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Effect of soil variability on the bearing capacity of clay and in slope stability problems

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ABSTRACT

Site-specific geotechnical data are always random and variable in space. In the present study, a procedure for quantifying the variability in geotechnical characterization and design parameters is discussed using the site-specific cone tip resistance data (q_c) obtained from static cone penetration test (SCPT). The parameters for the spatial variability modeling of geotechnical parameters i.e. (*i*) existing trend function in the *in situ* q_c data; (*ii*) second moment statistics i.e. analysis of mean, variance, and auto-correlation structure of the soil strength and stiffness parameters; and (*iii*) inputs from the spatial correlation analysis, are utilized in the numerical modeling procedures using the finite difference numerical code FLAC 5.0. The influence of consideration of spatially variable soil parameters on the reliability-based geotechnical deign is studied for the two cases i.e. (*a*) bearing capacity analysis of a shallow foundation resting on a clayey soil, and (*b*) analysis of stability and deformation pattern of a cohesive-frictional soil slope. The study highlights the procedure for conducting a site-specific study using field test data such as SCPT in geotechnical analysis and demonstrates that a few additional computations involving soil variability provide a better insight into the role of variability in designs.

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1. Introduction

Soil is a natural material and it exhibits considerable spatial variation of its engineering properties due to its formation (depositional and weathering process) in different physical and chemical environments. In geotechnical engineering perspectives, this brings uncertainty and variability in the estimation of engineering parameters defining the strength and stiffness characteristics of *in situ* soil and also brings uncertainty in the safety indices required for assessing the safety and performance of the structures. The various sources of uncertainties include inherent variability, measurement errors, and model transformation uncertainties (Phoon and Kulhawy, 1999a). To take into account these sources of uncertainties, in the conventional approaches, the choice of representative engineering soil parameters (i.e. the design soil parameters) are based on practical experience and sometimes it is also influenced by personal preference to be on the safer side (Schweiger et al., 2001). The consideration of variability and uncertainty in the selection of representative input soil parameters, in the conventional geotechnical analysis and designs, do not appear in an explicit manner. Further, the safety of the geotechnical structures is assessed in terms of global *factor of safety*. Based on past experience and expert's judgments it is recognized that the calculated *factor of safety* should be in the range of 1.5–3.0 (Terzaghi et al., 1996) in order to ensure long term stability as well as for the consideration of various sources of uncertainties involved. Uzielli et al. (2007) indicated that uncertainty-based approaches should be utilized because of the following advantages:

(i) There is explicit inclusion of uncertainty in the input parameters and the explicit declaration of uncertainty in the outputs;
(ii) It provides complete and realistic information regarding the level of safety of design;
(iii) It allows a more rational design as the designer can consciously calibrate his decisions on a desired or required performance level of a structure.

2. Uncertainties in geotechnical parameters

There are three major sources of uncertainty associated with geotechnical engineering practice (Phoon and Kulhawy, 1999a), viz., (*a*) the natural heterogeneity or inherent variability (the physical phenomenon contributing to the variability), (*b*) measurement error (due to equipment, procedural-operator, and random testing errors), and (*c*) model transformation uncertainty (due to approximation present in empirical, semi-empirical or theoretical models to relate measured quantities to design parameters). Quantitative assessment of soil uncertainty modeling requires use of statistics, as well as probabilistic modeling to process data from laboratory or *in situ* measurements. Probability theory is useful in modeling the observed behavior of a variable parameter if a set of measurements are available. Any quantitative geotechnical variability relies on sets of measured data which are often limited in size and hence, it is referred

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to sample statistics. The uncertainty in the measured data is expressed in terms of sample mean (μ) and variance (σ^2) evaluated from the following expression:

Sample mean

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

Variance (σ^2): it is a measure of dispersion of data about the mean value. The square root of variance is defined as standard deviation (σ).

$$\sigma^2 = \frac{1}{(n-1)}\sum_{i=1}^{n} (x_i-\mu)^2 \tag{2}$$

The coefficient of variation (*CoV*), which is obtained by dividing the sample standard deviation by the sample mean, is commonly used in quantifying the geotechnical uncertainty analysis because of the advantages of being dimensionless as well as providing a meaningful measure of relative dispersion of data around the sample mean. Several studies in the past (Phoon et al., 1995; Lacasse and Nadim, 1996; Baecher and Ladd, 1997; Duncan, 2000) provided the generic range of coefficient of variation (*CoV*) in the geotechnical parameters as summarized in Table 1. Consideration of these uncertainties in the input soil parameters and its impact on the performance of a geotechnical system are studied using the reliability-based design procedures. Reliability analysis focuses on the most important aspect of performance i.e. probability of failure (p_f).

In the reliability analysis, the input soil parameters are modeled as continuous random variables defined by their probability density functions (*pdf*s) and the parameters of distributions. Normally, in geotechnical practice, the input soil parameters are either modeled as normally distributed or log-normally distributed continuous random variables (Baecher and Christian, 2003). The parameters of the normal and log-normal probability distribution function (*pdf*) are directly related to the unbiased estimates of statistical moments i.e. sample mean (μ) [Eq. (1)] and variance (σ^2) [Eq. (2)] of the measured data set.

3. Spatial variation in geotechnical parameters

It is well understood that second moment statistics, i.e. mean (μ) and variance (σ^2), alone are insufficient to describe the spatial variation of soil properties, which vary in the 2- or 3-dimensional space, whether measured in the laboratory or *in situ*. Structured explanations of the statistical techniques used for the investigation of spatial variability are provided by Priestley (1981) and Baecher and Christian (2003). While the former provides an exhaustive insight into the mathematical framework of time series analysis, the latter focuses specifically on the application of such techniques to geotechnical engineering. Fig. 1 shows a typical spatial variation of soil properties [$\xi(z)$] in a 2-dimensional space characterized by (i) the vertical scale of fluctuation (δ_v) or correlation distance (r_o), (ii) trend function [$t(z)$], and (iii) deviation from the trend [$w(z)$], which constitute important parameters for site characterization and reliability-based design.

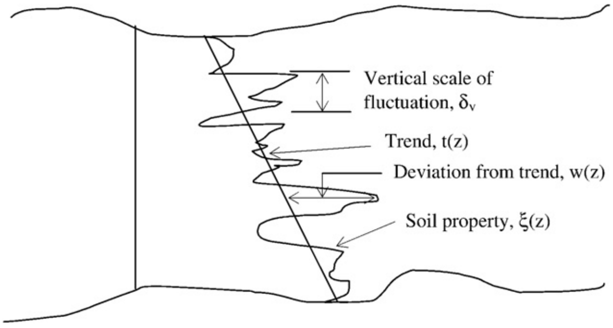

Fig. 1. Statistical description of soil variability (Phoon and Kulhawy, 1999a).

The analysis of sources of uncertainties as well as spatial variation of soil properties and its influence on design decisions and implications has been carried out extensively (Phoon and Kulhawy, 1999a,b; Sivakumar Babu et al., 2006). With the advent of high speed computing facilities, the effect of spatial variation of the input soil parameters in various geotechnical applications has also been studied by Griffiths and Fenton (2001), Griffiths and Fenton (2004), and Fenton and Griffiths (2003) using random field finite element method (RFEM) in combination with the probabilistic analysis using Monte Carlo simulations.

In spite of these studies, it is felt that there is a need to present a procedure which can be used to perform a site-specific study based on available field test data such as cone tip resistance (q_c) obtained from SCPT (static cone penetration test) to study the influence of modeling of the spatially variable soil profile on the performance of the geotechnical systems.

Table 1
Coefficient of variation (*CoV*%) for geotechnical parameters.

Property	*CoV*% range
Dry unit weight (γ_d)	2–13
Undrained shear strength (c_u)	6–80
Effective friction angle (ϕ')	7–20
Elastic modulus (E_s)	15–70

4. Objectives of the present study

The following are the objectives of the present work: (i) to discuss a methodology for incorporating the spatial variation of soil strength and stiffness parameters into the numerical modeling procedures using the site-specific q_c profile (i.e. corrected cone tip resistance obtained from SCPT), (ii) to discuss an approach for the determination of statistical parameters involved in the spatially variable modeling of the soil properties, and (iii) to investigate the influence of spatially variable soil parameters on the performance assessment of geotechnical systems considering the two cases, i.e., (a) bearing capacity of shallow strip footing resting on a clayey soil and (b) stability analysis and deformation pattern of the give soil slope.

5. Modeling spatially variable soil properties

A spatial variation of soil deposit in any direction can, in principle, be characterized in detail if a sufficiently large number of measurements are taken. This, however, is impossible in practice, and, therefore use of statistical techniques for investigating the spatial variability of soil properties is needed. For the characterization of spatial variability of the geotechnical properties, SCPT results are preferred over the other methods of *in situ* tests such as static penetration tests (SPT) due to the fact that the former can provide large number of data sets at smaller spacing (Huang and Mayne, 2008).

The statistical modeling of soil spatial variability relies heavily on the hypothesis of data stationarity. If the data set of interest is not stationary, the results of the statistical analysis can be erroneous or biased (Jaksa, 1995). The stationarity denotes the invariance of a data set's statistics to spatial location and normally, *weak stationarity*, is deemed sufficient to allow application of statistical technique. Vanmarcke (1983) defined that a *weak stationarity* process must have three features, i.e., (*i*) its mean is constant (there are no trend in the data), (*ii*) its variance is constant, and (*iii*) the correlation

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