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Dynamic Reliability Analysis of Three-Dimensional Slopes Considering the Spatial Variability of Soil Parameters

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Abstract: This research aims to investigate 3D slope dynamic reliability considering the spatial variability of soil parameters. In this paper, practical expressions for the cohesion and friction angle in each part of the soil are simulated as two lognormal random fields by using the spectral representation method. Then, the finite element method is introduced to simulate the conditions and obtain the safety factor of the 3D slope. An efficient probabilistic analysis method for stochastic seismic analysis named the generalized probability density evolution method is performed, and the failure probability is provided. This technique, designed to use less data to obtain more accurate results, is helpful for analyzing high-dimensional stochastic problems. The results demonstrate that the dynamic failure probability of the slope can be reduced by appropriately increasing the variation coefficient of the parameters over a suitable range. In addition, the spatial variability of the friction angle has a strong influence on the slope reliability. Thus, the significance of the dynamic reliability analysis of 3D slopes is indicated and the realistic impact of the spatial variability of soil parameters is highligted.

Keywords: Three-dimensional slope; Generalized probability density evolution method (GPDEM); Random field; Reliability analysis; Spatial variability

1 Introduction

Catastrophic landslides are considered geological disasters that cause severe casualties and economic losses. Especially for large slopes, because the sliding body has a large volume, large mass, and certain speed during sliding, a landslide can easily have a severe impact on the hill and along the slope, causing destructive and fatal disasters in the surrounding human communities (Zheng et al. 2012). Various types of landslide accidents have occurred in many places, among which the mountainous areas in China are particularly susceptible. The 2008 Wenchuan earthquake triggered more than 15000 landslides, resulting in more than 20000 deaths. Landslides destroy many essential transportation facilities, which also brings great difficulties to postdisaster relief work and poses a disastrous threat to the safety of humans and property in nearby areas (Yin et al. 2009). As Chile is a Latin American country with a high earthquake risk level, frequent earthquakes have brought considerable casualties and hundreds of millions of dollars of economic losses to this country, and tsunamis and volcanic eruptions caused by earthquakes have inflicted severe follow-up disasters (Brodsky E et al. 2014). Landslides have become the most common and severe geological disaster with loss. The economic losses and casualties caused by slope instability are alarming. And for avioding the skewing the results of 2D model, the distinction between 2D simulation and real slope should be considered, especially in dynamic processes, so the importance of slope dynamic reliability analysis and research which is modeled as real slope is urgent and should be taken into account (Ji et al. 2018; Ji et al. 2020; Huang et al. 2020).

To comprehensively evaluate the dynamic reliability of a 3D slope considering the spatial variability of soil parameters from the probability level, this study is arranged as follows. In Section 2, the method for 3D slope stability analysis under dynamic action is introduced. Then, the influences of different working conditions are considered and compared to the dynamic response based on the spatial variability of the soil parameters (cohesion and friction angle (Auvinet G et al. 2000; Niu et al. 2018; Mostafaei H et al. 2021)). The analysis results provide a reference for slope reliability design and optimization. Conclusions are provided to summarize the results of this study in the last section.

2 Three-dimensional slope stability analysis method

The sliding surface stress method is used to analyze 3D slope stability, and the element stress of each component can be calculated by the finite element method in this study. Subsequently, the stress component of a point on the sliding surface is calculated, and the normal and tangential stresses of the sliding surface are determined (Song et al., 2019).

A general space problem encompasses 15 unknown functions: 6 are stress components, 6 are deformation components, and the last 3 are displacement components. These are all functions of x-, y-, and z-coordinate variables. The cosine of the normal direction external to the plane being considered is $\cos(n,x)=l, \cos(n',y)=m, \cos(n',z)=n.$

Through the equilibrium conditions of the tetrahedron in which $\sum F_x = 0, \sum F_y = 0,$ and $\sum F_z = 0,$ the parameters P_x, P_y, and P_z are expressed as follows:

$$
\begin{aligned}
P_x &= l\sigma_x + m\tau_{yx} + n\tau_{zx} \\
P_y &= m\sigma_y + n\tau_{zy} + l\tau_{xy} \\
P_z &= n\sigma_z + l\tau_{xz} + m\tau_{yz}
\end{aligned} \tag{1}
$$

The normal stress of plane ABC can be obtained such that $\sigma_n = lP_x + mP_y + nP_z$, and then $\sigma_n = l^2\sigma_x + m^2\sigma_y + n^2\sigma_z + 3mn\tau_{yz} + 3nl\tau_{zx} + 3lm\tau_{xy}$ can be obtained.

According to the function, , and the shear stress of the plane is shown as . Therefore, the normal stress and shear stress of any 3D slope can be obtained from the above equations. The safety factor can be obtained as follows (Zhang, 2018):

$$
F_s = \frac{\sum_{i=1}^{n}(c_i + \sigma_i \tan\phi)S_i}{\sum_{i=1}^{n}\tau_i S_i} \tag{2}
$$

where c_i and ϕ_i are the adhesion angle and internal friction angle of each corresponding ith element, respectively, and S_i is the area of the ith element passed by a sliding arc. In addition, σ_i and τ_i are respectively the normal stress and tangential stress of the ith element on the sliding arc surface.

In this study, the enumeration method is employed to evaluate the potential sliding surface for the stability analysis of the 3D slope. The search is based on a specified sphere center space range and long/short axial radii of an ellipsoid, and the calculation of the safety factor follows a predefined sequence. In the slope stability analysis at each moment, the minimum safety factor of all sliding surfaces is selected as the minimum safety factor of the slope. Therefore, in the whole process of the 3D slope dynamic response, this operation should be repeated to obtain the minimum safety factor of the studied slope dynamic stability during the duration of an entire ground motion.

3 Numerical analysis

3.1 Finite element model establishmentub-heading settings

The 3D geometric model is presented in Figure 1 (unit: m). The figures show the mesh of the slope for the following calculations and analysis, which has 13410 finite elements and 15190 nodes. Moreover, the boundary conditions set in this 3D model are setting as follows: The bottom displacement of the slope is blocked in all directions, and the horizontal displacement of the surrounding elements is blocked to avoid lateral movement.

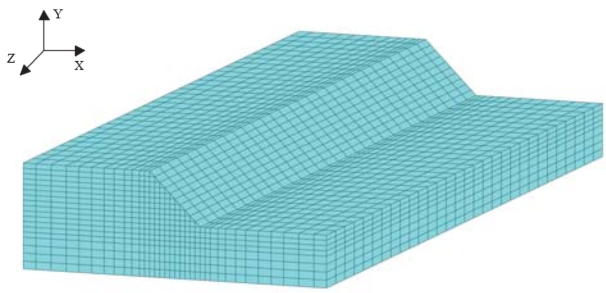


Figure 1. Computing models of the 3D slope.

3.2 Material parameters setting

The density is setted as 1800 kg/m3, the μ is 0.3 and the E is 20 MPa for the stational part. But in the further analysis, as shown in Table 1, two different setting of analysis for cohesion and friction angle are divined.

Table 1. Statistical properties of random parameters of soil parameters

Parameters	Mean value	Coefficient of variation	Distribution pattern	Autocorrelation distances
$c/(kPa)$	30	0.1 0.2 0.3	lognormal distribution by spectral reprsentation method	Lx= 20 m Ly= 2 m Lz= 20 m
$\varphi/(^{\circ})$	15			

3.3 Dynamic input

In this study, based on the research results of Song et al (2019), a nonstationary earthquake acceleration time history that is generated via a spectrum expression random function is chosen as the dynamic action. Then, the ground motions are selected to be applied at the base of the finite element model in the x direction as dynamic loading, as shown in Figure 2.

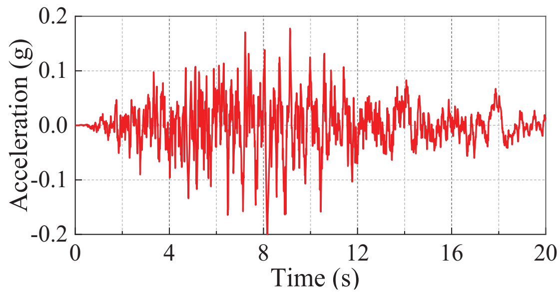


Figure 2. Horizontal ground motion.

4 Result and discussion

To better understand the effects of the soil parameters and analyze the sensitivity of variables on the slope reliability in the dynamic process. There are two cases combined with the ground motion used to study, and the soil parameters with uncertainty using the GPDEM are considered. The slope stability is analyzed by a finite element method using the custom program 3D-Slop-Stability (three-dimensional finite element method of dynamic stability analysis) (Zou et al, 2005; Zhang, 2018), which was developed by the Institute of Earthquake Engineering, Dalian University of Technology, and the fundamental theory of the calculation method.

4.1 Case study 1

When only the cohesion is considered to be random, the reliability of the 3D slope dynamic process can be obtained by the evolution process of the GPDEM, i.e., the PDF and cumulative distribution function (CDF) curves of the equivalent extreme safety factor, as shown in Figure 3 below. Under the same ground motion input, the larger the COV of cohesion is, the wider the overall curve, the greater the right shift of its position, and most significantly, the higher the safety factor, which is relative to the beyond part without considering the spatial variability of the cohesion. The safety factor of deterministic finite element analysis refers to the average value of a 3D slope under uniform strength. The results show that the randomness of cohesion weakens the reliability of the slope to some extent. As the cohesion of each part of natural soil inevitably changes, that is, as each part of the soil exhibits a difference, the deterministic analysis based on the average cohesion may lead to unsafe designs or suggestions.

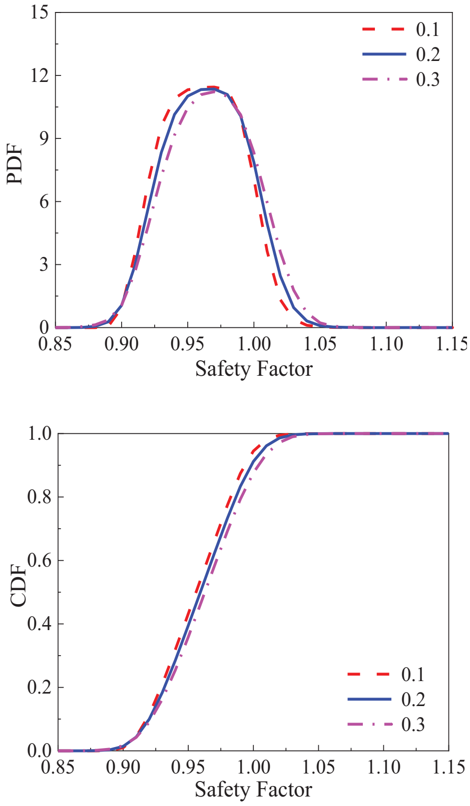
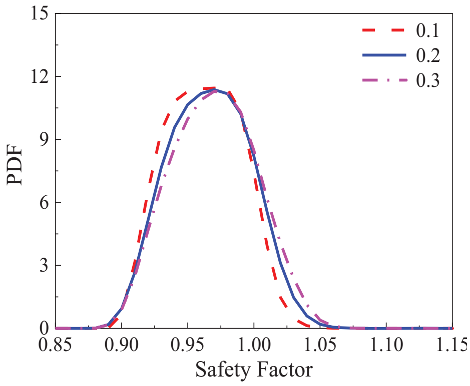


Figure 3. PDF and CDF of the 3D slope safety factor considering a random field of c based on extreme events.

4.2 Case study 2

Different from case 2, the friction angle is considered to be a random field with the value of the cohesion constant. For the sake of clarity, Figure 4 depicts the equivalent extreme-value event PDFs and CDFs of the safety factor corresponding to the three different COVs; the findings reveal that the COV in this model increases the safety factor, which makes the slope a safer state. A higher COV makes the whole curve move in the direction of a larger safety factor, and the distribution is wider than that when the COV is smaller than currently considered. The safety factor of deterministic finite element analysis refers to the average value of a 3D slope under uniform strength. The results signify that the randomness of the friction angle also weakens the reliability of the slope.



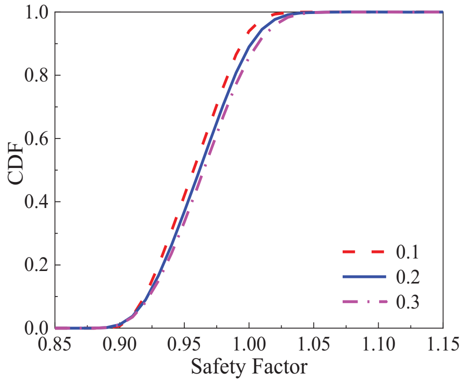


Figure 4. PDF and CDF of the 3D slope safety factor with a random field of φ considered based on extreme events.

5 Conclusion

Herein, the dynamic reliability of a 3D slope is studied and evaluated from the perspective of randomness and probability by using the finite element analysis method, describing the cohesion and friction angle as a lognormal random field and combining it with the analysis method of probability density evolution. The following conclusions are drawn:

(1) Because of the spatial change in soil properties and their real spatial state, it is necessary to use a 3D slope model to analyze the reliability of soil to consider the influence of randomness on soil properties.

(2) From the results of stochastic finite element analysis, the randomness of the cohesion and friction angle exhibits a key impact on the reliability of 3D slopes in both static and dynamic states. However, in the static state, a consideration of the spatial variability can avoid the occurrence of risk due to the overestimation of safety factors in only deterministic research. In the dynamic action process, consideration of the spatial variability of actual slope soil parameters significantly increases the safety factor, which indicates that the deterministic analysis facilitates conservative results. Additionally, the variability of the 3D slope safety factor is much more sensitive to the friction angle than the cohesion in the same variation coefficient range (0.1 to 0.3).

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References

Auvinet, G. and Gonzalez, J.L. (2000). Three-dimensional stability analysis of earth slopes. *Comput. Geotech*, 26 (3–4): 247–261. https://doi.org/10.1016/S0266-352X(99)00041-5

Brodsky, E. and Thorne L. (2014). Recognizing Foreshocks from the 1 April 2014 Chile Earthquake. *Science.* https://doi.org/10.1126/science.1255202

Huang, Y., Zhao, L., Li, X.R. (2020). Slope-Dynamic stability Analysis Considering Spatial Variability of Soil Parameters. *International Journal of Geomechanics 2020.* https://doi.org/10.1061/(ASCE)GM.1943-5622.0001708.

Ji, J., Zhang, C.S., Gao, Y.F., and Kodikara, J. (2018). Effect of 2D spatial variability on slope reliability: a simplified FORM analysis. *Geoscience Frontiers*, 9 (6), 1631-1638.

Ji, J., Zhang, W.J., Zhang, F., Gao, Y.F., and Lü, Q. (2020). Reliability Analysis on Permanent Displacement of Earth Slopes Using the Simplified Bishop Method. *Computers and Geotechnics 117*, 103286. https://doi.org/10.1016/j.compgeo.2019.103286

Mostafaei, H., Behnamfar, F., Kelishadi, M., & Aghababaie, M. (2021). The effects of friction coefficient on the nonlinear behavior of an arch dam with jointed foundation. *Journal of Numerical Methods in Civil Engineering*, 5(4), 36-45.

Niu, Y., Zhou, X., Qian, Q. (2018). Three-dimensional stability assessment of rock slopes based on random fields. Tumu Jianzhu yu Huanjing Gongcheng/Journal of Civil, *Architectural and Environmental Engineering*, 39(3):129-137. https://doi.org/10.11835/j.issn.1674-4764.2017.03.017

Song, L.F., Xu, B., Kong, X.J., Zou, D.G., Pang, R., Yu, X., Zhang, Z.Y. (2019). Three-dimensional slope dynamic stability stability assessment based on the probability density evolution method. *Soil Dynamics and Earthquake Engineering*, 120 (2019) 360 – 368. https://doi.org/10.1016/j.soildyn.2019.02.006

Yin, Y., Pan, G., Liu, Y. (2009). Great Wenchuan earthquake: Seismogeology and landslide hazards. *Beijing: Geological Publishing House 2009*.

Zou, D.G., Kong, X.J. (2005). User manual for geotechnical dynamic nonlinear analysis. *Dalian: Institute of Earthquake Engineering, Dalian University of Technology 2005*. [in Chinese]

Zheng, T., Zheng, Y. (2012). Review of earthquake damage losses in mainland China in 2011. *Journal of Natural Disasters*, 21(5): 88-97.

Zhang, Z.Y. (2018). Three-dimensional aseismic stability analysis of high concrete face rockfill dam based on finite element sliding-surface stress method. [inChinese]