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Research Paper

A practical approach for reliability analysis of unsaturated slope by conditional random finite element method

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ABSTRACT

The paper presents a method for reliability analysis of slopes in unsaturated soils. Conditional random fields are simulated by consideration possible fluctuations of the measured soil properties. To predict the unsaturated soil behaviour, suctions are estimated and implemented in a finite element analysis. Numerical results of a case study demonstrate that the use of conditional random fields, affects not only the standard deviation of the safety factor distribution, but can also cause considerable variation in the mean value. It is concluded that unsaturated conditions can result in higher slope reliability, but with potentially more extensive failure zones.

1. Introduction

By increasing in demands for appropriate infrastructures, design of soil slopes in urban and industrial areas is currently required more than ever, given the fast growing world population and developing countries. This subject becomes crucial when accounting for the unsaturated state of soil where a typical slope analysis is carried out. The occurrence of failures in such situations is not uncommon and collapses may bring irreparable consequences to both life and property [1,2]. Therefore, it is of great significance to study the problems of unsaturated slope deformation and failure. Recently, several studies have been assigned to this subject using different deterministic methods of analysis such as limit equilibrium [3,4], limit analysis [5]and elastic-plastic Finite Element Method (FEM) [6,7].

In unsaturated soils, textural properties can affect the stability of slopes almost as much as mechanical properties. These soil properties which involved in stability analysis imply many uncertainties though. The degree of uncertainty is influenced by both the lack of knowledge (as in sampling, testing and modelling) and the inherent spatial variability of the subsoil. The importance of spatial variability in geotechnical properties has long been recognized by some investigators [8,9]. Starting in the early 90s, a new method called the Random Finite Element Method (RFEM), which combines unconditional random field theory and the FEM, was developed to use in probabilistic geotechnical engineering [10]. Using the random field methodology, the influence of spatial variability of soil properties on the stability of slopes has been investigated for undrained and drained conditions [11–13]. The unconditional random field has also been used to study the uncertainties of hydraulic property parameters and their effects on the reliability of slopes under rainfall condition [14–16].

In all previous studies, the unsaturated soil behaviour was modelled by solving differential equations based on flow laws for air and water phases with considering predefined head or flux boundary condition. As it is reported by Griffiths and Lu [17], in these methods, the results are highly dependent on the water table level and infiltration or evaporation conditions.

In spite of great achievements in the context of reliability analysis for spatially variable soils, the traditional unconditional random field uses only the statistics such as mean, standard deviation and autocorrelation distance of limited site investigation data. This method discards the actual data which reflect the true values of the soil properties at certain locations. Neglecting the known data increases the simulation variance of random fields and results in conservative design which represents a waste of site investigation effort. On the other hand, the conditional approach takes full advantage of the available data which in turn minimizes the level of uncertainty.

Stability analysis based on the conditional random field has not been paid enough attention in the literature and there are only a few studies have been conducted. Kim and Sitar [18] investigated the effect of a specific number of cored samples on the probability of slope failure. Liu et al. [19] evaluated the reliability of a slope in spatially variable soils while considering the known data at particular locations. Although they both used conditional simulation in stability analysis, cross-correlation was not considered in their studies which means only univariate interpolation was carried out in random field simulation. Besides, in both researches a soil slope was analyzed by limit equilibrium method discarding the soil saturated/unsaturated conditions.

The main aim of this study is to present a practical approach for

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reliability analysis of unsaturated slopes via conditional simulation. For this purpose, a real unsaturated slope with shotcrete-face is considered. The slope stability analysis is carried out with a finite element-based program coded in MATLAB. The analysis is performed deterministically and it is then extended to the probabilistic context in order to take spatial variability of soil properties into consideration. To achieve this aim, conditional random fields are simulated by consideration of possible fluctuations of the measured textural and mechanical soil properties. To assess the advantage of conditional simulation relative to unconditional simulation of random field, their safety factor probability density curves are compared with each other. The effects of unsaturated conditions on reliability analysis of slope stability are also studied and the probability density function (pdf) of the conditional simulation are investigated with and without considering suction. In another part of this paper, the uncertainty in the shape and location of the critical slip surface is assessed by taking advantage of the FEM ability in determination of the maximum deviatoric strain.

2. Modelling of unsaturated condition

An optimized design of many geotechnical problems such as slope stability analysis above the water table is based on shear strength of unsaturated soil. Unsaturated soil shear strength may be determined directly in the laboratory [20] or indirectly using the developed models. The indirect methods can be categorized in two major groups; in the first group, the models are developed by considering two independent stress state variables, namely suction, and net stress. The model proposed by Fredlund et al. [21] falls in this category. The second group includes the effective stress based methods. In these methods, the shear strength (τ) is simply expressed in terms of the effective stress by:

$$\tau = c' + \sigma' \tan\varphi' \quad (1)$$

where c' and φ' are effective cohesion and effective friction angle, respectively. σ' is the effective stress.

In unsaturated soils, all mechanical aspects such as volume change and shear strength are governed by the effective stress. A wide variety of attempts have been made to develop a concept for effective stress in unsaturated soil [22,23]. Among all these studies, Bishop formulation [24] which is widely cited and is basically the expanded Terzaghi's classical effective stress theory was used in this paper as well. The equation is given by:

$$\sigma' = (\sigma - u_a) + \chi (u_a - u_w) \quad (2)$$

where σ is total stress, u_a is the pore air pressure and u_w is the pore water pressure. The term $(u_a\text{-}u_w)$ is called matric suction and χ is the matric suction coefficient. According to Eq. (2), it is clear that the calculation of χ and $(u_a\text{-}u_w)$ is the main task in determining of unsaturated soils effective stress. While the χ can be determined by different proposed models such as Vanapalli et al. [25], the determination of soil suction depends on the water flow state in unsaturated soils.

2.1. Estimation of soil water retention curve

When there is a flow in unsaturated soil, water and air tend to follow a relatively tortuous flow pass during the infiltration or evaporation process. In this condition, the suction head in different soil depth is conventionally computed by solving equations based on flow laws for air and water phases. Scientists have developed a good comprehension of the flow laws role in saturated/unsaturated slope stability problems [26,27].

On the other hand, when there is no considerable flow of water from ground surface (i.e. static equilibrium condition), the pore water pressures will be negative. This negative pore water pressure head which is known as the matric suction causes the shear strength to increase.

There is an alternative approach to estimate the current matric suction in any point of the soil by virtue of available textural soil properties, with no necessity of locating the water table. This approach was implemented in this study to conduct a practical unsaturated stability analysis. For this purpose, the Soil Water Retention Curve (SWRC) was estimated by physico-empirical method and the suction value at each point was obtained by corresponding water content value. Then, the matric suction coefficient (χ) was directly calculated using model proposed by Vanapalli et al. [25]. In the end, the suction stress was calculated as product of suction value and matric suction coefficient, then, it was substituted to the shear strength of the unsaturated soil to use in stability analysis.

The SWRC represents the amount of water contained in the pores at a given soil suction and it is a key factor in this approach to predict the unsaturated soil behaviour. There have been several methods presented to obtain the SWRC for the particular soil. However, time consuming and excessive cost associated with laboratory and field procedures encourage the researchers to use empirical methods [28,29].

Among empirical methods, the Arya and Paris model [30] has dominated unsaturated zone application. This approach converts the Grain Size Distribution (GSD) into a Pore Size Distribution (PSD), which in turn is related to a distribution of water content and associated pore pressure. The modified form of this model [31]was carried out in this study on account of reasonable predictive ability and available textural input data. The advantages of obtaining suction stress by using the proposed procedure are described as follow:

(a) The proposed approach has the ability to model the existing water flow needless to straggling with solving complex differential flow equations and tedious numerical solving process.
(b) locating the water level is not necessary, especially when the water table is far below the surface.
(c) The matric suction coefficient (χ) is more compatible with suction values, in view of the fact that it is obtained from the same SWRC.
(d) The probabilistic analysis, which is the main object of this paper, becomes more efficient given that the uncertainties of soil textural properties are taken into account.

Yet, the effect of stress history, fabric, confinement and hysteresis are not addressed.

3. Geostatistics

The inherent variability of the soil properties dictates that stability problems are of a probabilistic nature rather than being deterministic. Moreover, in-situ tests in particular can provide a good characterization of soil properties at the location where tests are performed, but inevitable uncertainty remains at locations which are not examined.

As a solution, geostatistical approaches are applied in geotechnical engineering for assessing the effect of uncertainties in geotechnical predictions and quantifying the spatial variability of soil properties. The main purpose of using geostatistical technique is providing a best estimate of the soil properties between known data, especially when sampling covers a very scarce portion of the total volume of soil.

3.1. Semivariogram analysis

The first step in the geostatistical analysis is to estimate semivariogram. The semivariogram is a measure of the degree of spatial dependence between samples along a specific orientation, and represents the degree of continuity of the property in question. In this study, the anisotropic exponential model was selected for experimental semivariogram data on account of its accuracy and numerical robustness. The formula used for this model is:

$$\gamma(h) = C_0 + C(1 - \exp(-h/A)) \quad (3)$$

where $\gamma(h)$ is the anisotropic exponential semivariogram model for the lag distance h. C_0 and C are the nugget effect parameter and the