# THE FAILURE MECHANISM OF 3D SLOPE CONSIDERING THE SOIL SPATIAL VARIABILITY

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## 1. INTRODUCTION

The spatial viability of material properties and the uncertainty of soil profile affect soil behavior such as slope stability. These should include the concept of reliability design, which evaluates the safety of slope and the probability of failure. This paper presents the effect of spatial variability on slope stability number and failure mechanism for the 3D slope stability. In detail, the cohesion, friction angle and soil unit weight for 3D slope are treated as random field, and Limit Equilibrium Method (simplified Bishop) is used to investigate the slope stability. Finally, a Monte-Carlo simulation is used to evaluate the effect of spatial variability on the stability number and slope failure mechanism.

## 2. RANDOM FIELD LIMIT EQUILIBRIU ANALYSES

### 2.1 Limit Equilibrium ANALYSES (LEA)

In this study, the Limit Equilibrium Analyses is carried out by using Scoops3D, which is a computer program to evaluate slope stability using a digital landscape represented by a digital elevation model (DEM). The program uses a simplified 3D Bishop method assuming by spherical trial slip surface with the global minimum factor-of-safety (F). One of the advantages of this method is short computational time compared with other analysis methods such as 3D-FEM. For this advantage, statistical interpretation by Monte-Carlo simulation is able to carry out for 3D space.

Fig. 1 is a typical 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 long $l/H$ = 5.0 and the width $w/H$ = 5.0, where $H$ is the height of the slope. Fig. 1 also illustrates the spatial distribution of shear strength and soil unit weigh for each cell (cube), with 1.0 m resolution, as one realization with the input parameter of mean friction angle $\mu_{tan\phi}$ = 0.5774 (corresponding to 30°), mean cohesion $\mu_c$ =100 kPa and mean soil unit weight $\mu_\gamma$ = 20 kN/m$^3$. The detail input parameters are summarized in Table 1.

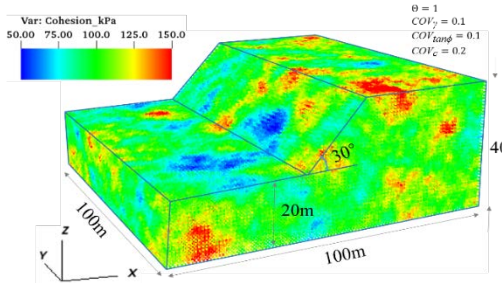


Fig. 1. Model considering the spatial variability of shear strength.

Table 1. Input parameters.

| Parameter | Value |
|---|---|
| Angle of slope, $\beta$ | 30° |
| Mean cohesion, $\mu_c$ | 100 kPa |
| $COV$ of cohesion, $COV_c$ | 0.2, 0.4, 0.6, 0.8 and 1.0 |
| Mean friction angle, $\mu_{tan\phi}$ | 0.5774 ($\mu_\phi$=30°) |
| $COV$ of friction angle, $COV_{tan\phi}$ | 0.1, 0.2, 0.3, 0.4 and 0.5 |
| Mean soil unit weight, $\mu_\gamma$ | 20 kN/m$^3$ |
| $COV$ of soil unit weight, $COV_\gamma$ | 0.1 |
| Ratio of vertical and horizontal correlation length | 1 (Isotropic) |
| Normalized correlation length, $\Theta = \theta_{lnc}/H = \theta_{lntan\phi}/H = \theta_{ln\gamma}/H$ | Random, 0.05, 0.25, 0.5 and 1.0 |
| Cross correlation coefficient between $c$ and $tan\phi$, $\rho_{ctan\phi}$ | 0.5 |
| Monte-Carlo iteration | 1000 |

### 2.2 Random field iterations

In this study, the spatial variability of shear strength, $tan\phi$ and $c$, and unit weight, $\gamma$, are treated as a homogeneous random field. The shear strength and unit weight are assumed to underly log-normal distribution with mean, $\mu_{tan\phi}$, $\mu_c$ and $\mu_\gamma$, and standard deviation $\sigma_{tan\phi}$, $\sigma_c$ and $\sigma_\gamma$ and an isotropic correlation length, $\theta_{lntan\phi} = \theta_{lnc} = \theta_{ln\gamma}$. Current study uses a normalized correlation length normalized by slope height, $\Theta = \Theta_{lntan\phi}/H = \Theta_{lnc}/H = \Theta_{ln\gamma}/H$ as an input parameter. The coefficient of variation of unit weight ($COV_\gamma = \sigma_\gamma/\mu_\gamma$) 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.

## 3. SIMULATION RESULTS

The stability number $N_{si}$ is used to evaluate the stochastic property of slope stability with the spatial variability as follows:

$$N_{si} = \frac{F_{si} \cdot \mu_\gamma \cdot H}{\mu_c} \tag{1}$$

where $N_{si}$ is stability number for each iteration, $i$, $F_{si}$ is a factor-of-safety of slope for $i$th iteration.

In order to evaluate the effect of spatial variability, stability number ratio $R_{N_s}$ and sliding volume ratio $R_V$ are introduced as follow:

$$R_{Ns} = \frac{N_{si}}{N_{s\_hom}}, \qquad R_V = \frac{V_i}{V_{hom}} \tag{2}$$

where $N_{s\_hom}$ is the stability number of homogeneous slope with the slope angle $\beta$ = 30°, uniform shear strength $tan\phi$ = 0.5774 and $c$ = 100 kPa, and unit weight $\gamma$ = 20 kPa; and $V_i$ is the sliding volume for each iteration $i$, $V_{hom}$ is the sliding volume of homogeneous slope.

The 4 failure modes were identified regarding the shape of sliding soil body as shown in the follow figures. The failure mode 1 characterized as a large volume failure with the slide

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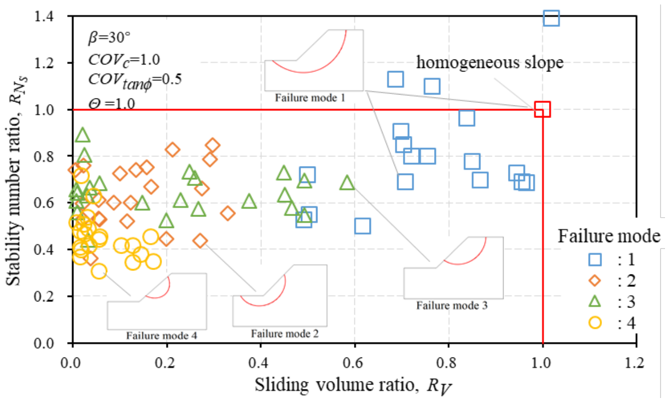


Fig. 2. Failure mode considering stability number ratio and sliding volume ratio.

surface includes the both upper slope crest and the lower slope toe. As alternative failure modes, slip surface for failure mode 2 includes the slope face and the slope toe while failure mode 3 includes the slope face and slope crest. For failure mode 4, its slide surface crosses only within the slope face, which should be referred as a typical small and local failure.

In order to examine the failure mechanism in terms of the stability number and sliding volume, the relationship among $R_{Ns}$, $R_V$ and failure mode is plotted in Fig. 2 for $\beta$ = 30°, $COV_{tan\phi}$ & $COV_c$ = 0.5 &1.0 and $\Theta$ = 1.0. It is noted that the failure mode 1 is the deterministic mode for homogeneous slope ($COV_{tan\phi}$ & $COV_c$ =0) with angle = 30°. It can be seen that that the failure mode 1 has large possibility when $R_{Ns}$ & $R_V$ close to 1.0. For the failure mode 4, it is demonstrated that the values of $R_{Ns}$ & $R_V$ became small compared with other three modes. It is evident that the small and local failure generates a small stability number and sliding volume. From this notable observation, it is confirmed that there is a positive correlation between stability number and sliding volume.

In order to evaluate the probability of occurrence of each failure mode considering the variability of soil shear strength, the percentage of failure mode against *COV* of shear strength and normalized correlation length are plotted in the Fig. 3 and Fig. 4.

For Fig. 3, It is noted that failure mode 1 is the deterministic mechanism for homogeneous slope ($COV_{tan\phi}$ & $COV_c$ =0), and the occurrence possibility of this failure gradually decreases as the *COV* of shear strength increases. On the other hand, the occurrence possibility of failure mode 2 to 4 gradually increases with increasing *COV* of shear strength. It should be pointed out that the occurrence of failure mode 4, referred as small and local failure, increases with increasing $COV_c$ & $COV_{tan\phi}$, which indicates that small and local failure occurs by increasing the variation of shear strength. Nevertheless, the mode 1 (varied from 100 % to 29.1 %) and mode 3 (varied from 0 % to 31.1 %) are the two most sensitive failure mode caused by the variation of shear strength. It also should be emphasized that the slope failure mechanism shows a great diversity at large $COV_{tan\phi}$ & $COV_c$.

For Fig. 4, it is noted that "random" in horizontal axis means the correlation of shear strength is very small that could be regarded as a "random" distribution.

It should be noted that the failure mode 1 is deterministic mechanism (100% of possibility of occurrence) for mentioned-above two conditions, and the occurrence possibility of this failure decreases with the increasing the normalized correlation length. Besides, other three modes increase especially for mode 3 and mode 4. Similar to the ef-

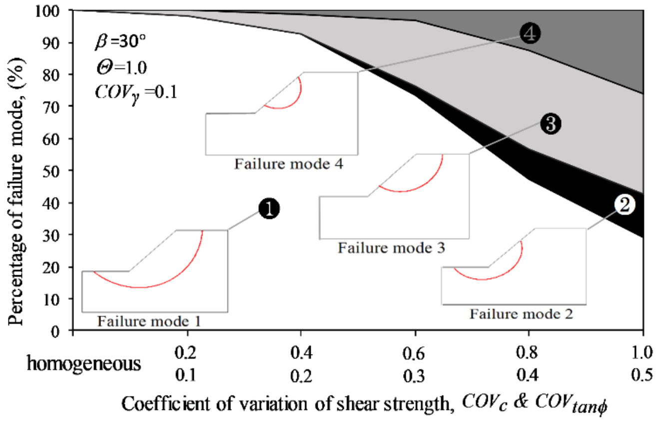


Fig. 3. Percentage of failure mode against *COV* of shear strength.

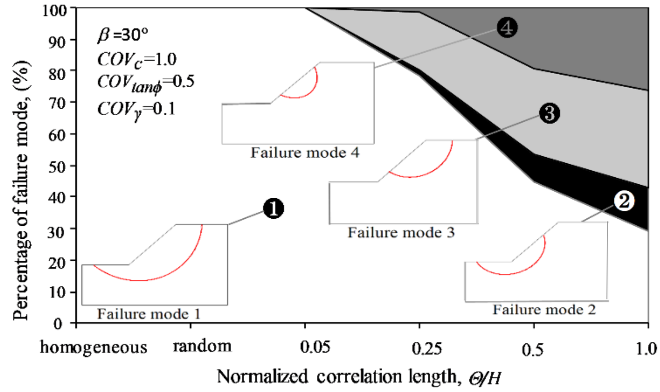


Fig. 4. Percentage of failure mode against normalized correlation length.

fect of variation of shear strength discussed in Fig. 3, the mode 1 and mode 3 are optional failure mode caused by the change in correlation length. It also should be informed that diverse failure mode appears at large correlation length.

## 4. CONCLUSIONS

The main conclusion are as follows:

(1) The failure mode 1 is the deterministic mechanism of a slope with angle = 30°, and the possibility of occurrence of mode 1 increases when the value of stability number and sliding volume close to the value of homogeneous slope.

(2) The small and local failure occurs with increasing the coefficient of variation of shear strength and correlation length, and generates a small stability number and sliding volume.

(3) The slope failure becomes more diversity at large $COV_{tan\phi}$ & $COV_c$ and correlation length, and the failure mechanism 1 and 3 are optional failures.

## REFERENCES

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