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Stability analyses of geosynthetic-reinforced earth structures using limit equilibrium and numerical methods

Han, J.
Dept. of Civil, Environmental, and Architectural Engineering, the University of Kansas, 2150 Learned Hall 1530 W. 15th Street, Lawrence, Kansas 66045-7609, USA

Leshchinsky, D.
Dept. of Civil and Environmental Engineering, University of Delaware, Newark, DE 19716, USA

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ABSTRACT: Limit equilibrium methods have been commonly used in practice for analyzing the stability of unreinforced and geosynthetic-reinforced earth structures, such as slopes and walls. Numerical methods including finite element and finite difference methods have become increasingly used for the same purposes in recent years. Strength reduction technique is the basis for numerical methods to determine factors of safety of earth structures against a critical failure mode. Numerical and limit equilibrium methods both have advantages and limitations. This paper follows recent research work conducted by the authors using both the limit equilibrium software and the finite difference software to analyze the stability of geosynthetic-reinforced slopes and walls, geosynthetic-reinforced tiered walls, and geosynthetic-reinforced earth walls with limited reinforced space. The new information provided in this paper is focused on the comparisons of critical slip surfaces predicted by these two methods in addition to the factors of safety. All the results from these studies show that properly adopted limit equilibrium methods can reasonably analyze the stability of geosynthetic-reinforced earth structures as compared with the numerical method.

1 INTRODUCTION

Limit equilibrium (LE) methods have been commonly used in practice for decades to analyze the stability of unreinforced and geosynthetic-reinforced earth structures, such as slopes. Bishop's simplified method, utilizing a circular arc slip surface, is probably the most popular LE method used for analyzing slope stability. Numerical methods including finite element and finite difference methods have become increasingly used for the same purposes in recent years. Strength reduction technique is the basis for numerical methods to determine factors of safety of earth structures against a critical failure mode. However, geosynthetic-reinforced earth walls have been commonly designed based on lateral earth pressures, such as Rankine's or Coulomb's method. An arbitrary face inclination of 70° (or 20° batter) is used to differentiate between reinforced steep slopes and walls in a number of design standards or guidelines, such as AASHTO 98 as well as the British Standard BS8006 (1995). Very different methods have been recommended to design reinforced slopes and walls. Obviously, the earth structures would not know how people define them as slopes or walls so that they do not necessarily behave as what people expect. To analyze the stability of geosynthetic-reinforced earth structures, numerical methods do not need to pre-define the failure mode so that they are suitable to analyze both reinforced slopes and reinforced walls.

This paper follows the studies conducted by the authors in the recent years to investigate the stability of geosynthetic-reinforced earth structures using limit equilibrium and numerical methods and focuses on the comparisons of the critical slip surfaces predicted by these two methods in addition to the factors of safety.

2 METHODS OF ANALYSIS

2.1 *Limit equilibrium method*

Bishop's simplified method, utilizing a circular arc slip surface, is probably the most popular limit equilibrium method. Although Bishop's method is not rigorous in a sense that it does not satisfy horizontal force limit equilibrium, it is simple to apply and, in many practical problems, and it yields results close to rigorous limit equilibrium methods. In our studies, Bishop's simplified method was modified to include reinforcement as a horizontal force intersecting the slip circle, which is incorporated in ReSSA(2.0) software, developed by ADAMA Engineering (2002).

This modified formulation is consistent with the original formulation by Bishop (1955). The mobilized reinforcement strength at its intersection with the slip circle depends on its long-term strength, its rear-end pullout capacity (or connection strength), and Bishop's factor of safety. The analysis assumes that when the soil and reinforcement strengths are reduced by the factor of safety, a limit equilibrium state is achieved (i.e., the system is at the verge of failure), meaning that under this state, the soil and reinforcement mobilize their respective strengths simultaneously.

2.2 *Numerical method*

The finite difference program (FLAC 2D Version 4.0, developed by the Itasca Consulting Group, Inc.) was adopted in these studies for numerical analyses of the stability of geosynthetic-reinforced earth structures. A shear strength reduction technique was adopted in this program to solve for a factor of safety of stability. In this technique, a series of trial factors of safety are used to adjust the cohesion, c and the friction angle, ϕ, of soil as follows:

$$c_{trial} = \frac{1}{FS_{trial}} c \tag{1}$$

$$\phi_{trial} = \arctan\left(\frac{1}{FS_{trial}} \tan\phi\right) \tag{2}$$

Adjusted cohesion and friction angle of soil layers are re-inputted in the model for limit equilibrium analysis. The factor of safety is sought when the specific adjusted cohesion and friction angle make the slope become instability from a verge stable condition (i.e., limit equilibrium). The critical slip surface often can be identified based on the contours of the maximum shear strain rate. In all the cases discussed later, soil is modeled as a linearly elastic perfectly plastic material with a Mohr-Coulomb failure criterion. Geosynthetics are modeled as cables with grouted interface properties between cables and soil, in which the interface strength is assumed to be 80% the soil strength.

However, being of a higher hierarchy in mechanics and if properly used, it can serve effectively to substantiate the validity of a simpler limit equilibrium approach which uses an *a priori* assumed failure mechanisms and which fails to rigorously satisfy limit equilibrium (e.g., Bishop's Method in this case). That is, it can justify the use of a simpler and more tangible approach.

2.3 *Parallel studies*

In order to compare the results of stability analyses of geosynthetic-reinforced earth structures, two parallel studies were conducted for each case using limit equilibrium and numerical software. Obviously, limit equilibrium is physically meaningful only at the verge of failure, regardless whether reinforcement is invoked. Each case was firstly sought at the factor of safety equal to 1.0 using the limit equilibrium method then the same design section was analyzed by the numerical method. If both methods yield the same factor of safety, they are proved to be equivalent in terms of analyzing the stability of geosynthetic-reinforced earth structures.

3 STABILITY OF SLOPES AND WALLS

3.1 *Reinforced walls*

Figure 1 presents the results of a 6 m high vertical geosynthetic-reinforced wall. In the FLAC analysis, the elastic modulus, E = 40 MPa, the Poisson's ratio, $\nu = 0.25$, the cohesion, c = 0 kPa, the friction angle, $\phi = 34°$, and the unit weight, $\gamma = 18$ kN/m^3 of the soil were used. A small value of cohesion equal to 2.5 kPa was used for blocks to prevent possible local failure of the block facing thus enabling one to focus on global failure modes. The last two blocks were assumed to have cohesion of 0.01 kPa to ensure the exit of the slip surface through the toe. The tensile strength of geosynthetics with a length of 6.6 m spaced at 0.6 m vertically is 11.1 kN/m. Since geosynthetic-reinforced walls are commonly designed based on Rankine's lateral earth pressure method, the failure surface (i.e., FS = 1.00) based on the Rankine's method is also presented in Figure 1 for comparison purposes.

As shown in Figure 1, the critical slip surface determined by Bishop's method starts from the toe and follows the Rankine's slip plane up to 1/3 height of the wall then bends towards the wall facing. This outcome results from the assumptions of Bishop's method. Bishop's method, by solving the moment equilibrium equation, attempts to minimize the effects of the upper layers. The center of the critical circle is at the same elevation as the crest in this case, which makes the moment contribution of upper layers minimal. In addition, the limit equilibrium software

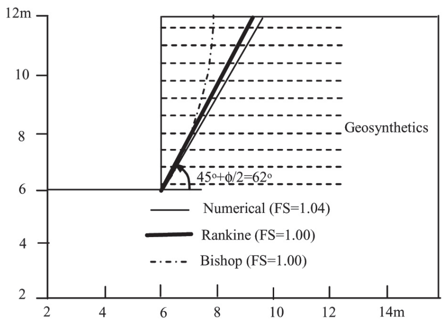

Figure 1. Critical slip surfaces and factors of safety of geosynthetic reinforced walls (modified from Han and Leshchinsky, 2004).

also calculates the imbalanced horizontal force. In this case, the imbalanced horizontal force is about 20% of the total weight of slices. In other words, the horizontal force equilibrium is grossly violated.

Figure 1 also shows that the critical slip surface determined based on the contours of shear strain rate in the numerical method develops closely along the Rankine slip plane. However, this result is different from that by Bishop's method. In spite of this difference, the calculated factor of safety by the Bishop's method and that by the numerical method are close (1.00 versus 1.04).

3.2 *Reinforced slopes*

A geosynthetic-reinforced steep slope of 70° face inclination was selected in this study since this face inclination is commonly considered as a boundary line to distinguish between slopes and walls. The same soil and geosynthetic properties (except the tensile strength of geosynthetics, T_a = 6.2 kN/m) as those for the reinforced wall in Section 3.1 were used in this FLAC analysis. As shown in Figure 2, the 6 m high steep slope yields almost the same factor of safety (FS = 1.0) based on the numerical and Bishop's methods. In addition, the critical slip surfaces determined from both methods are circular and close. In this case, the imbalanced horizontal force calculated by the limit equilibrium method is about 5% of the total weight of slices, which is much less than that for the vertical wall.

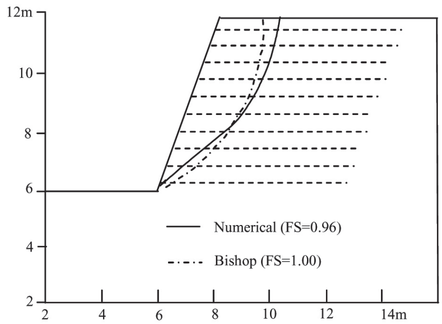

Figure 2. Critical slip surfaces and factors of safety of geosynthetic reinforced slopes.

3.3 *Tiered walls*

Tiered walls are an intermediate earth retaining structure between vertical walls and slopes, which have the advantages of both walls and slopes, such as no erosion concern and lower reinforcement requirements. However, there is no well-developed and theoretically sound design method available for this earth structure system. Leshchinsky and Han (2004) investigated the behavior of multitiered walls considering a number of influence factors, such as the offset between walls, the reinforcement length, the number of tiered walls, the quality of backfill and foundation soil, and the existence of water. Figure 3 presents a comparison of the critical slip surfaces and the factors of safety predicted by the numerical method and the limit equilibrium method. The comparison clearly shows that these two methods yield almost identical results in terms of the critical slip surfaces and the factors of safety. In the numerical analysis, the same soil and geosynthetic properties (except the tensile strength of geosynthetics, T_a = 11.4 kN/m and the length of geosynthetics, L = 4.2 m) as those for the reinforced wall in Section 3.1 were used.

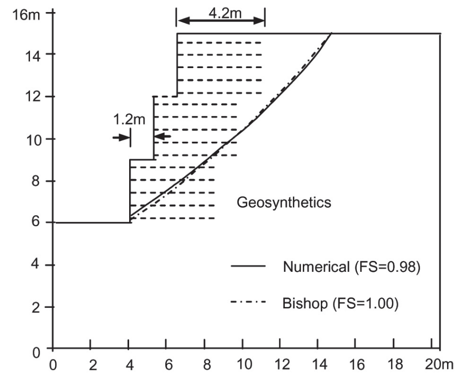

Figure 3. Critical slip surfaces and factors of safety of geosynthetic reinforced tiered walls.

3.4 *Reinforced walls with limited space*

Geosynthetic-reinforced earth walls are typically designed assuming reinforcement having enough length extended into the backfill material. However, there are cases where the space behind the reinforced earth wall is constrained due to, for example, natural rock formation, manmade shoring system, or even back-to-back wall system. In such cases the reasonable installed length of the reinforcement could be physically restricted by the project. Furthermore, the Rankine or Coulomb wedge that produces the full thrust of lateral earth pressure might not develop within the reinforced soil thus affecting the reactive force in the reinforcement. Leshchinsky et al. (2004) proposed a design method for this special application with a reduced lateral earth pressure coefficient based on limit equilibrium and numerical methods. Figure 4 presents the comparisons of the critical slip surfaces and the factors of safety predicted by both the limit equilibrium method and the numerical method. In the FLAC analysis, the elastic modulus, E = 40 MPa, the Poisson's ratio, ν = 0.25, the cohesion, c = 0 kPa, the friction angle, ϕ = 35°, and the unit weight, γ = 18 kN/m^3 of the soil were used. A high value of cohesion equal to 75 MPa was used for blocks to prevent possible local failure of the block facing and pullout of the reinforcement from the front thus enabling one to focus on global failure modes. The last two blocks were assumed to have cohesion of 10 kPa to ensure the exit of the slip surface through the toe. The tensile strength of geosynthetic layer is 67 kN/m. It is shown that the critical slip surface predicted by the numerical method is close to that by the limit equilibrium method from the toe of the wall up to 1/3 the height of the wall and deviates towards the boundary of the backfill and the bedrock. The sudden changes of the mesh sizes and shapes at the boundary of the backfill and the bedrock may contribute the deviation of the critical slip surface in the numerical analysis. However, the factors of safety calculated by both methods are close. As compared with Figure 1, the critical slip surface in Figure 4 for a vertical wall is nearly planar rather than circular. This is because one reinforcement layer was used in this analysis and no existence of upper reinforcement to make the critical slip surface turn curvature for the minimal moment requirement.

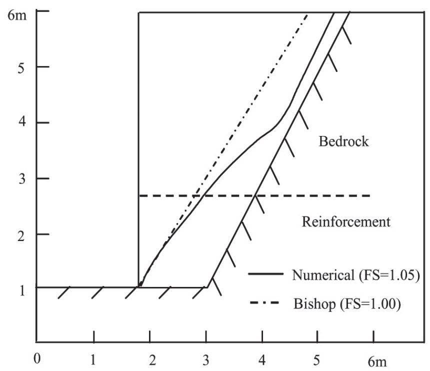

Figure 4. Critical slip surfaces and factors of safety of geosynthetic reinforced walls with limited space.

4 CONCLUSIONS

The comparisons presented above have shown that the numerical method and the limit equilibrium method produce almost identical results in terms of factors of safety for the geosynthetic-reinforced earth structures ranging from vertical walls, slopes, tiered walls, and earth walls with limited space. The critical slip surfaces for slopes and tiered walls predicted by the numerical method and the limit equilibrium method are close. Bishop's method, by solving the moment equilibrium equation, attempts to minimize the effects of the upper layers in the vertical walls to lower the center of the critical circle to the same elevation as the crest to make the moment contribution of upper layers minimal. This treatment makes the critical slip surface in the upper portion of the wall deviate from those determined by the numerical method and the Rankine method. The sudden change of mesh dimensions and shapes at the boundary between the backfill and the bedrock in the numerical analysis may have contributed the deviation of the critical slip surface for the geosynthetic-reinforced earth wall with limited space.

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