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INFLUENCE OF SPATIAL VARIABILITY OF SHEAR STRENGTH PARAMETERS ON RELIABILITY-BASED ASSESSMENT OF DYKES

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ABSTRACT

The Dutch dyke network includes 14,000 km of regional dykes that are regularly assessed in order to reduce the risk of flooding. The current strategy for maintenance and/or upgrading of existing dykes is based on safety assessments using partial factors and reliability-based characteristic values of material properties, interpreted from Eurocode 7 (EC7). In this paper, an historic dyke in the Netherlands has been analysed for stability using two methods: (a) based only on the point statistics of the material properties, as is widely adopted in Dutch practice based on a simplified interpretation of EC7, and (b) based on both the point and spatial statistics of the material properties, using a probabilistic approach in line with the full requirements of EC7. The results of safety assessments by the two methods show that a consideration of the spatial variability leads to a narrower range of possible responses, and thereby to a higher computed factor of safety at the target reliability of 95%. Moreover, for the dyke section considered, it results in much reduced remedial action compared to that suggested as a consequence of using the simplified approach, and thereby to a more economic design and reduced environmental impact.

Keywords: Dykes, Eurocode 7, Reliability, Spatial Variability.

1. INTRODUCTION

The factor of safety against instability is often expressed as the ratio of resisting to disturbing forces or moments. However, a deterministic analysis does not allow for a quantifiable assessment of the impact of uncertainties on the calculated factor of safety. The three primary sources of geotechnical uncertainty are: the inherent variability of soil arising due to a combination of various geological, environmental and physico-chemical processes; measurement errors caused by equipment and/or procedure followed; and transformation errors introduced when field or laboratory measurements are transformed into soil properties using empirical equations or other models [1]. Although the relative contribution of these components to the overall variability is dependent on various conditions, the latter two, i.e. the measurement and transformation errors, can be reduced by quality control and/or taking other measures. Hence, only the inherent spatial nature of variability of soil properties will be considered in this paper.

Various reliability-based methods have been developed to account for the inherent variability of soil parameters in performance assessments of geotechnical structures; for example, the first order reliability method, stochastic response surface method and random finite element method (RFEM) [2]. RFEM has proven to be an effective and versatile method due to it not making any prior assumptions regarding the shape of the failure mechanism, and accounting fully for the spatial nature of inherent variability. Much research has been done to understand the influence of spatial variability in mechanical and hydraulic parameters on the reliability of geotechnical structures in 2D, i.e. assuming an infinite correlation between the parameters in the third dimension. Moreover, a limited amount of research has been done in 3D slope reliability analysis, which has shown the importance of considering the finite correlation length of soil parameters relative to the slope length in the third dimension. However, in practice, the performance of geotechnical structures is usually assessed using a deterministic analysis, i.e. by ignoring the spatial variability of soil parameters, and often results in the over-designing of structures in order to meet safety requirements.

This paper illustrates the advantages of incorporating spatial variability of soil parameters in the reliability-based assessment of one section of a dyke ring in the Netherlands. A representative cross-section of the dyke has been analysed for slope stability using two methods: (a) based only on the point statistics of the material properties, as widely adopted in Dutch practice and based on a simplified interpretation of Eurocode 7 (EC7) [3], and (b) based on both the point and spatial statistics of the material properties, using a stochastic RFEM analysis satisfying the requirements of EC7. The practical implications of the latter approach are illustrated by the relative extent of remedial actions suggested by the two methods in order to meet the required safety level.

2. DYKE SAFETY ASSESSMENTS IN THE NETHERLANDS

Stability assessments of regional dykes in the Netherlands are based on the EC7 [3] philosophy of partial factors defined by the code and characteristic values of soil properties chosen by the engineer, often through a simplified interpretation of the statistical approach proposed in EC7. The derivation of characteristic soil property values according to EC7 is revisited in the following sub-section, and the implication of using a simplified interpretation of EC7 is illustrated by the reliability-based assessment of a dyke section.

***Table 1.** Clause (11): Extract from Section 2.4.5.2 of Eurocode 7 [3]*

(11)	If statistical methods are used, the characteristic value should be derived such that the calculated probability of a worse value governing the occurrence of the limit state under consideration is not greater than 5%. NOTE: In this respect, a cautious estimate of the mean value is a selection of the mean value of the limited set of geotechnical parameter values, with a confidence level of 95%; where local failure is concerned, a cautious estimate of the low value is a 5% fractile.

2.1. Characteristic Value According to EC7

Table 1 states Clause (11) from Section 2.4.5.2 of EC7, which gives guidelines for when statistical methods are used in deriving characteristic values. From the table it can be inferred that the characteristic value should be selected so as to give a structural reliability (relative to the limit state under consideration) of at least 95%.

However, this appears to be contradicted by the footnote, in that the first part of the footnote refers to a mean value and the second part refers to the 5% fractile of the soil property distribution. However, Hicks [4] and Hicks and Nuttall [5] demonstrated that the clause and the footnote are entirely consistent, and can be explained by considering the scale of fluctuation (θ) of the property values (i.e. the distance over which they are significantly correlated) relative to the size of the problem domain (D). They demonstrated that by selecting the 5 percentile of a modified "effective" property distribution (back-figured from the response of the structure) as the characteristic value, the requirements of EC7 would be fully satisfied.

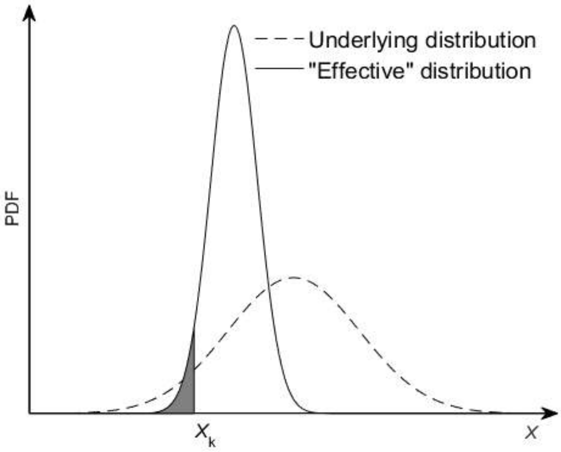


Figure 1. *Characteristic value satisfying Eurocode 7 (based on [4,5])*

For three possible scenarios of θ/D (i.e. very large, very small and intermediate values), there exist three scenarios for the "effective" property distribution relative to the underlying property distribution, although it is intermediate values of θ/D that are generally encountered in practice. For a soil property X modelled by a normal distribution (as illustrated by the underlying probability density function (PDF) in Figure 1), the resulting "effective" property distribution for the general case, i.e. for intermediate values of θ/D, is shown. It is seen that the mean and standard deviation of the effective distribution are lower than those of the underlying distribution, due to the tendency for failure to be attracted to semi-continuous weaker zones and due to the averaging of soil property values over the failure surface, respectively. Consequently, the 5 percentile of the "effective" property distribution, representing the characteristic value (X_k), is generally greater than the 5 percentile of the underlying property distribution. However, for reasons of simplicity and/or conservatism, Dutch practice often uses the 5 percentile of the underlying property distribution as the characteristic value.

2.2. Problem Description and Analysis Methodologies

The Starnmeer polder, situated in the Dutch province of North Holland, lies within a 13 km dyke ring managed by the water board Hollands Noorderkwartier (HHNK). Stability assessments of 10 dyke sections based on the characteristic values derived from the simplified interpretation of the statistical approach (i.e. based on the 5-percentile soil property values) revealed that 5 sections did not meet the safety requirements. Moreover, for one particular dyke section, a factor of safety (F) as low as 0.5 was reported [6], for which, a re-design was proposed by HHNK to meet the safety requirements. This re-design presented a significant economic burden due to the large volume of material required, as well as having a considerable impact on neighbouring property. Hence, the stability of the dyke section was reassessed [7] by using a stochastic approach that is entirely consistent with the requirements of EC7.

The two methodologies adopted herein for the safety assessment of the dyke section can be summarised as follows:

- Method (I) - safety assessment using 5-percentile soil property values and partial factors, as adopted in Dutch practice, based on a simplified interpretation of the statistical approach proposed in EC7.
- Method (II) - safety assessment using the point and spatial statistics of soil properties and partial factors, based on a stochastic approach fully consistent with the requirements of EC7.

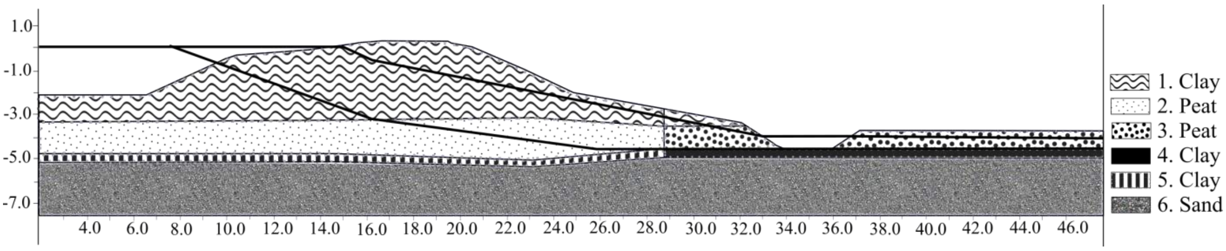


Figure 2. *Dyke cross-section (scale in metres)*

Table 2. *Unit weights and strength parameter values used in analysis of dyke cross-section:*

(a) Layers 1–6

Layers	γ (kN/m^3)	c'				$\tan\phi'$			
		Mean (kPa)	COV	Partial factor	Design value (kPa)	Mean	COV	Partial factor	Design value
1	13.9*	4.4	0.773	1.20	0.917	0.580	0.081	1.15	0.429
2	9.9	3.2	0.656	1.20	0.833	0.398	0.058	1.15	0.310
3	9.8	2.0	0.775	1.20	0.417	0.358	0.145	1.15	0.241
4	15.0	4.5	0.544	1.20	1.417	0.559	0.012	1.15	0.465
5	15.0	5.4	0.352	1.20	2.417	0.601	0.007	1.15	0.503
6	20.0	0.0	0.000	-	0.000	0.637	0.000	1.20	0.531

$^*\gamma = 6.9$ kN/m^3 above the phreatic surface

(b) Layers 7–8

Layers	γ (kN/m^3)	c'				$\tan\phi'$			
		Mean (kPa)	COV	Partial factor	Design value (kPa)	Mean	COV	Partial factor	Design value
7	17.0	6.2	0.773	1.20	1.333	0.531	0.081	1.15	0.403
8	20.0	0.0	0.000	-	0.000	0.637	0.000	1.20	0.531

2.3. Results and Discussions

Figure 2 shows a cross-section through Dyke Section 8 at Starnmeer. The unit weight (γ) and shear strength properties of the various material layers are summarised in Table 2(a). The coefficients of variation (COV) of cohesion (c') and tangent of friction angle ($\tan\phi'$) have been back-calculated using the respective mean and 5-percentile values reported in [6]. Note that the lognormal distribution has been adopted to model each soil property for each material layer in order to avoid the possibility of negative values, especially for properties with higher values of COV. Also listed in the table are the design soil property values that have been calculated by dividing the 5-percentile soil property values with their respective partial factors.

Figure 3 shows the results obtained by re-evaluating the stability of the dyke section using an in-house finite element software using the strength reduction method. The value of $F = 0.54$ obtained by using Method (I) is based on analysing the stability of the dyke section using the design soil property values from Table 2(a); that is, it does not consider the spatial nature of soil variability and is not consistent with the intention of EC7 (Table 1).

The cumulative distribution function (CDF) of F using Method (II) has been obtained by analysing the dyke section using the design soil property distributions (generated by scaling down the distributions for c' and $\tan \phi'$ by the respective partial factors listed in Table 2(a)), but additionally, for each soil property and each material layer, vertical (θ_v) and horizontal (θ_h) scales of fluctuation have also been considered by using a fully stochastic RFEM.

The RFEM combines random fields (i.e. the mathematical representation of spatial variability) of soil property values with finite elements within a Monte Carlo framework. The random fields have been generated by covariance matrix decomposition using the Markov autocorrelation function (see [8] for details). As insufficient spatial data were available for the cross-section, $\theta_v = 0.5$ m and $\theta_h = 6.0$ m were assumed for each soil property and each material zone, which would result in a conservative estimate based on the range of values of θ_v reported [9] for similar soils and based on the results obtained with other values of θ_h [7].

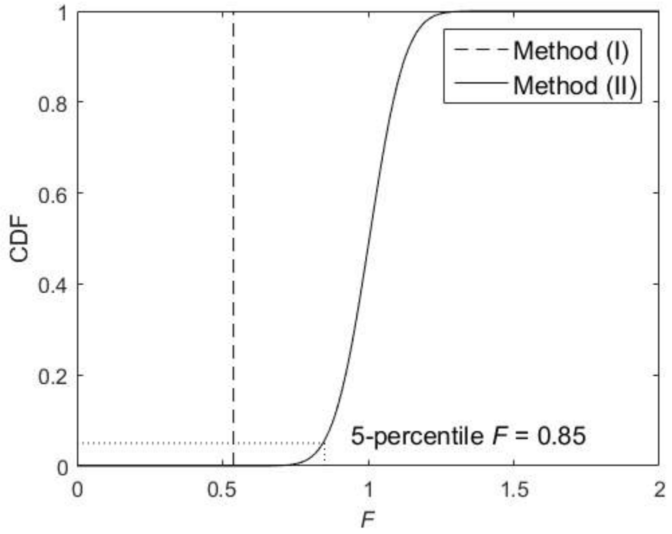


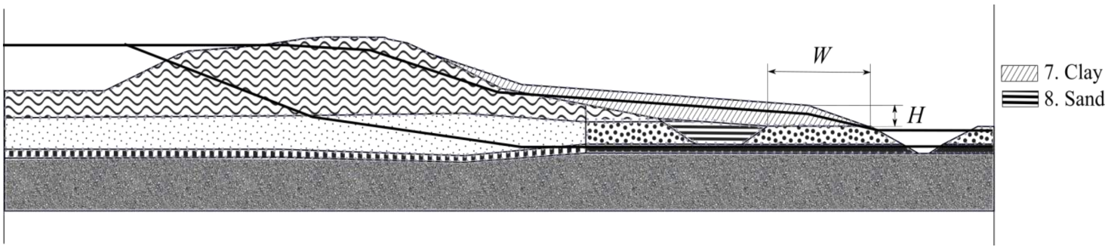
Figure 3. *Comparison of F calculated by the two methods*

Figure 3 shows that for a 95% reliability (R) of the dyke section, $F = 0.85$ is obtained by using Method (II), which is significantly higher than the value of F computed using Method (I). Note that characteristic soil property values have not been calculated explicitly in Method (II); instead, the reliability-based factor of safety has been calculated directly, and is this value that is needed in the safety assessment. Hicks et al. [7] have shown (via a simple re-analysis) that, for this particular dyke section, the characteristic soil property values correspond to the 34 percentiles of their respective underlying distributions.

2.3.1. Re-designing the dyke section

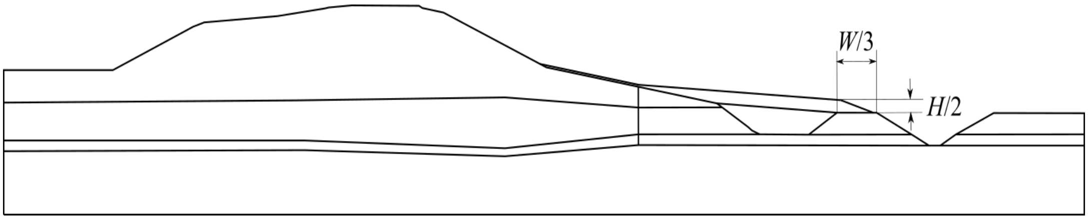
Although the results obtained by Method (II) represent a 57% increase in the computed value of F, some upgrading of the dyke section is needed as it is still less than the required $F = 0.95$ (the limit of $F = 0.95$ includes partial factors and is dictated by the standard [6]). Figure 4 shows the initial re-design of the dyke section proposed by HHNK, following on from the estimate of F obtained using Method (I).

This involves moving the ditch further away from the dyke, infilling the original ditch, and construction of a clay berm to increase resistance against failure. The value of *F* obtained by analysing the re-designed dyke section using the in-house finite element software (with the unit weights and shear strength properties of the sand infill and clay berm listed in Table 2(b)) using Method (I) is also shown in Figure 4, demonstrating that the proposed upgrade of the dyke section would be over-conservative and uneconomical since the calculated *F* is significantly greater the required *F* of 0.95.



F = 1.21 by Method (I)

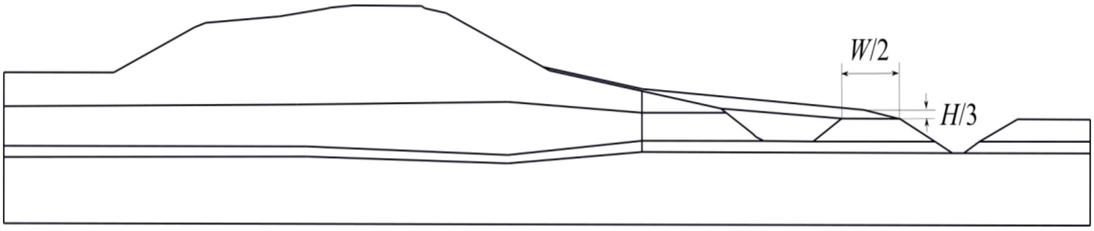
Figure 4. *Initial re-design for dyke cross-section and the value of F obtained by Method (I)*



F = 0.719 by Method (I)

F = 1.015 by Method (II)

(a)



F = 0.713 by Method (I)

F = 1.003 by Method (II)

(b)

Figure 5. *Proposed alternative re-designs for the dyke cross-section, the value of F calculated by Method (I) and the value of F at R = 95% calculated by Method (II)*

Therefore, further analyses have been carried out for re-designing the dyke section using Method (II), for a range of berm heights and inter-ditch spacings. Figure 5 shows two of the alternative proposals: these are (a) constructing a berm of half the initially proposed height and reducing the inter-ditch spacing to 1/3 of its original dimension, and (b) constructing a berm of 1/3 of its initially proposed height and reducing the inter-ditch spacing to half of its original dimension.

Both give a factor of safety satisfying the safety requirement (F > 0.95 with a 95% confidence) when analysed using Method (II). Also shown in Figure 5 are the values of F obtained by analysing the stability of the alternative re-designs using Method (I). The comparisons for F obtained by the two methods show that accounting for spatial variability in the reliability-based safety assessment is important as it results in a significant saving relative to the original proposed re-design.

3. CONCLUSIONS

An historic dyke section in the Netherlands has been analysed by two methods. The first is based only on the point statistics of the material properties, and is an approach which is widely adopted in practice and based on a simplified interpretation of Eurocode 7. The second is based on the point and spatial statistics of material properties, and is an approach which is fully consistent with the requirements of Eurocode 7. The results of the safety assessments by the two methods show that a consideration of the spatial variability leads to a narrower range of possible responses, and thereby to a higher computed factor of safety at the target reliability of 95% (approximately 57% higher than the factor of safety computed using the former approach for the dyke section, although still lower than the safety requirement). An initial proposal for re-designing the dyke had been suggested based on analysis using the former approach. However, it has been shown that, through a proper consideration of spatial variability of soil properties, the extent of the upgrade can be significantly reduced, thereby resulting in economy of design and reduced environmental impact.

ACKNOWLEDGEMENTS

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