibration are described in *RWS (2017)*.

2.4 Semi-probabilistic versus full probabilistic

As mentioned above, there is a clear relation between full probabilistic and semi-probabilistic assessment and design for civil engineering structures. In essence, as illustrated in Figure 5, we compare a design value of the load S_d (low probability of exceedance) with a design value of the resistance R_d (high probability of exceedance) in order to ensure that the probability of failure is sufficiently small. Design values can be obtained by combining characteristic (or representative) values with partial factors.

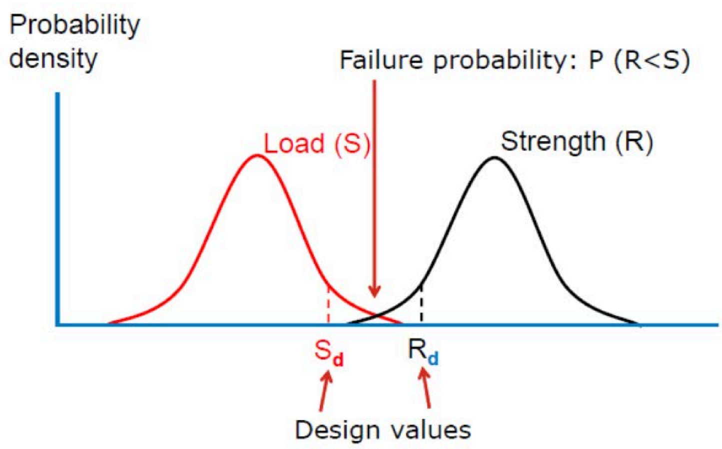

Figure 5: Illustration of the relationship between full probabilistic and semi-probabilistic design or assessment

Often, the above mentioned calibration exercises to obtain partial factors contain conservative elements. Practically speaking, the partial factors are chosen such that a minimum level of reliability is achieved with a high degree of confidence. The disadvantage is that individual designs or assessment decision can be safer than necessary and, hence, more costly. This drawback can be overcome by full probabilistic analysis, leading to more cost-effective designs and assessments.

3 Illustration of assessments with new instruments

The following examples illustrate the assessment with the new standards. Due to the available space, the examples will not be exhaustive nor reproducible; they merely provide an impression of the main features. For details, refer to the relevant background documents; for example, *Geerse (2011)* describes how hydraulic boundary conditions are determined.

3.1 Wave overtopping

In this first example we contemplate the assessment with respect to wave overtopping and subsequent erosion of the inner slope. Figure 6 shows a top view and the cross section of the example dike location, both directly obtained from the newly-developed Riskeer assessment software (*Slomp, 2016*).

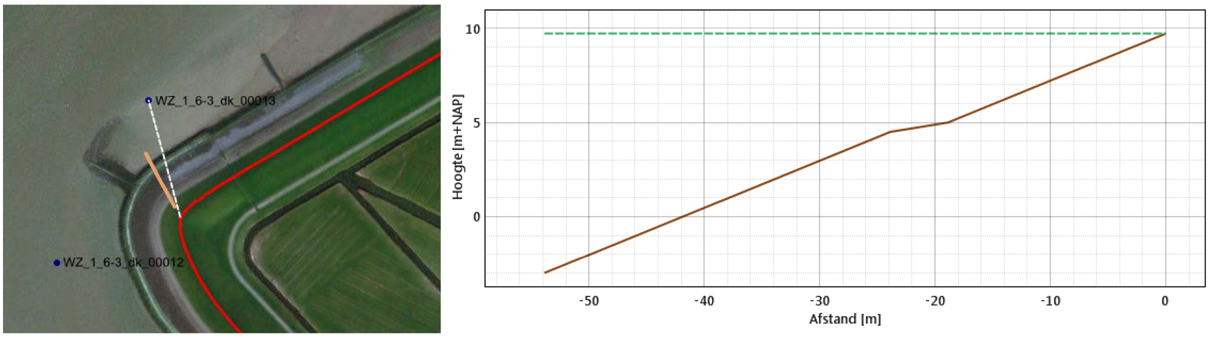

Figure 6: Top view (left) and cross-section profile (right) of the example dike section located in the Wadden Sea south of Harlingen obtained from Riskeer software

The assessment is based on first computing the overtopping discharge based on the incoming waves and the properties of the waterside slope of the dike profile (e.g. geometry, roughness), and then comparing the discharge to a critical discharge depending on the properties of the landside slope (e.g. geometry, grass quality). The overtopping assessment is full probabilistic and looks at all potential combinations of water levels, wave heights, wind directions, model uncertainty, strength properties etc. with their associated, estimated probabilities. Hence, the outcome is the probability of failure, or more specifically, the probability of exceedance of the critical overtopping discharge.

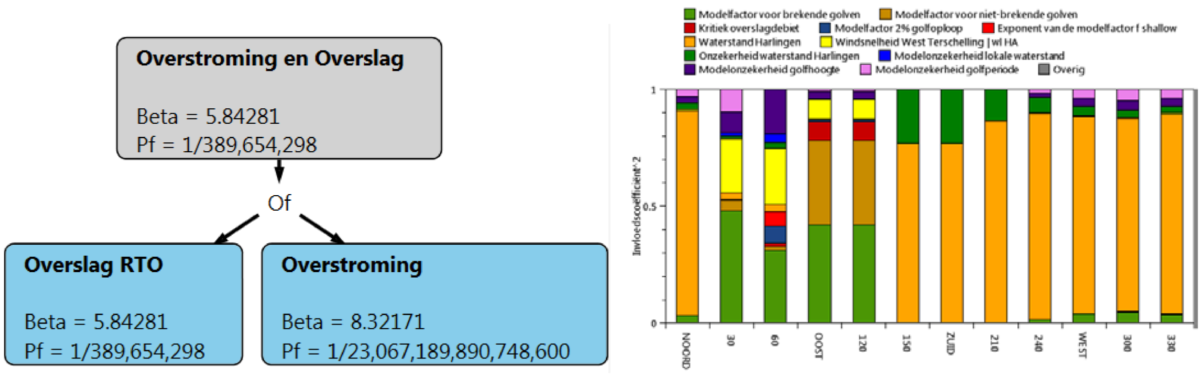

Figure 7: Main outcomes of the overtopping analysis in terms of the probability of failures Pf / reliability index β (left) and influence coefficients per wind direction (right)

The results summary in Figure 7 (Riskeer screenshots) implies that the calculated annual probability of overtopping failure is $2.6 * 10^{-9}$ with an equivalent reliability index of $\beta = 5.84$. Further analytics not displayed here due to space restrictions indicate that the dominant wind direction (not only with highest frequency, but also with highest contribution to the probability of failure) is North. The influence coefficients shown on the right-hand side of Figure 7 furthermore indicate that the uncertainty in the water level at Harlingen dominate the overall result. That is plausible, as the waves along the Wadden Sea coast are depth-limited, such that wave heights are mostly influenced by the storm surge levels. Contemplating the acceptability of the result we need to take into account the safety standard at the location of interest, which is an acceptable annual probability of failure of 1/3000 at the Wadden Sea, as well as the presence of different failure modes and the length-effect as explained in section 2.4:

$$P_{f,\mathrm{T,overtopping}} = \frac{\omega \cdot P_{f,\mathrm{T}}}{N} = \frac{0.24 \cdot 1/3000}{3} = 2.7 \cdot 10^{-5} \quad \Leftrightarrow \quad \beta_{T,overtopping} = 4.04$$

in which ω = 0.24 implies that the share of the total acceptable probability failure assigned to the failure mode overtopping is 24%, and N = 3 is a factor to account for the length-effect. These numbers vary per failure mode; for details refer to *Schweckendiek et al. (2012)*. Hence, the assessed reliability index largely exceeds the required value (5.8 >> 4.0) and the conditions are considered safe. The advantage of the full probabilistic analysis for wave overtopping is that no discrete choice needs to be made for the 'design' water level and wave parameters, as all potential wind directions, water levels etc. enter the assessment with their respective probabilities. Furthermore, the influence coefficients obtained from the analysis as exemplified in Figure 7 allow obtain a thorough understanding of the dominant variables, which in turn helps very much in making appropriate choices in the reinforcement design, if required.

3.2 Slope stability

The following example of a slope stability assessment, also located in the Dutch Wadden Sea area, illustrates the main features of the semi-probabilistic and full probabilistic assessment of this failure mechanism. Details on the case can be found in *Kanning et al. (2017)*. The cross section is depicted in Figure 8.

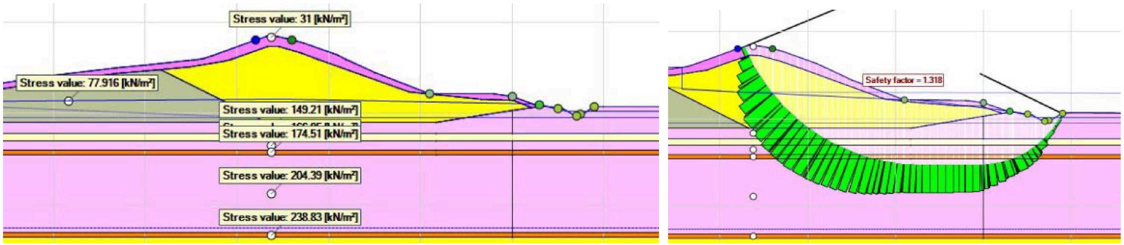

Figure 8: Cross-section profile of the slope stability example (left) and critical sliding surface obtained by LEM-analysis (right)

This typical sea dike profile has a shallow outer slope and the dike body consists of a sand core with a clay cover. Slope stability is usually not critical for sea dikes, here also reflected in the relatively high factor of safety of 1.32 obtained with design values for soil properties. The legal safety standard for the area entails that the acceptable annual probability of failure is 1/10,000. As for wave overtopping, we derive a specific requirement for slope stability on cross section level through:

$$P_{f,\mathrm{T,overtopping}} = \frac{\omega \cdot P_{f,\mathrm{T}}}{N} = \frac{0.04 \cdot 1/10000}{26.5} = 1.5 \cdot 10^{-7} \quad \Leftrightarrow \quad \beta_{T,stability} = 5.1$$

Notice that the N-value is much higher for slope stability than for overtopping, implying a larger length-effect (see *Kanning et al. 2017* for its derivation), as can be expected for a geotechnical dominated mechanism compared to a hydraulic-dominated one. That together with the lower ω-value leads to a significantly higher target reliability index of 5.1.

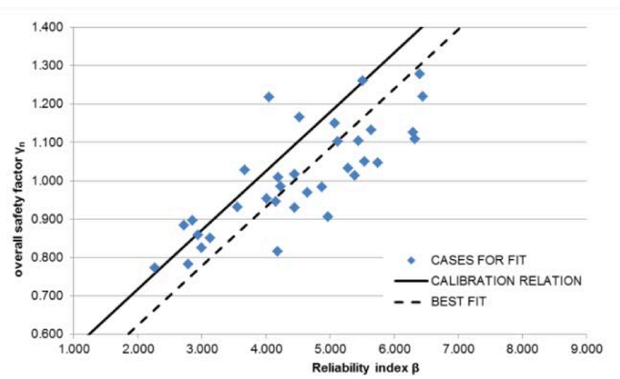

Figure 9: Calibrated relationship between required factor of safety and reliability index according to *Kanning et al. (2017)*

For semi-probabilistic assessments with design values of the soil properties we can obtain the required factor of safety (γ_n) for this target reliability by the relation calibrated by *Kanning et al. (2017)*, as depicted in Figure 9: $\gamma_n = 0.15 \cdot \beta_T + 0.41$. Hence, the required factor of safety for this particular case would be γ_n = 1.18 and we can assess the slope stability to be safe, as the factor of safety obtained from the analysis was 1.32.

Though not necessary in this case, we can also analyze the slope stability in a full probabilistic fashion. Figure 10 shows the so-called fragility curve for this case in terms of the conditional reliability index per water level. We see that the water level has some influence on the reliability, slightly decreasing the stability as the water level rises, but not much. The overall reliability index including the probability distribution of the water level amounts 8.5, implying a very low probability of failure. Hence, also in full probabilistic terms we would assess the dike as safe, even with a greater margin than based on the semi-probabilistic assessment.

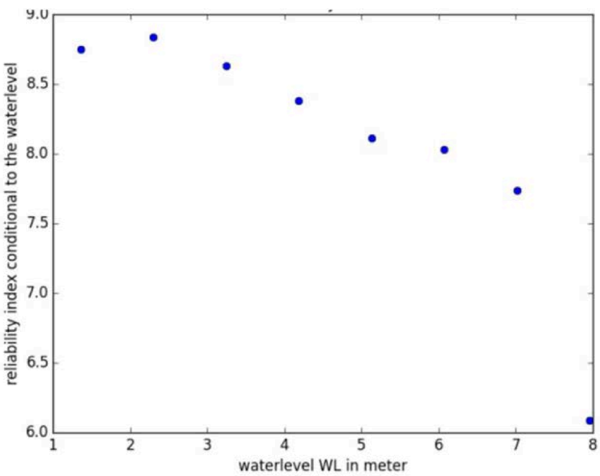

Figure 10: Fragility curve (reliability index versus water level) for the slope stability example

So far, we have the results of a detailed assessment (see Figure 3) with standardized and mostly conservative modeling choices. If the detailed assessment is negative, more realistic modeling can be applied to see if the assessment can still be positive with less conservative yet well-founded modeling choices. For example, in detailed stability assessments the pore water pressures are always modeled as a steady state response to the maximum water level during the load event, i.e. assuming a very long-lasting high water situation. In many instances, transient analysis can lead to a much more favorable assessment. Furthermore, the full probabilistic analysis also opens new opportunities. For example, the effect of having observed the survival of load events in the past can be included through reliability updating (*Schweckendiek et al., 2014*).

4 Concluding remarks

The main changes between previous safety assessments of flood defenses in the Netherlands and the assessments with the new safety standards are summarized in Table 1.

Table 1 Summary of differences between previous and new assessments

1996, 2001, 2006-2014	**2017-2023**
Flood defense assessed to safely withstand a design load event with certain probability of exceedance	Flood defense assessed based on acceptable probability of failure
Assessment every 6 years	Assessment every 12 years
Assessment of (representative) cross sections	Assessment of entire reaches (10-20 km long)
Deterministic, semi-probabilistic (partial factors) only	Semi-probabilistic & full probabilistic
Result: does or does not meet legal standard (binary)	Result: probability of flooding (allows for relative comparisons)

The new approach is follows more closely the risk acceptance criteria underlying the reliability targets of the new safety standards. It should, hence, be more cost-effective in terms of risk mitigation than the previous assessment standards. Furthermore, full probabilistic analysis provides more accurate assessments and avoids the necessary conservatism involved with the derivation of partial factors. Last but not least, being science-based, the new approach contributes to more transparency in the decision process for investments in reinforcement measures and maintenance.

The greatest challenge in implementing the new approach is undoubtedly making the transition together with about 300 to 400 practitioners. Even though large progress was made before introducing the new standards on January 1st 2017, not all technical documentation and software have been fully adapted yet. It will also take some time to gain experience with and ‘fine-tune’ the new rules, documents and software. Also education and training have been recognized as crucial for a successful transition.

Ultimately, the goal is to have all 3760 km of primary flood defenses in the Netherlands comply with the new safety standards by 2050. First estimates are that more than half of the flood defenses will need reinforcement, which is a considerable challenge financially, but also in terms of engineering and construction resources.

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