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Improvement of the Strength Reduction Method on the basis of FLAC3D in Slope Stability

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Abstract: Traditional strength reduction methods employ same reduction factor to get safety factors of frictional angle φ and cohesion c of slide slopes. In the actual slope destruction, however, different shear strength parameters have different action effects. For this reason and considering that sliding resistance effect of sliding mass is much bigger than the difference of shear resisting factor φ and c. Taking a side slope for example, the finite difference software FLAC3D is used to search the cut-through area of shear strain increment under limiting condition to find potential slip surface. Then the shear resisting factor φ and c of sliding mass are reduced. Each reduction method has different safety factors and slip surface, and several slip surface form a potential gliding area. Results indicate that the traditional single safety factor method is a special case of two safety factors method. With increasing strength reduction factors of frictional angle and cohesive force, gliding surface gradually moves from deep layers to superficial layers. Slip surfaces found by different strength reduction methods form a certain gliding area with the sole reduction of shear resisting factor φ and c as its upper and bottom boundary. Stability analysis by two safety factors is more accurate than that by traditional strength reduction method and provides reliable technical support for study of side slope stability and its reinforcement.

Keywords: *analysis of slope stability, strengthen reduction method, safety factor, FLAC3D*

1. Introduction

At present, strength reduction method is widely used in study of side slope stability. Hu Hui et al. [1] used FLAC3D to specify a data model of side slope, where strength reduction method was used to do stability analysis and study the dynamic change and characteristics of slope instability. He Bengui et al. [2] studied the sensibility of influencing factors for side slope through orthogonal analysis and FLAC3D analysis. Based on double strength reduction method and the upper bound theorem of ultimate analysis, Zhao Lianheng et al. [3] discussed the influence of different definitions of safety factor on the calculation results. Chen Guoqing et al. [4] proposed the method to analyze the dynamic stability of side slope based on dynamic and overall strength reduction method. Liu Chunling et al. [5] used FLAC3D to do dynamic analysis for side slope and discussed such questions as dynamic, condition setting, choosing of resistance and synthetic input of seismic wave, which provided scientific basis for solving dynamic issues of side slope by FLAC3D. Chen Hang, et al [6] set up a FLAC3D numerical model and uses strength reduction method for stability analysis under natural condition, raining condition, earthquake condition and raining-earthquake coupling condition. Pradhan, et al [7] established the effect of slope angle on the stability of waste dump for accommodation of flyash and found that the dump slope of 60 m height with 36° slope can be critically stable with 20% flyash randomly mixed with overburden materials whereas flatter slopes provide higher factor of safety. Singh, et al [8] made an attempt to characterize the materials of the mine for simulation of existing slopes and employed a two-dimensional finite difference tool to simulate the existing slope geometry as well as relevant parameters of the rock units. The numerical simulation indicated various vulnerable points which were prone to failure as well as displacements at various points along the slope. Sarkar, et al [9] dealt with instability analysis of slopes of the Amiyan area, near Kathgodam, Nainital, Uttarakhand and found that threedimensional slope stability studies provide a better understanding than two-dimensional numerical models of the mechanism of failure as well as zone of influence. Singh, et al [10] proposed a procedure which is based on Chau's model, for estimating the FOS of a slope due to gravitational force and found that the proposed method to estimate the FOS of a slope is useful over the LEA if one takes into account the rate and state dependent failure strength of a solid.

Side slope is commonly consisted of slip mass, slip surface and slip bed. Traditional strength reduction method employs single factor with the whole slope as reduction object. Same reduction factor is used to calculate the shear resisting factor φ and c. But in the actual process of slope instability, rock-soil bodies on the upper and bottom layers of slip surface have different resistance abilities to the slope slide. The performance degree and sequence of shear resisting factor φ and c are also different in slip mass and slip bed. [11] Therefore, the single factor reduction cannot effectively reflect the process of slope sliding, and the safety factor is not an accurate judgment of the safety of slope.

In this paper, the cut-through area of shear strain increment under limiting condition is used to find slip surface that is taken as a interface between slip mass and slip bed, and two reduction factors are used to judgment the stability of soil bodies of slip mass and slip bed with different values of φ and c. Taking a side slope for example, FLAC3D is used to conduct comparatively study of slope stability by overall single reduction factor and by two reduction factors in different parts of slope.

1.1 Theory of Traditional Strength Reduction Method

It has been nearly 50 years since strength reduction method was put forward. Traditional strength reduction method reduces the shear resisting factors (cohesion c, internal friction angle φ) by certain reduction factors to get new shear resisting factors that, instead of original parameters, are used to analyze the stability of soil bodies. [12] The method, together with traditional ultimate equilibrium method, can be named as strength margin safety factor method as they share same ideas in analyzing slope stability. It emphasizes the relationship between force and strength. It is based on the concept of strength margin to confirm if the slope is stable. The safety factor is defined as the reduction degree of shear resisting strength of rock-soil bodies in the critical failure of slope. That is the specific value of actual shear strength of rock-soil bodies to the reduced shear strength in the critical failure of slope. By using strength reduction method, it is important to use the formula (1) and (2) as below to adjust the strength factor c and φ of rock-soil bodies. Then numerical calculation and analysis is conducted by gradually increasing reduction multiples until the slope is about to fail, when the reduction multiple is the safety factor F_s.

$$c' = c / F_s \tag{1}$$

$$\varphi' = \arctan\left(\tan\varphi / F_s\right) \tag{2}$$

Where: c and φ denote the cohesion and internal friction angle of soil bodies respectively; c', φ' denote the reduced cohesion and internal friction angle; F_s is the reduction factor. Existing criterions of the instability of slope include: (1) determine failure status by the convergence of finite element solution; (2) connection status of shear strain increment and plasticity areas; (3) displacement mutation of feature points of slope. [13] Considering the practicability and simplicity, this paper takes displacement mutation of feature points and connection status of shear strain increment area as criterions of slope instability. Observation points, as many as possible, are installed on the feature points of slope crest and toe to observe the change rules of displacement and plastic area with strength reduction factors.

2. Modified Strength Reduction Method

2.1 Introduction of Method and Relevant Ideas

Plastic area or equivalent plastic strain cut through from slope crest to slope toe, strain and displacement mutation on slip surface and non-convergence of finite element calculation are indicators of overall slope instability in the static condition. [14] According to traditional strength reduction method, attenuation degrees of different parts of slope are same as sensitive degrees of influencing factors. Thus a same reduction factor is used to do reduction for the whole slope without considering the complex loading and environment conditions. For this reason, the analysis results cannot accurately reflect the failing process of slope in the real environment, which will inevitably cause potential safety hazard in practical engineering. In order to eliminate the deficiencies of traditional strength reduction method of single factor, this paper introduces a modified strength reduction method. It is based on the local strength reduction and considers slope stress and engineering geological conditions when determining potential slip surfaces of the slope. Sensitivity coefficients of shear resisting factors (cohesion c, internal friction angle φ) of slip mass and slip bed are calculated. The reduction factors F_{s1} and F_{s2} are calculated to get the reduction of shear strength. The final safety margins of slip mass and slip bed under equilibrium state are taken as their safety evaluation indexes.

2.2 Determine Potential Sliding Surface

The stability of slope is determined by complex structural surfaces in it, so it is critically important to determine the position of slip surface. [15] With the development of slope stability analysis, five methods such as ultimate equilibrium theory, numerical analysis and calculus of variations are put forward to determine slip surfaces of a slope. [16] This paper uses the cut-through area of shear strain increment under limiting condition as criterion to determine slip surface as displacement mutation may occur to soil bodies of slip surface. Meanwhile, the stress change in slope is also a criterion to find potential slip surface in the slope.

2.3 Two Factors Reduction Method

Every calculation method is sensitive to soil parameters, especially the cohesion c, internal friction angle φ, and pore water pressure u, which impact the reliability of calculation results. [17] During the practical engineering, main influencing factors for safety of slope include shear resisting factors of soil body (cohesion c, internal friction angle φ). As the two factors have different action degrees and decay rates. The modified strength reduction method employs different safety factors to do reduction to them, that is, the two factors reduction:

$$\tan\varphi_1 = \frac{\tan\varphi}{F_{s1}} \tag{3}$$

$$c_1 = \frac{c}{F_{s2}} \tag{4}$$

Where: F_{s1} is the reduction factor of internal friction angle; F_{s2} is the reduction factor of cohesion; φ_1 and c_1 denote the reduced internal friction angle and cohesion of soil bodies respectively.

3 Analysis of Example

3.1 Determine Parameters and Specify Numerical Models

Mohr-Coulomb model and following formula of elastic mechanics are used to calculate the values of bulk modulus (K) and shear modulus (G).

$$K = \frac{E}{3(1-2\upsilon)} \tag{5}$$

$$G = \frac{E}{2(1+\upsilon)} \tag{6}$$

Where, K is bulk modulus; G is shear modulus; E is elasticity modulus and υ is Poisson ratio.

FLAC3D software is used to model an ideal homogeneous slope of 50m long, 35m high and 10m wide. The model is consisted of 15,364 nodes and 83,238 units. It is only used to test the reliability of modified strength reduction method without considering the influence from rainfall, earthquake and human activities. The model is illustrated in Figure 1 and soil parameters are listed in Table 1.

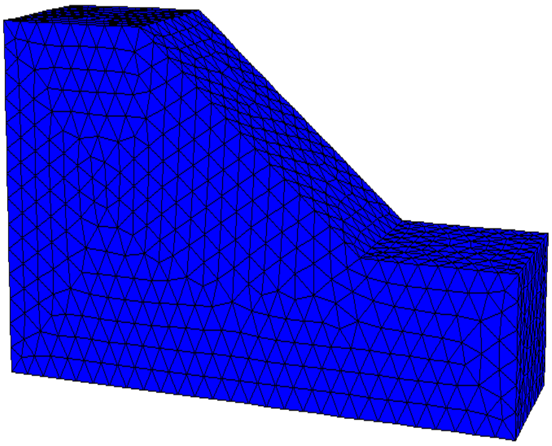

Figure 1: *The model of slope*

Table 1: *The soil parameters*

Name of soil mass	Unit weight (kg.m^3)	Internal cohesive force(Pa)	Friction angle (°)	Elasticity modulus (Pa)	Poisson's ratio
Gravel soil	2300	1.15E+04	35.5	8.35E+08	0.24

3.2 Results of Traditional Strength Reduction Method

Single factor reduction is conducted according to the theory of traditional strength reduction: in a 3D model a single factor F_s is employed to do proportional reduction to the whole slope and the shear resisting factors of soil body c and φ that will have new values. Same procedures are repeated with these new values until the slope in the edge of destruction. The final factor is the safety factor of the slope F_s =1.324 calculated by traditional strength reduction method, when the slope remains stable.

Figure 2 and 3 describe the stress maps of the slope model in vertical direction and horizontal direction under dead load working condition. As shown in Figure 2, the stress distribution of the slope in vertical direction conforms to the theoretical calculation results, thus the conclusion of the numerical modeling is reliable. From Figure 3, we can see that the maximum horizontal displacement of the slope is 8.172cm and occurs to the upper part of mid-slope under deal load working condition. The slope remains stable.

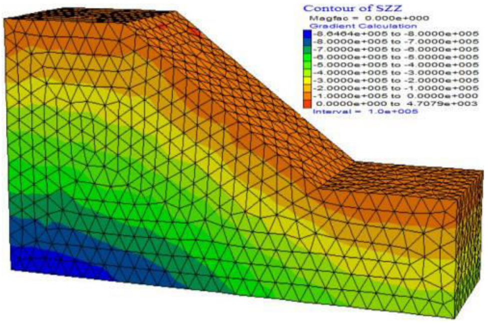

Figure 2: *Stress nephogram in the vertical direction under natural conditions*

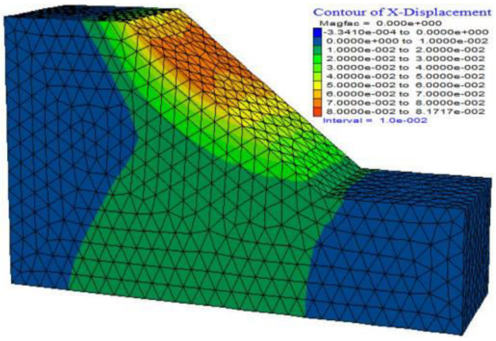

Figure 3: *Horizontal displacement nephogram under natural conditions*

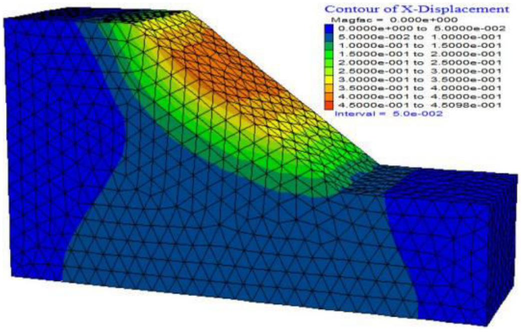

***Figure 4:** Horizontal displacement nephogram under the limit conditions*

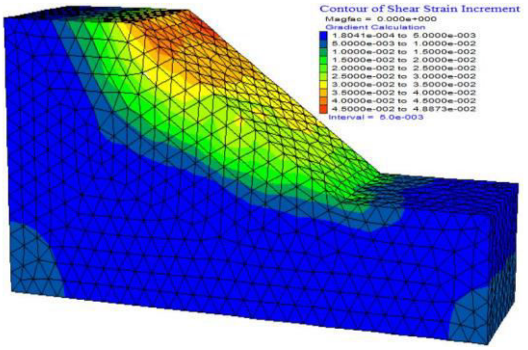

***Figure 5:** Shear strain increment nephogram under the limit conditions*

Figure 4 and 5 describe the stress map of the slope model in horizontal direction and its shear strain increment map under limiting condition. As shown in Figure 4, the maximum horizontal displacement of the slope is 45.10cm and occurs to the upper part of mid-slope under limiting condition. The whole slope is almost cut through by the high value area, which indicates that the slope has endured noticeable displacement and may be seriously destroyed by adverse factors from environment. Figure 5 tells that the maximum shear strain increment is 0.049 and the high values cover the area from slope shoulder to slope toe under limiting condition. Thus it can be certain that the potential slip surface is the area enveloped by the high values of shear strain increment.

3.3 Results of Modified Strength Reduction Method

The method to determine potential slip surface of slope is same in both traditional and modified strength reduction. Shear resisting factors have different influences on the skid resistance of slope, and the soil bodies in the upper and lower part of slip surface show much different contribution to the skid resistance. Thus the modified strength reduction method is used to do reduction to the confirmed dangerous slip surface. Factor F_{s1} and F_{s2} are used to reduce the φ and c of the slip mass and get new values. Then φ and c continue to be reduced with increased F_{s1} and F_{s2} until the slope reaches the critical condition of destruction. Finally we get the safety factors of φ and c, and the arithmetic mean value of the two factors is the final safety factor. When the slope destructs, skid resistance can be affected in three cases according to the safety factors of φ and c:

First: $F_{s2}=1$, reduction of factor of friction F_{s1} is the only factor to be calculated when the slope reaches an ultimate equilibrium. The skid resistance of cohesion is bigger than that of friction on the slip surface, or cohesion shows skid resistance earlier than friction does. Friction is a supplement to the effect of cohesion.

Second: $F_{s1}=1$, reduction of factor of cohesion F_{s2} is the only factor to be calculated when the slope reaches an ultimate equilibrium. The skid resistance of friction is bigger than that of cohesion on the slip surface, or friction shows skid resistance earlier than cohesion does. Cohesion is a supplement to the effect of friction.

Third: $F_{s1}=F_{s2}$, there is little difference between the skid resistance of cohesion and that of friction on the slip surface, or cohesion and friction show skid resistance on the roughly same time.

The former two cases are special cases and the third case almost cannot be found in practical engineering. We cannot determine the type of skid resistance only because the effect of a shear factor is absolutely bigger than another factor as geological and hydrological conditions also play important roles. According to the theory of strength reduction and considering above three cases, 7 reduction methods are used and the final results are comparatively analyzed. As shear resisting factor c and φ have different effects, different relative ratios are given to them by referring to the Table 2 in order to analyze the slope stability and get the safety factors.

***Table 2:** Different cases of shear parameters reduction and the comparison of safety coefficients*

Type	Parameter reduction status	Dual safety coefficients	Final safety coefficient	Error (%) compared to traditional strength reduction method
1	φ reduce, c no reduce	$F_{s1}=1.714$, $F_{s1}=1$	$F_s=1.357$	2.5
2	$\varphi/c=1.2$ reduce	$F_{s1}=1.609$, $F_{s1}=1.073$	$F_s=1.341$	1.3
3	$\varphi/c=1.1$ reduce	$F_{s1}=1.465$, $F_{s1}=1.199$	$F_s=1.332$	0.6

4	φ / c =1.0 reduce	F_{s1}=1.324, F_{s1}=1.324	F_s=1.324	0
5	φ / c =0.9 reduce	F_{s1}=1.136, F_{s1}=1.388	F_s=1.262	-3.7
6	φ / c =0.8 reduce	F_{s1}=0.999, F_{s1}=1.499	F_s=1.249	-4.7
7	φ no reduce， c reduce	F_{s1}=1, F_{s1}=1.458	F_s=1.229	-7.2

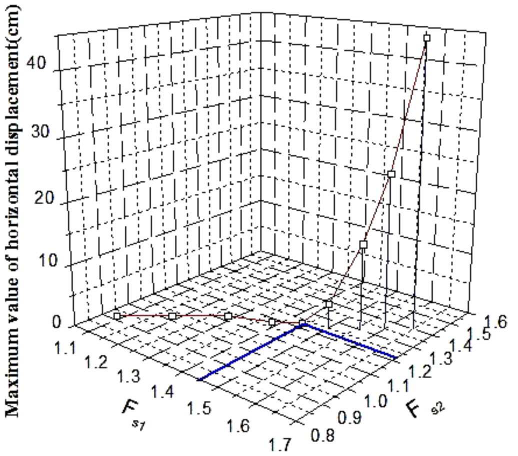

Figure 6: *Relation between the maximum value of the horizontal displacement and dual safety coefficients (Type 3)*

Two safety factors F_{s1} and F_{s2} are calculated by the relation curve of maximum horizontal displacement on the upper part of mid-slope and the reduction factors. Taking the third reduction method as example, the two reduction factors and displacement of upper part of mid-slope under ultimate equilibrium are shown in Figure 6. From the figure, we can see that the displacement of slope is small and the calculation result is convergence when strength reduction factors are smaller than the critical strength reduction factors F_{s1}=1.456 and F_{s2}=1.199. The displacement increases sharply and the calculation result is not convergence when the strength reduction factors are larger than the critical values. That is to say, the critical strength reduction factors F_{s1}=1.456 and F_{s2}=1.199 are the two safety factors and the average value is 1.332. Other six methods get similar safety factors.

Safety factors of each reduction method are listed in Table 2. Generally, the skid resistance, sequence and degree of c and φ are different from each other under different cases, and their safety margins also differ. But there is certain regularity among safety factors calculated by different two factors reduction methods: the deviation of safety factors is small when the reduction factor of friction angle is bigger than that of cohesion; and the deviation is large when the reduction factor of friction angle is smaller than that of cohesion. In addition, safety factor of friction angle F_{s1} decreases while that of cohesion F_{s2} rises with increasing reduction ration between friction angle and cohesion. Moreover, F_{s1} decreases faster than F_{s2} rises.

Based on the distribution of high displacement values and shear strain increment with different reduction factors under the ultimate equilibrium of slope stability, the potential slip surfaces of reduced factors are shown in Figure 7.

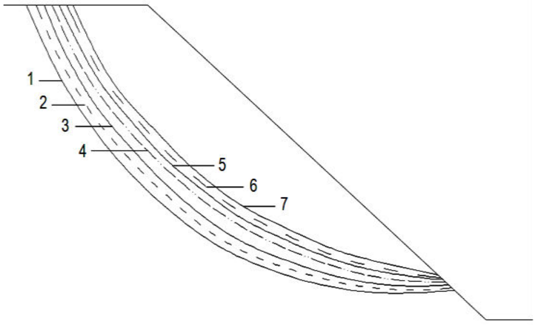

Figure 7: *Positions of maximum potential failure surface under different reduction conditions*

As shown in Figure 7, each reduction method has different slip band if it uses different reduction factor. For each reduction method, different values of friction angle and cohesion under corresponding ultimate equilibrium determine different locations of slip surface, that is, the equilibrium of each reduction method is on different slip surface. Slip band of each method distributes in certain area. The center line of the slip band got from the first method is the lower boundary of the area and the upper boundary is the slip band got from the seventh method. In the potential slip area, the upper width is about 2.53m; lower width is about 0.28m; the maximum depth is 3.1m and the sectional area is about 35.6m^2. Safety factor and slip band got from single reduction factor method is a special case among reduction methods, and it is unable to reflect the change of friction angle and cohesion and the actual sliding process and location of slope. Therefore, it is reasonable to employ two factors strength reduction method. But for a specific slope, choosing stability study methods depends on many factors. In terms of soil texture, the effect of φ is more noticeable than that of c if it is mainly consisted of gravels and cobbles. Thus the method should give bigger value to the reduction factor of φ than that of c. On the contrary, the effect of c is more noticeable than that of φ if the soil is mainly cohesive soil, and the reduction factor of φ should be smaller than c in order to get an accurate judgment on the slope stability. Many other elements need to be considered, which will be the main work for further researches.

4. Conclusions

This paper introduces a strength reduction method with different factors considering the diversity of slope stability influenced by slip mass, slip bed as well as c and φ. Our contrast tests get following conclusions:

(1) According to FLAC3D strength reduction analysis, local instability may only occur to upper part of mid-slope under natural condition. Test results are consistent with the theoretical calculation results, so the model and parameter choices have practical meanings.

(2) Single factor strength reduction method is only a special case of two factors strength reduction methods. Two factors strength reduction methods, compared with traditional strength reduction methods, give more details about the contribution of shear resisting factors to slope stability during the destruction.

(3) When analyzing slope stability by strength reduction methods, slip surface gradually moves from the deep layers to superficial layers with increasing reduction ratios between friction angle and cohesion. Slope stability changes with different values of any factor of cohesion and friction angle.

(4) Different strength reduction methods have their own safety factors and potential slip surfaces. The envelope lines of slip surfaces surround a potential slip area that may provide data and technical support for enforcement of slope.

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