Advances in Engineering Research, volume 184
2nd International Conference on Sustainable Energy, Environment and Information Engineering (SEEIE 2019)

A Reliability Analysis Method for the Earth–Rock Aggregate Slope

Jianping Zhang[1,*] and Dong Zhou[2]
[1]Civil Aviation Flight University of China, Guanhan, Sichuan, 618300, China
[2]Institute of Mechanics, Chinese Academy of Sciences, Haidian, Beijing, 100190, China
[*]Corresponding author

***Abstract*—A reliability analysis method is proposed to evaluate the stability state of the earth-rock aggregate slope which consists of rock blocks and soft soil. In order to describe the heterogeneity and discontinuity of the slope of this kind, uncertainty of the strength and spatial variation of the strength is considered. The reliability of an earth-rock aggregate slope can be obtained with the combination of the Monte Carlo method and Continuum-Discontinuum Element Method (CDEM). The relative displacement between monitoring points are used as the critical index for the failure criteria. An ideal and typical model for the earth-rock aggregate slope is established to demonstrate the analytical procedure of the reliability method. The results show that the reliability of a slope is greatly influenced by the distribution characteristics of the strength parameters. The reliability method based on probability statistics can obtain the correlation between the stability of a slope and the distribution property of the parameters, which provides more comprehensive results compared to the traditional deterministic methods.**

Keywords—earth-rock aggregate slope; heterogeneity; reliability; Monte Carlo method; CDEM

I. INTRODUCTION

An earth–rock aggregate [1] slope is composed of rock blocks and soft soil, with the characteristics of heterogeneity, discontinuity, and large deformation. This type of slope, which frequently causes critical landslide disasters, is extensively distributed in China. The discreteness for the material and strength of such slopes is obvious, which leads to the difficulty for the stability analysis of these slopes. Presently, the main methods used in slope stability analysis are the limit equilibrium method (LEM) [2] and several other methods developed from the LEM [3, 4], the numerical analysis method [5] (such as finite element method and discrete element method), and the critical slip surface search method [6]. Most of the work on slope stability analysis mentioned above can provide an important basis for the safety assessment of slopes through these methods, with deterministic factors being considered. However, uncertain factors in actual situations may not be considered, possibly leading to the difference between the analysis results and the actual state of the slope. Therefore, landslide disasters may also take place even if the safety factor meets the design requirements in practical engineering.

Presently, some valuable research on the uncertainty of the slope instability has been reported [7, 8] but considering the uncertainty of the strength and its spatial variability simultaneously is not found in actual calculations.

In this article, the uncertainty of the slope strength and its spatial variability are considered in the stability analysis of earth–rock aggregate slope. Criteria of landslide instability are proposed on the basis of deformation. The statistical reliability of the slope can be determined by using the Monte Carlo method and the continuum–discontinuum element method (CDEM) [9, 10]. Considering typical landslides, we obtain a series of random slope samples by using the Monte Carlo method. Then, CDEM is used for the simulation of the state for each slope sample, and the reliability of the slope is statistically derived from the results. This method can reflect the stability level of the slope through instability probability and help improve the accuracy of the quantitative assessment for the slope, which is of great significance in safe and rational slope design.

II. RELIABILITY ANALYSIS METHOD OF THE SLOPE

Two strength parameters, namely, cohesive C and internal friction angle φ, are the key indexes affecting slope stability. However, accurately measuring these two parameters in actual engineering is difficult. The physical and mechanical properties of earth and rock vary with their position in a slope, and the spatial variability of C and φ is noticeable. In the analysis, we assume that C and φ are independent random variables and follow certain distribution law. Based on these assumptions, the slope reliability analysis method is proposed.

III. ANALYTICAL PROCEDURE OF THE SLOPE RELIABILITY METHOD

The procedures are described as follows:

Step 1. The target slope is surveyed in detail, in order to obtain a comprehensive information of the slope.

Step 2. On the basis of the surveyed information, the geometric parameters of the slope are identified, such as height, angle, inclinations, and fault location, and the corresponding geometric models are established.

Step 3. Through field test or sampling, the strength characteristics and distribution rules of each stratum are analyzed, and the distribution parameters of the slope strength are determined.

Step 4. Based on the geometric model and the strength distribution parameters, a series of samples with random strength is generated by using the Monte Carlo method. The samples have the same geometric configuration, but the mean value of strength and the spatial distribution of the strength are constructed randomly on the basis of the distribution parameters determined in Step 3.

Step 5. CDEM is used for the simulation and calculation of each sample, and the deformation or the instability state of each sample is obtained.

Step 6. The reliability of the slope is analyzed statistically by using the samples.

IV. CDEM

CDEM is a unified expression for continuum and discontinuum problems, which is a dynamic explicit algorithm based on dividable element under the Lagrange system, whose control equations are established with the Lagrange equation. The explicit iteration is based on the dynamic relaxation method when solving the equations. CDEM combines the advantages of continuous and discontinuous methods, which can simulate the whole failure process from continuous deformation, fracture, to the motion of fractured materials. The finite element method can be used for the continuous calculation, and the discrete element method is used for the discontinuous calculation. Thus, CDEM can address three kinds of problems: continuum, continuum–discontinuum, and discontinuum, which is quite suitable for the slope instability analysis and simulation.

V. Reliability Statistical Method for Slope Analysis

The reliability statistical method of the slope is described as the following.

If n numerical examples are present based on CDEM in a sample, and r, p, and q indicate the number of the stable cases, quasi-stable cases, and instable cases, respectively. Therefore,

$$n = r + p + q\,. \tag{1}$$

Then, the probability of slope instability is

$$\eta_b = \frac{q + 0.5p}{n} \times 100\%\,. \tag{2}$$

Moreover, the reliability of the slope is

$$\eta_s = \frac{r + 0.5p}{n} \times 100\%\,. \tag{3}$$

where 0.5 is the weight parameter, which indicates that the probability of slope failure is 50%. The greater the number of numerical examples n, the closer the reliability is to the reality.

VI. Slope Failure Criteria

For a monitoring slope, if the distance among the adjacent monitoring points is L and the relative displacement among the monitoring points is Δd. If a shear failure between the two monitoring points occurs, and the maximum shear strain is $\varepsilon_{\max} = \varepsilon^e + \varepsilon^p$, where ε^e is the elastic strain and ε^p is the maximum plastic strain. Then, the critical failure displacement is

$$|\Delta d| = L\varepsilon_{\max}\,. \tag{4}$$

For a large landslide with overall instability, the relative displacement of the slope body and bedrock is generally the largest, hence, L is considered to be the relative displacement of the slope body and bedrock.

VII. Analysis and Application

A. Numerical Model

A typical earth–rock aggregate slope is used as an example to expound the reliability analysis method.

The slope calculation model is shown in Fig. 1. The length is 80 m, the height is 40 m, the slope height is 20 m, and the slope angle is 26.5°. The upper part of the model is the earth–rock aggregate (called “slope body” thereafter), and the bottom is the bedrock. Thirty-eight monitoring points are set up equidistantly along the slope surface, from the bottom to the top, where Nos. 1 and 38 are located on the bedrock and the rest are located on the surface of the slope body. The distance of the adjacent monitoring points is approximately 0.5 m. The maximum plastic strain of the slope body is 5%. Thus, the critical failure displacement of the slope body is 5% × 0.5 = 0.025 m. When the displacement of the monitoring points is less than 20% of the critical failure displacement (0.005 m), the slope is stable. When the overall displacement of the slope relative to the bedrock is around 20%–50% of the critical failure displacement (0.005–0.0125 m), the slope is quasi-stable and should be protected and maintained. When the overall displacement of the slope relative to the bedrock is more than 50% of the critical failure displacement (0.0125 m), the slope is instable.

The parameters of the bedrock and the elastic parameters of the slope body are shown in Table 1. The values for C and φ of the slope body are set as controllable random variables, regardless of the strength distribution characteristics of the bedrock. The mean value of the strength follows the normal distribution and the strength of different locations for a model is uniformly distributed in space. Assume that the value of the tensile strength T is equal to that of C. Evidently, the distribution laws and values of the actual problems should be determined through field investigation and sampling test.

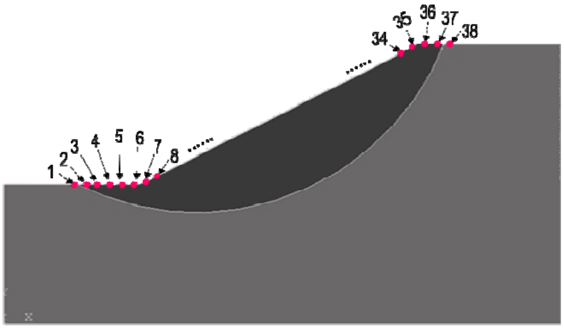


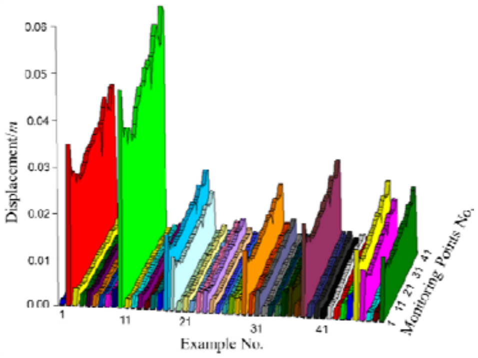
FIGURE I. THE SLOPE MODEL AND MONITORING POINTS

TABLE I. CONSTANT PARAMETERS OF THE SLOPE

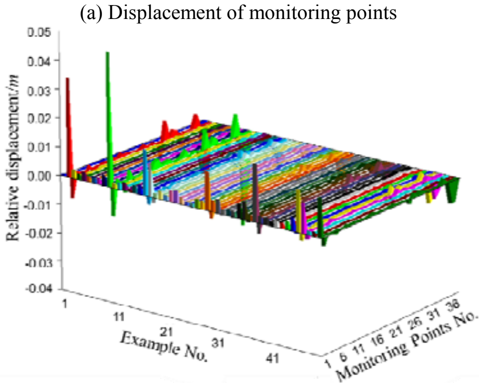
Position	Elastic modulus [GPa]	Poisson ratio	Density [kg·m^{-3}]	Cohesive [Mpa]	Internal friction angle [°]	Tensile strength [MPa]
Bedrock	30	0.3	2100	100	30	100
Slope body	5	0.3	1800	-	-	-

VIII. NUMERICAL ANALYSIS

50 samples are simulated with this method, and the reliability of the slope is evaluated. The result is shown in Fig. 2.



(a) Displacement of monitoring points



(b) Relative displacement of adjacent monitoring points

FIGURE II. DISPLACEMENT OF MONITORING POINTS OF 50 NUMERICAL EXAMPLE

The displacement of each monitoring point of the 50 examples is shown in Figure 2(a). Meanwhile, the relative displacement of adjacent monitoring points of the 50 examples is shown in Figure 2(b). As a result of the distribution of strength, the displacement also shows a discrete characteristic. The results of the statistics are shown in Table 2.

TABLE II. STATISTIC RESULT OF 50 NUMERICAL CASES

Example scale	Stable	Quasi-stable	Instable
50	41	2	7

According to the formula of reliability (3), the reliability can be calculated as follows:

$$\eta_s = \frac{41 + 0.5 \times 2}{50} \times 100\% = 84\% \quad (5)$$

The reliability of the slope is 84% and the slope tends to be generally stable, but occurrence of instability is possible. Therefore, when such a situation is encountered in actual slope engineering, monitoring and precautions should be considered.

In traditional analysis method based on the determined parameters, the values of C and φ are fixed to C = 25 kPa and φ = 20° without considering the variability. The slope converges at a stable state as shown in Figure 3. However, the safety of the slope may be overestimated and potential threat may be ignored.

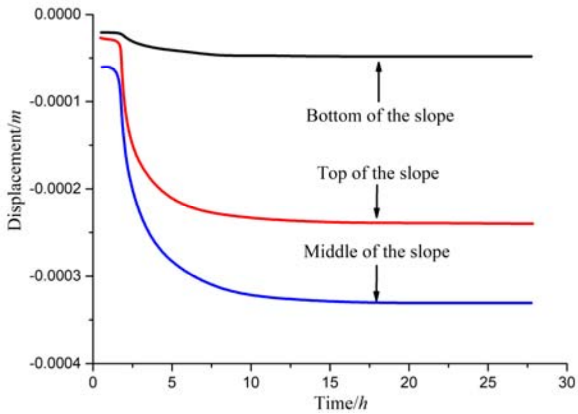


FIGURE III. THE TIME-HISTORY CURVE FOR THE DISPLACEMENT OF THE SLOPE SURFACE

IX. CONCLUSION

The dual variability of the slope strength, the uncertainty of mean strength, and the spatial variability of strength are considered in this work. A statistical analysis method for slope reliability is proposed on the basis of the Monte Carlo method and CDEM.

In this study, the relative displacement between monitoring points is used as the index to determine the state of a slope. With the method proposed in this paper, the reliability of a slope can be identified immediately from qualitative and quantitative aspects through the displacement distribution map of the monitoring points.

The result shows that the distribution characteristics of the slope strength have direct influence on the result of slope stability analysis. The proposed method can obtain the relationship between the statistical law of the strength and the stability state of a slope. Compared with traditional analysis methods based on determined parameters, the proposed method is relatively more practical and effective.

The reliability analysis method of the slope is discussed in detail from theory to the actual calculation, and a systematic theoretical analysis system is established. However, the applicability of this method needs further inspection in practical slope engineering.

REFERENCE

[1] Y.S. Sun, R. L. Hu. Experimental study of different shape bedrock surfaces about deformation and failure of soil and rock mixture. Chinese Journal of Rock Mechanics and Engineering, a01 (2016) 2907-2914.

[2] A. W. Bishop. The use of the slip circle in stability analysis of slopes. Geotechnique, 5 (1955) 7-17.

[3] X. P. Zhou, H. Cheng. The long-term stability analysis of 3D creeping slopes using the displacement-based rigorous limit equilibrium method. Engineering Geology, 195 (2015) 292-300.

[4] D. Wang, X. M. Zhang, L.Z. Cao, et al. 3Dlimit-equilibrium method for concave slope and its application[J]. China Safety Science Journal,26 (2016) 91-95.

[5] V. Bonilla-Sierra, L. Scholtès, F. V. Donzé, et al. Rock slope stability analysis using photogrammetric data and DFN–DEM modelling[J]. Acta Geotechnica, 10 (2015) 497-511.

[6] H. H. Mo, C. H. Tang, S. Y. Liu. Determination of most dangerous slip surface with pat-tern search method[J]. Chinese Journal of Geotechnical Engineering, 21(1999) 696-699.

[7] X. T. Yin, S. L. Wang. Stability and its influential factors analysis of landslides based on reliability theory. Rock and Soil Mechanics. 29 (2008) 1551-1556.

[8] S. Z. Cao, A. Wang, D. Wang, et al. Research on theory and method of landslide early warning in open-pit mine. China Safety Science Journal, 27 (2017) 163-168.

[9] S. H. Li, D. H. Tang, J. Wang. A two-scale contact model for collisions between blocks in CDEM[J]. Science China Technological Sciences, 58 (2015) 1596-1603.

[10] S. H. Li, C. Feng, D. Zhou. Mechanical methods in landslide research. Beijing: Science Press, 2018: 400-402.