THE SOIL RUNOUT ANALYSIS OF 3D SLOPE **CONSIDERING THE SOIL SPATIAL VARIABILITY**

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1. INTRODUCTION

The runout analysis refers to mobilized soil mass of failed slope and is important for slope stability evaluation. It is well known that the spatial viability of soil properties affects soil behavior such as slope stability. To illuminate the spatial variability effect on the runout analysis, the concept of reliability design with evaluating the runout character (apparent friction coefficient tan ϕ_p in this study) should be considered. This paper firstly investigates the contribution of various soil parameters (the cohesion c, friction angle ϕ and soil unit weight γ) on soil runout, then evaluates the effect of spatial variability on 3D slope runout analysis considering the tan ϕ_p , sliding volume and failure mechanism. In detail, c, tan ϕ and γ for 3D slope are treated as random field, and depth-averaged model is used to evaluate the soil runout analysis. Finally, a Monte-Carlo simulation is used to evaluate the effect of spatial variability on tan ϕ_p and slope failure mechanism.

2. RANDOM FIELD RUNOUT ANALYSES

2.1 Random field

In this study, the spatial variability of shear strength, $\tan \phi$ and c, and soil unit weight, γ , are treated as a homogeneous random field, which are assumed to underly log-normal distribution with mean, $\mu_{tan\phi}$, μ_c and μ_{γ} , and standard deviation $\sigma_{\tan\phi}$, σ_c and σ_{γ} , and an isotropic correlation length, $\theta_{\ln\tan\phi} = \theta_{\ln c}$ $=\theta_{\ln y}$. Current study uses a normalized correlation length by slope height, $\Theta = \Theta_{\text{intan}\phi}/H = \Theta_{\text{inc}}/H = \Theta_{\text{inj}}/H$ as input parameter. The coefficient of variation of γ (*COV* $_{\gamma}=\sigma_{\gamma}/\mu_{\gamma}$) is fixed as 0.1 while the incremental combination of $COV_{tan\phi}$ and COV_c are considered as $COV_{tan\phi}$ varied from 0.1 to 0.5 simultaneously COV_c changed from 0.2 to 1.0. In addition, an isotropic vertical and horizontal fluctuation is considered meaning that the ratio of vertical and horizontal correlation length equals to 1.0.

Fig. 1 is a 3D DEM model for the slope angle of 30° with the soil spatial variability. It considers a soil base layer with depth d/H = 1.0, the horizontal length l/H = 5.0 and the width w/H = 5.0, where H is the height of the slope. It should be noticed that the Fig. 1 illustrates one realization for cohesion c at the condition of $COV_c = 0.2$ and $\Theta = 1.0$. Detail input parameters are summarized in Table 1. It should be noticed that the shear strength reduction ratio R is used for runout analysis, since there is strength reduction from peak strength to residual strength due to water pressure build-up at slip surface.

2.2 Random runout model

The depth-averaged runout model is used in this study and its methodology was proposed by reference (1), which divided the collapsed soil into vertical soil columns, and the driving force by self weight of soil columns and active and passive earth pressure from surrounding soil columns. This runout model can be coupled with a stability analysis, which directly utilizes the sliding mass and critical slip surface estimated by Random Limit Equilibrium Analysis (RLEM) (2). A soil runout analysis considers spatial variability of soil properties is referred to as random soil runout analysis.

3. SIMULATION RESULTS

In order to evaluate the effect of spatial variability on soil runout, a sliding volume ratio R_V and apparent friction coefficient tan ϕ_p are introduced as follow equations:

Keywords: Slope stability, 3D spatial variability, runout analysis



Fig. 1 Slope model and realization of spatial variability Initial shape of slope



Apparent friction coefficient: $tan\phi_a = H / L$ Fig. 2 The apparent friction coefficient for runout analysis

Table 1. Input parameters

Parameter	Value
Mean soil cohesion, μ_c	100 kPa
COV of cohesion, COV_c	0.2, 0.4, 0.6, 0.8, 1.0
Mean friction angle, $\mu_{tan\phi}$	0.5774 (μ _φ =30°)
COV of friction angle, $COV_{\tan\phi}$	0.1, 0.2, 0.3, 0.4, 0.5
Mean unit weight, μ_{γ}	20 kN/m ³
COV of unit weight, COV_{γ}	0.1
Ratio of vertical and horizontal	1 (Isotropic)
correlation length	- (
Normalized correlation length,	Random, 0.05,
$\Theta = \theta_{\ln \tan \phi} / H = \theta_{\ln c} / H = \theta_{\ln \gamma} / H$	0.25, 0.5 and 1.0
Cross correlation coefficient	0.5
between <i>c</i> and tan ϕ , $\rho_{c-\tan\phi}$	0.0
Monte-Carlo iterations	1000
Shear strength reduction ratio, R	0.50

$$R_{v} = \frac{V_{i}}{V_{\text{hom}}}$$
(1)
$$\tan \phi = H/_{r}$$
(2)

$$\phi_a = \frac{H}{L} \tag{2}$$

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considering spatial variability

where V_{hom} is the sliding volume for homogeneous slope with the slope angle $\beta = 30^{\circ}$, uniform shear strength tan $\phi = 0.5774$ ($\phi = 30^{\circ}$) and c = 100 kPa, and unit weight $\gamma = 20$ kN/m³; and V_i is the sliding volume for *i* th iteration. And tan ϕ_p is a ratio of collapsed height *H* overs deposit distance *L* shown in Fig.2.

Fig. 3 demonstrate the different parameters contribute to the variance of the apparent friction coefficient, tan ϕ_a . it is obviously seen that the random variable of soil unit weight γ is important, and denotes maximum contribution (64.3%) for variance of tan ϕ_a , $V[\tan \phi_a]$. It is suggested that spatial variability of soil unit weight γ has prime influence on the soil runout analysis, and it is reasonable since the variable γ accounts for gravitational driven force and the normal stress for calculating shear strength and earth pressure in this random runout model. In addition to compare the contribution of shear strength random variable c and ϕ , it can be seen that random variable c has larger influence on the variance of soil runout, whereas ϕ has less variance contributions.

Fig. 4 shows the effect of spatial variability on the tan ϕ_a , which is evaluated by using a fixed critical slip surface and sliding volume. It is seen that the mean value of tan ϕ_a is almost constant irrespective the increasing COV_s (refers to COV_c and $COV_{tan\phi}$) as the maximum decreases of $\mu_{tan\phi a}$ is from 0.28 to 0.27 with COV_s changes from 0 to 1.0. Except the mean values, the standard deviation (*SD*) plotted as dash lines. It is shown that *SD* generally increases with the COV_s , and Θ ($COV_s = 1.0$ and $\Theta = 1.0$). It is suggested that the runout behaviour meanly affected by the volume of collapsed soil (refer to runout source), and the spatial variability of soil property only has minor influence, which mainly affects the variation of tan ϕ_a .

In order to evaluate the soil runout with respect to the sliding volume and failure mechanism, Fig. 5 shows tan ϕ_a and sliding volume ratio R_V considers failure modes. The sliding volume and critical slip surface are estimated by RLEM, as well as the demonstrated four different failure modes (2). In general, it can be seen that $\tan \phi_a$ influenced by the sliding volume and the failure modes, $\tan \phi_a$ decrease with increasing of R_V , indicates a serious runout consequence. For small failure mode M4, it can be seen that the R_V is very small, which yields relatively large tan ϕ_a (0.40 ~ 0.69), and for large failure mode M1, whose R_V is large yields small tan ϕ_a (0.27) ~ 0.40). A small range of tan ϕ_a for M1 (ranges 0.13) which is smaller than that for others, indicates a stable runout behaviour for large failure. Moreover, it is shown that a lower asymptotic line for the smallest value of tan ϕ_a is found as 0.19 irrespective the sliding volume further increases. Such



Fig. 5 tan ϕ_a against R_V considers failure modes

asymptotic behaviour for the smallest tan ϕ_a implies that the runout behaviour is not permanently influenced by increasing of sliding volume.

4. CONCLUSIONS

The main conclusion are as follows:

1) The spatial variability for soil unit weight γ is the controlling parameter in this random soil runout analysis, which donates the maximum contribution of variance of apparent friction coefficient, $V[\tan \phi_a]$.

2) The spatial variability for collapsed soil with a fixed critical slip surface has very less influence on the mean value of tan ϕ_a , which only influences the variation of tan ϕ_a .

3) The random runout analysis for collapsed slope estimated by *RLEM* suggests that the large failure mode with large sliding volume generates stable tan ϕ_a (small range 0.13 for tan ϕ_a), and tan ϕ_a . decreases with increasing of sliding volume and the smallest value 0.19 for tan ϕ_a suggests the runout is not permanently influenced with increasing of sliding volume.

REFERENCES

(1) Kasama, K, Furukawa, Z and Yasufuku, N, Cyclic Shear Property and Seismic Runout Analysis for Pumice Fall Deposit. Soil Dynamics and Earthquake Engineering, vol. 143, pp. 1-11, 2021.

(2) Lihang HU and Kasama, K, The Failure Mechanism of 3D Slope Considering the Soil Spatial Variability. Conference paper of Japan Society of Civil Engineers 2020 Annual Meeting, section III-10, 2020.