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Marco Barla
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Reliability-Based Partial Factors Considering Spatial Variability of Strength Parameters

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Abstract. The stability of six regional dyke cross-sections in the Netherlands was re-assessed using the random finite element method (RFEM), which explicitly accounts for the spatial variability of strength parameters. The RFEM assessments of the cross-sections were shown to result in significantly narrower response distributions than those obtained by ignoring the spatial variability, and therefore would result in more economical designs. Given the complexity of RFEM for applications in daily engineering practice, the results obtained from the re-assessments of the six dyke cross-sections were used to propose partial factors that can be used in practice to achieve the desired reliability levels for regional dykes. When applied in a conventional semi-probabilistic assessment of a dyke cross-section, these partial factors would result in the same level of reliability as would have been obtained by carrying out an RFEM analysis of the same cross-section.

Keywords: Dykes · Partial factors · Random fields · Reliability · Spatial variability

1 Introduction

The three primary sources of geotechnical uncertainty are: the inherent variability of soil arising due to various geological, environmental and physicochemical processes; measurement errors; and transformation errors. Of these, the spatial nature of soil variability is considered to be an aleatoric uncertainty, whereas the latter two are epistemic in nature. There are various ways of dealing with these uncertainties, ranging from (a) a semi-probabilistic approach, accounting for uncertainties within a deterministic design by applying partial factors to characteristic values of strength parameters, to (b) fully probabilistic methods such as the random finite element method (RFEM) (Fenton and Griffiths 2008). RFEM combines random fields, that are used to model the spatial variability of soil properties, with finite elements within a Monte Carlo framework to directly estimate the probability of failure. Owing to its complexity, RFEM is seldom used in engineering practice, whereas the semi-probabilistic method is widely used because of its simplicity due to the various assumptions involved. For example, the semi-probabilistic method of dyke safety assessment in the Netherlands uses a combination of partial factors and characteristic property values to achieve a target reliability level of the dyke.

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In this paper, the stability of six regional dyke cross-sections in the Netherlands has been re-assessed using RFEM. The data used for the re-assessments in this paper are from a technical report on the initial assessment of these cross-sections (van der Krogt et al. 2018). The RFEM results obtained in the re-assessments are used to calibrate reliability-based partial factors that can be directly used in future semi-probabilistic analyses of regional dykes.

2 Methodology

In this paper, the shear strength of the dyke body and of the sand layer underneath it was modelled as drained using a linear elastic, perfectly-plastic Mohr Coulomb soil model, defined by the effective stress state ($\boldsymbol{\sigma}'$) and the material strength parameters (cohesion (c') and tangent of the friction angle ($\tan\phi'$). In contrast, the clay and peat layers underlying the dyke were modelled as undrained using the Stress History and Normalised Soil Engineering Properties (SHANSEP) method (Ladd and Foott 1974). In this model, the undrained shear strength is a function of the effective major principal stress (σ_1'), and is given by

$$s_u = S \times \sigma_1' \times \left(\frac{\sigma_{1,\max}'}{\sigma_1'} \right)^m \tag{1}$$

where S and m are the normalised soil parameters representing the undrained shear strength ratio and the strength increase exponent, respectively.

Each cross-section was analysed using an in-house finite element code incorporating the strength reduction method for computing the factor of safety (F). The initial stress state was generated by applying gravity loading. Then, further loading was applied in two stages: these were to account for the normal daily water level condition in the initial stage, and a high water level condition (to account for an annual exceedance probability of 0.1%) along with a traffic load on top of the crest in the final stage.

To carry out an RFEM analysis, the spatial variability of each strength parameter (c' and $\tan\phi'$ for the drained layers and of the properties S and m for the undrained layers) was explicitly modelled using random fields. The random fields were generated by covariance matrix decomposition (see van den Eijnden and Hicks (2017) for details) using the Markov auto-correlation function:

$$\rho(\Delta x, \Delta z) = \exp\left(-2\sqrt{\left(\frac{\Delta x}{\theta_\mathrm{h}}\right)^2 + \left(\frac{\Delta z}{\theta_\mathrm{v}}\right)^2} \right) \tag{2}$$

where Δx and Δz are the lag distances in the horizontal and vertical directions, and θ_h and θ_v are the corresponding scales of fluctuation in the respective directions (representing the degree of spatial correlation). As insufficient data were available, conservative estimates (de Gast et al. 2021) of $\theta_\mathrm{h} = 6.0$ m and $\theta_\mathrm{v} = 0.5$ m were assumed for all properties in all material layers.

3 Results and Discussions

For a cross-section of the dyke at Broekermeer (shown in Fig. 1), the means and coefficients of variation (COV = standard deviation/mean) of the lognormal distributions of shear strength parameters (X) for the various material layers are listed in Table 1 (van der Krogt et al. 2018). The 5th percentile values of these distributions are generally used as the characteristic property values (X_k) in practice. A deterministic finite element strength reduction analysis of the dyke cross-section based on these 5% values resulted in a factor of safety $F(X_k)$ of 0.86.

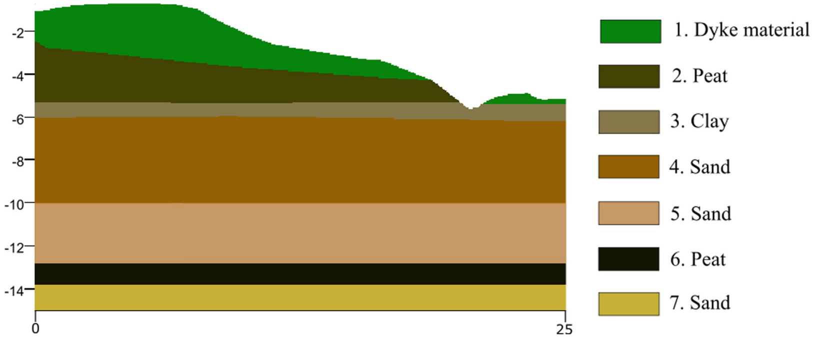

Fig. 1. Dyke cross-section at Broekermeer (scale in metres)

Table 1. Shear strength parameters used in the assessment of the dyke cross-section at Broekermeer

Layers	Drained				Undrained			
	c'		$\tan\phi'$		S		m	
	Mean (kPa)	COV	Mean	COV	Mean	COV	Mean	COV
1	0.00	–	0.63	0.07	–	–	–	–
2	–	–	–	–	0.39	0.10	0.90	0.03
3	–	–	–	–	0.29	0.20	0.90	0.03
4	0.00	–	0.67	0.03	–	–	–	–
5	0.00	–	0.58	0.05	–	–	–	–
6	–	–	–	–	0.31	0.09	0.90	0.03
7	0.00	–	0.68	–	–	–	–	–

Following this, an RFEM analysis of the cross-section was carried out using the point and spatial statistics of the strength parameters. These point statistics comprised the same mean values as listed in Table 1, but the COVs were double those in the table. This was done to remove the implicit averaging (full local averaging and a value of 0.75 for the ratio of local over regional variations) that had been assumed for the distributions in Table 1. The cumulative distribution function (cdf) of F obtained from 500 realisations of the RFEM analysis of the cross-section is shown in Fig. 2. Also shown in the figure are the deterministic value of $F(X_k)$ as well as a cdf of F obtained using only the point statistics of the properties, to highlight the significance of spatial averaging in the RFEM analysis. Although the consideration of spatial variability is shown to result in a much narrower response distribution, the probability of failure (= cdf ($F = 1$)) for this dyke cross section is still quite high (16.3% using RFEM compared to 31.9% using only the point statistics).

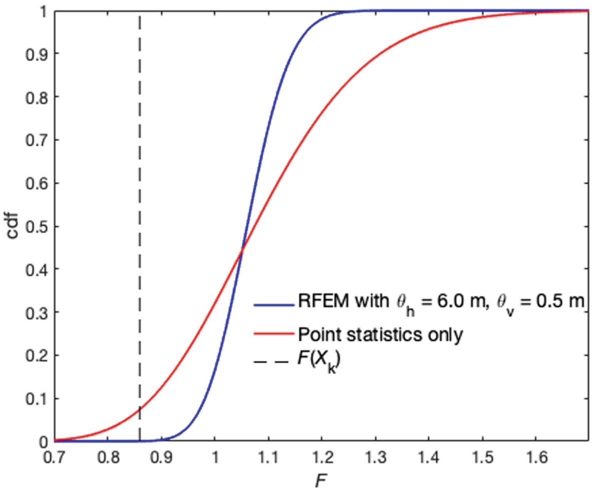

Fig. 2. Deterministic and RFEM solutions of F for the dyke cross-section at Broekermeer

Similar deterministic and RFEM analyses were carried out for five other cross-sections (one more from Brookermeer and four from other dykes in the Netherlands). For each cross-section, RFEM analysis resulted in a much narrower distribution of F than that obtained by ignoring the spatial variability. These results have been used to propose partial safety factors (γ) that can be used to achieve target reliability levels (β) of regional dyke cross-sections. Note that the RFEM result can even be used to back-calculate the characteristic strength property values that fully satisfy the requirements of Eurocode 7 (see Hicks et al. (2019) and Varkey et al. (2020) for details).

3.1 Calculating the Reliability-Based Partial Factors

In order to calibrate the $\gamma - \beta$ relationship, γ is assumed to be equal to $F(X_k)$, so that the design value of $F = F(X_k)/\gamma = 1$. The value of β at $F = 1$ is obtained by using the cdf of an RFEM analysis using the relationship,

$$\beta = -\Phi^{-1}(\mathrm{cdf(F = 1)}) \tag{3}$$

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

With reference to Fig. 2 as an example, $F = 1$ in the RFEM analysis corresponds to $\beta = -\Phi^{-1}$ (0.16) = 0.98, and the partial factor corresponding to $F = 1$ is $\gamma = F(X_k)$ = 0.86. Similarly, the values of γ corresponding to the RFEM-based values of β for the other five cross-sections were computed and are shown in Fig. 3. Also shown in the figure is the $\gamma - \beta$ relationship ($\gamma = 0.08 \times \beta + 0.76$) obtained by drawing a regression line through these points. It can be seen from the figure that, for a target reliability level in the range of 2.1–3.6 (the approximate range for the annual target cross-sectional reliability for regional dykes in the Netherlands), the required value of γ based on the proposed $\gamma - \beta$ relationship ranges from 0.93 to 1.05.

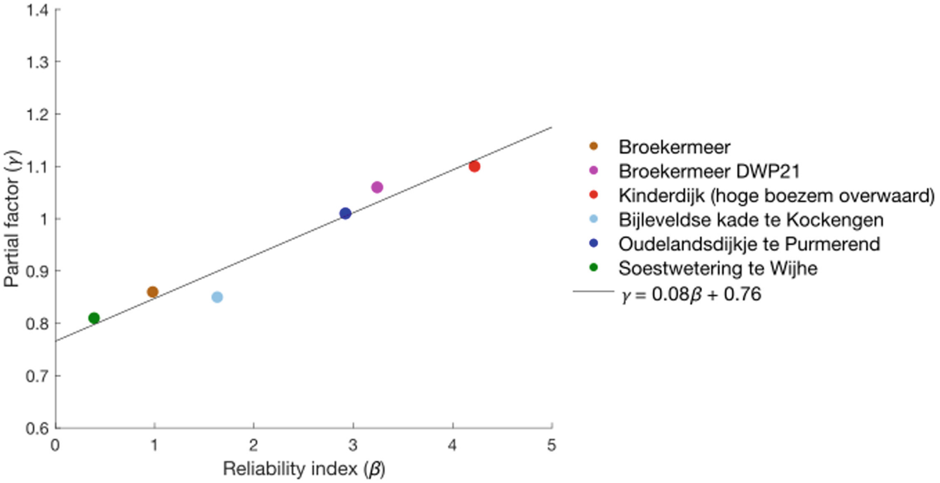

Fig. 3. Reliability-based partial factors calculated in the re-assessment of various dyke cross-sections

4 Conclusions

Six regional dyke cross-sections in the Netherlands were re-assessed using RFEM, which involves the explicit modelling of the soil spatial variability and thereby fully accounts for spatial averaging of properties along the failure surface. An underlying assumption in the re-assessments presented in this paper is that the only uncertainty is in the spatial variability of the shear strength parameters, which is modelled using the chosen auto-correlation function. Any uncertainty in the input statistics or in the model has not been accounted for in this study.

The results of the re-assessments were used in calibrating partial factors that are required to achieve the desired reliability levels. Partial factors in the range of 0.93–1.05 were obtained for desired annual cross-sectional reliabilities of 2.1–3.6 for the regional dykes. When applied in future semi-probabilistic assessments of regional dykes, the proposed partial factors would result in the same level of reliability as would be obtained by carrying out a more complex and robust RFEM analysis of the same dyke cross-section.

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