Computers and Geotechnics 89 (2017) 213–225

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research paper

System reliability analysis and risk assessment of a layered slope in spatially variable soils considering stratigraphic boundary uncertainty

Lei-Lei Liu [a], Yung-Ming Cheng [a,*], Xiao-Mi Wang [b], Shao-He Zhang [c,d], Zhong-Hu Wu [e]

[a] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong Special Administrative Region
[b] School of Resource and Environment Engineering, Wuhan University, 129 Luoyu Road, Wuhan 430072, China
[c] Key Laboratory of Metallogenic Prediction of Nonferrous Metals and Geological Environment Monitoring (Central South University), Ministry of Education, 932 Lushan South Road, Changsha 410083, China
[d] School of Geosciences and Info-Physics, Central South University, 932 Lushan South Road, Changsha 410083, China
[e] School of Mining, Guizhou University, Qianlong Road, Guiyang 550025, China

ARTICLE INFO

Article history:
Received 22 December 2016
Received in revised form 25 April 2017
Accepted 7 May 2017

Keywords:
Slope stability
System reliability analysis
Risk assessment
Spatial variability
Layered slope
Stratigraphic boundary uncertainty
Monte Carlo simulation (MCS)

ABSTRACT

Due to complex geological deposition, post-deposition processes and limited site investigation data in engineering practice, soil properties are often spatially variable and the stratigraphic boundary in layered soils is generally characterized by uncertainty. The spatial variability of soil properties has been well investigated in past years, whereas the question of how the stratigraphic boundary uncertainty affects the slope stability remains unanswered. This paper attempts to investigate the effects of the stratigraphic boundary uncertainty on the system reliability and risk of a layered slope in spatially variable soils. In this paper, the spatial variability of soil properties is simulated by non-stationary random fields that are generated by an extended Cholesky decomposition technique, while the stochastic nature of the stratigraphic boundary location is simulated by a discrete random variable. Monte Carlo simulation (MCS) is suggested for evaluating the system failure probability and risk. Various comparisons between probabilistic analysis results obtained from considering and neglecting the stratigraphic boundary uncertainty have been made for different statistics of soil properties. Results show that the stratigraphic boundary uncertainty plays an important role in identifying the slope failure mechanism. Moreover, neglecting the stratigraphic boundary uncertainty would generally overestimate the slope failure risk for different statistics, except at small coefficients of variation of the friction angle, where the results are underestimated.

1. Introduction

During the past few decades, the inherent spatial variability of soil properties has been widely considered in slope reliability analysis and risk assessment. For example, Griffiths and Fenton [1] investigated the failure probability of a cohesive slope using a random finite element method (RFEM) and concluded that neglecting the spatial variability of soil properties would lead to unconservative estimates of the probability of slope failure. Such a finding is more profound when the coefficient of variation (COV) of the soil strength is relatively high. Similar observations were also reported by other researchers (e.g., [2]). Recently, Li et al. [3] compared the effects of different theoretical autocorrelation functions (ACFs) that are used to simulate the spatial variability of soils on the probability of slope failure by using a multiple response surface method (RSM), and they found that no large differences exist among different ACFs. Additionally, many other remarkable achievements (e.g., [4–18]) have also been made using different probabilistic approaches. Overall, these achievements are significantly beneficial to geotechnical engineers for understanding the slope failure mechanism in spatially variable soils. However, the achievements are less than perfect and suffer from a common criticism of neglecting the stratigraphic boundary uncertainty between different soil layers.

The stratigraphic boundary uncertainty generally exists in layered soils where soil property parameters such as cohesion c and friction angle φ are characterized by significant variability and heterogeneity on various scales [19–21]. This variability and heterogeneity is due not only to the complex geological deposition and post-deposition processes but also to the limited amount of

* Corresponding author.
E-mail address: ceymchen@polyu.edu.hk (Y.-M. Cheng).

http://dx.doi.org/10.1016/j.compgeo.2017.05.014
0266-352X/

site investigation data that we can obtain in engineering practice [22]. Identification of the stratigraphic boundary uncertainty is essential to geotechnical design. Many efforts have been made to characterize this uncertainty in the literature (e.g., [23–27]). The common method in these studies is to use Bayesian methods to estimate the soil stratification based on the available site investigation data such as cone penetration test (CPT) data. It is also observed from these studies that few of them have incorporated such uncertainties in slope reliability analysis and risk assessment because the existen reliability studies focus mainly on nominally homogeneous slopes but rarely on heterogeneous or layered slopes. However, in geotechnical engineering practice, it is more common to encompass layered soils than nominally homogeneous soil layers. Hence, the question of how this type of uncertainty affects the slope reliability and slope failure risk in multilayered soils remains unanswered.

When the aforementioned uncertainties are incorporated into a slope stability analysis model, the critical slip surface associated with the minimum factor of safety (FS) is also uncertain, leading to numerous potential slip surfaces in a slope. Slope failure occurs when a slope slides along any individual slip surface, and the failure probability and failure consequence associated with different potential slip surfaces might be different. Evaluating the slope reliability and failure risk based on a single slip surface such as the deterministic slip surface would be underestimating (e.g., [28]). Likewise, evaluation of the slope stability based on the summation of the reliability and risk results associated with each potential slip surface would be inaccurate since the FSs of different potential slip surfaces are generally highly correlated [29]. Therefore, the overall probability of failure and consequences of a slope should be calculated considering all the possible failure modes in a systematic manner, especially in layered soils where the systematic effects are more significant [30–33]. Various studies on slope reliability considering multiple slip surfaces have been reported in the literature (e.g., [3,8–10,31,32]), but few of these studies involved a quantitative risk assessment, with the exception of Huang et al. [7], Li and Chu [34] and Zhang and Huang [29]. To the best of our knowledge, perhaps Huang et al. [7] are the first authors to investigate the systematic effect on slope failure risk assessment using limit analysis and Monte Carlo simulation (MCS). However, only undrained cohesive slopes are considered in their work, and the effects of cross-correlations and COVs of different shear strength parameters on failure risk have not yet been investigated. Recently, inspired by Huang et al. [7], Li and Chu [34] developed a quantitative approach for risk assessment of slope failure based on several representative slip surfaces with limit equilibrium method, which provides an efficient and quantitative tool for identifying the key group of representative slip surfaces in the planning of slope risk mitigation. Zhang and Huang [29] proposed an efficient RSM-based MCS for risk assessment considering multiple failure surfaces, but they did not consider the heterogeneity of soils. Obviously, none of these studies involve the consideration of stratigraphic boundary uncertainty. Overall, how to quantify the systematic effects from stratigraphic boundary uncertainty on slope reliability analysis and risk assessment remains an open problem.

With the abovementioned problems in mind, this paper mainly aims at investigating the stability reliability and failure risk of multi-layered soil slopes with a particular emphasis on the effects of the stratigraphic boundary uncertainty. The paper starts with the characterization of uncertainties in multilayered soils, followed by the introduction of system reliability analysis and risk assessment using MCS. Then, a detailed implementation procedure for accomplishing the whole study is described. Next, a hypothetical layered slope example is provided for illustration of the effects of the stratigraphic boundary uncertainty on the slope stability. Finally, the major conclusions from this study are presented.

2. Characterization of uncertainties in layered soils

2.1. Simulation of inherent spatial variability of soil properties

Random field theory has been widely used to characterize the inherent spatial variability of soil properties [1,8,16]. Within the framework of random field theory, the soil parameters at particular locations are often considered as random variables. In general, a stationary or weakly stationary random field is usually applied to model the spatial variability of soil parameters in a nominally homogeneous soil layer, whereas a non-stationary random field is essential for layered soils [3]. To simulate non-stationary random fields in layered soils, many methods such as the trend removal scheme [35], Karhunen-Loève expansion [36] and those given in [37] can be adopted. However, an extended Cholesky decomposition technique is employed in this study since it is conceptually simple and easily implemented with ideal simulation results (e.g., [3,11,38,39]). The simulation procedure is described below.

Generally, soil parameters at a particular location are more similar to the soil parameters at adjacent locations than those parameters at a remote location [3]. This property is the so-called spatial variability of soil properties, which is controlled by the autocorrelation coefficient between soil properties at two points. The auto-correlation between any two parameters at different points is usually characterized by an ACF, which is very difficult to obtain due to the limited site investigation data. Instead, theoretical ACFs are often used as alternatives [3,11,39,40]. To the best of our knowledge, the single exponential ACF and the squared exponential ACF are probably the most commonly used ACFs in reliability analysis of slopes in spatially variable soils (e.g., [1,8,11,14,15]). In addition, some other functions such as the cosine exponential ACF, the binary noise ACF and the second-order Markov ACF are also occasionally used when appropriate (e.g., [3,41,42]). Obviously, differences must exist among these ACFs. For example, the squared exponential ACF and the second-order Markov ACF are differentiable near the origin, whereas the other three ACFs are not (e.g., [3,43]). Additionally, the autocorrelation matrix obtained from the squared exponential ACF is generally not positive definite, and thus cannot be easily decomposed by the Cholesky decomposition technique that will be utilized in the following. A more thorough and comprehensive comparison of these ACFs can also be found in the literature (e.g., [3,43]). However, the differences between the aforementioned ACFs have little influence on slope reliability analysis, as demonstrated by Li et al. [3]. Since the single exponential ACF is conceptually simple and easily implemented, it is utilized herein and described as

$$\rho(\tau_x, \tau_y) = \exp\left[-2\left(\frac{\tau_x}{\delta_h} + \frac{\tau_y}{\delta_v}\right)\right] \quad (1)$$

where $\tau_x = |x_i - x_j|$ and $\tau_y = |y_i - y_j|$ are the absolute distances between two points in the horizontal and vertical directions, respectively; δ_h and δ_v are the horizontal and vertical scale of fluctuations (SOFs) of soil parameters, respectively. Consider, for instance, a slope with N soil layers, and each layer is discretized into a certain number of random field elements. For the kth layer, suppose the centroid coordinates of each element are denoted as (x_i, y_i), where $i = 1, 2, \ldots, n_e^k$, and n_e^k is the number of the discretized random field elements in the kth layer. Based on Eq. (1) and these coordinates, the autocorrelation matrix $\boldsymbol{C}^k$ for the kth layer is expressed as