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Macro-stability assessment of dikes using two different probabilistic models

Évaluation de la macro-stabilité des digues à l'aide de deux modèles probabilistes différents

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ABSTRACT: This paper presents the reliability analyses in combination with stability calculations aiming to assess the safety of a primary dike in the Netherlands against the sliding of the inner slope, known as macro-instability. The reliability analyses are dedicated to one of the dike sections located between Krimpen aan den IJssel and Gouderak in the province of Zuid-Holland. There are two proposed modelling approaches. In the first approach, the reliability index is calculated by means of Probabilistic Model Macro Stability (PMMS), using the inputs that are derived from the macro-stability calculations using the finite element model PLAXIS. In the second approach, the reliability index is obtained using Probabilistic ToolKit (PTK) in combination with the limit equilibrium model D-Geo Stability. This study suggests that there is a global coherence between these two approaches even if they are methodologically different. Therefore, PMMS can be used as an alternative model besides PTK to assess the reliability of dikes with regard to macro-stability.

RÉSUMÉ: Cet article présente les analyses de fiabilité en combinaison avec des calculs de stabilité visant à évaluer la sécurité d'une digue primaire aux Pays-Bas contre le glissement de la pente intérieure, connu sous le nom de macro-instabilité. Les analyses de fiabilité sont dédiées à l'une des sections de digues situées entre Krimpen aan den IJssel et Gouderak dans la province de Zuid-Holland. Deux approches de modélisation sont proposées. Dans la première approche, l'indice de fiabilité est calculé au moyen du modèle probabiliste de macro-stabilité (PMMS), à l'aide des données dérivées des calculs de macro-stabilité à l'aide du modèle par éléments finis PLAXIS. Dans la seconde approche, l'indice de fiabilité est calculé à l'aide du Probabilistic ToolKit (PTK) en combinaison avec le modèle d'équilibre limite D-Geo Stability. Cette étude révèle qu'il existe une cohérence globale entre ces deux approches, même si elles sont différentes sur le plan méthodologique. Par conséquent, le PMMS peut être utilisé comme modèle alternatif à la PTK pour évaluer la fiabilité des digues en ce qui concerne la macro-stabilité.

Keywords: dike; macro-stability; safety assessment; probabilistic model; reliability index

1 INTRODUCTION

All primary flood defences in the Netherlands, such as dikes, are by law periodically evaluated to investigate whether or not they still comply with the safety standards according to the Water Act. Since 01 January 2017, the new risk-based safety standards have been introduced, which is defined in terms of a maximum acceptable probability of flooding, abolishing the use of former standards, which are based on the exceedance frequencies of water levels that a dike should safely withstand.

Figure 1. New safety standards for primary flood defences in the Netherlands valid from January 2017

The difference in comparison with the former standards is that a wide range of possible load events with their respective probabilities as well as uncertainties on the resistance side can now explicitly be considered in the assessment. Two national policy studies, WV21 (Flood Protection in the 21st Century) (Kind, 2010) and VNK2 (the National Flood Risk) (Jongejan et al., 2011), provided essential information to establish these new safety standards.

According to the new policy, the maximum acceptable probability of dike failure per area in the Netherlands varies from 1/300 to 1/100.000 per year (Slomp, 2016). The reason for this variety is the difference in risks for each area. To facilitate the move towards the new safety standards, the Dutch government has developed new guidelines and procedures, called WBI2017, for assessing the safety of dikes. The assessment consists of a layered approach, i.e. simple (semi-probabilistic with partial safety factors), detailed (probabilistic with approximations), or advanced (full-probabilistic), depending on the complexity of the problem and the quality of the available data.

In comparison to semi-probabilistic analyses, probabilistic analyses provide a sharper safety picture and therefore may offer the possibilities for a more economical design for the strengthening of dikes. The application of the new safety standards is still new in the Netherlands, such as addressed in this paper.

This paper reports a case study of a primary dike located between Krimpen aan den IJssel and Gouderak in the province of Zuid-Holland, and concentrates only on a detailed probabilistic safety assessment of the dike against the sliding of the inner slope, known as macro-instability.

The reliability analyses are performed using the CRUX in-house Probabilistic Model Macro Stability (PMMS). Herein, the results of macro-stability calculations obtained by means of the SHANSEP MC model in PLAXIS as presented in Simanjuntak et al. (2018), are used as model inputs to compute the reliability index.

First, the shear strength model for the macro-stability assessment according to the WBI2017 is introduced followed by the relevant information to set-up the target reliability index. Then, calculation procedures and various aspects to perform reliability analyses in PMMS are briefly described. Finally, the results of reliability index are presented and discussed. As for verification, they are compared with those obtained using the combined model Probabilistic

ToolKit (PTK) and D-Geo Stability program of Deltares.

2 SHEAR STRENGTH MODEL

In the WBI2017, the dike resistance against the macro-instability needs to be evaluated using the CSSM (Critical State Soil Mechanics) theory (Schofield and Wroth, 1968). Furthermore, the undrained shear strength has to be determined according to the SHANSEP (Stress History and Normalised Soil Engineering Properties) method (Ladd and Foott, 1974) that enables the effect of stress history and stress path of the soils to be taken into account when characterising the soil strength.

Within the framework of the CSSM, the undrained shear strength of soils, s_u, is modelled as follows:

$$s_u = \sigma'_v \; S \; (OCR)^m \tag{1}$$

with

$$OCR = \frac{\sigma'_y}{\sigma'_v} = \frac{\sigma'_v + POP}{\sigma'_v} \tag{2}$$

in which s_u is the undrained shear strength (kPa), σ'_v is the in-situ effective vertical stress (kPa), σ'_y is the yield stress (kPa), *OCR* denotes the over-consolidation ratio (-), *POP* represents the pre-overburden pressure (kPa), *S* indicates the undrained shear strength ratio (-), and *m* is the strength increase exponent (-).

The relation between *POP* and *OCR* is:

$$POP = \sigma'_v \; (OCR - 1) \tag{3}$$

For drained layers, cohesion *c'* is zero in the critical state. Based on the Mohr-Coloumb criterion, the shear stress is calculated by:

$$\tau = \sigma'_n \sin \varphi' \tag{4}$$

in which φ' representss the friction angle at the critical state (°) and σ'_n is the normal effective stress along the slip plane (kPa).

3 TARGET RELIABILITY INDEX FOR MACRO-STABILITY

It is essential to realise that the new safety standard is applied for an entire dike segment, which consists of numerous dike sections. It is part of a dike system, where a breach would have a similar impact irrespective of the precise location of the breach. When a breach occurs as a result of different failure mechanisms, the overall maximum acceptable probabilities of different failure mechanisms may not exceed the safety standard (Jongejan and Calle, 2013).

In the WBI2017, the safety standard can be translated into the maximum acceptable failure probability per failure mechanism and dike section. For macro-stability, the safety requirement at the cross-section level can be determined by (Rijkswaterstaat, 2017):

$$P_{T,stability} = \frac{\omega \, P_{norm}}{N} = \frac{\omega \, P_{norm}}{1 + \left(\frac{a \, L}{b} \right)} \tag{5}$$

where P_{norm} is the maximum acceptable failure probability of a dike segment (year^{-1}), ω is the failure probability factor, *N* is the length-effect factor (-), *L* is the total length of the segment (m), *a* denotes the fraction of the length that is sensitive to the slope stability (-), and *b* denotes the equivalent auto-correlation length of the performance function (m).

The length-effect *N* is defined as the increase of the failure probability with the length of a dike due to imperfect correlations between different cross-sections. Principally, the smaller the correlation distances of important random variables, the higher the increase of the probability of failure.

According to the Expertise Network on Flood Safety (ENW, 2007), the value for *a* and *b* are 0.033 and 50 m, respectively. In the WBI2017, the default value for ω for slope stability is 0.04, while for piping and rupture of the cover layer the default value is 0.24 (Rijkswaterstaat, 2017).

The failure probability can also be expressed in terms of a reliability index, β as follows:

$$\beta_{T,\,stability} = \Phi^{-1}\left(1 - P_{T,\,stability}\right) \tag{6}$$

where Φ^{-1} is the inverse of the standard normal probability function.

Additionally, the required factor of safety for macro-stability with regard to a reliability index can be recalculated using the calibrated relation given by Kanning et al. (2017):

$$SF_{required} = 0.15\,\beta_{T,\,stability} + 0.41 \tag{7}$$

4 ADOPTED METHODOLOGIES

It has been widely accepted that the First Order Reliability Method (FORM) (Rackwitz, 2001) is the most versatile method compared to the other approximate methods of reliability analysis. In a FORM-analysis, a limit state function Z that will have a value smaller than zero in case of failure, is normalized and linearized in the design point, which is the combination of parameter sets with the highest probability density, for which the Z equals to zero.

4.1 PMMS

PMMS is one of the few probabilistic methods available to compute the probability of failure of geotechnical structures, such as dikes, in combination with a finite element model. This model holds the main principle, i.e., the shear strength distribution and the slip circle obtained from the finite element model PLAXIS are assumed to be approximately equal to the shear strength distribution and the critical slip circle obtained from the probabilistic computations.

In PMMS, the limit state function, Z, and the reliability index, β, are defined as follows:

$$Z = E - E_c \tag{8}$$

$$\beta = \frac{\mu(Z)}{\sigma(Z)} \tag{9}$$

in which E denotes the dissipated energy in the failure mechanism that corresponds to the actual shear strength (-), E_c is the dissipated energy in the failure mechanism that corresponds to the critical shear strength before the dike fails (-), $\mu(Z)$ is the mean of Z, and $\sigma(Z)$ is the standard deviation of Z.

E and E_c are determined from the displacements in the failure mechanism and the distribution of the shear strength across the slip circle. For details on PMMS, the reader is referred to Bakker (2005) and Bakker et al. (2019). When adapted for the reliability assessment of macro-stability according to the WBI2017, the following step-by-step procedure is proposed:

a) identify the slip line using the SHANSEP Mohr-Coulomb model in PLAXIS based on the mean value of the soil parameters and the yield stress. Provide the factor of safety from PLAXIS in PMMS;
b) since the slip line will cut several soil layers, specify the relevant soil layers, which are intersected with the slip line, and distinguish between drained and undrained layers;
c) divide the slip line in a soil layer into several elements proportionally. An element is part of the slip line that intersects with the top boundary of a soil layer on the one hand and with the bottom boundary of the same soil layer on the other hand. At least one element exists in a soil layer;
d) for each element, define the element point that is located in the middle of an element;

e) introduce the uncertainties in soil parameters by specifying their mean values and variation coefficients;
f) for the drained layers, input the value of both the vertical and the horizontal effective stress obtained from the calculation phase prior to the safety analysis in PLAXIS. The input values are the stresses that correspond to the level where the element point is located;
g) analogously apply for the undrained layers but only the vertical effective stress is given;
h) for the undrained layers, determine the value of vertical effective stress for the daily water level conditions. Again, the input values have to correspond to the level where the element point is schematized;
i) for the undrained layers, provide the mean value of the yield stress for the daily water level conditions, and the yield stress obtained from the calculation phase prior to the safety analysis in PLAXIS that correspond to the location of the element point. At the same time, introduce the uncertainty in the yield stress based on a lognormal distribution and by providing its variation coefficient;
j) provide the correlation coefficient between the soil parameters of different soil layers;
k) perform the reliability analysis using FORM to calculate the limit state function Z, and PMMS will deliver β when Z reduces to zero.

4.2 Probabilistic ToolKit (PTK)

The reliability index for macro-stability in PTK is obtained in combination with the limit equilibrium model D-Geo Stability. The safety factor is calculated using the Uplift-Van model, which accommodates uplift conditions.

With SF denotes the safety factor (-) and m_d is the model factor (-), the limit state function, Z, in PTK is defined as:

$$Z = (SF.\, m_d) - 1 \tag{10}$$

Herein, the model factor for the Uplift-Van model follows a lognormal distribution with a mean value of 0.995 and a standard deviation of 0.033 (Schweckendiek et al., 2017).

Unlike in PMMS, the value of yield stress in PTK is given at a yield stress point schematized in the middle of an undrained soil layer. This is done by defining two verticals. One vertical is located in the dike and the other is in the hinterland. Each vertical consists of at least one yield stress point.

The uncertainty in the yield stress is modelled based a lognormal distribution, using a shift that is equal to the vertical effective stress for the daily water level conditions. The guidelines on the use of PTK for reliability assessments of macro-stability are presented in Schweckendiek et al. (2017).

5 COMPUTATIONAL EXAMPLE

5.1 Study area

This study focusses on the implementation of the CRUX in-house Probabilistic Model Macro-Stability (PMMS) for assessing the safety of a river dike against macro-instability. The dike is located between Krimpen aan den IJssel and Gouderak in the province of Zuid-Holland that has an important role in protecting the dike ring 15 Lopiker- en Krimpenerwaard.

5.2 Reliability requirement

The total length of the dike segment is 19.2 km. The maximum acceptable probability of flooding for the area studied is 1/3000 year^{-1}. For this project, the failure probability factor for macro-stability is adjusted by fully taking into account the factor for piping. That together, leads to the target reliability index at the cross-section level of 4.35 or to the required safety factor of 1.06.

5.3 Loading scenarios

In the WBI2017, the maximum high water level (HWL) is defined as the water level with an exceedance probability that is equal to the maximum acceptable probability of flooding. In this study, the maximum HWL is at NAP +3.32 m and the dike is considered fully saturated.

Table 1. Loading scenarios

Scenario	Traffic Load	HWL
1	5 kPa	NAP +3.32 m
2	12 kPa	NAP +2.60 m
3	15 kPa	NAP +1.20 m

Besides the water levels, a uniform temporary traffic load over a width of 2.5 m is schematized at the inner side of the dike crest. Since traffic decreases during high water level events, the reliability of the dike is evaluated for various loading scenarios as listed in Table 1.

5.4 Soil parameters

In this study, the uncertainty in the soil parameters is modelled using a lognormal distribution, which is basically selected to rule out negative values in the soil parameters that are physically not possible.

Table 2. Soil parameters

Undrained	μ_S	σ_S	μ_m	σ_m
Clay (dike)	0.37	0.02	0.91	0.02
Clay (organic)	0.32	0.02	0.88	0.01
Peat	0.39	0.02	0.85	0.02
Drained		μ_φ	σ_φ	
Coarse granular fill		32	1.5	
Pleistocene sand		35	1.5	

For the undrained soil layers, the mean value μ and the standard deviation σ for the parameters S and m are given in Table 2, with reference to de Koning et al. (2019). For the drained soil layers, the mean value and the standard deviation for the parameter φ' are derived according to the schematisation manual for macro-stability (Rijkswaterstaat, 2016). Eventhough parameter c', is irrelevant for macro-stability assessments, it is yet defined as the parameter with a deterministic value equal to zero.

5.5 Yield stress

The yield stress, σ'_y, is a measure for the stress history of the soil. Its magnitude is the result of creep processes, which can lead to a decrease of pore volume over time influencing the vertical effective stress, and thus the shear strength.

From the CPT's, the level of yield stress can be determined locally. Its variation coefficient, $VC_{\sigma'y}$, i.e. the ratio of the standard deviation to the mean, is given in Table 3. More details on this regard is found in de Koning et al. (2019).

Table 3. Variation coefficients

Soil type	$VC_{\sigma'y}$
Clay (dike material)	22%
Clay (organic)	16%
Peat	23%

5.6 Correlation for different soil layers

Due to the same geological conditions, the shear strength between soil layers can be correlated. The clay layers (dike material) under the dike are correlated to the clay layers (dike material) in the hinterland. This is also applicable to the organic clay layers under the dike and those in the hinterland. The peat layer in between two organic clay layers under the dike is correlated to the two peat layers in the hinterland.

6 RESULTS

The reliability indices obtained from PMMS and PTK are presented in Table 4. For completeness, the safety factors, which are based on the mean values of soil parameters obtained from the macro-stability computations using PLAXIS and D-Geo Stability as presented in Simanjuntak et al. (2018), are also given herein. The results in Table 4 suggest that the dike stability slightly decreases as the traffic load increases. However, unlike in the case of partially saturated dikes, the river water levels barely affect the reliability, if the dike is fully saturated.

Table 4. Results of SF and β

Models	**Scenario**		
	1	**2**	**3**
Safety Factor		*SF*	
SHANSEP MC	1.44	1.43	1.42
Uplift-Van	1.44	1.43	1.42
Reliability Index		*β*	
PMMS	5.84	5.66	5.46
PTK	5.17	5.00	4.91

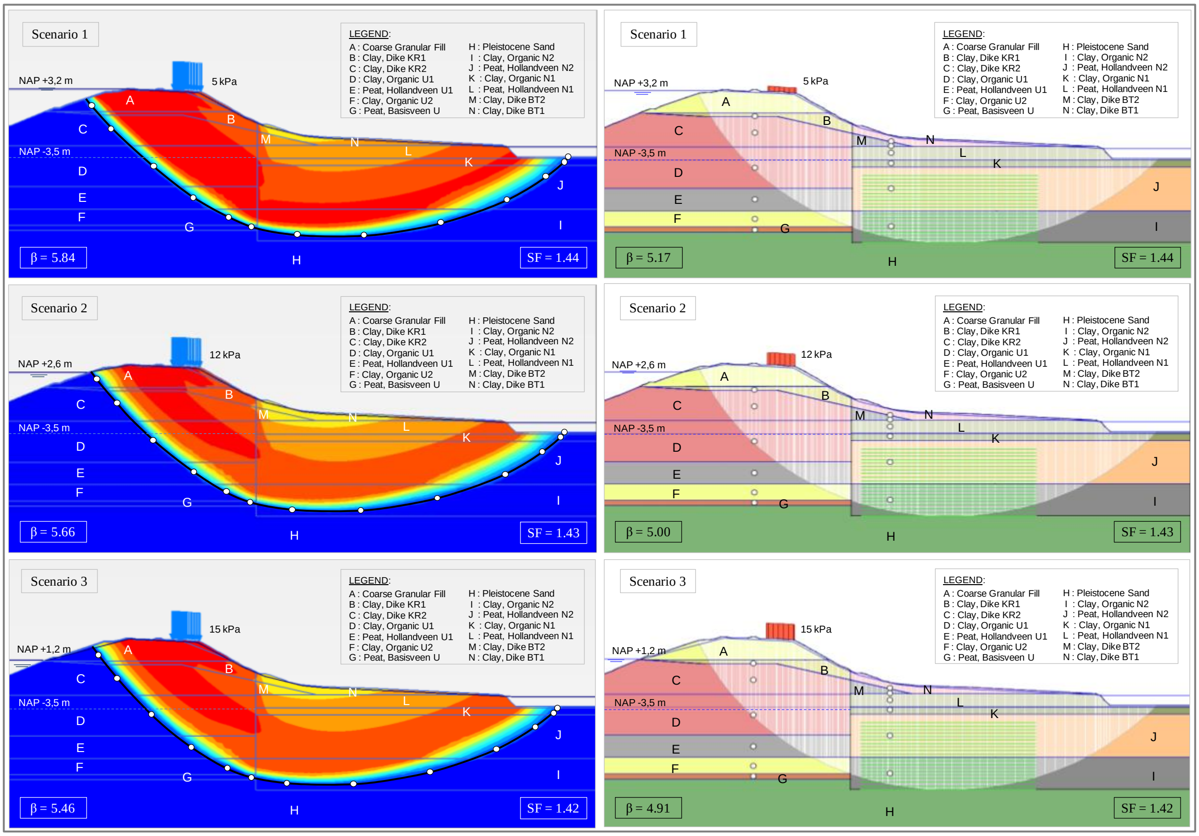

Figure 2. Results of β for various loading scenarios (left PMMS & PLAXIS, right PTK & D-Geo Stability)

In this particular example, the factor of safety obtained using the SHANSEP MC model is identical to that using the Uplift-Van model. The similarity of the results is due to the fact that the influence of the rotation of principal axes on the *OCR* and therefore the undrained shear strength is negligible for cases of dikes with deep slip circle. Nevertheless, this is not the case if the slip circle is shallow (Simanjuntak et al., 2018).

If the dike is assessed based on the detailed probabilistic assessment, the obtained reliability indices from either PMMS or PTK exceed the target value, implying that the macro-stability of the dike is satisfactory.

7 CONCLUDING REMARKS

This paper presents the implementation of the new safety standards to the primary dike located between Krimpen aan den IJssel and Gouderak, in the Netherlands. It deals with the probabilistic safety assessment of the dike at the cross-section level for macro-stability.

The probabilistic analyses were performed on the one hand by means of Probabilistic Model Macro-Stability (PMMS) in combination with the results from PLAXIS, and on the other hand by using the combined Probabilistic ToolKit (PTK) and D-Geo Stability program.

The study shows that there is a global coherence between these two modelling approaches and therefore, PMMS and PTK can be compared even if they are methodologically different. For this reason, PMMS may be applied to assess the reliability of primary dikes in regard to macro-stability.

In terms of application, PMMS is more efficient model due to its versatility to compute the reliability index in which the undrained shear strength can also be derived based on the major effective principal stress. In the case of dikes, this is thought to be a more suitable parameter compared to the vertical effective stress in view of the stress rotation near to the dike slope.

It has to be mentioned that the research on the PMMS is ongoing. Topics that will be included in this model are the model factor, which allows for model uncertainties, and the precise location of the probabilistic critical slip circle. To date, the model factor for the SHANSEP MC model has not yet been identified, which can affect the reliability index calculated using PMMS. The same also accounts for the precise location of the probabilistic critical slip circle and thus the location of the yield stress. To what extent and under which conditions they affect the reliability index is a challenging topic for the future study.

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