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The History of Safety Factors for Dutch Regional Dykes

T. DE GAST [a] , P.J. VARDON [a], C. JOMMI [a] and M.A. HICKS [a]
[a] *Section of Geo-Engineering, Delft University of Technology, The Netherlands*

Abstract. Regular dyke assessment is part of reducing the risk of flooding in the Netherlands. 18 000 km of dykes are assessed at regular intervals, of which 14 000 km are classified as regional dykes and their main aim is to defend polders from inundating. The methods of assessing regional dykes are strongly inter-twined with the methods of assessing primary dykes; however, regional dykes differ due to lower consequence levels and significantly shorter individual dyke lengths. Initially, local experience was relied upon for maintaining dykes, prior to the utilisation of soil mechanics calculations to determine the safety/stability of the dykes. Over the years, the approaches have been developed leading to different assessment criteria. This paper aims to give insight into the development of the assessment criteria for regional dykes in Dutch norms/guidelines since the devastating storm surge of 1953, starting with the probabilistic assessment of water heights and global factors for slope stability, through to the adaption of statistical models which enabled the use of partial factors in dyke assessment. Partial factors in assessments allow for improved and more detailed knowledge to limit the uncertainties and lead to more detailed assumptions in the calculations. The introduction of risk-based design enables assessment criteria based on the expected damage due to inundation. The paper discusses assumptions, levels of safety and information required to complete the assessment. Including consequence based assessment and risk based design, leads to a larger possible range in the required factors of safety.

Keywords. Dyke, partial factors, slope stability assessment.

1. Introduction

While the delta-works were still being constructed to reduce the coastal length of the Netherlands, on 14 January 1960 a breach of a regional dyke (the flood defence of the polder) of the Noorder IJpolder occurred, flooding the Amsterdam district Tuindorp Oostzaan, and triggering a long term research initiative to assess the safety of the Dutch polders against flooding. The methods and guidelines of assessing was described in COW (1973) and the assessments were also performed by Centrum Onderzoek Waterkeringen (COW), which was part of Rijkswaterstaat. However, added information, experience, research and increases in computing power have led to changes in the assessment criteria over the years. This paper discusses the various assumptions that have been made and their effects on the required (global) factor of safety.

The initial guideline (COW, 1973) was based on experience gained from 11 assessed dykes and archive data on past dyke failures. Different failure mechanisms which need to be taken into account during an assessment were discussed: overtopping, breaching, erosion, elements with significant stiffness difference, construction and (lack of) maintenance. In this initial guideline, the main focus for the assessment was based on breaching, overtopping and erosion, which are considered to be slow failure mechanisms that ‘announce’ themselves. In contrast, elements with significant stiffness difference, construction and maintenance are temporary and very local occurrences. This paper will focus, among the previous mechanisms, on the prevention of breach and associated slope stability analysis.

2. Slope stability assessment

In this paper, only the circular Bishop stability method is considered to calculate stability. In this section an overview is given on the changes in assessment criteria in chronological order. The different assessment criteria prescribe different factors of safety. To facilitate comparison of the different assessment criteria through time,. For the purpose of comparison, partial factors (introduced in 1993) are converted to global reduction factors using the formulae:

$$\frac{F}{\gamma_g} \geq 1 \qquad (1)$$

$$\gamma_g = \gamma_d \gamma_m \gamma_n \qquad (2)$$

Where F is the calculated factor of slope stability, γ_g is the global reduction factor, γ_d is sensitivity factor for the calculation method, γ_m is the material reduction factor and γ_n is the damage factor.

The calculated factor of stability F is divided by γ_g to give a combined factor of safety (FoS) that should be equal to, or greater than, one. The comparison of the global reduction factors (which is the same as the required calculated factor of stability) is presented in figure 1. In the case that the required partial material factors for cohesion and friction angle are different from each other, an average partial material factor was used. Sections 2.1-2.6 provide a detailed overview of the changes in the assessment methods.

2.1. COW (1973)

The COW (1973) assessment was based on average values obtained from local site-investigation and laboratory testing (Dutch cell test). The factor of stability was calculated using Bishop (1955), which was chosen because it was the most (internationally) accepted method to calculate slope stability at that time. However, COW (1973) noted that the Bishop method was not suitable in very deformable (soft) soils, because failure was expected not to be circular and anisotropy and heterogeneity would influence the shape of a possible failure. In small embankments, low stresses, cohesion, shear cracks and the shape of the failure can lead to large errors. The safety factors presented in yellow in figure 1 give a range of safe values, based on the unit weight of the material and the number of laboratory tests performed on the material. If the calculated factor of stability was in the orange range in figure 1, more investigation would be required before the dyke safety could be considered acceptable. A factor of stability lower than 1.0 was never deemed acceptable.

This assessment was explicitly based on information from the cross-section being evaluated; therefore, the calculated stability was not a combination of worse case geometry, soil profile and material properties. However, using average material values is known to lead to an overestimate of safety (Hicks, 2012).

2.2. 1973-1993

According to TAW (1993) and STOWA (2007), the required global safety factor before 1993 was 1.3. However the authors have not found original documents reporting this required global factor of safety.

The single value reported to have been used is lower than all single values for the unconditional approval of the previous requirement.

2.3. TAW (1993)

In 1993, partial factors were introduced. The sensitivity factor γ_d was introduced to account for uncertainty in calculation method and given a value of 1.0 for Bishop's analysis.

The material factor γ_m was introduced to account for uncertainty in the material and determination of material parameters. The material factor for cohesion was constant (value) while the material factor for friction angle changes per material and type of laboratory test used to determine the friction angle. The material factors are equal to the material factors listed in TAW (1989), a guideline for primary dykes, and range from 1.10 to 1.25.

The damage factor γ_n was introduced to account for the consequences of inundation. This was varied based upon the method being used to obtain the material parameters. In calculations using average strength parameters, γ_n was 1.1, whereas, for the case in which the characteristic strength was determined according TAW (1993), γ_n was 0.9.

TAW (1993) reported the damage factor was chosen so as to keep the global factor equal to 1.3 by using,

$$\gamma_n = 1.3 \frac{r_{n,V}}{\gamma_d \gamma_m} \qquad (3)$$

shear strength stated as ≈ 0.85.

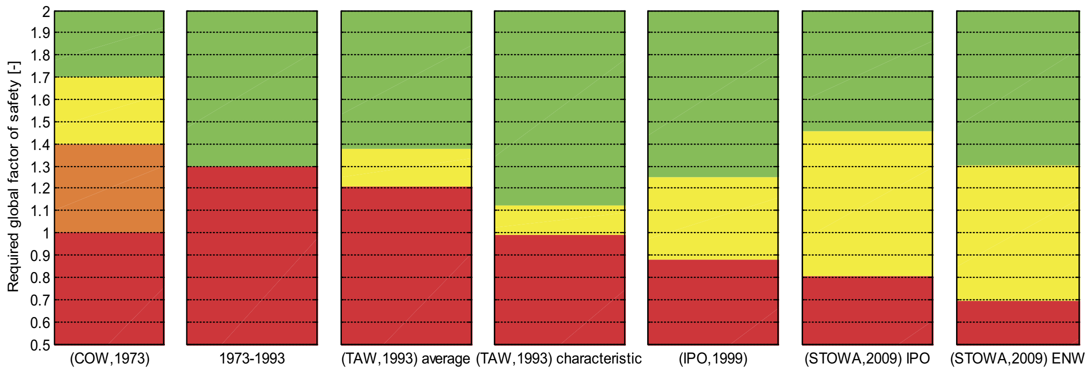

Figure 1: Overview of the required global factors of stability. In red (lowest), factor of stability not acceptable; in orange, more detailed research is required; in yellow, acceptable depending on the material and economic value of the polder and in green (highest) acceptable.

In which $r_{n,V}$ is a factor given in TAW (1993) representing a measure of distribution of the γ_{m} is therefore responsible for the range of required FoS for the labels '(TAW, 1993)' in figure 1. Changing to the use of partial factors should give the opportunity that different uncertainties can be evaluated independently. To avoid complications when updating on uncertainties, partial factors have to be independent. However in the case of partial factors γ_{n} this was not the case, this hinders the potential of partial factors. In this case, γ_{n} is chosen to prevent change in required global factor of safety.

For the calculation model Bishop a sensitivity factor for γ_{d} is given as 1.0 which implies a perfect calculation model, as the calculated factor of stability is not reduced in contrary to the note in COW (1973).

Applying characteristic values leads to a cautious estimate of the slope stability. However, the cautiousness of the estimate is reduced when a γ_{n} of less than 1 is applied.

2.4. IPO (1999)

The economic implications of inundation were taken into account in IPO (1999). The polders were divided into 5 different classes, with different safety norms of once per 10, 30, 100, 300 and 1000 years. These safety norms are translated into a reliability index β using the inverse of the standard normal distribution. The obtained β was used in equation (4) to approximate the required damage factor.

$$\gamma_n = \frac{K*k}{K-\beta} \tag{4}$$

where β is the reliability index, k is stated to be 0.7, K is stated to be 10.6; and is said to depend on the ratio between the effect of the cohesion and friction angle on the stability, the variation coefficient of the cohesion and friction angle and the location of the phreatic surface. k was defined based on γ_{d}, γ_{m} and the range of shear strength parameters, $r_{n,V}$, in a similar way as equation (3).

The required damage factor was implemented into the assessment. The requirements for a type III polder (safety norm 1/100 year) are the same as in the assessment according to TAW (1993) i.e. γ_{n} is equal to 0.9. The value of γ_{n} range from 0.8-1.0 using equation (4) leads to an equivalent β of 1.3-3.2.

Splitting the partial factors based on expected damage can improve the allocation of funds for maintenance and improvement and fits in a framework of risk based approach where the costs are weighted to the expected benefits.

However as γ_{n} is derived from the effects of the material parameters on shear strength and effects of phreatic line and variation coefficients of friction angle φ and cohesion c it remains an mixed parameter depending on expected damage, material and sensitivity of the calculation.

Because the range of γ_n is increased the range of required global factors of safety is increases.

2.5. STOWA (2007)

After a failure of a peat dyke during a dry summer in 2003 (Van Baars, 2005), a new standard for the assessment of rural dykes was introduced. This standard collected the assessment methods from the previous standards and added a drought criterion and became the new standard.

The requirements for the macro stability assessment did not change hence it is also represented in figure 1 as '(IPO, 1999)'.

2.6. STOWA (2009)

This document is not a new norm, however the document offers a discussion of changing γ_m based on the required reliability index, β.

The material factors were changed based on the required β. This approach was an extension of ENW (2007), written for the primary dykes, in which the material factor was determined for $\beta = 4.0$. In STOWA (2009) the material factors are provided for a range of β from 2.0-4.0.

In TAW (1989), TAW (1993) and IPO (1999) γ_n depends on γ_m and γ_d, this relation was discussed in STOWA (2009). However, because of the dependence of γ_n on γ_m, an iteration would be required to obtain a new γ_n value after γ_m is calculated. If this is not done, it would lead to an less conservative estimate in the case $\gamma_m < 1.2$.

In ENW (2007) the damage factor was determined according to the relationship

$$\gamma_n = 1 + 0.13(\beta - 4.0) \quad (5)$$

As equations (4) and (5) calculate the damage factor in different ways both have been presented in figure 1 as IPO equation (4) and ENW equation (5).

Using equation (4) γ_n ranges from 0.86-1.12, using equation (5) γ_n ranges from 0.74-1.0. both lead to a wider range of required safety factor than IPO (1999) method which has a range of γ_n of 0.8-1.0. Equation (5) is less conservative than equation (4) and therefore leads to lower required factors of safety.

A possible further partial factor, schematisation factor, γ_b, was described that could be included in analysis, but it was not part of the main discussion. This factor aimed to capture uncertainty of the interpretation of the field data and was initially quantified at 1.0-1.2. Because this factor was at this time not decided, it has not been taken into account in this paper and therefore it has not been included results presented in figure 1 and is not mentioned in the following section.

3. Effect on an example calculation

As both partial factors have been introduced in the assessment criteria and the determination of the Mohr-Coulomb material parameters for calculations have changed, two example calculations have been performed using the different approaches.

In the example calculation a dykes has been assessed. Where the material either peat or clay. The calculations were performed using the software D-Geo Stability (version 10.1 Build 3.2) using the Bishop module.

The γ_n, where needed, has been chosen to be 0.9, representing an inundation chance of 1/100 IPO (1999) which can be translated to an expected inundation damage of between €25m and €80m, i.e. a maximum of €0.8m/year, following STOWA (2008). The parameters used for the materials are presented in table 1, and have been obtained from two non-published datasets of triaxial CU tests (5% s' t' points). In order to obtain the coefficient of variation (CoV) values for cohesion and friction angle, several sets of ten points were randomly selected from the dataset to determine a Mohr Coulomb failure envelope, from which the CoV was determined for the individual parameters.

Combining the individual parameters without taking into account their (negative) correlation in an assessment will lead to an underestimation of the strength of the material. In order to prevent this, the material parameters have been determined using equation (6) from TAW (1989). This method estimates characteristic values based on the entire population of the data set.

$$\tilde{\tau}_{kar} = \bar{\tau} - t_{0.05}^{n-1}\sigma\sqrt{\Gamma^2 + \frac{1}{n}} \quad (6)$$

Where $\tilde{\tau}_{\mathrm{kar}}$ is the characteristic estimation (0.05 lower confidence limit) of the local over the slip surface averaged shear strength, $\bar{\tau}$ is the average shear strength, n is the number of tests, $t_{0.05}^{n-1}$ is the students t-value associated with a confidence limit of 0.05 and (n-1) degrees of freedom, Γ^2 is the reduction factor representing averaging along the slip surface a value of 0.25 TAW (1989).

Table 1: Soil parameters obtained from 179 peat and 50 organic clay TXCU 5% s' t',

		Peat	Clay
Unit weight	kNm^{-3}	12	16
Friction angle (Avg)	°	27.3	30.5
Friction angle (Char)	°	21.6	25.5
Friction angle CoV	-	0.24	0.17
Cohesion (Avg)	kNm^{-2}	7.8	6.1
Cohesion (Char)	kNm^{-2}	1.9	0.9
Cohesion CoV	-	0.46	0.51

To calculate the characteristic values equation (6) was applied on the entire population of s' and t' values, not on the set of cohesion and friction angle values obtained from the individual laboratory tests. The material factors were applied on the cohesion and friction angle whereas the damage and sensitivity factors were applied according to equation (1) after the stability factor (F) was calculated. If $\gamma_{m;c}$ and $\gamma_{m;\varphi}$ are equal applying equation (1) or the method described above results in the same FoS calculated. The resulting calculated safety factors are presented in table 2 and figure 3. In case β is required to compute partial factors, β has been estimated by equation (4).

As can be seen from figure 3, high factors of safety are obtained from global factors (1973, 1973-1993). The difference between peat and clay is large for 1973 and becomes smaller 1973-1993. After the introduction of the characteristic values for material parameters in 1993 TAW (1993) the calculated factor of safety drops, even though the safety is designed to be comparable to the average parameter determination (TAW, 1993 and before).

The effect of using characteristic strength parameters leads to lower factors of stability, the STOWA (2009) discussion on reliability index dependent material factors does increase the calculated factor of safety as can be observed in table 2, in this example γ_{n} was not recalculated after updating γ_{m}.

Table 2: Resulting calculated factors of safety with the inclusion of partial factors.

Year		γ_g		Peat		F	FoS
1973	Avg	1.6	-	-	-	2.67	1.67
	Avg	1.3	-	-	-	2.67	2.05
		γ_n	γ_d	$\gamma_{m;c}$	$\gamma_{m;\varphi}$		
1993	Avg	1.1	1.0	1.25	1.2	2.14	1.95
1993	Char	0.9	1.0	1.25	1.2	1.12	1.08
1999	Char	0.9	1.0	1.25	1.2	1.12	1.08
2009	Char	0.9	1.0	1.19	1.11	1.24	1.09
2009	Char	0.8	1.0	1.19	1.11	1.24	1.25
		γ_g		Clay		F	FoS
1973	Avg	1.4	-	-	-	2.76	1.97
	Avg	1.3	-	-	-	2.76	2.12
		γ_n	γ_d	$\gamma_{m;c}$	$\gamma_{m;\varphi}$		
1993	Avg	1.1	1.0	1.25	1.15	2.27	2.06
1993	Char	0.9	1.0	1.25	1.15	1.24	1.38
1999	Char	0.9	1.0	1.25	1.15	1.24	1.33
2009	Char	0.9	1.0	1.06	1.06	1.38	1.53
2009	Char	0.8	1.0	1.06	1.06	1.38	1.74

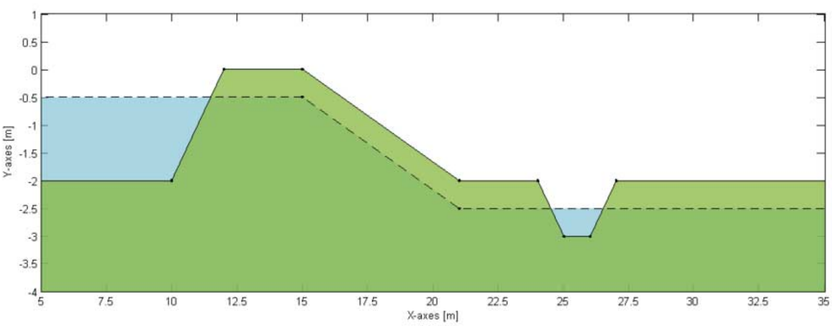

Figure 2: Geometry and boundary conditions used in the example calculations (ground)water levels are presented in blue and bounded by a dashed line, dyke geometry is presented in green and bounded by a solid line.

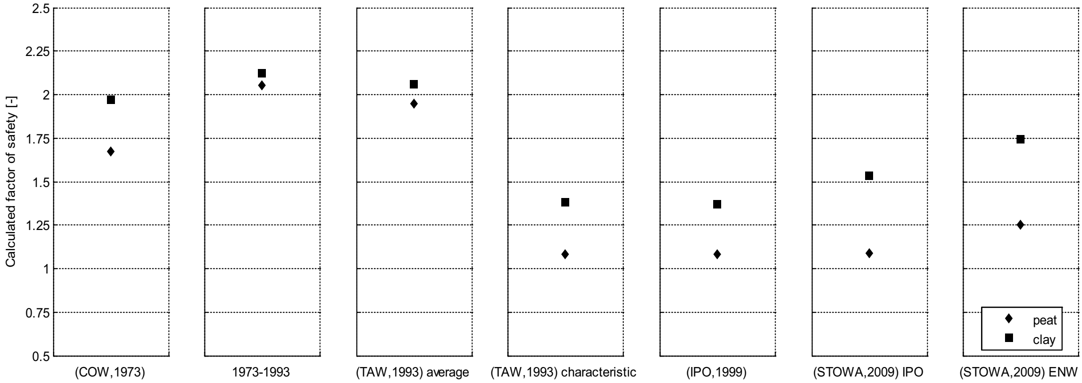

Figure 3: An overview of the effect of different assessment criteria on two example calculations. The example calculations have identical geometry and boundary conditions. Change is only made in material parameters (average or characteristic) and application of global or partial factors.

4. Conclusion

In this paper, the evolution of the required global safety factor for regional dykes in the Netherlands has been described, using the main norms and guidelines provided by various institutes who have dealt with the assessment of rural dykes.

In all guidelines and reports the sensitivity factor for Bishop was set to 1.0. However, according to COW (1973) Bishop is not suitable for soft clays and peats which is contradictory to a γ_d of 1.0. Therefore it is possible that the actual factor of safety could indeed be lower.

In order to avoid errors when updating individual partial factors, it is preferable for the individual partial factors to be independent, for γ_n this is not the case.

A required factor of safety described, by an average material parameter compared to a characteristic material parameter has a large impact on the required factor of stability leading to a drop in calculated factor of safety. This however is not necessarily in conjunction with a lower safety.

The range of required factor of safety is larger as the range of aspects taken into account has increased. It is noted that since 1973 the required factor has decreased, but more recently, after the introduction of characteristic values the possible required factor of safety can be both higher and lower.

The trend in the assessment guidelines is that reliability and expected economic damage has received more attention allowing for more optimised assessment. However, the choice of these factors, has been, in part, empirical.

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