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Effects of Desiccation Cracks on Slope Reliability

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Abstract: An important factor in rainfall induced slope failure is the depth of desiccation cracks, which cause preferential flows during rainfall infiltration. This paper presents a probabilistic framework to assess the influence of the depth of desiccation cracks on the probability of slope failure. The upper desiccation cracks and lower soil layer are simulated by two independent random fields where the soil spatial variability is taken into account. Since modelling individual cracks in a slope is not feasible, their effects on soil shear strength can reasonably be captured using simple empirical models. The shear strength of lower soil layer is modelled by non-stationary random field where the mean strength increases linearly with depth while the coefficient of variation remains constant. Numerical results presented in this paper show that the desiccation cracks can significantly affect the estimated failure probability.

Keywords: Rainfall; probabilistic analysis; desiccation crack; non-stationary random field.

1   Introduction

Landslides cause damage to buildings, infrastructure, agricultural land and crops. In the majority of cases the main trigger for landslides is heavy or prolonged rainfall (Brand 1984; Fourie 1996). The research of rainfall-induced landslides has been developed tremendously during the past 30 years along with the development of unsaturated soil mechanics (e.g., Lim et al. 1996; Ng et al. 2003; Zhang et al. 2012).

An important factor in rainfall induced slope failure is the desiccation cracks, which cause preferential flows during rainfall infiltration. The infiltration of rainfall results in the rise of groundwater level, and the increase in water pressure or the decrease in matric suction of unsaturated soils. On the other hand, the matric suction has been found to be absolutely crucial to the stability of unsaturated slopes (Fredlund et al 1993). Both the increase in the water pressure and the decrease in the matric suction cause the decrease in the shear strength of soils. This, in turn, possibly leads to the occurrences of landslides and slope failures. Desiccation cracking is a major issue in the field of geotechnical engineering. In places prone to long drying periods, extensive desiccation can occur with cracks reaching depths of a few meters or more in high plasticity soils. Cracks are widely present in soil slopes and decrease the stability of the slopes. Thus, it is important to investigate the influence of cracks on the stability of slopes.

Most studies involving rainfall-induced landslides are deterministic in nature, where the soil is assumed to be homogeneous and averaged (or design) soil properties are considered in the analysis (e.g., Michalowski 2013). The uncertainties associated with the soil parameters are usually dealt with by adopting "reasonably averaged" parameters, coupled with practical experience (Duncan 1996). However, a great number of uncertainties are involved in the analysis of slope stability under rainfall conditions. Measured soil properties are subject to inherent spatial variability, measurement error, and statistical error because of a limited number of samples. A probabilistic method provides a systematic and quantitative way to account for the uncertainties involved in a complicated geotechnical system. A few studies focused on the effects of the spatial variability of the soil properties on rainfall infiltration and subsequent slope stability by using random field theory (e.g., Zhang et al. 2004; Santoso et al. 2011; Ali et al. 2014; Wu et al. 2017; Tang et al. 2018). The effect of desiccation cracks on slope stability is not well known and current published literature is quite varied in their research. There is no consensus on how to represent the effect of desiccation cracking into slope stability modelling (e.g., Reitsma and Kueper 1994; Persoff and Pruess 1995).

In this paper, the shear strength of lower soil layer is modelled by non-stationary random field where the mean strength increases linearly with depth while the coefficient of variation remains constant. The shear strength of upper desiccation cracks is modelled by stationary random field which is characterized by its mean (μ_{crack}), coefficient of variation (v_{crack}) and spatial correlation length (θ_{crack}). The effects of the depth of the

desiccation cracks were investigated. The results show that deep cracks lead to a greater probability of failure. The study of the influence of crack depth on slope stability can enhance the understanding of a wide spectrum of geotechnical and geologic problems.

2   Methodology

In reality, the cracks would vary in depth and thickness and thus infiltration rates would not be uniform. Since modelling individual cracks in a slope is not feasible in a continuum framework, their effects on soil shear strength can reasonably be captured using simple empirical models (Fredlund et al. 2010). According to Li et al. (2011), the cracked soil can be modeled as a continuum. The bimodal character arises out of the independent behavior of the cracks and the intact soil. The soil property functions for the cracked and intact soil are initially treated as being two independent materials and then the results are combined. The problem is idealized with two discrete layers; the top layer representative of a uniform depth of desiccation cracks, and the lower layer.

The underlying assumption that the desiccation crack layer translates to immediate rainfall infiltration and hence reduction in surface soil shear strength. For simplicity, the effect of rainfall infiltration was idealized as a reduction in shear strength in the soil. For the lower layer of the slope, the effect of the rainfall infiltration can be neglected.

2.2   Undrained shear strength for the intact soil

Examination of many in situ test data revealed that soil properties generally fluctuate about a mean trend that typically increases with depth (Phoon and Kulhawy 1999). The resultant random field is called non-stationary, where the statistics (i.e., means and standard deviations) are non-constant over the domain of the random field. Many researchers (i.e., Griffiths et al. 2015; Jiang et al. 2018) have realized the importance of the non-stationary characteristics of soil properties and have taken into account the depth-dependent nature of soil properties in the reliability analyses of geotechnical systems. Therefore, in this paper intact soil with non-stationary random fields will be described, in which the mean and standard deviation of soil strength increase linearly with depth. The mean strength is a linear function of depth according to the equation

$$\mu_{cu_z} = \mu_{cu_0} + tz \tag{1}$$

where μ_{cu_z} is the mean strength at depth z, μ_{cu_0} is the mean strength at crest level (which z=0) and t is the gradient of mean strength. In this study the standard deviation of shear strength is also assumed to be a linear function of depth with a gradient that results in a constant coefficient of variation υ_{cu} .

In addition to the mean and the coefficient of variation, a third parameter, the spatial correlation length θ , is required to completely define a random field. The spatial correlation length defines the distance over which the soil properties are significantly correlated; with properties separated by a distance greater than θ being generally uncorrelated. A large spatial correlation length means that the soil properties are highly correlated over a large distance, implying less spatial variability and more uniformity in soil properties. Conversely, a small correlation length implies a higher spatial variability and less uniformity in the soil properties. In the context of random fields, the spatial correlation lengths are generally incorporated through a correlation function. The correlation function ρ assumed for the present study is an exponential one of the form

$$\rho = \exp\left(-\frac{|\tau|}{\theta}\right) \tag{2}$$

where τ is the absolute distance between two points in the random field.

Initially, removing the trend, a homogeneous, stationary, lognormal random field based on the parameters at crest level is generated across the mesh. Suppose c_0 and c_z are random variables at crest level and depth z, respectively. Adding the trend back, the element values are then scaled to account for depth z using

$$c_z = c_0 \frac{\mu_{cu_0} + tz}{\mu_{cu_0}} \tag{3}$$

Eq.(3) shows that c_z can be transform from the initial stationary random field c_0 . For details of the derivation of equation (3), see Zhu et al. (2017).

In this paper, the random fields are generated by the local averaging subdivision method, which fully accounts for spatial variability and local averaging over each finite element. The case of stationary random fields in slope stability analysis was reported in detail by Griffiths and Fenton (2004) , who also presented an analytical solution corresponding to the case of an infinite spatial correlation length.

3   Example

An illustrative example is given here for a slope of $18.4°$ (3:1 slope) in inclination, with a height $H = 10\text{m}$, and a depth ratio to an underlying firm layer $D = 1.5$. The slope profile with the finite element mesh is shown in Figure 1. The soil unit weight $\gamma = 20.0\text{kN/m}^3$, which are all held constant. If the random variable is assumed normal distributed, both negative and positive values are possible, which is not acceptable for non-negative geotechnical parameters. To avoid negative values a non-Gaussian distribution is desirable. Hence, the undrained shear strength is assumed to be lognormally distributed and the mean and standard deviation of soil properties increases linearly with depth. The mean shear strength at the crest level, $\mu_{c_0} = 18\text{kPa}$, the gradient of mean strength $t = 2.4\text{kN/m}^3$ and constant the coefficient of variation, $v_{cu} = 0.5$. The spatial correlation length θ is assumed to fix at 10m. A finite element mesh size of $0.5\text{m} \times 0.5\text{m}$ is selected. Based on the parameters given above, 2,000 RFEM simulations are performed and the probability of failure (p_f) is found to be 0.1495.
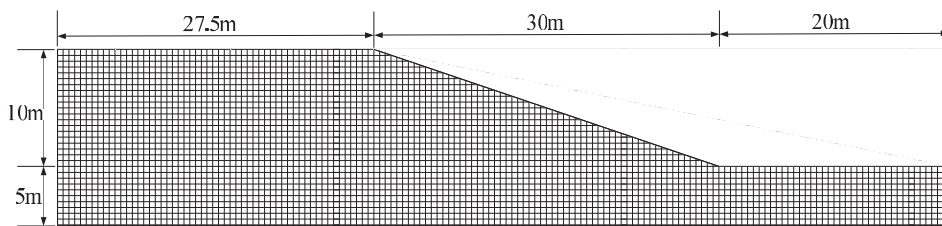

Figure 1. Finite element mesh.

Cracks are occurrence at the top of soil slopes, and the proposed method is adopted for including the presence of cracks in slope reliability analysis based on random field simulation. The undrained shear strength of the desiccation cracks is reduced due to rainfall infiltration. Assumpt the desiccation crack layer is idealized as a uniform depth layer. The continues model is used to simulate the crack soils for two different depths, $L = 0.5\text{m}$ and $L = 1.0\text{m}$. The shear strength of crack layer is also assumed to be lognormally distributed. To investigate the influence of the depth of the cracks on slope stability analysis, an incremental reduction in shear strength for the crack soils is applied. The mean undrained shear strengths of crack soils used in this study are $\mu_{crack} = 3.6\text{kPa}$ and $\mu_{crack} = 7.2\text{kPa}$. The spatial correlation length θ_{crack} is fix at 10m. And the coefficient of variation is $v_{crack} = 1.0$. It is also assumed that rainfall would not affect the properties of the lower intact soil. Two thousand RFEM simulations are generated to estimate the probability of failure. The typical failure mechanisms can be seen from Figure 2. The locations of desiccation cracks for $\mu_{crack} = 3.6\text{kPa}$ and $\mu_{crack} = 7.2\text{kPa}$ are above the red lines as shown in Figure 2 (b) and (d), respectively. Figure 2 (c) and (e) show that the crack soil properties are reduced when compared to the slope with no crack.
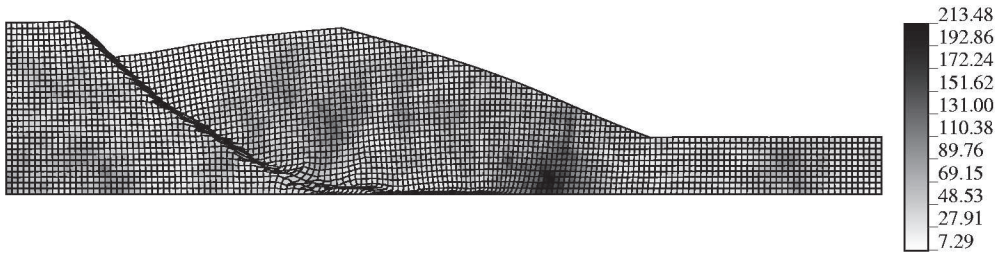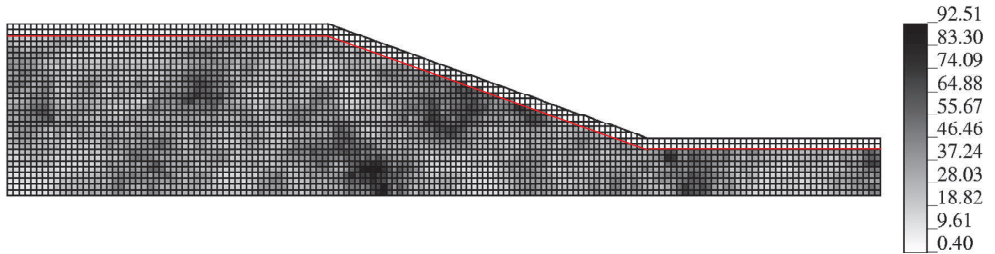
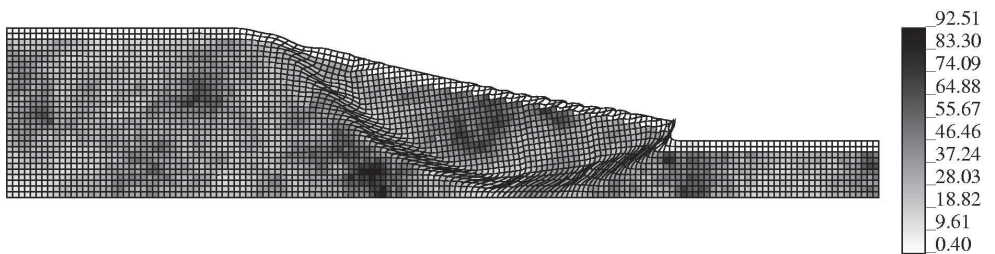(a) Typical failure mechanism for the case slope with no crack.
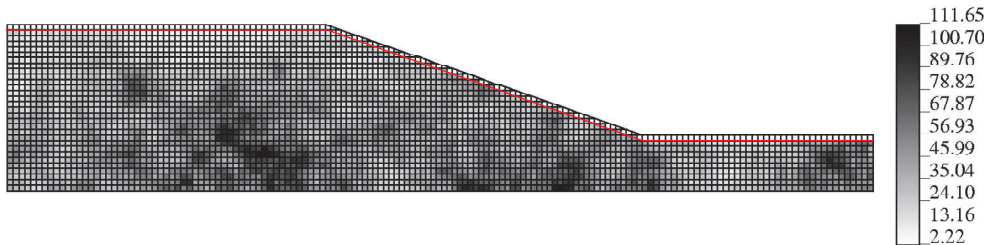
(b) Desiccation crack locations for the case slope with crack depth $L = 0.5$m and $\mu_{crack} = 3.6$kPa .
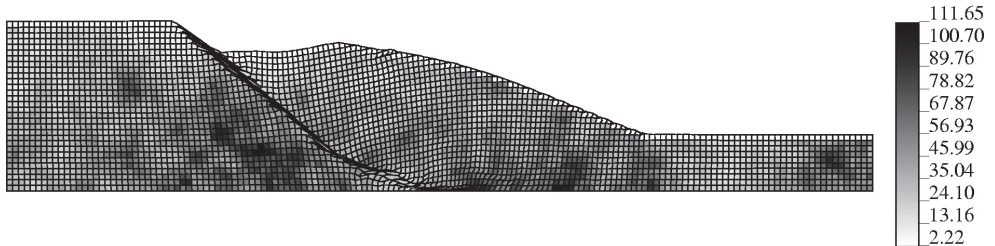
(c) Typical failure mechanism for the case slope with crack depth $L = 0.5$m and $\mu_{crack} = 3.6$kPa .

(d) Desiccation crack locations for the case slope with crack depth $L = 1.0$m and $\mu_{crack} = 3.6$kPa .

(e) Typical failure mechanism for the case slope with crack depth $L = 1.0$m and $\mu_{crack} = 3.6$kPa .

Figure 2. Typical failure mechanisms

Table 1 shows the probability of failure for different depths of crack. As expected, the greater the depth of the desiccation crack the faster the rainfall infiltration and hence the reduction in shear strength, leading to reduced slope stability. Increased the depth of cracks has a greater influence on the probability of failure when

the mean strength is relatively small ($\mu_{crack} = 3.6\text{kPa}$). The probability of failure sharply increases from 0.182 to 0.4075 when the depths of crack increases from 0.5m to 1.0m. When the crack depth is small ($L = 0.5\text{m}$), the undrained shear strength has little influence on the probability of failure.

Table 1. Comparison of probability of failure for different depths of crack.

	$L = 0.5\text{m}$		$L = 1.0\text{m}$	
v_{crack}	1.0		1.0	
μ_{crack}	3.6kPa	7.2kPa	3.6kPa	7.2kPa
p_f	0.182	0.162	0.4075	0.2245

4   Conclusion

In this paper, a method is proposed for the stability analysis of soil slopes with existing cracks based on random finite element method. The probabilistic method can account for the spatial variability of soil properties. It is demonstrated that crack is an important factor affecting the outcome of reliability analyses of slopes. The results indicate that increasing the depths of crack, the probability of failure is significantly increased.

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