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Impact of the Spatial Variability of Soil Shear Strength on the Stability of an Undrained Clay Slope

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Abstract: Random fields have been a widely applied method to describe the inherent spatial variability of soil properties, but the correlation structures used in random fields are mainly concentrated on isotropy or transverse anisotropy. This paper attempts to investigate the influence of the spatial variability of the undrained shear strength on slope stability for a two-dimensional rotated anisotropy correlation structure. The rotated anisotropy random fields are simulated using the covariance matrix decomposition method. Within Monte-Carlo framework, sensitivity studies are performed to explore the effects of the rotation angle under the exponential correlation structure on the slope reliability and failure mechanism. The quantified classification for three types of failure mechanisms, namely face failure, toe failure and base failure, is suggested using the failure depth. The results indicate that the rotation angle shows a dual effect on the reliability of slope in comparison to the case transverse anisotropy. This study can improve our understanding of the effect of a rotated anisotropy correlation structure on slope stability.

Keywords: Slope stability; random field; anisotropy; failure mechanism.

1 Introduction

Uncertainty is a prominent characteristic of geotechnical engineering, and the character also is one of the key factors that limit its development. Morgenstern (2000) indicated that the following three sources of uncertainty can be concluded: parameter uncertainty, model uncertainty and human uncertainty. Soil parameter uncertainty is considered of this paper. Among several types of geotechnical field problems has been studied that take into account the soil heterogeneity over the past few decades (e.g., Griffiths and Fenton, 2004). All of their works has improved the understanding of the influence of the spatial variability of soil properties on the responses of engineering structure. Probabilistic analysis has been proved to be a more appropriate method in slope reliability (e.g., Alonso, 1976). There are several probabilistic analysis methods in slope reliability taking into account the soil heterogeneity, such as the First Order Reliability method (FORM), the direct Monte Carlo simulation (MCS), the Response Surface method (RSM) or Stochastic Response Surface method (SRSM), the Random Finite Element method (RFEM) (e.g., Griffiths and Fenton, 2000; Griffiths et al., 2009; Hicks et al., 2014), the Random Finite Difference method (RFDM) (e.g., Cheng et al., 2018). Describing how soil parameters vary is of vital importance in stochastic analyses of slope reliability, because the variability does have a significant influence on local material and global reliability which has been proved in above lectures. For the method of FORM, MCS, RSM and SRSM, soil parameters are seen as simple random variables, which cannot reflect the character of correlation and local averaging in soil. Random field theory was firstly adopted to model the variability based on statistics of soil parameters (Vanmarcke, 1977), and the correlation function is used to quantify the correlation in random models established. Combining with the Finite Element code or the Finite different code, RFEM or RFDM were proposed for stochastic analysis. However, the above lectures using RFEM or RFDM are mainly focus on isotropy correlation structures in random field modeling, which shows less agreement with the depositional characteristics of soil. Due to deposition or other geologic processes, the spatial variability of soil properties shows apparently anisotropy (Phoon and Kulhawy, 1999). Anisotropy can be further divided into four anisotropy patterns, including transverse anisotropy, rotated anisotropy, general anisotropy and general rotated anisotropy, (Zhu and Zhang, 2013). Hicks and Samy (2002) discussed the influence of horizontal anisotropy correlation structure in stochastic analysis of undrained clay slope stability, and pointed out that the anisotropy can show a significant influence on slope stability. The reliability of slope decreases with the increase of the vertical scale of fluctuation, and the slip surface propagates along semi-continuous weak zones. Zhu et al. (2019) took into account the rotational orientation of the principal axes of anisotropy.

This paper is aim to investigate the influence of the undrained shear strength on slope stability for a two-dimensional rotated anisotropy correlation structure. Random field modeling of the variability of the undrained shear strength is firstly introduced. Then, procedure is described for implementing the stochastic analyzing method RFDM and illustration is provided by applying the method on a 1:1 slope. Three typical failure mechanisms are defined according to the failure depth to identify the influence of the rotation angle and anisotropy. The results promise to help designers better understand the potential risks of slope caused by soil heterogeneity.

2 Rotated anisotropy slope model

A 1:1 slope in undrained clay is employed in this paper and geometry parameters H, α are shown in Figure 1. The two-dimensional model has been analyzed by Hicks and Samy (2002), but there is no base below the slope. The clay is modeled using an elastic, perfectly plastic, Von Mises soil model. In the model, only the undrained shear strength cu is considered as random fields and a log-normal distribution is assumed. Soil parameters used are listed in the Table 1. To generate random fields, another parameter scale of fluctuation is necessary, which is an index of correlation between spatial points. A larger scale of fluctuation means a stronger correlation.

There are a variety of methods of generating random fields, and the Covariance Matrix Decomposition Method (CMDM) is employed for the simplicity and adaptability of generating anisotropy random field (El-Kadi and Williams, 2000). Specially, CMDM can serve as the bridge between random field and the finite difference element mesh special for anisotropic correlation structures and irregular meshes. The sequence for stochastic analyzing a transfer anisotropic slope model by RFDM is as follows:

Step a: Base on the geometry in Figure 1, the finite difference element mesh is generated by FLAC3D 5.0, and the center coordinates is derived for each element.

Step b: The transfer anisotropic random field model is generated by CMDM based on MATLAB.

Step c: A new FISH code is used to realize one-to-one mapping from random field to the finite difference mesh. Safety of factor of the slope is calculated by the shear strength reduction method, and the failure depth also recorded for each realization.

Step d: Within Monte-Carlo framework, stochastic analysis of slope stability is achieved by repeating Steps b and c.

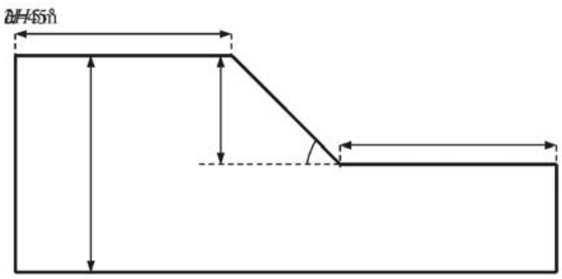

Figure 1. Geometry of the 1:1 slope.

Table 1. Physico-mechanical parameters in the model.

Soil	Elastic, perfectly plastic model
Unit weight, γ (kN/m^3)	18
Fiction angel, φ (°)	0
Cohesion, c (kPa)	Log-normal distribution
Poisson's ratio, v (-)	0.3
Young's modulus, E (MPa)	100

3 Analysis

The variability of c_u can be expressed by the dimensionless parameter Coefficient of Variation (COV). In this paper, the mean of undrained shear strength and a moderate COV=0.2 are employed. Phoon and Kulhawy (1999) indicated that the vertical scale of fluctuation θ_v is in a range of 1 to 2 m for the general soil type, and θ_v=1 m is assumed in stochastic analysis. The horizontal scale of fluctuation θ_h is larger than θ_v. The degree of anisotropy of soil variability is identified with $\xi=\theta_h/\theta_v$. When ξ=1, the corresponding model is isotropic heterogeneity. Only the maximum ξ=60 (θ_h=60 m) selected is based on the concerning the geometry of slope. For each ξ>1, there are eight rotation angles β (0°, 30°, 45°, 60°, 90°, 120°, 135°, 150°) considered. When β=45°, the direction of the longest scale of fluctuation is perpendicular to the dip direction of the slope, and the longest scale of fluctuation parallels to the dip direction for β=135°.

As stated above, the shear strength reduction method is employed to study slope stability. With the let-in

FISH code, a simple bisection method is realized for determining factor of safety Fs. In the method, the upper and lower brackets are established with a wide range of [1.0, 3.0] considering a moderate COV=0.2 selected. Then by constantly adjusting the reduction factor.

Within Monte-Carlo framework, the number of realization shows a great influence on probabilistic problems. Generally, the larger the number of realization leads to an increase of the accuracy of results, but induces a longer computation time. For each case of adopted ξ and β values, 1000 realizations have been conducted for the plane strain analyses in the view of balancing accuracy and efficiency of calculation in this study.

4 Results

Generally, one of the important issues of slope risk analysis is to determine the critical slip surface. The spatial variation of the undrained strength parameter can be attributed to a different triggering mechanism for each realization. For a straightforward quantification of the potential failure mechanism, Figure 2 presents three typical failure mechanisms, face failure, toe failure and base failure (Gao et al., 2013). The mechanisms are defined based on the depth of the critical slip surface. In general, a deep failure tends to cause more damage and a more severe consequence (Ali et al., 2014). In the paper, the failure depth is only used to identify different failure mechanisms for simplicity. The failure depth h_f is defined as the depth from the top of slope to the deepest of the critical slip surface. For the above three failure mechanisms, a general h_f is shown in Figure 2. For $h_f \leq 5$ m, a face failure is to happen. For 5 m $\leq h_f \leq 6$ m, a toe failure is, and the other h_f corresponds to the base failure. Contour of shear strain increment is used to determine the critical slip surface in the finite difference code. Thus, h_f is researched and recorded with the aid of the let-in FISH code for each realization. Theoretically, there are 1000 critical slip surfaces for 1000 times of stochastic analysis. Several possible failure mechanisms are illustrated in Figure 3. The left figures indicate the location of the critical slip surface with the contour of shear strain increment, and the right gray figures are the corresponding distribution of c_u in the model. The darker regions indicate stronger soil, and the lighter represent weaker soil. The red dash lines represent the critical slip surface from the left figures.

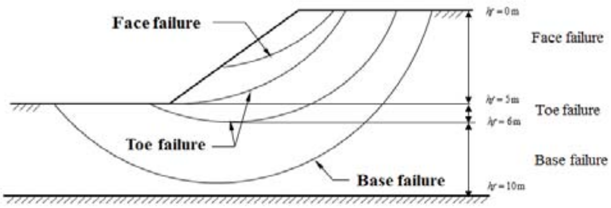

Figure 2. Three typical slope failure mechanism (After Gao et al., 2013).

Figure 4 illustrates the distribution of factor of safety and failure depth. Then the consequence of each failure can be quantified with the corresponding safety of factor. Note that the direction shows the strongest correlation parallel to the slope, which can be seen is as a consequent slope. On the contrary, the direction shows the strongest correlation perpendicular to the slope, which can be seen is as an anti-dip slope. In Figure 6, for anti-dip slopes, a higher factor of safety but larger proportion of deep failure is predicted, and the corresponding consequence may show a high level. For consequent slopes, a lower factor of safety and smaller proportion of deep failure relatively are predicted. Overall, to assessing the consequence of slope slide, both the failure mechanism and the corresponding safety of factor should be considered.

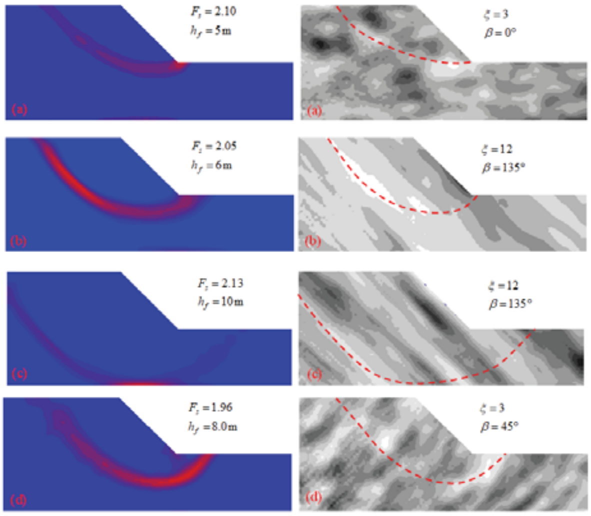

Figure 3. Failure mechanisms for different realizations.

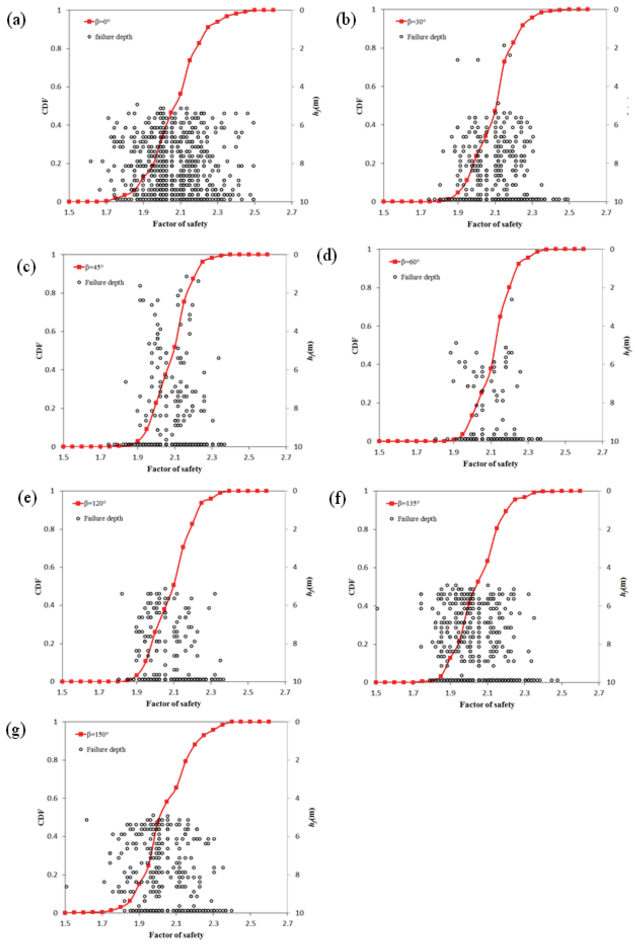

Figure 4. Distributions of factor of safety and failure depth: (a) β=0°, (b) β=30°, (c) β=45°, (d) β=60°, (e) β=120°, (f) β=135°, (g) β=150°.

5 Conclusions

This study provides a preliminary investigation that the influence of soil heterogeneity on slope stability for a two-dimensional rotated anisotropy correlation structure. The spatial variability of the undrained shear strength following the log-normal distribution is considered. Employing the Random Finite Difference method (RFDM), probabilistic analysis is conducted to explore the effect of the rotation angle on the reliability of slope. The rotation angle does show a partly influence on the stability of slope, and triggers multi-failure mechanisms. A dual effect on slope reliability caused by rotated anisotropy correlation structure is obtained comparing to a transverse anisotropy based on the results of the mean factor of safety. The critical slip surface mainly depends on the potential weak layer. The proportion of the critical slip surfaces at the base of the anti-dip slope is higher than the consequent slope.

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