Slope Stability Analysis Based on the Limit Equilibrium Method and Strength Reduction Method

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Abstract. To evaluate the stability of the slope in Tianmogou, Southeast Tibet, the results of 3D modeling were introduced into the computer-aided design section for the numerical analysis of the limit equilibrium method (LEM) and strength reduction method (SRM). The analysis results show that the safety coefficients calculated by the LEM and SRM are similar and more accurate than those of other ideal models. The LEM and SRM are applied to the slope stability analysis, which can reflect the slope stability more accurately.

Key words: Limit equilibrium method; Finite element strength reduction method; GNSS landslide monitoring; Slope stability.

1. Introduction.
China is a mountainous country with a large proportion of hills and plateaus. The unique geological conditions of the mountainous areas make natural disasters spread all over the country. Among these natural disasters, landslide is one of the most serious disasters, characterized by high occurrence frequency, multiple types, wide distribution, and heavy disasters [1]. With the influence of human activities, climate change, and other factors, the frequency of landslide disasters is gradually increasing, which makes the study of slope stability paramount in the field of geotechnical engineering. In the slope stability research field at present, the limit equilibrium method (LEM) and numerical simulation method are most commonly used, e.g., Ataei [2] in central Iran to Dole: distribution of iron ore for slope stability analysis through the quality grade of mining rock and calculating the cohesion and angle of internal friction of each design area using the LEM for stability analysis, the results show that increasing the slope height may produce some unstable problem; Pan Jianping et al[3]. conducted a research on the open dump. Taking the Panzhihua dump as an example, FLAC3D software was used to conduct stability analysis, thereby providing reference and basis for subsequent protection and management of dumps.

2. Project Overview
Tianmogou debris flow is located in Bomi County, Nyingchi City, Tibet Autonomous Region, and belongs to the area where quaternary moraines and other loose deposits develop. On the left bank of the middle and lower reaches of Palongzangbo Basin, the coordinates of Gully are 29°59'16"N, 95°19'08"E, with an altitude of 2461 m. Surrounded by mountains, the highest and lowest altitudes are 5590 and 2460 m, respectively.
3. 3D Modeling and Profile Interception of Tianmogou

After the 3D model is obtained by modeling software, and the section software is used to intercept the slope section, the LEM and strength reduction method (SRM) are calculated.

![Figure 1. Three-dimensional modeling diagram of the research area](image)

![Figure 2. CAD profile map of the side slope](image)

4. LEM

4.1. Limit Equilibrium Theory

Here, the extreme equilibrium theory is explained with the example of Bishop bar division.

The vertical force of a soil strip is balanced as follows:

\[ N_i \cos \theta_i = G_i + \Delta X_i - T_f \sin \theta_i - u_i b_i \]  \hspace{1cm} (1)

where \( G_i \) is the weight of the soil strip, \( b_i \) is the width of the soil strip, \( N_i \) is the effective normal reaction, and \( T_f \) is the shear resistance at the bottom of the soil strip. When the soil slope is not damaged, it is expressed as the effective stress, and the shear resistance on the sliding surface is as follows:

\[ T_f = c' \frac{b_i}{w} + N_i \frac{\tan \phi'}{w} \]  \hspace{1cm} (2)

where \( c' \) is the effective cohesive force of the soil, \( \phi' \) refers to the angle of internal friction of the soil, and \( w \) is the safety factor of the soil slope. Then, by solving the effective normal reaction, the moment balance of the entire soil toward the center of the circle is solved. At this time, the moment of the acting force between adjacent soil strips in some soil strips is offset and eliminated as follows:
\[
\sum G_i x_i - \sum T_{fi} R = 0
\]

(3)

where \(x_i = R \sin a_i\) and \(b = \lambda_i \cos a_i\) are substituted in, a general formula for calculating safety coefficient can be obtained.

\[
W = \frac{\sum \frac{1}{m_i} c' b + (G_i - u_i b + \Delta x_i) \tan \phi^*}{\sum G_i \sin a_i}
\]

(4)

4.2. Analysis of Slope Stability with LEM

After investigation and study, it was found that the development of the Tianmore Trench consists of metamorphic rock series of the foreshock gangdese rock group, and there are a large number of quaternary moraines in the trench [4]. According to Foundation and Foundation [5], the mechanical parameters of the study area are shown in Table 1.

| Parameter       | Severe(KN/m³) | Cohesion(KPa) | Internal friction angle(°) |
|-----------------|---------------|---------------|----------------------------|
| Value           | 25            | 30            | 40                         |

Table 1. Rock and soil parameter table

According to the mechanical parameters in Table 1, under the influence of external factors such as rainfall and earthquake, three methods—Morgenstern–Price, Bishop, and Janbu—are used to analyze the slope stability in GeoStudio software, and the analysis results are shown in Figure 8.

Figure 3. Finite element analysis result of the side slope stability

The safety factors calculated by the three LEMs are shown in Table 2.

Table 2. Safety factors evaluated using different limit equilibrium methods

| Method          | Morgenstern-Price | Bishop | Janbu |
|-----------------|-------------------|--------|-------|
| Safety factor   | 1.260             | 1.265  | 1.224 |

From Table 2, the safety factors obtained by different calculation methods are different, but the results of each method are random. According to the characteristic values of the random variable, the expected value of the sample can be taken as its mean value, thus the standard deviation (SD) and relative standard deviation (RSD) of the calculated results can be obtained. See Table 3 for the calculation results.

Table 3. Calculation results of safety factor sample

| Arithmetic mean | Standard deviation | Relative standard deviation |
|-----------------|--------------------|-----------------------------|
| 1.25            | 0.018              | 0.014                       |
From Table 3, the three calculation results are between 1.22 and 1.27 with very small SD and RSD, so the arithmetic mean can be taken as the safety factor value of the slope. The calculated results of safety factors are all greater than 1.1, hence indicating that the slope is generally stable.

5. Finite Element SRM (FESRM)

5.1. Strength Reduction Theory
Strength subtraction with the purpose of the LEM is to calculate the coefficient of slope stability, and the different method and LEMs, is constantly reduce the research in the calculation of the slope safety factor, the calculation result of reduction constantly into the model of software code, and repeated in calculation, damage until the research model, and thus it is concluded that the safety factor of slope [6]. The formula is expressed as follows:

\[ c_m = c / F_r \]  \hspace{1cm} (5)

\[ \varphi_m = \arctan(\tan\varphi / F_r) \]  \hspace{1cm} (6)

where \( c \) and \( \varphi \) are the shear strength provided by the soil in the study, \( c_m \) and \( \varphi_m \) are the actual shear strength of the soil, and \( F_r \) is the strength reduction coefficient.

5.2. Analysis of Slope Stability by FESRM
According to the geological profile of the study area, the SRM is calculated using the GeoStudio software, the safety factor is calculated by manual reduction, and the corresponding safety factor and sliding surface are obtained.

![Figure 4. Stress redistribution result when the soil body is unstable](image)

![Figure 5. Side slope stability analysis results when the soil body is unstable](image)
According to the reduction multiples and analysis results of the SRM, the stability coefficient of the slope can be obtained as 1.153, which is not different from the result calculated by the LEM; it can also indicate that the slope is generally stable at present.

6. Conclusion
(1) Numerical simulation based on 3D modeling can be used to obtain a more realistic numerical model, thus reducing some actual parameter problems caused by the ideal model. Therefore, the stability of the slope can be studied and described by the combination of finite element analysis, LEM, and 3D model.

(2) Different LEMs are used to analyze the stability of the slope. The results obtained by the different methods are different, but the overall difference is not significant, among which the safety coefficient calculated by the Bishop method is the largest.

(3) Due to the special geological and climatic conditions in the study area, although the results calculated by the LEM and SRM are both greater than 1.1, according to the actual investigation on the site and the collection of monitoring data, it is found that the slope still has a continuous displacement fluctuation, and there is still a risk of landslide disaster under the continuous influence of permitted rainfall.

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