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Numerical Modelling of Spatial Variability and Geotechnical Uncertainty

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Abstract: The spatial variability of soil properties influences material behaviour and the performance of geotechnical structures. It also leads to uncertainty in design, because one can never be certain about what the ground conditions are at every location across a site. This article introduces the concept and implications of spatial variability, and illustrates some of the opportunities afforded by utilising numerical methods within a probabilistic framework.

1 Introduction

The spatial variability of properties within so-called uniform soil layers influences soil material behaviour and geo-structural response. It also causes uncertainty in ground conditions and thereby in geotechnical performance. Conventional (i.e., deterministic) analysis involves the selection of so-called representative values of soil properties for individual soil layers, and this invariably leads to a single factor of safety (for which there is no information regarding probability of failure). In contrast, stochastic analysis makes use of all data and leads to probabilistic definitions of structure performance; for example, reliability, the probability that failure will not occur. This short article aims to introduce the reader to the concept and implications of spatial variability, as well as to illustrate opportunities that arise through the numerical modelling of such problems within a probabilistic framework.

2 Spatial Variability

For a so-called uniform soil layer, the pointwise variability of a material property X can be represented by a probability density function (pdf). This function defines the range and relative likelihood of values of X, and is constrained by the mean value of the material property, X_m, and the standard deviation of the material property.

Figure 1 illustrates the simple case of a normally distributed variable. An obvious question arising from such a figure is: "What representative value of X should be used in carrying out a design assessment?" In the case of Eurocode 7 (EC7) (CEN 2004), for example, the guideline suggests a characteristic value of X giving a level of reliability of the structure of 95% (i.e., before application of partial factors to achieve some target reliability index). With reference to Figure 1, this characteristic value, X_k, is not given by the 5-percentile of the underlying property distribution, as such a percentile merely indicates the confidence in the value of X being smaller than (or larger than) X_k. Instead, X_k should be derived from a modified ("effective") distribution, as illustrated in the figure. This distribution is a function of the underlying property distribution, the problem being analysed and, most importantly, the spatial correlation of property values. With respect to the latter, the scale of fluctuation (θ) may be defined as the distance over which material properties are significantly correlated (Vanmarcke 1983).

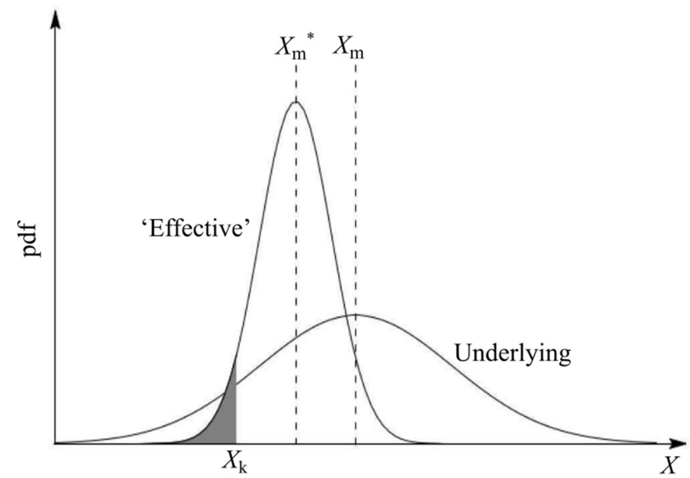

Figure 1: Derivation of characteristic property value satisfying EC7 (based on Hicks, 2012; Hicks and Nuttall, 2012; Hicks et al., 2019; Varkey et al., 2020)

Figure 1 highlights two main differences between the effective and underlying distributions of X: (a) the effective distribution is narrower due to the spatial averaging of material properties (e.g., along potential failure planes); (b) the mean of the effective distribution is lower than that of the underlying distribution due to, for example, the tendency for failure to be attracted to weaker zones. Note that, even though the mean of the effective distribution is lower than the underlying mean, the derived value of X_k is usually higher than the 5-percentile of the underlying distribution due to the reduction in standard deviation caused by local averaging. Moreover, if additional information about a site becomes available (e.g., through monitoring data, or additional testing), the effective property distribution becomes narrower still, and this reduction in uncertainty usually (though not always) leads to more cost-effective assessments and designs.

3 Propagation of Uncertainty

Figure 1 may be viewed as a simple analogy to the propagation of uncertainty from the material level to the structure level, as represented by the respective underlying and effective property distributions. In this article, the propagation of uncertainty is mainly computed through linking random fields for modelling the spatial variability of soil properties, with the finite element method for computing the response of the structure, within a Monte Carlo framework. This approach is known as the random finite element method (RFEM) (Fenton and Griffiths, 2008).

In an RFEM analysis, there are multiple realisations of the same problem, in which each realisation involves the generation of a random field (based on the point and spatial statistics of the soil property) and the accompanying finite element analysis of the problem. The results of all the realisations enable the structure performance to be represented probabilistically.

4 Illustrative Application Areas

4.1 Characterisation and Modelling of Spatial Variability

The characterisation of spatial variability within soil layers is generally carried out using cone penetration test (CPT) data, and provides the point and spatial statistics needed as input for 2D and 3D random field models of spatial variability. Of particular interest is the determination of scales of fluctuation, especially in the horizontal plane. For example, Lloret-Cabot et al. (2014) proposed a strategy utilising conditional random fields for determining the vertical and horizontal scales of fluctuation, and demonstrated its performance for a hydraulically placed sand fill. de Gast et al. (2021a) evaluated a large number of very closely spaced CPTs to derive guidelines for the number and spacing of CPTs as a function of the required confidence level in the computed horizontal scale of fluctuation. Meanwhile, other research has investigated reducing uncertainty through the conditioning of random fields using CPT data. For example, Li et al. (2016) demonstrated how uncertainty in the reliability of an embankment slope (modelled in 3D) was reduced when random fields were conditioned to CPTs located at regular intervals along the embankment crest (i.e., along the third dimension); this was shown to lead to more efficient slope designs for a given target reliability. Other papers have investigated how data assimilation, for example using pore pressure monitoring data, can be used to reduce the uncertainty in an embankment's performance over time (Vardon et al. 2016; Liu et al. 2018).

4.2 Stochastic Modelling of Slope Stability Using RFEM

RFEM has been used to gain insight into how soil spatial variability influences the initiation and propagation of failure mechanisms in slopes, and how this in turn influences the computed slope reliability. Hicks and Samy (2002a) investigated the influence of depth trend in the point statistics of shear strength on 2D slope stability, and demonstrated that a depth trend generally leads to a greater range of solutions and also to a decrease in reliability. Meanwhile, Hicks and Onisiphorou (2005) used RFEM, together with a sophisticated constitutive model for sand, to investigate the failure of the Nerlerk underwater berm, which failed during construction due to apparent liquefaction even though CPT data had indicated a predominantly dilative fill. The RFEM analyses demonstrated that failure of the berm was possible through the liquefaction of semi-continuous looser zones arising from deposition-induced anisotropy.

Hicks and Spencer (2010) investigated the influence of horizontal scale of fluctuation on the stability of embankment slopes, by carrying out 3D RFEM analyses for slopes that were very long in the third dimension. They demonstrated that 3 categories of failure mode were possible, depending on the horizontal scale of fluctuation relative to the embankment dimensions. This was reinforced by Hicks et al. (2014), who computed the distributions of slide volumes associated with the different failure mode categories. They demonstrated that nearly all failures are

3D, even for problems (such as embankments) which appear to be 2D from a geometric point of view. Hicks and Spencer (2010) highlighted that such problems require 3D analysis and that the reliability of such structures is problem-length dependent; that is, the longer the embankment, the greater the chance of encountering a zone that is weak enough to trigger failure. However, they also demonstrated that a full 3D analysis was not needed for very long embankments; instead, the results of a detailed 3D RFEM analysis for a representative length of the embankment (of around 10 times the embankment height) could be combined with simple probability theory to accurately compute the reliability of embankments of different length. This strategy was used by Hicks and Li (2018) to benchmark existing simpler 3D and 2.5D semi-analytical methods. Most recently, Varkey et al. (2022) demonstrated that the horizontal scale of fluctuation along the length of an embankment has a greater influence on the computed reliability than the horizontal scale of fluctuation perpendicular to the line of the embankment.

In recent years, the material point method has been linked with random fields for modelling problems involving large deformations. This so-called random material point method (RMPM) was first introduced by Wang et al. (2016). Remmerswaal et al. (2021) used RMPM to investigate the residual strength of dykes; that is, the ability of a dyke to withstand retrogressive slides, potentially leading to flooding, following an initial slope instability.

4.3 Probabilistic Assessments and Characteristic Values

RFEM has been used to provide an interpretation of characteristic values as defined in EC7. Hicks and Samy (2002b) demonstrated that characteristic values should be a function of not only the point statistics of a material property, but also the scales of fluctuation in the coordinate directions and the geotechnical problem under consideration. Hicks (2012) and Hicks and Nuttall (2012) took this further, and explained how Clause 11 of Section 2.4.5.2 in EC7, "Characteristic Values of Geotechnical Parameters," could be interpreted by considering the scale of fluctuation relative to the domain of influence of the structure. Recently, this line of research has taken on an increased level of importance in the Netherlands. In brief, climate change, increased external loadings and new design guidelines mean that much of the Dutch flood defence and rail networks (i.e., dykes and embankments, respectively) no longer meet the required safety standards. This has prompted the use of advanced methods of analysis that explicitly account for uncertainties (Hicks et al. 2019; Varkey et al. 2020; de Gast et al. 2021b).

5 Concluding Comments

The spatial variability of soil properties can have a dramatic effect on the initiation, nature and propagation of failure mechanisms in geotechnical structures. Research has shown that probabilistic analysis and consideration of spatial variability can lead to a reduction in over-conservatism in design. Moreover, further reductions in over-conservatism are possible through the optimal use of available data and through the acquisition of additional (e.g., monitoring) data.

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