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A pragmatic, performance-based approach to levee safety assessments

Stephan Johannes Hendrikus Rikkert[1] | **Matthijs Kok**[1] | **Kasper Lendering**[2] | **Ruben Jongejan**[3]

[1]Delft University of Technology, Faculty of Civil Engineering and Geosciences, Department of Hydraulic Engineering, Delft, The Netherlands

[2]AWA Consult, Willemstad, Curacao

[3]Jongejan Risk Management Consulting B.V., The Hague, The Netherlands

Correspondence
Stephan Johannes Hendrikus Rikkert, Delft University of Technology, Faculty of Civil Engineering and Geosciences, Department of Hydraulic Engineering, Delft, The Netherlands.
Email: s.j.h.rikkert@tudelft.nl

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Abstract

Flood prone areas are often protected against flooding by an extensive network of flood defenses. To ensure their structural integrity, these flood defenses are periodically assessed. Many levees have been functioning well for decades, and have survived several relatively high hydraulic loads within their lifetime. However, information on survived load conditions is seldom included in levee safety assessments. Observed degradation from levee inspections is also not taken into account. That way, information that is useful to improve the accuracy of estimations of the actual strength of the levee remains unexploited. This study proposes a pragmatic approach to include observations of survived loads and levee degradation in the levee safety assessment. This approach consists of three steps: (1) a prior estimation of the failure probability, based on levee characteristics, (2) a posterior estimation of the failure probability, based on observed hydraulic loads, and (3) correction of the posterior failure probability estimation, based on levee inspections. In a case study, the estimated failure probabilities using this approach were much lower than when information on levee performance was not included. This study demonstrates the value of levee performance observations and how they could be included to improve levee safety assessments.

KEYWORDS

embankments and levees, risk analysis, risk assessment, statistical methods

1 | INTRODUCTION

Globally, floods have been the most frequent climate and weather related hazards in the past decades (IFRC, 2020). Extensive systems of flood defenses protect flood prone areas by reducing the probability of flooding in many parts of the world (O'Dell et al., 2021). A large part of these flood defenses consists of earthen levees. Several failure mechanisms can cause a levee to lose its structural integrity, which can eventually lead to breaching and flooding of the hinterland (Özer et al., 2020). Therefore, periodic assessment of the reliability of these levees is needed to ensure that they meet the required protection levels, which are often based on the acceptable risk of flooding (Vrijling, 2001; Vrijling et al., 1998). In addition, regular inspections are required to detect levee

deterioration in an early stage, since damage to a levee can significantly reduce the levee's strength (van Bergeijk et al., 2021).

In a safety assessment, levees are assessed on their relevant failure mechanisms. According to the International Levee Handbook (CIRIA, 2013) the assessment process must provide an estimation of the potential for failure given one or more different loading events for each of these failure mechanisms. A levee fails when the load on the levee section exceeds the levee's resistance. Quantifying the probability of failure of a levee requires explicit and consistent treatment of uncertainties related to load and resistance parameters (Jongejan & Maaskant, 2015). In a semi-probabilistic approach, the levee's strength is determined based on characteristic values for the strength parameters (with safety factors) in combination with a statistically defined hydraulic load (often the water level). A full-probabilistic approach takes into consideration the variability and uncertainty in both load and strength (Lendering, Schweckendiek, & Kok, 2018).

This paper focuses on polder drainage canal levees, in this paper called canal levees, which are common in the lower parts of the Netherlands, but low-lying polders are also present in many other parts of the world (Martín Antón et al., 2016). Such levees keep the water in the drainage canals. The primary function of these canals is to discharge excess water from the polders to the sea, the large lakes or the main rivers. The canal water level is regulated at a constant level, and the canal levees permanently withstand water. But extreme rainfall events increase the water levels in the canals, and also the groundwater table in the levees. Both the extreme events and the average conditions pose a continuous threat of flooding from these canals. Therefore, the levees along these canals require a continuous effort of inspection, safety assessment and maintenance.

During their lifetime, levees have often successfully withstood several hydraulic load conditions. Including observations of levees surviving specific load conditions could improve failure probability estimations by reducing uncertainties in the levee's strength (Schweckendiek, 2014). The effect of this reliability updating approach has been demonstrated for individual failure mechanisms, such as piping (Schweckendiek et al., 2014), and slope instability (Lendering, Van der Krogt, et al., 2018; Schweckendiek et al., 2016), as well as for the overall levee failure probability (Lendering, Schweckendiek, & Kok, 2018). In addition to survived loads, levee inspection observations can improve the assessment to better represent the current levee condition. Examples of such inspection observations, called "levee performance indicators," include subsidence, cracks and animal burrows. Including these effects directly in the safety assessment contributes to a more representative estimation of the actual levee safety (Kwakman & Van Loon, 2019; USACE, 2015).

Although both survived loads and levee inspection results are a valuable source of information to improve levee safety assessments, a pragmatic approach to incorporate both sources in the safety assessment does not yet exist.

Therefore, the aim of this study is to develop an approach to assess the reliability of levees, which utilizes both the information from observed survived loading conditions, as well as observations of levee performance indicators resulting from recent levee inspections. A pragmatic method is developed, which is able to calculate levee failure probabilities. As stated above, the paper focuses on water bodies with regulated water levels, such as the canals along polders. The method is applied to a case study in the Netherlands. And the results are compared to the outcomes of the safety assessment according to current safety assessment practices in the Netherlands. The study is limited to one failure mechanism: inner slope instability, since this is the dominant stability-related failure mechanism for which canal levees are not fulfilling the safety standard in the levee stability assessment (see De Leau et al., 2019; HHNK, 2015).

This paper is organized as follows: Section 2 gives a brief overview on approaches to deal with uncertainty in stability assessments, after which Section 3 explains the developed approach. The case study, the Eilandspolder, is presented in Section 4. In this case study, the applicability of the approach is demonstrated and the outcomes are compared to the outcomes of the current approach. Section 5 contains a discussion of the approach and the results, followed by the conclusions and recommendations in Section 6.

2 | UNCERTAINTY IN LEVEE SLOPE STABILITY ASSESSMENTS

Levee stability assessments are often performed with limit equilibrium methods. These models calculate a factor of safety (SF). In the slip circle method of slices, a potential rotational sliding soil body mass is divided into a number of finite vertical slices and the equilibrium of each slice is considered in determination of the factor of safety (Tsuchida & Athapaththu, 2014). Several commercial tools exist to perform such calculations. This paper uses D-Geo Stability software (Deltares, 2016) to calculate levee slope stability based on Bishop's method of slices, in which the assumption is made that the forces acting on the sides of each slice have a resultant of 0 kN in the vertical direction (Bishop, 1955).

Slope stability assessments include several load factors, of which the water level in the canal, the phreatic surface in the levee, and traffic loads (if a road present is present) are dominant. The importance of traffic loads on failure probability was already presented in earlier studies (Lendering et al., 2015). However, this study focuses on the impact of degradation of the levees, and for the sake of simplicity, traffic loads are excluded from the analysis. Possible effects of this simplification are included in Section 5.

2.1 | Probability analysis

In a semi-probabilistic analysis, the load parameters (i.e., high water level and high phreatic line) are often included by conditions corresponding to a defined protection level. For example, the design water level is obtained through a statistical analysis of historical water level measurements and hydraulic calculations. The phreatic line is often estimated by experts, because measurements are usually lacking.

While the semi-probabilistic approach uses one load combination, the probabilistic approach accounts for the entire range of possible load combinations. For the water level, this can be either done through using the continuous probability density function of the load, or by discretizing the continuous probability density function, to limit the amount of load combinations, and hence, the number of necessary stability calculations. But for the phreatic line in a levee, measurement data is usually lacking, and at the same time the phreatic line is very location specific (Flanagan & Tigchelaar, 2016). Therefore, Lendering, Van der Krogt, et al. (2018) discretized the phreatic line into three possible conditions: (1) average, under normal conditions; (2) high, under wet conditions, and; (3) low, under dry conditions. Under normal conditions, the phreatic surface is interpolated linearly between crest and toe. Under dry conditions, the phreatic surface is assumed to have a concave shape, whereas, during wet conditions, the schematized phreatic surface is expected to have a more convex shape. These possible (discretized) conditions of phreatic lines are shown in Figure 1.

The failure probability can be determined, as follows:

$$P(F) = \sum_{i,j} P\left(F|h_i, S_j\right) P\left(h_i, S_j\right) \tag{1}$$

where $P(F)$ is the overall failure probability, and $P\left(F|h_i, S_j\right)$ is the conditional failure probability given water level h_i and phreatic surface level S_j, and $P\left(h_i, S_j\right)$ is the probability of occurrence of the combination of water level h_i and phreatic surface level S_j. This failure probability is called the a-priori failure probability as it is calculated prior to applying reliability updating.

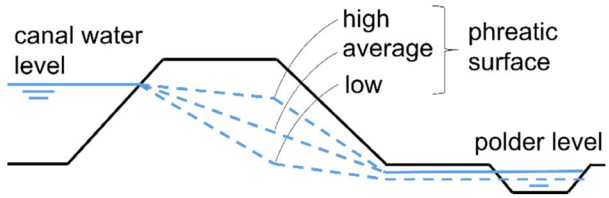

FIGURE 1 Schematic representation of possible phreatic surface levels (high, average, and low)

2.2 | Including observed condition in slope stability assessment

This section explains how field observations can be included in slope stability assessments to reduce uncertainty in levee stability analysis. It also elaborates how degradation of a levee might influence its stability.

2.2.1 | Reliability updating to calculate the posterior probability

Reliability updating means that the a-priori failure probability is updated by including information on survived loads. Applicability of the "reliability updating" method strongly depends on the availability of accurate and reliable observations of hydraulic loads that a levee has successfully withstood in the past (STOWA, 2009). We explain reliability updating through one loading variable: the canal water level.

The base of the reliability updating approach is Bayes' theorem:

$$P(F|\epsilon) = \frac{P(F \cap \epsilon)}{P(\epsilon)} = \frac{P(\text{Failure} \cap \text{observation})}{P(\text{observation})} \tag{2}$$

In which $P(F|\epsilon)$ is the probability of failure, given observation ϵ. This is illustrated in Figure 2: the failure probability is determined by the probability density of the load (in red) and the probability density of the resistance (in green). When the levee resistance is constant in time, a survived load (at dashed vertical black line) serves as evidence that the probability of failure for that load (and smaller loads) equals zero. The probability density under that load is then redistributed over the probability density above that survived load, reducing the levee's overall failure probability.

This paper follows the "direct approach" for reliability updating, which exploits the definition of the

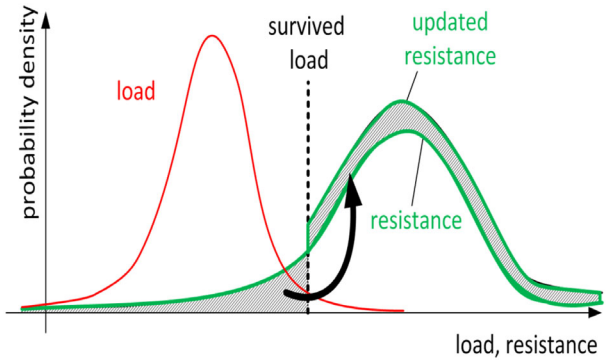

FIGURE 2 The concept of "reliability updating," where the probability density under the survived load is redistributed over the probability density above the survived load (Schweckendiek, 2014)

conditional probability of failure from Equation (2), by defining a new limit state of the intersection (cut set) of failure and the observation ($F \bigcap \epsilon$), as described by Schweckendiek et al. (2016). The correlation between the survived load and the current (or future) situation was assumed equal to one: the strength does not change. In other words, there have been no changes in the levee that might have led to an increase or decrease of its strength properties. This leads to an adjusted probability density of the estimated levee's resistance. Figure 2 shows how the probability density function of the resistance is redistributed following a truncated normal distribution (Schweckendiek, 2014). The figure shows there is no probability density left below the observed water level.

In the analysis not only the canal water level is taken into account, but also the phreatic line, which adds a dimension to the reliability updating, as was already done by Lendering et al. (2015) and Lendering, Van der Krogt, et al. (2018). We use the same combination of canal water levels (low, average and high) and phreatic surface levels (low, average, and high), with each combination having a specific conditional failure probability (Table 1) and probability of occurrence.

The probability that a certain load combination occurs, depends on its assumed conditional probability of occurrence of the phreatic surface, given a water level. As measurements of the phreatic line are often lacking, Lendering, Van der Krogt, et al. (2018) made an estimate of the conditional probabilities of occurrence of a phreatic line, given the canal water level (see Table 2). These conditional probabilities are based on the assumption that during wet conditions, in which a high canal water level is observed, there is a larger chance of observing a high phreatic surface. This is caused by the dependency of the canal water level and the phreatic surface on rainfall. Under normal or dry conditions, when the water level is average or low, the probability of a high phreatic surface is relatively small.

Even though observations are not always present, the following combinations of loads can reasonably be assumed to have occurred in the past:

1. An average water level with a high phreatic surface: it is reasonable to assume that this combination has occurred in the past, for instance during heavy local rainfall which did not have sufficient volume to raise the water level in the entire canal.
2. A high water level with an average phreatic surface: this assumption is reasonable, if high water levels were observed from historical data of canal water levels, although it is not sure if, for a specific location, the phreatic surface was also raised.
3. An average canal water level and a low phreatic surface: it is reasonable to assume that, during dry conditions, the canal water level was artificially kept at an average level, while the phreatic surface is low.

This means that the following combination of load conditions from Table 1 is assumed to have occurred: h_1 and S_1, h_2 and S_3, h_3 and S_2.

2.2.2 | Effects of degradation

Degradation processes of levees negatively influence the levee strength. Examples of such processes are unwanted vegetation on or near the levee (Lanzafame, 2017), subsidence of the hinterland (Kwakman & Van Loon, 2019), cracking of the cover layer (Jamalinia et al., 2020), and animal burrows (Kwakman & Van Loon, 2019). A distinction should be made between local damages and more general degradation processes. Examples of local damages are local subsidence due to trampling by livestock, which would require direct repair measures. More general degradation processes occur over a longer time span, such as the formation of cracks due to seasonal climatic influences and subsidence of the hinterland. The Levee Screening Tool (USACE, 2015) explicitly uses observable indicators of levee performance, so that results from a levee inspection can be used to improve estimations of levee stability. Figure 3 shows several examples of observable levee performance indicators. In this section, we describe degradation effects and how they influence levee stability. We hereby focus on observable levee performance indicators that can be observed in a levee inspection. Further, we limit ourselves to an earlier study that has been performed on regional levees.

TABLE 1 Conditional failure probability, given a combination of load conditions

	Low phreatic surface (S_1)	Avg. phreatic surface (S_2)	High phreatic surface (S_3)
Low water level (h_1)	$P(F\|h_1,S_1)$	$P(F\|h_1,S_2)$	$P(F\|h_1,S_3)$
Avg. water level (h_2)	$P(F\|h_2,S_1)$	$P(F\|h_2,S_2)$	$P(F\|h_2,S_3)$
High water level (h_3)	$P(F\|h_3,S_1)$	$P(F\|h_3,S_2)$	$P(F\|h_3,S_3)$

TABLE 2 Example of conditional probabilities of phreatic surface, given a water level (Lendering, Van der Krogt, et al., 2018)

	Low phreatic surface (S_1)	Avg. phreatic surface (S_2)	High phreatic surface (S_3)
Low water level (h_1)	0.01	0.98	0.01
Avg. water level (h_2)	0.01	0.98	0.01
High water level (h_3)	0.01	0.01	0.98

FIGURE 3 Examples of performance indicators. Local subsidence due to trampling by livestock (upper left; picture from STOWA, 2018), severe subsidence (upper right; picture from STOWA, 2018), animal burrowing (lower left, picture taken by S.J.H.Rikkert, 2020), and wet spots at the levee toe (lower right; picture from STOWA, 2018)

In their analysis, Kwakman and Van Loon (2019) calculated the effects of varying levee performance indicators on levee stability. They focused on existing Dutch canal levees with very different characteristics, and included the following levee performance indicators:

- Reduction of hydraulic resistance of canal bottom;
- Subsidence of hinterland;
- Lower water level in ditch at levee toe;
- Deepening of the ditch at levee toe;
- Animal burrows.

For each of these performance indicators they used three levels of severity:

0. Good (reference case with no reduced performance)
1. Light
2. Severe

The performance indicators resulted in changes in geometry, soil structure, the phreatic water level, and the hydraulic head in the aquifer, which was used in their calculations. Their results show that the extent to which

performance indicators influence the levee stability varies with levee characteristics.

Konings and Van Hemert (2020) followed the same approach, but they performed their calculations on a selected set of typical Dutch canal levees, based on combinations of local subsoil characteristics, levee slope, crest width, water retaining height (difference between canal water level and the polder surface level), and the presence of a berm. They also included subsidence as one of the performance indicators in their study and made the same distinction: no subsidence (0 m), light subsidence (0.25 m), and severe subsidence (0.5 m). They have found reductions of up to 25% in the factor of safety for severe subsidence for levees with varying water retaining height, and inner slope, and a crest width of 5 m. Therefore, when levee inspection observations are included in a safety assessment, indicators of reduced levee performance will have a direct influence on the strength and cannot be neglected.

3 | OBSERVED LEVEE STRENGTH METHOD

In this section, we develop a three-step approach for levee stability assessments that optimally utilizes evidence of observed levee strength, and results of levee inspections. The proposed method is a pragmatic approach to perform a full-probabilistic stability assessment. It reduces the uncertainty that is initially included in the partial safety factors, by adjusting the relation between factor of safety SF and the failure probability, expressed as the reliability index β. The failure probability P_f corresponds to the reliability index through Equation (3), in which Φ is the standard cumulative normal distribution function:

$$P_f = \Phi(-\beta) \tag{3}$$

Figure 4 shows a schematization of the proposed approach. The first step of this method is to estimate the failure probability, based on levee specific load and strength parameters. In the two following steps, this estimation is improved by including observed levee behavior.

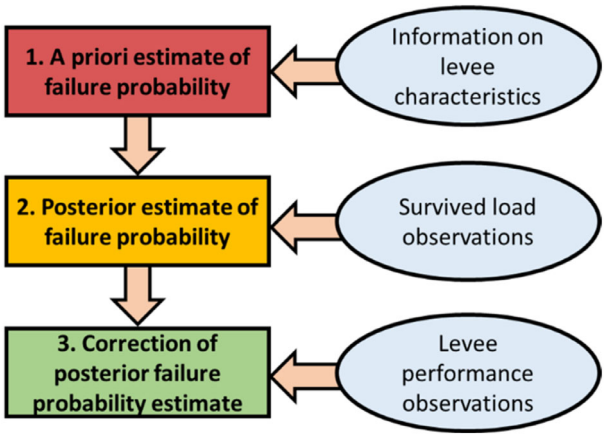

FIGURE 4 Schematization of the proposed method to estimate the failure probability, utilizing information on levee performance under critical conditions and levee inspection results

1. The first step is to determine the a priori annual failure probability (P_F). Probabilistic stability calculations are performed for each levee section, providing both the safety factor SF and the reliability index β. This can be done with a slope stability model. Levees with comparable characteristics, such as inner slope, soil structure and geotechnical parameters, can be grouped into one levee type to obtain a specific relation for this type of levee. Based on results for multiple levee sections within the same levee type the relation between SF and β is established through a best fit (see step 1 in Figure 5). Through this β–SF relation the failure probability of other levees can be determined if the safety factor is calculated, without doing the probabilistic calculations.
2. Observations of performance of the levee under various loading conditions can be included, using the approach described in Section 2.2.1 on reliability updating. The initial relation found in step 1 can be improved, by fitting a line through the points after reliability updating, as is shown in (see step 2 in Figure 5).
3. The final step is to correct the posterior failure probability by including results of levee inspections in the form of levee performance indicators, in addition to the survived loads from the previous step. These levee performance indicators contain information about the actual condition of the levee, and they influence the stability factor, and hence the probability of failure. Ideally, the same approach as in step 2 would be used here: including the effects of a certain performance observation, based on Bayes theorem. However, in this study a more pragmatic approach was used to limit the processing time of the study. Besides, discretization of the load and resistance in reliability updating makes it difficult to take into account gradual degradation. Therefore, we assumed that the effect of an observation (e.g., animal burrows) on the stability factor can be expressed as a reduction factor that is dependent of the levee type, the performance indicator and the level of severeness (see step 3 in Figure 5).

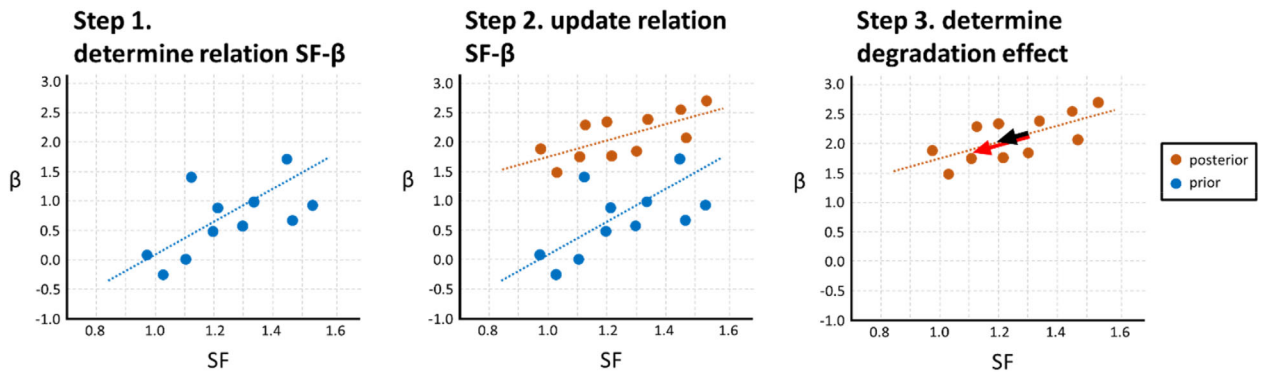

FIGURE 5 The approach explained through three steps. Step 1: Relation between safety factor SF and reliability index β for one levee type, based on probabilistic stability assessments. Step 2: Updating the prior relation between safety factor SF and reliability index β for one levee type, based on observations of survived hydraulic loads, with the prior relation in blue and the relation after updating in orange. Step 3: The arrows indicates how different degrees of degradation (black: light degradation; red: severe degradation) affect the stability factor, and hence the reliability index, of one levee type is influenced by levee degradation. The arrows are indicative, and effects on the stability factor depend on levee characteristics and degradation type

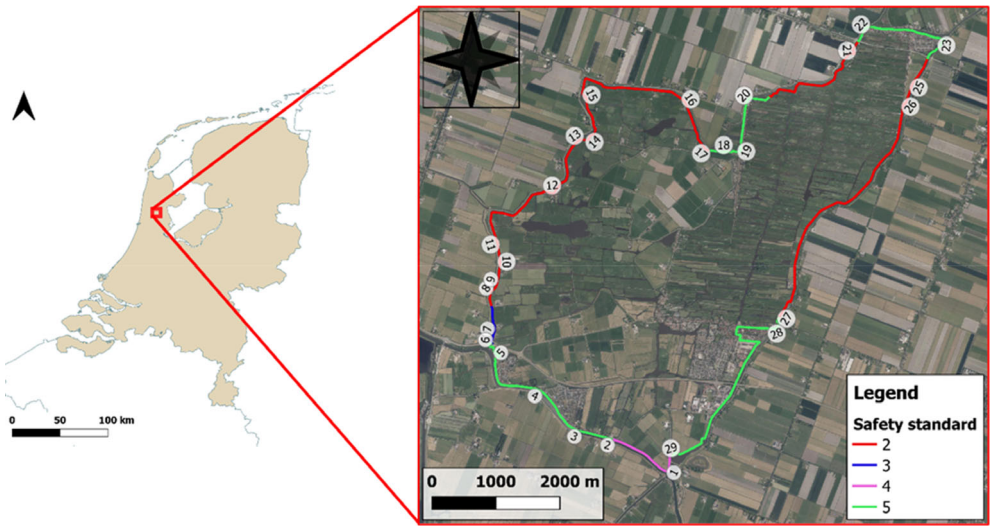

FIGURE 6 Left: Map of the Netherlands, with the location of the Eilandspolder. Right: Overview of levees protecting the Eilandspolder, the distinction into separate, numbered, levee sections, and their assigned flood protection standard

4 | CASE STUDY

4.1 | Description of Eilandspolder

The Eilandspolder is a polder in North Holland, the Netherlands, managed by the Water Authority Hoogheemraadschap Hollands Noorderkwartier (HHNK). The polder is surrounded by the Schermer boezem, which is a canal system with an average daily water level of −0.5 m with respect to Amsterdam Ordnance Datum (Dutch abbreviation: NAP) and an extreme water level of about −0.2 m NAP. The results of the proposed method were compared to the outcomes of the currently used semi-probabilistic approach. A total of 26.9 km of regional levees protect the Eilandspolder from flooding (Figure 6), including their assigned safety standards. In addition, a distinction into different levee sections in Figure 6 is derived from a recent levee safety assessment (De Leau et al., 2019).

For this type of levee, there are five safety standard classes, based on the expected flood damage after a levee breach (IPO, 1999). The system for flood protection standards distinguishes between five safety standard classes, based on the expected flood damage. Each class prescribes an annual exceedance frequency of the load that should be used in the semi-probabilistic safety assessment. It is reasonable to assume that the failure probability, which is defined as the probability that a levee breaches consequently leading to flooding, is much lower than the exceedance probability. The levees are designed in a conservative way: if the design water level will occur, the levee will not immediately fail. An estimate of a factor 5 (following Fugro, 1998) between the exceedance probability and the failure probability is given in Table 1. For comparison, levees with safety standard class 1, 2, and 3 have allowable annual failure probabilities of 1/50, 1/150, and 1/500, respectively, while, according to

TABLE 3 Safety standard class with corresponding required probabilities of exceedance and failure

Safety standard class	Annual exceedance probability	Annual failure probability
1	1/10	1/50
2	1/30	1/150
3	1/100	1/500
4	1/300	1/1500
5	1/1000	1/5000

Rikkert and Kok (2019) the average annual failure probability of a levee section is 1/600 or smaller (Table 3).

For the slope stability assessment, the levees were schematized, and several sections were distinguished, based on similarities and differences in geometry (crest height, inner slope, and hinterland surface level), and soil structure. As mentioned in Section 3, it is not always possible to derive a single SF–β relation for all polder canal levees; hence, a classification is made based on aspects such as inner slope, soil structure, and geotechnical parameters. For the Eilandspolder, however, we assume that all levees can be classified as one levee type, since they have very similar slopes, water retaining heights and subsoil material.

4.1.1 | Survived loads

In our analysis, we use the nine load combinations following Table 1. We assume that the following three load scenarios have been observed as survived:

- An average water level (−0.5 m + NAP) with a high phreatic surface: it is reasonable to assume that this combination has occurred in the past, for instance during heavy local rainfall.
- A high water level (−0.2 m + NAP) with an average phreatic surface: this assumption is reasonable, if high water levels were observed from historical data of canal water levels.
- An average canal water level (−0.5 m + NAP) and a low phreatic surface: it is reasonable to assume that during drought conditions the canal water level was artificially kept at an average level, while the phreatic surface is low.

4.1.2 | Inspection of degradation

From the results of levee inspection for the Eilandspolder, in the period July 2014 until June 2020, it is found that the most frequently observed performance indicators at the levee crest, inner slope and inner berm were levee subsidence (38%), followed by wet spots (27%). For each performance indicator a score was indicated: light and severe. In our study, we focus solely on the most frequently observed performance indicator for the Eilandspolder: levee subsidence.

Konings and Van Hemert (2020) studied the effect of levee subsidence on the stability factor for different representative schematizations of the subsoil of levees within the management area of HHNK. We have used one of these schematization that resembles our levee sections best. Besides the schematization for the subsoil, Konings and Van Hemert (2020) also distinguished between other levee characteristics, such as inner slope, crest width, retaining height, and the presence of a berm. While they found that effects of degradation on the safety factor depend on these levee characteristics, we have chosen to average these effects to values that roughly resemble the values calculated by Konings and Van Hemert (2020). Light and severe subsidence is assumed to reduce the the safety factor with 7.5% and 15%, respectively. It should be noted that Konings and Van Hemert focused more on subsidence of the hinterland. However, they also included partial subsidence of the berm and the toe of the levee, which also influences the inner slope. Therefore, we assume that these reduction factors of 7.5% and 15% can be applied to our case, when light and severe subsidence on the slope is observed, respectively.

4.2 | Results of semi-probabilistic approach

Following the levee safety assessment results of the water authority, out of the 26.9 km of levees, 16.1 km (about 60%) do not meet the required levee safety standard for macro-stability. Figure 7 gives an overview of levees that do not meet the safety standard and the distribution per safety standard class.

In this case study, only levee sections that do not meet the safety standard according to the current approach were taken into account, to determine if the new approach is less conservative and leads to less rejections. These levee sections are divided into five representative schematizations, based on inner slope, subsurface composition and water retaining height (see Table 4). This table also includes the results of the stability assessment, using the semi-probabilistic approach.

4.3 | A-priori failure probability

In this section, the a-priori failure probability per levee section is estimated. Different than in the current

approach, both load and resistance parameters are considered as stochastic variables, rather than using design values.[1]

For the water level statistics of the Schermerboezem and the phreatic surface, we applied the distributions as estimated by Lendering, Van der Krogt, et al. (2018). Specifically, for the phreatic surfaces, we distinguished between the three possible conditions, as assumed by Lendering, Van der Krogt, et al. (2018): low, normal and high. The conditional probability of a phreatic water level condition, given a canal water level, was already presented in Table 2 as an example, and we consider them as reasonable values in this case study.

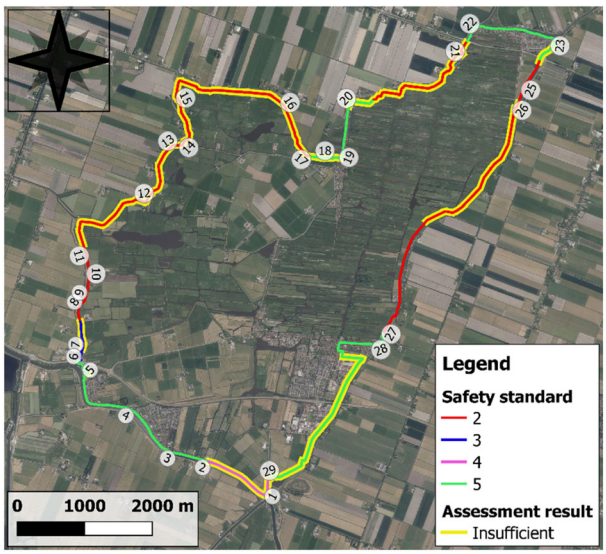

FIGURE 7 Overview of levees that do not meet the required safety standard for the failure mechanism macro-instability

By assessing all nine possible combinations (3 water levels multiplied by 3 phreatic surface levels) in a stability calculation and including the probability of occurrence of each of these combinations, both a (weighted) Stability Factor and a reliability index were calculated (Figure 8, in blue). The weighted Stability Factor was found by multiplying the Stability Factor that was found for each of the nine load combinations with their probability of occurrence (as described in Table 2). A linear relation provides a good fit ($R^2 \approx 0.97$) between the prior reliability index and the safety factor:

$$\beta_{\text{prior}} = 6.43 \times \text{SF} - 6.57 \tag{4}$$

4.4 | Failure probability after reliability updating

The a priori failure probability was updated, following the approach as presented in Section 2.2.1. The survived loads that are included in this analysis are:

- Low phreatic water level in combination with average water level (−0.5 m + NAP);
- Average phreatic water level in combination with high water level (−0.2 m + NAP);

TABLE 4 This table shows which 5 levee sections are used as representative levee sections, which levee sections they represent, and some distinctive characteristics

Levee section	7	29	18	26	1
Represents levee sections	13, 14, 15, 16, 17	12, 21, 24	20	—	—
Subsurface composition (the lowest sand layer is where the boring stopped)	~1.4 m sand ~0.8 m peat ~1.4 m clay sand	~0.5 m clay ~1.4 m peat ~3.3 m clay sand	0.8 m sand 0.5 m clay 1.0 m peat 1.0 m clay sand	0.3 m clay 1.3 m sand 0.5 m peat 3.0 m clay sand	1.5 m clay ~0.8 m peat 1.0 m clay sand
Slope [1/x]	~1:3.8	~1:3.6	~1:3.3	~1:2.7	~1:2.4
Berm present	No	No	No	No	Yes
SF (Bishop) from semi-probabilistic approach	0.83–0.87	0.87–0.90	0.82–0.88	0.79	0.68

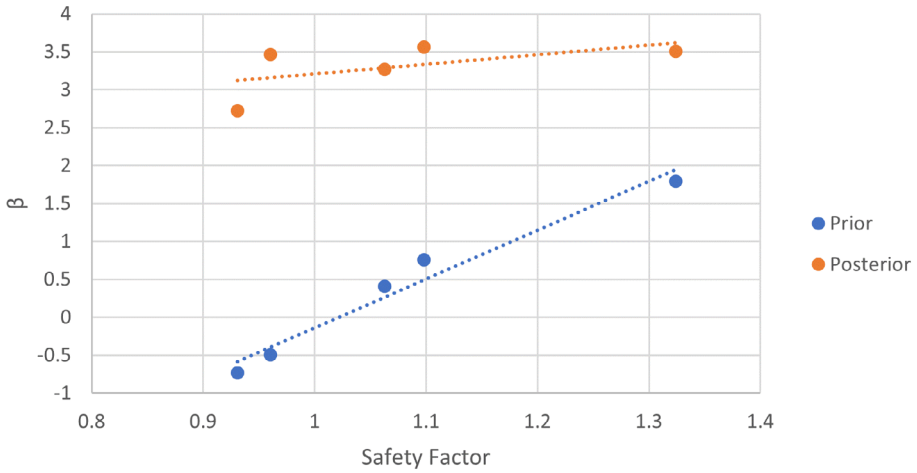

FIGURE 8 Results of probabilistic stability assessment for a-priori (blue) calculations and after reliability updating (orange)

- High phreatic water level in combination with average water level (−0.5 m + NAP).

Figure 8 shows the results of the stability analysis before and after reliability updating. As the figure shows, including observations of survived loads result significantly increase the estimated reliability index. The new Safety Factor and reliability index were found by assuming a failure probability of 0 during the survived load combinations.

The following linear relation was found between the posterior reliability index and the safety factor:

$$\beta_{\text{posterior}} = 1.27 \times \text{SF} + 1.94 \tag{5}$$

With this posterior SF–β relation, an increased reliability index can be found for the same safety factor, compared to the a-priori SF–β relation. This means that the estimated failure probability has decreased, which could result to approving a levee, that was initially rejected. Interesting to note is that the slope of the SF–β relation changes after updating. This is further discussed in Section 5.

4.5 | Effects of levee degradation on failure probability

Figure 9 shows the severity of levee subsidence per location, observed during levee inspections over a course of about 2 years (2016–2018). The figure only includes observations of levees that were unsafe according to the semi-probabilistic safety assessment. A distinction is made based on the degree of severity of subsidence:

- Light subsidence: about 0.25 m subsidence is observed in section 12;

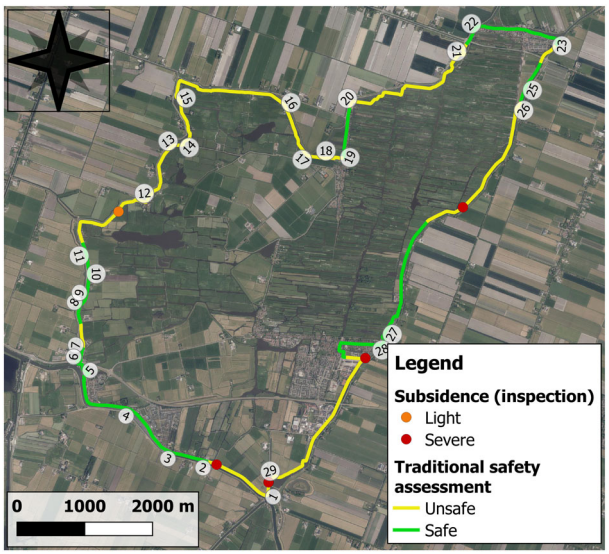

FIGURE 9 Map showing the subsidence observations from the levee inspection. Light subsidence is observed in section 4.5, and severe subsidence is observed in section 1 (on 2 locations), 8.2, and 9.2

- Severe subsidence: about 0.5 m subsidence is observed in section 1, 26, and 29.

The relative reduction of light and severe subsidence on the safety factor is assumed 7.5% and 15%, respectively. These values are based on Konings and Van Hemert (2020). To illustrate how observations of levee degradation influence the reliability index, an example is elaborated for levee section 1 (where severe subsidence was detected). Results for levee section 12, 26, and 29 were derived in the same way and are presented in Table 5.

Levee section 1

Step 1 Determining the a-priori reliability index β_{prior}:

TABLE 5 Overview of effect of including levee performance indicator observations on the reliability index

Levee section	1	12	26	29
Initial safety factor SF_{prior} (step 1)	0.93	1.06	1.1	1.06
Initial reliability index β_{prior} (step 1)	−0.59	0.25	0.50	0.25
Reliability index after including survived loads $\beta_{posterior;survived\ load}$ (step 2)	3.12	3.29	3.34	3.29
Subsidence observation	Severe	Light	Severe	Severe
Relative reduction on safety factor (%)	15	7.5	15	15
Reliability index after including degradation observations $\beta_{posterior;after\ degradation}$ (step 3)	2.94	3.19	3.13	3.08
Target reliability index $\beta_{required}$	3.21	2.47	2.47	3.54
Failure probability (1/return period)	1/620	1/1380	1/1130	1/980

Initially, a safety factor of 0.93 was calculated for levee section 1 with the probabilistic approach. Which, according to Equation (4) corresponds to a $\beta_{prior} = 6.43 \times 0.93 - 6.57 = -0.59$.

Step 2 Determine the a-posterior reliability index after including information on survived loads $\beta_{posterior;survived\ loads}$: Through the observations of survived loads, the SF–β relation was updated. When filling in the a priori factor of safety in Equation (5) the β after reliability updating increases from −0.59 to a

$$\beta_{posterior;survived\ loads} = 1.27 \times 0.93 + 1.94 \approx 3.12.$$

Step 3 Determine the adjusted reliability index from step 2 after including levee inspection observations of degradation $\beta_{posterior;observed\ degradation}$: During the inspection, severe subsidence was observed in this levee section. For severe subsidence we expected a reduction of the safety factor of 15% (see Section 4.1). This coincides with a reduction of 5.7% of the reliability:

$$\beta_{posterior;\ observed\ degradation} = 1.27 \times (100\% - 15\%) \times 0.93 + 1.94 \approx 2.94$$

This equals an annual failure probability of 1.62×10^{-3} (or a return period of about 620 years).

An overview of the effect of observations from levee inspections on the reliability index is shown in Table 5. It becomes clear that step 2 (reliability updating through survived load observations) significantly increases the reliability index. This is also the case for the other 10 initially rejected levee sections that are not presented in this table. Even after inclusion of levee degradation observations, the reliability indices of levee section 12 and 26 exceed the required reliability index, whereas with the traditional semi-probabilistic approach they were rejected. For levee section 1 and 9 the reliability indices after including degradation observations do not exceed the required reliability index, but still a significant increase in the reliability index is obtained through inclusion of observed levee performance. Repairs of the levee degradation will increase the levee strength, although for levee section 1 and 29 repairs will not be sufficient to meet the safety standard.

4.6 | Result comparison of both approaches

A comparison of both methods is presented in Table 6, which contains the initial factor of safety (using the traditional approach), the posterior reliability index (including survived loads and, if available, observations from levee inspections) and the required reliability index, and a new judgment, following from the observed levee strength approach. We have only included the levee sections that were rejected in the traditional approach. From the initially 14 levee sections (16.1 km) that were rejected using the traditional approach, 9 sections (11.0 km) can be considered safe, when the observed levee strength approach is applied. Important to note is that the approach from this pilot study quantifies the reliability indices (and failure probabilities), which show how far the outcome of the safety assessment is from the target reliability index.

TABLE 6 Results of both the traditional approach (safety factor) and the observed levee strength approach ($\beta_{posterior}$), the required reliability index ($\beta_{required}$), and the final judgment when the observed levee strength approach is used

Levee section	Safety factor traditional approach	$\beta_{posterior}$	$\beta_{required}$	New safety judgment
1	0.68	2.94	3.21	Unsafe
7	0.83	3.62	2.88	Safe
12	0.90	3.19	2.47	Safe
13	0.87	3.62	2.47	Safe
14	0.93	3.62	2.47	Safe
15	0.87	3.62	2.47	Safe
16	0.83	3.62	2.47	Safe
17	0.87	3.62	2.47	Safe
18	0.82	3.16	3.54	Unsafe
20	0.88	3.16	3.54	Unsafe
21	0.88	3.29	2.47	Safe
24	0.87	3.29	3.54	Unsafe
26	0.79	3.13	2.47	Safe
29	0.88	3.08	3.54	Unsafe

5 | DISCUSSION

In this study, a new approach for levee safety assessment was developed in such a way that the effects of observations of survived loads and levee degradation on the levee's failure probability could be taken into account in a pragmatic way. The loading conditions consisted of combinations of the canal water level and the phreatic line. Traffic loads were not included in the assessment, which means that the calculated reduction in failure probability is overestimated. In a follow-up study, the proposed methods could be extended by including traffic loads in a probabilistic way.

In the case study, the 14 levee sections that initially did not meet the safety requirements according to the semi-probabilistic approach, were reduced to five different representative levee sections. For these five sections, the relation between the estimated safety factor and the levee reliability was established. Due to the limited number of levee sections treated in this study, we have compiled all results from our safety assessments (factors of safety and reliability indices) into a single plot to find the relation between β and SF. However, and this can also be seen in Table 4 and Figure 8, there are several important variations in levee characteristics, such as the presence or absence of a berm and the variations in retaining height. It is likely that the SF–β relation becomes more accurate if more levee sections are assessed, and the levees are grouped, based on individual levee characteristics, such as retaining height, presence of a berm, inner slope, crest width, and sub soil composition. Then, a SF–β relation can be established per levee typology, which should, ideally, lead to a distinctive SF–β relation per levee type.

There are several performance indicators, which all affect the levee reliability in different ways. Some important examples are: animal burrows, cracks, and subsidence. Levee characteristics determine how a levee's reliability is affected by a levee performance indicator. In this study, we have focused only on levee subsidence, and have assumed that all levees are affected by subsidence in the same way. Further development of the observed levee strength approach should include performance indicators that are used in an inspection, and estimations of how levees are affected by these degradation types. A distinction should be made between levee types, based on levee characteristics.

The relation between β and SF after reliability updating shows a different, milder, slope than before updating, as can be seen in Figure 8. A possible explanation for this change in slope is that reliability updating might have a larger effect on stability assessments that resulted in low safety factors (low values for β), than on high safety factors, especially if the lower safety factors are caused by high uncertainties. Observations of survived loads will then result in a large uncertainty decrease and, consecutively, in higher reliability indices. If uncertainties are smaller, reliability updating is expected to have a smaller effect, resulting in a decreased slope.

Not all inspection results have been included in this study, since many of them contain levee performance indicators of which the effect on the factor of safety is not yet known. Therefore, the results from this study may be

seen as a proof-of-concept, and not as a complete safety assessment. As the authors aimed to show how to determine the effect of subsidence on levee stability, not only the most recent inspection results (2018), but also results from older inspections (2016 and 2017) were used.

It is not possible to use the same probabilities of occurrence of different loading combinations for all types of levees, like we did in this study. In practice, it seems reasonable to derive probabilities of occurrence through a location-specific analysis of loads and their combinations. Another approach is to derive a table of probabilities of occurrence per levee type. These levee types should then be determined, based on levee characteristics, such as geometry, soil type and geotechnical properties. Whether this is a feasible approach, can be assessed by measuring the phreatic surface in levees with similar properties and compare the behavior of the phreatic surface under varying conditions. Consequently, these measurements can be used to determine levee type specific probabilities of occurrence.

6 | CONCLUSIONS AND RECOMMENDATIONS

6.1 | Conclusions

In this study, we proposed an approach for stability assessment of polder canal levees, with the aim to improve the accuracy of levee reliability analyses by including observations of survived loads and current levee performance observations from levee inspections.

The observed levee strength approach, proposed in this paper, shows that it can significantly reduce the estimated failure probability of levees by optimally utilizing information on actual levee performance and performance under observed extreme conditions. Through inclusion of observed levee behavior, the estimated failure probabilities become significantly lower, which is more in line with the estimation of Rikkert and Kok (2019). In this study, this has resulted in approval of 11.0 of the 16.1 km of levees that was rejected initially. This emphasizes the value of proper levee performance observations and the importance of levee monitoring and inspection.

The proposed approach leads to estimations of levee failure probabilities, whereas the current semi-probabilistic approach is only able to assess whether or not the levee meets the safety requirement, without giving further estimation of the actual failure probability. While a probabilistic approach requires an additional effort in terms of levee stability calculations, it allows for the inclusion of survived loads and levee inspection results, with major improvement of the safety assessment as a result. The additional effort is therefore often rewarded in more accurate estimations of failure probabilities, which give insight into how much room there is left between the actual levee strength and the requirements, and possibly how much degradation can be allowed, before reparations become urgent. Estimations of levee failure probabilities provide opportunities to assess the flood probability and corresponding risk of a flood defense system, and prioritize interventions based on their (cost) effectiveness in terms of risk reduction.

6.2 | Recommendations

The currently used approach for stability analysis of polder canal levees calculates the safety factor, following a semi-probabilistic: one extreme loading scenario is considered. The proposed approach follows a probabilistic approach and determines the failure probability of a levee, expressed as the reliability index. The approach we propose in this paper does not comply with the current safety standard system, which is based on exceedance probabilities of the water level and prescribes a required factor of safety. For the observed levee strength approach to be directly applicable, safety standards should be expressed in probabilities of failure. In a future study, it can be explored how observations of past performance could be included in such a way that it complies with current safety assessment practices.

We recommend to further investigate a levee typology classification in which levee sections can be divided, so that levee type-specific SF–β relations can be determined. A larger number of levee sections should be included in an advanced study in such a way, that the sample set is representative for all canal levees in the Netherlands and includes all levee typologies.

In this study, reasonable assumptions of survived loads allowed us to perform reliability updating. However, more evidence of survived load conditions is essential to further improve levee strength estimations. This pleads for ongoing monitoring of hydraulic loads (canal water level and phreatic water level), especially under extreme circumstances. Monitoring is also recommended to further improve and justify the estimation of probability of occurrence of specific combinations of loading conditions. Due to a lack of measurements, we had to assess these probabilities by expert judgment (Table 2), and applied it to each levee section, while in practice these probabilities might be location-specific.

For further research into the effects of levee performance indicators on levee failure mechanisms, it is recommended to select the levee performance indicators

that are actually included in levee inspections. In this way, actual levee conditions can easily be included in analysis of levee safety.

Finally, as our approach has shown, optimally utilizing the information from observed levee performance, significantly reduces the estimated failure probability by reducing uncertainty. Levee performance observations can be obtained relatively easy and at low cost. Especially, when compared to the high costs of reinforcement of (unnecessary) rejected levees. Therefore, further development and improvement of the observed levee strength approach requires a shift of focus towards monitoring and inspection, but potentially saves money.

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CONFLICT OF INTEREST

The authors confirm that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Stephan Johannes Hendrikus Rikkert https://orcid.org/0000-0002-5073-5123
Matthijs Kok https://orcid.org/0000-0002-9148-0411
Kasper Lendering https://orcid.org/0000-0002-6820-1840

ENDNOTE

[1] To perform the probabilistic calculations with D-Geo Stability, an older version of the set of regional geological parameters was used. Using this model, similar safety factors were calculated as were found in the safety assessment done by the Water Board. This check proved that a fair comparison can be made between the results of our approach and the outcomes of the safety assessment done by the Water Board.

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