Structural Safety 49 (2014) 45–55

Contents lists available at ScienceDirect

Structural Safety

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

Effect of spatially variable shear strength parameters with linearly increasing mean trend on reliability of infinite slopes

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ARTICLE INFO

Article history:
Available online 15 November 2013

Keywords:
Soil slopes
Slope stability
Shear strength
Spatial variability
Random field
Reliability

ABSTRACT

This paper studies the reliability of infinite slopes in the presence of spatially variable shear strength parameters that increase linearly with depth. The mean trend of the shear strength parameters increasing with depth is highlighted. The spatial variability in the undrained shear strength and the friction angle is modeled using random field theory. Infinite slope examples are presented to investigate the effect of spatial variability on the depth of critical slip line and the probability of failure. The results indicate that the mean trend of the shear strength parameters has a significant influence on clay slope reliability. The probability of failure will be overestimated if a linearly increasing trend underlying the shear strength parameters is ignored. The possibility of critical slip lines occurring at the bottom of the slope decreases considerably when the mean trend of undrained shear strength is considered. The linearly increasing mean trend of the friction angle has a considerable effect on the distribution of the critical failure depths of sandy slopes. The most likely critical slip line only lies at the bottom of the sandy slope under the special case of a constant mean trend.

1. Introduction

Slope stability is a typical problem in geotechnical engineering (e.g., [3,26,33]). It is well known that soil is a complex engineering material that has been formed by a combination of various geologic, environmental, and physio-chemical processes. Because of these natural processes, all soil properties in situ will vary vertically and horizontally [27]. Hence, a realistic assessment of slope reliability should consider the spatial variability of shear strength parameters [1,6].

Different aspects of spatial variability of shear strength parameters on slope reliability have been studied in the past (e.g., [15,12,24,32,8,16,13,17,40,41]). For example, Hicks and Samy [15] studied the influence of heterogeneity of undrained shear strength on the stability of a clay slope. Griffiths and Fenton [12] studied the effect of spatial variability of the undrained shear strength on the probability of failure of a slope. Low et al. [24] proposed a practical EXCEL procedure to analyze slope reliability in the presence of spatially varying shear strength parameters. Srivastava and Sivakumar Babu [32] quantified the spatial variability of soil parameters using field test data and evaluated the reliability of a spatially varying frictional/cohesive soil slope. Cho [8] investigated the effect of spatial variability of shear strength parameters accounting for the correlation between cohesion and friction angle on slope reliability. Hicks and Spencer [16] conducted a reliability analysis of a long 3D clay slope. The influence of spatial heterogeneity on the failure mode was studied. Griffiths et al. [13] performed a probabilistic analysis to explore the influence of spatial variation of shear strength parameters on the reliability of infinite slopes. Ji et al. [17] adopted the First Order Reliability Method (FORM) coupled with a deterministic slope stability analysis to search for the probabilistic critical slip surface when spatial variability of shear strength parameters is considered. Zhu et al. [41] explored the variance of matric suction and factor of safety of a slope subjected to steady-state rainfall infiltration in the presence of spatially varying shear strength parameters.

In the majority of these studies, the spatial variability of shear strength parameters was modeled as a stationary random field. In other words, the means of the shear strength parameters are constant with depth. However, it is well recognized that a soil property fluctuates about a trend that typically increases with depth [27]. The fluctuating component is viewed as the inherent soil variability, while the trend function is viewed as the mean of the soil property at various depths. Many in-situ test data revealed that soil properties of a statistically homogeneous soil layer did exhibit non-constant trends with depth [2,15,10,11,18,31,32,5,36,29,37,38]. For example, Wilson et al. [36,37] investigated the undrained stability of circular and square tunnels where the shear strength

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0167-4730/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.strusafe.2013.08.005

increases linearly with depth. Wu et al. [38] studied the reliability of basal heave stability of deep excavations in which the undrained shear strength varies with depth. Hence, while the detrended fluctuations can be modeled as a zero-mean stationary random field, the actual value of the soil property consisting of the trend and the fluctuation is generally non-stationary (in the mean) and this effect should be studied in slope reliability problems.

This paper aims to study the reliability of infinite slopes in the presence of spatial varying shear strength parameters that increase linearly with depth on the average. To achieve this goal, this article is organized as follows. In Section 2, the mean variation of shear strength parameters with depth is discussed. In Section 3, the spatial variabilities in the undrained shear strength and the effective stress friction angle are modeled by random fields, which are discretized by Karhunen-Loeve (KL) expansions. In Section 4, a method to determine the reliability of infinite slopes is presented. In Section 5, infinite slope examples are analyzed to study the effect of spatial variability in the presence of a linearly increasing mean trend on the most likely depth of the critical slip line and the probability of failure. Discussions on shallow landslides related to spatial variability are presented in Section 6.

2. Spatial variability of soils

2.1. Trend of undrained shear strength with depth

The undrained shear strength is often used for undrained stability analysis of clay slopes. It is well known that the undrained shear strength is not a fundamental soil parameter, and its value depends on the effective confining stress, among others. An increase in effective confining stress generally causes an increase in undrained shear strength. For slightly plastic and medium plastic soil, the undrained shear strength, s_u, can be expressed as [19]:

$$s_u/\sigma'_v = (0.23 \pm 0.04)\mathrm{OCR}^{0.8} \tag{1}$$

where σ'_v is the effective vertical stress which can be calculated by $\sigma'_v = \gamma' Z$, in which γ' denotes the effective unit weight of the soil and z denotes the depth below the ground surface. The OCR is the overconsolidation ratio, which is defined as:

$$\mathrm{OCR} = \sigma'_p/\sigma'_v \tag{2}$$

where σ'_p is the effective preconsolidation stress, which is the maximum vertical effective stress experienced by a point in a soil mass in the past. If the present ground surface is defined as $z = 0$ and the maximum overburden depth in the past is d, σ'_p at any given depth z would be $\gamma'(z + d)$. In this case, Eq. (2) can be written as:

$$\mathrm{OCR} = (z + d)/z \tag{3}$$

For normally consolidated soil, OCR is equal to 1. For overconsolidated soil, OCR usually lies between 1 and 50. For highly plastic soil, the undrained shear strength depends not only on the effective vertical stress and the overconsolidation ratio, but also on the plasticity index [19].

Eq. (1) is adopted to characterize the depth trend of the undrained shear strength in an approximate but realistic way. The following parameters are adopted: $\gamma' = 10$ kN/m^3, $d = 35$ m, and the maximum value of the OCR is capped at 50. The lower and upper bounds of s_u are calculated using Eq. (1), i.e. lower bound = 0.19OCR$^{0.8}$ and upper bound = 0.27OCR$^{0.8}$. Fig. 1 shows the variation of these lower and upper bounds with depth. A simple linear trend falling within these bounds is selected in this study (i.e. the line with triangle marker in Fig. 1). Asaoka and A-Grivas [2] also pointed out that s_u can increase linearly with depth from a non-zero value for overconsolidated soils. This conclusion is consistent with the simple model adopted in this study. A vertical line

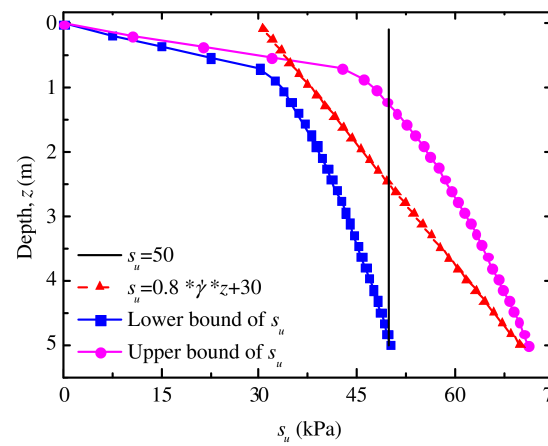

Fig. 1. Trend of undrained shear strength of overconsolidated soil with depth.

representing a constant s_u = 50 kPa scenario is also plotted in Fig. 1. This vertical line has been widely used in geotechnical engineering practice due to its simplicity (e.g. [12,8,16,13,17]). It is evident that the resulting undrained shear strength significantly exceeds the upper bound of s_u when the depth is less than 1.2 m. Although this difference looks minor, it can be important for shallow landslides.

2.2. Trend of effective friction angle with depth

Unlike the undrained shear strength, the effective friction angle is a more fundamental soil parameter. For brevity, the effective friction angle is referred to as the friction angle from hereon. The trend function of friction angle with depth is not widely reported in the literature, possibly because undisturbed sand samples are difficult to obtain.

In this paper, some in-situ test data and an empirical relation between friction angle and in-situ test data are used to estimate a reasonable trend function for the friction angle. The following empirical relation for sand is adopted in this study. It relates the friction angle with the cone tip resistance measured in a cone penetration test (CPT) [19]:

$$\phi = 17.6 + 11.0\log_{10}\left(\frac{q_c/p_a}{\sqrt{\sigma'_v/p_a}}\right) \tag{4}$$

in which ϕ is the friction angle of sand; q_c is the cone tip resistance, and p_a is the standard atmospheric pressure ≈100 kPa.

To characterize the trend of friction angle with depth using Eq. (4), CPT data for sandy soils at four different sites are used. Based on these data, the ϕ-z functions can be obtained using Eq. (4) as shown in Fig. 2. Note that $\gamma' = 10$ kN/m^3 is adopted for calculating σ'_v in Fig. 2(a, b, d) because the sandy soil layers are below the ground water table while $\gamma' = 20$ kN/m^3 is adopted in Fig. 2(c) because the ground water table is very deep at the site. It can be seen that the friction angle increases with depth. This is consistent with the trend of friction angle of fine to medium-grained sand layer in Nakdong River Delta [30]. The normalization using σ'_v in Eq. (4) does not remove the depth trend in the CPT data, although it is tempting to think that this will happen and the friction angle can be assumed to be constant along depth. It should be pointed out that there also exists a trend of friction angle decreasing with depth due to the reduced dilatancy of sand with increasing stress level. However, only the case of friction angle of sandy soil increasing with depth is investigated in this study for consistency. Moreover, since all the q_c data in Fig. 2 are collected from field cone penetration tests, it is reasonable to assume that the trend of