Application of Strength Reduction Method in Checking Safety Factor of a Fiber Grid Reinforced Soil Slope

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ABSTRACT

The suitability of calculating safety factors by reducing only the soil strength (the Strength Reduction Method of Soil, SRMS) and both the soil strength and the geotextile strength (the Strength Reduction Method of Soil and Geotextile, SRMSG) is examined. The results of theoretical analysis show that when only the soil strength was reduced, the safety factor was larger than the actual value; when both the soil strength and the geotextile strength were simultaneously reduced; the calculated safety factor was smaller than the actual value. The results obtained through FLAC3D agreed with those from the theoretical analysis, as follows: (i) the safety factor obtained by SRMS was greater than that obtained by SRMSG; (ii) with an increase of geotextile length, the difference between safety factors obtained via SRMS and SRMSG was zero initially, then increased, and finally stabilized, (iii) as the slope increased, the final difference in safety factor correspondingly decreased. Based on the consideration of the slope safety reserve, in reinforced soil slopes, the objects of strength reduction methods should include the strengths of the soil and the geotextile, and when the geotextile strength is reduced, the yield strength of the geotextile should be reduced.

Keywords: reinforced soil slope; safety factor; strength reduction method; soil strength; geotextile strength

INTRODUCTION

With the implementation of a new round of development strategy in West China (Li et al., 2012), increasing numbers of large-scale projects, particularly fill slope projects, have appeared in loess areas of West China. It is uneconomical to fill gentle slopes because too much land is covered. Steep slopes are commonly used for high fill slopes, and reinforced soil techniques are used to ensure slope stability. Since emerging in 1965, reinforced soil technology has been widely applied to roads, airports, railways and other projects. Because of easy construction and low cost, reinforced soil has been termed “another composite material benefiting mankind following reinforced concrete.” However, because of the particularity of geomaterials, the diversity of reinforced materials and the limitations of current understanding, rigorous standards for the application of reinforced soil materials do not currently exist, and the academic community remains divided on this issue. Reinforced soil is applied increasingly and it is therefore urgent to conduct further studies regarding reinforced soil.

Slope stability analysis is a classic subject in soil mechanics. At present, the commonly-used stability analysis methods include the limit equilibrium method and strength reduction method based on finite elements. The limit equilibrium method is recommended by many codes, such as the Swedish slice method and the Bishop method. The strength reduction method is used for calculating the slope safety factor, which was proposed in the 1970s. In the late 1990s, the strength reduction method came into prominence. Zhao et al. (2002, 2005) systematically studied the strength reduction method and his research promoted the popularization of the strength reduction method.

For safety factor analysis of reinforced soil slopes, Chen et al. (2016) believed that the stability analysis of a reinforced soil slope could be roughly divided into a limit equilibrium method component based on static equilibrium conditions and an upper limit solution system component in plastic mechanics based on displacement compatibility conditions. He also proposed active Coulomb and passive sliding modes and developed corresponding safety factor diagrams to facilitate engineering design by quickly finding the safety factor. His research made great contributions to the design and checking calculations of reinforced soil slopes, but the method of calculating safety factor is complex. Some researchers have introduced the reliability index into the calculation of safety factor of reinforced soil slopes. For example, Liu et al. (2012) used a reliability method to analyze the safety factor of a reinforced soil slope. Yang and Liu (2012) used the point safety factor method to analyze the stability of a reinforced soil retaining wall. These two methods are complex and difficult to popularize, which is not conducive to practical application in engineering. At present, the more common practice in engineering is to transplant the strength reduction method to the calculation of safety factor of reinforced soil slopes. Jie et al. (2012) used the strength reduction method to calculate the safety factor of a reinforced high slope. He concluded that the combination of reduction of strength parameters of the soil and geotextile made the calculation more complex. Moreover, geotextile failure was not allowed, so only the strength parameter of soil was reduced. Tang et al. (2011) introduced the finite element reduction method to the design calculation of a geogrid-reinforced retaining wall of an airport. He proposed that the geotextile strength is the corresponding tensile force when the geotextile strain reaches 10%, and the reduction method only reduces soil strength. Huang et al. (2010) studied application of the finite element strength reduction method to the reinforced steep slope retaining structure. He thought that the finite element strength reduction method reduced the strength of materials which constitute the structure. Therefore, the strength reduction method for reinforced soil structures should incorporate strength reduction of both filler and geotextile. However, because of the limitations of calculation tools, he only reduced the relevant parameters of filler and did not find appropriate reduction methods for bar elements such as geotextiles. The contribution of geotextiles to structural stability was considered as an external load.

Previous research indicates that the strength reduction method is an effective and practical method to calculate the safety factor of a reinforced soil slope, but the strength reduction method is also faced with the problem of reduction object selection. It is worthwhile to study not only whether the choice of different reduction objects has an influence on the calculation result but also to study the value of the reduction object. To study these problems, the effects of reducing different objects used to calculate the safety factor were studied, starting with the definition of the strength reduction method. The FLAC3D program was used to analyze the difference between SRMS and SRMSG, and the value of the reducing object in the strength reduction method was also analyzed.

METHOD AND MATERIALS

Theoretical Derivation

The principle of the strength reduction method is shown in *Figure 1*.

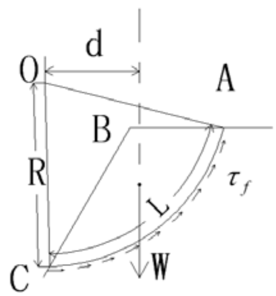


FIGURE 1. Schematic diagram of the slip surface of a simple soil slope.

For a simple cohesive soil slope, the arc AC is an assumed arc with its center at the point *O* and its radius R. The soil ABC will rotate around the center O under the action of gravity W and slide down. The safety factor of the soil slope is given by Eq. (1):

$$F_s = \frac{M_R}{M_S} = \frac{\tau_f LR}{Wd} \tag{1}$$

where M_R is sliding resistance, and M_S is the slip moment, τ_f is shear strength on the sliding surface, L is arc length of the arc AC, W is the gravity of soil ABC, and d is the horizontal distance from the center of soil to the point O.

When checking the stability of a known soil slope, the shear strength of the soil in the slope is reduced continuously until it reaches failure, that is, τ_f is reduced continuously until $\tau_f LR$ is equal to Wd, which means that the sliding resistance moment is equal to slip moment. The multiple by which τ_f is reduced is the safety factor of the slope.

For non-reinforced soil slopes, the source of τ_f is the shear strength of soil:

$$\tau_f = c + \sigma \tan\phi, \tag{2}$$

where c is the cohesive force, σ is the normal stress, ϕ is internal friction angle.

When τ_f is reduced, take Eq. 2 as Eq. 3:

$$\tau_f' = (c + \sigma \tan\phi) / K = \frac{c}{K} + \sigma \times \frac{\tan\phi}{K} \quad (3)$$

For reinforced soil slopes, the source of the sliding resistance moment includes not only the shear strength of soil on the sliding surface, but also the pulling force of the geotextile, as shown in *Figure 2*.

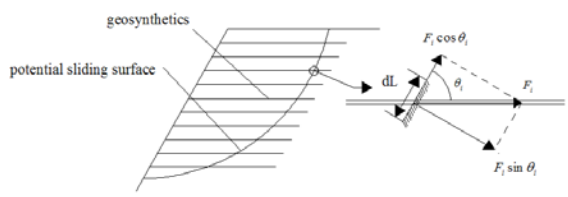


FIGURE 2 Schematic diagram of the intersection of the slip surface and the geotextile.

The following two assumptions are made in *Figure 2*: the geotextile is horizontally arranged and the shear strength of the soil on each segment of the sliding surface is considered to be uniform.

From *Figure 1*, it can be seen that in reinforced soil slope, there are different expressions of F_s, as shown in *Figure 3*.

$$F_s = \frac{M_R}{M_S} = \frac{\tau_f LR}{Wd} = \frac{\int_{i=1}^{n} [c + \sigma \tan\phi] RdL + \sum_{i=1}^{n} (F_i \sin\theta_i \tan\phi + F_i \cos\theta_i) R}{\gamma g S_{abc} d} \quad (4)$$

where F_i is the tensile force provided by the i-th layer of geotextile in the slip surface and θ is the angle between the potential slip surface and the geotextile.

If, according to the classic strength reduction method, c and $\tan\phi$ are reduced based on the proportion *K*, that is

$$F_s' = \frac{M_R}{M_S} = \frac{\tau_f LR}{Wd} = \frac{\int_{i=1}^{n} \left[\frac{c}{K} + \sigma \frac{\tan\phi}{K}\right] RdL + \sum_{i=1}^{n} \left(F_i \sin\theta_i \frac{\tan\phi}{K} + F_i \cos\theta_i\right) R}{\gamma g S_{abc} d} \quad (5)$$

when $F_s' = 1, K > F_s$ that is, the strength reduction method is used to calculate reduction of soil cohesion and the internal friction angle. When the slip moment is equal to sliding resistance moment, the multiple by which soil cohesion and internal friction angle are reduced is greater than the ratio of sliding resistance moment to the slip moment. Therefore, the result is too large when the strength reduction method only is used on soil strength to calculate the safety factor of reinforced slopes, and is also unsafe.

If the improved strength reduction method is adopted, the strength of reinforced soil fillers and that of geotextile are reduced:

$$F_s' = \frac{M_R}{M_S} = \frac{\tau_f LR}{Wd} = \frac{\int_{i=1}^{n} \left[\frac{c}{K} + \sigma \frac{\tan\phi}{K}\right] RdL + \sum_{i=1}^{n} \left(\frac{F_i}{K} \sin\theta_i \frac{\tan\phi}{K} + \frac{F_i}{K} \cos\theta_i\right) R}{\gamma g S_{abc} d} \quad (6)$$

Reducing c, $\tan\phi$ and geotextile strength in accordance with the same parameter *K* will result in the following problems:

(1) Failure modes of reinforced soil slopes include tensile failure, pull-out failure, and excessive deformation. The geotextile strength should be determined first before reduction of the geotextile strength. If the ultimate geotextile strength is treated as a reduction object, it is only suitable for the tensile failure mode of the geotextile.

(2) When $F_s' = 1$, then $K < F_s$, which means that the reduction of geotextile and soil strength at the same time will lead to a conservative result for the safety factor.

(3) For the case of geotextile pull-out and excessive deformation, it is no longer appropriate to reduce the geotextile strength. In the case of geotextile pull-out, the frictional force of geotextile-soil interface should be reduced according to the strength reduction method. In the case of excessive deformation of geotextile, the tensile force of geotextile at the critical allowed deformation should be reduced. This reduction is possible through programming, but the computational efficiency is low. Calculations are conducted for the slope to obtain the stress on the geotextile and to determine whether the geotextile suffers from tensile failure, pull-out failure or excessive deformation. Then the calculation of the reduction of geotextile strength is repeated until the slope fails. According to the above procedures, this process consumes many resources.

The strength reduction method has two problems in its application to reinforced soil slopes. First, different reduction objects will lead to different calculation results. Second, failure modes are not considered in the selection of reduction objects. In order to further study the application of strength reduction methods in reinforced soil slopes, the FLAC3D program was used to calculate the safety factor.

Numerical Simulation

The FLAC3D program has a built-in algorithm for the strength reduction method, but it is only suitable for soil strength reduction. As FLAC3D is almost a fully open system; users can participate in the entire solution process through the establishment of a grid model, setting of boundary conditions, debugging of parameters and the output of calculation results using the unique command-driven mode. By using FISH, the built-in programming language of FLAC3D, new variables or functions can be defined to suit the needs of particular analysis. Therefore, the strength reduction process can be modified to add an element of reducing geotextile strength, in order to reduce soil and geotextile strength at the same time.

Overview of Calculation Model

The reinforced soil slope model was established. By changing the geotextile length and the slope gradient, different reduction methods were used to analyze the change in safety factor, and the effect of different reduction objects on the application of the strength reduction method was illustrated. For this calculation, slopes 10 m high with slope gradient values of 45°, 60°, 75° and 90° were considered. The reinforcing material was geotextile, and the spacing between each two layers was 1 m. The combination of the slope gradient and the geotextile length is shown in *Table I.*

TABLE I. Combination of the slope gradient and the geotextile length.

Slope gradient (°)	Geotextile length (m)													
45	0	1	2	3	4	5	6	7	8	9				
60	0	1	2	3	4	5	6	7	8	9	10	11		
75	0	1	2	3	4	5	6	7	8	9	10	11	12	
90	0	1	2	3	4	5	6	7	8	9	10	11	12	13

TABLE II. Mechanical parameters of soil.

Natural bulk density (kN/m^3)	Cohesion force (kPa)	Internal friction angle (°)	Compressive modulus (kN/m^2)	Poisson ratio
17	42	23	12.8	0.3

TABLE III. Mechanical parameters of geotextile and interface between geotextile and soil.

Elastic modulus (MPa)	Poisson ratio	Cohesion of coupled spring (MPa)	Internal friction angle of coupled spring (°)	Tangential rigidity of coupled spring (MPa)	Thickness of geotextile (mm)
26000	0.33	0	29	2.3	5

Reinforced slope soil is made up of clay with physical parameters shown in *Table II*. A spring - slider was used to simulate geotextiles, and the shear force on the contact surface between the geotextile and soil was determined by the hypothetical coupled spring cohesion and internal friction angle. Deformation characteristics of the interface between the geotextiles and soil were determined by the tangential rigidity of the hypothetical coupled springs. Mechanical parameters of geotextiles are shown in *Table III*.

The modeling overview is illustrated by the case of a geotextile length of 6 m and a slope gradient of 45°, as shown in *Figure 3*. The entire model had a width of 0.8m in the y direction, as an element width. The lower foundation part had a length of 20 m in the *x* direction, which was divided into 20 elements, and a height of 3 m in the *z* direction, which was divided into three elements. There were 60 elements in total. The bottom margin of the upper filling had a width of 18 m, while the top margin had a width of 8 meters. Each divided into 17 elements. The height was 10 m and was divided into 17 elements. There were 289 elements in total. The *x*, *y* and *z* directions of the model were constrained at the bottom of the foundation, and the *x* direction constraint was applied to the left and right boundaries of the foundation as well as the right boundary of the fill. The *y* direction velocity of all the nodes was constrained. The interface between the foundation and the fill had the same mesh and the system automatically defaulted its connection. The geotextile length was set to 6 m, while the width was 0.8 m, and the spacing between two adjacent geotextiles was 1 m. The Mohr–Coulomb model was used for both foundation and fill, and a geogrid element was used for the geotextile.

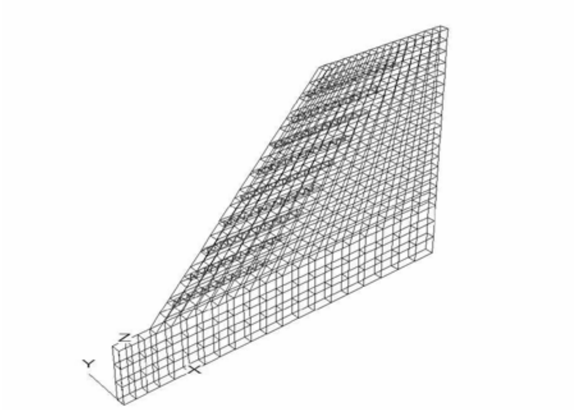


FIGURE 3. Schematic diagram of analysis model of reinforced soil retaining wall (with the geotextile length of 6 m and slope gradient of 45°).

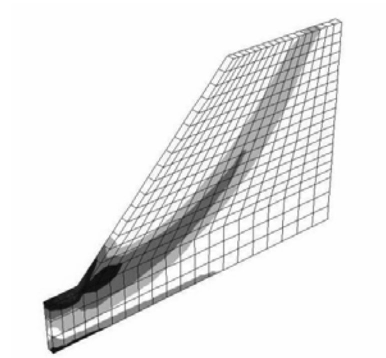
Convergence Condition

In this paper, strength reduction of the soil and geotextile was realized through the use of a loop language and dichotomy algorithm using FISH language. The termination condition of the calculation was convergence of numerical computation. When the force imbalance ratio was smaller than the critical value 9.8×10^{-6}, the current calculation was canceled and a new round of the reduction process began. In order to improve calculation efficiency, limitations were imposed on the searching range of the safety factor, and initial values were set as 1 and 4, respectively.

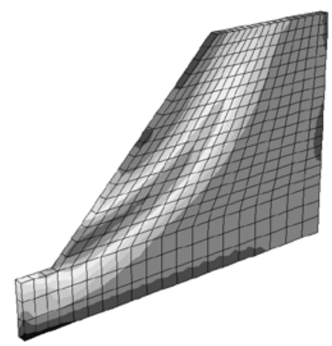
CALCULATION RESULTS AND ANALYSIS

Position and Shape of Failure Surface

Taking the model with a slope gradient of 45° and a geotextile length of 6 m as an example, the potential slip surface calculated by SRMS is shown in *Figure 4(a)* and the potential slip surface calculated by SRMSG is shown in *Figure 4(a).*



(a) The potential sliding surface calculated by SRMS



(b) The potential sliding surface calculated by SRMSG

FIGURE 4. Schematic diagram of the potential sliding surfaces calculated by the two methods.

The horizontal slope length was taken as the X-axis, and the slope height was taken as the Y-axis to facilitate analysis. After the potential slip surface was simplified, slope height vs. slope length was plotted as shown in *Figure 5*. Slope gradients were 45°, 60°, 75° and 90° and the geotextile length was always 6 meters.

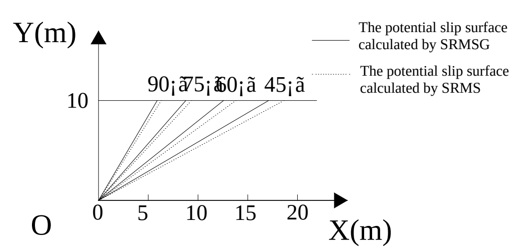
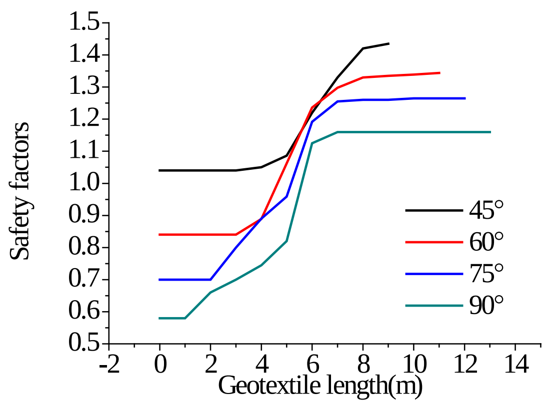


FIGURE 5. Simplified schematic diagram of simplified potential slip surfaces.

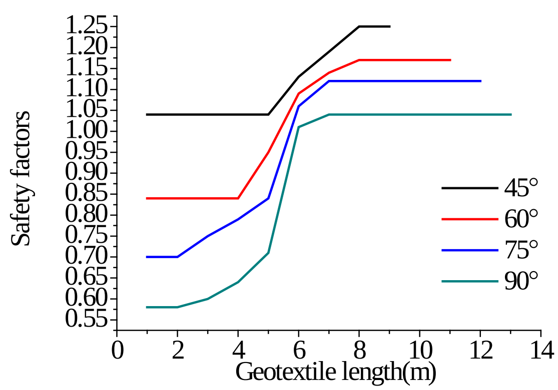
Figure 4 and *Figure 5* show that the obtained potential slip surface is different when the strength reduction was calculated using the two methods for the same slope. The potential slip surface calculated by SRMS was deeper than that calculated by SRMSG. When the slope gradient decreased, the difference in depth between two slip surfaces calculated by SRMS and SRMSG increased, whereas as the slope gradient increased, the difference decreased.

Safety Factor and Error Analysis

The geotextile length was taken as the X-axis, and the safety factor was taken as the Y-axis. The coordinate system was drawn and the obtained safety factors of various slopes were included in the coordinate system, as shown in *Figure 6*.



(6a) Safety factors calculated by SRMS



(6b) Safety factors calculated by SRMSG

FIGURE 6. Schematic diagram to indicate change of safety factors with geotextile length.

Figure 6 shows that the variation trend of the safety factors obtained through two reduction methods was similar. When the geotextile length increased from zero, the initial safety factor did not change at first, and then the safety factor began to increase and finally stabilized. As the slope gradient increased, the safety factor decreased. The safety factor obtained by SRMS was greater than that obtained by SRMSG.

The difference between the safety factor obtained by SRMS and that by SRMSG was calculated. The geotextile length was taken as the X-axis and the safety factor as the Y-axis to draw the coordinate system. The difference value of safety factors was drawn in the coordinate system, as shown in *Figure 7*.

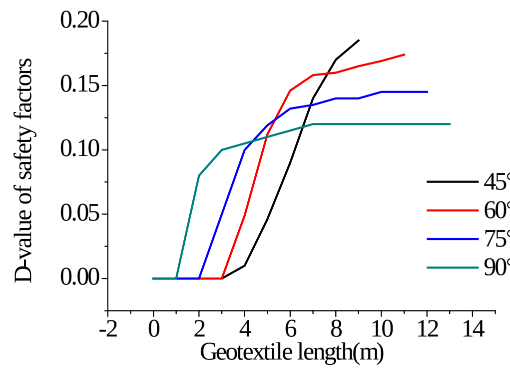


FIGURE 7. Schematic diagram of the difference between safety factors calculated by the two reduction methods.

Figure 7 shows that the difference value of safety factors of the reinforced soil slope calculated via the strength reduction method was related to the geotextile length and slope gradient. When the geotextile length was small, the difference in the safety factors was zero. As the geotextile length increased, the safety factor difference also increased. The length of the corresponding geotextile was shorter when the difference of the slope with larger gradient began to increase. The difference between safety factors finally stabilized. As the slope gradient increased, the final value of the safety factor difference showed a decreasing trend.

DISCUSSION

There has been no uniform method for analyzing the stability of reinforced soil slopes, and results from various theoretical calculations are quite different. The stability analysis of reinforced soil slopes can be roughly divided into two methods: a limit equilibrium method based on static equilibrium conditions and an upper bound solution method based on displacement compatibility conditions. The strength reduction method has been widely used to represent of the latter for only about 10 years and has been applied to reinforced slopes for a considerably shorter time.

Because of its close contact with finite element calculation technology, the strength reduction method is more convenient in practical application. Therefore, the strength reduction method has a wider potential application in the analysis of reinforced soil slopes.

Choice of Reduction Object

Through theoretical derivation and numerical simulation, we found that when the traditional strength reduction method (SRMS) was used to calculate reinforced soil slopes, the safety factor was too large and is not conducive to safety. However, the safety factor obtained by SRMSG at the same time was smaller than the actual value. Zhang (2008) used field tests of three different geogrid reinforced soil slopes to examine the pressure and deformation at the bottom of the geogrid reinforced soil slope. He believed that adequate safety reserves should be considered for reinforced soil slopes with a height greater than 12 m. From the point of view of improving safety reserves, SRMSG should be used when calculating the safety factor of the reinforced soil slope.

Effect of the Geotextile Length

Figure 5 and *Figure 7* show that the geotextile length had a strong influence on the value of safety factors and the difference value between safety factors calculated by the two methods. Regarding the geotextile length, Chen et al. (2016) suggested that the sliding face inside the soil should not cross the geotextile. He believed that if the effective geotextile length was insufficient, the actual number of stressed geotextiles corresponding to the critical slip surface would decrease, and the most dangerous slip surface could move out. Tang Chaosheng (2009) used the test method to determine the formula for critical geotextile length as follows:

$$l_c = \frac{R_f d}{2\tau_f} \tag{7}$$

here R_{f} is the tensile strength of a single geotextile, *d* represents the geotextile diameter, and τ_f is the interface shear strength.

Chen et al. (2002) obtained the curve to describe the relationship between slope stability and geotextile length via numerical simulation. The numerical simulation and experimental results show that the maximum geotextile deformation ranges from 4–6 m away from the slope surface, which is consistent with the calculated results in this paper. In the current study, when the geotextile length was small, the difference between the results of the two methods was almost zero, indicating that the geotextile did not work with the soil. This does not meet the original intention of the design. When the geotextile reached a certain length, and the geotextile length continued to increase, the safety factor did not change, indicating that the role of geotextile was fully played, and continuing to increase the length would result in waste. In the design of a reinforced soil slope, the purpose of ensuring the geotextile length is avoiding geotextile pull-out.

Effect of Slope Gradient

Increasing slope gradient has two effects on the safety factor difference calculated by the two methods. One is to decrease the geotextile length when the difference value between safety factors calculated by two methods change from zero, and the other is to decrease the final difference value after the change of safety factor is stabilized. *Figure 5* shows that an increasing slope gradient led to decreasing potential slip surface depth, which shortened the geotextile length passing through the potential slip surface, resulting in the reduction of the effective geotextile length. According to Eq. (6), the reduction in geotextile length leads to the reduction of F_{i}, thus causing reduction of the final safety factor difference.

Choice of the Geotextile Strength

The difference in safety factor obtained via SRMS and SRMSG is the result of the effect of the geotextile on the slope. Therefore, it is important to study the failure mode of the geotextile. Lee et al. (1996) believed that the failure behavior of geotextile can be divided into two categories: when the tensile strength of the geotextile is greater than the frictional force provided by the embedding length and confining pressure, the geotextile will be pulled from the soil. However, when the frictional force provided by the embedded length and confining pressure is greater than material strength, the geotextile will remain in the soil and undergo tensile failure. Ma et al. (2004) divided the tensile failure of geotextile into four stages: the initial stage, the development stage, the local yield stage, and the full yield stage. The main factor in determining the failure mode is the buried depth of the geotextile. According to previous analysis, when the strength reduction method is used to calculate the safety factor of reinforced soil slopes, there are three failure modes for the geotextile: pull-out failure, excessive deformation, and tensile failure. These three failure modes correspond to three kinds of strength. Pull-out failure corresponds to the frictional strength between the geotextile and soil, excessive deformation corresponds to yield strength of the geotextile, and tensile failure corresponds to the ultimate strength of the geotextile. In the test method 'Determination Method of the Long-term Design Strength for Geotextiles' established by the Geosynthetics Research Institution of America (1992), it is stipulated that the allowed tensile strength in geotextile design should be obtained from the measured ultimate tensile strength multiplied by the reduction factor, which various influencing factors (such as installation damage, creep, chemical action, biology and so on). Ding et al. (2012) believed that, for some reinforced soil works that have strict deformation requirements (such as roadbed and retaining wall), the design strength can be taken as the tensile strength corresponding to 2% or 5% strain in the stress-strain curve. She used a geogrid to simulate a series of reinforced soil tests under the actual state of the lateral stress restraint and creep. It was concluded that from the point of coordination deformation, it is better to introduce modulus in the design of reinforced soil as a measure of the mechanical properties, rather than using a single tensile strength to reflect the geotextile behavior in reinforced soil. From the results of previous studies and numerical simulations in this paper, it was found that when the strength reduction method was used to calculate the safety factor of reinforced soil slopes, it was better to use the yield strength as the strength value of the geotextile.

CONCLUSION

Through stress analysis of the intersection of the slip surface and the geotextile, it is proposed that when the traditional strength reduction method (SRMS) is used to calculate the safety factor of reinforced soil slopes, the calculation results are too large because the action of the geotextile is not taken into account. If both the geotextile and soil strength are reduced at the same time (SRMSG), the results are affected by failure modes of the geotextile.

The FLAC3D program was used to develop a model that reduces the geotextile and soil strength at the same time. The two reduction methods were used to calculate the safety factor of reinforced soil slopes. The results show that with an increase of the geotextile length, the difference value between safety factors obtained via SRMS and SRMSG was 0 initially, then increased and finally stabilized. The potential slip surface calculated by SRMS was deeper than the sliding surface calculated by SRMSG. Moreover, with increasing slope gradient, the difference in slip surfaces obtained through the two methods decreased.

It is proposed that, considering safety, the variables in the strength reduction method should include the soil strength and the geotextile strength. The geotextile strength value in the strength reduction method was considered and it was concluded that the yield strength of geotextile should be taken as the geotextile strength when the geotextile strength is reduced.

This study offers a theoretical basis for the application of the strength reduction method in checking the safety factor of a reinforced soil slope. This research provides a method for the safety evaluation of reinforced soil slopes.

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