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Influence of tensile stiffness of geosynthetic reinforcements on performance of reinforced slopes

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ABSTRACT: Geosynthetic-reinforced slopes are commonly designed using limit equilibrium methods, which assume geosynthetics and soil reaching a limit equilibrium state simultaneously. The design methodologies only ensure that the slopes have necessary factors of safety for global stability, sliding as well as internal stability by placing sufficiently strong and long geosynthetic reinforcements in the slopes. However, the performance of slopes also depends on deformations especially when structures, such bridge abutments or buildings, are on the top of the slopes. The deformation related performance is not considered in the limit equilibrium methods. This paper presents a numerical study on reinforced slopes with different tensile stiffness of geosynthetic reinforcements based on the deformation analysis. This study indicates that soil and geosynthetic reinforcements do not necessarily reach the limit equilibrium state at the same time. In other words, the soil may yield first before the geosynthetic reinforcements fully develop their tensile strengths or pullout capacities. The yielding of the soil results in excessive deformations of the slopes. The paper reveals that slopes with different tensile stiffness of geosynthetic reinforcements perform differently in many ways although all the slopes have the same factor of safety against stability by using the simplified Bishop's limit equilibrium design method. This paper investigates the influence of tensile stiffness of geosynthetic reinforcements on horizontal and vertical displacements, maximum shear strains and their locations, and tensile force distributions along the reinforcements. It is concluded that the tensile stiffness of geosynthetic reinforcements is an important factor that affects the performance of reinforced slopes, therefore, its influence should be taken into account in the design.

1 INTRODUCTION

Geosynthetic-reinforced slopes are commonly designed using limit equilibrium methods. The design methodologies only ensure that the slopes have necessary factors of safety for global stability, sliding as well as internal stability by placing sufficiently strong and long geosynthetic reinforcements in the slopes. In the internal stability analysis, the method assumes that geosynthetic reinforcements and soil reach the limit equilibrium state simultaneously. For circular arcs, the factor of safety for the internal stability of a reinforced slope can be expressed as follows:

$$FS = \frac{M_r + M_g}{M_d} \qquad (1)$$

where M_r = resisting moment of the soil; M_g = resisting moment of the geosynthetic reinforcements; and M_d = driving moment due to the weight of soil and external forces.

Equation 1 is also valid for an unreinforced slope when the term M_g equals to 0. This equation was developed based on the assumption that the same factor of safety is applied to the resisting moments by both the soil and geosynthetic layers for a reinforced slope. In reality, however, the soil and the geosynthetic reinforcements do not necessarily mobilize their resistance at the same rate. In other words, the soil may yield first before the geosynthetic reinforcements fully develop their tensile strengths or pullout capacities.

Like any other earth structures, the performance of slopes also depends on deformations especially when structures, such as bridge abutments or buildings are built on the crest. The deformation related performance is not considered in limit equilibrium analysis. The deformation-related performance is expected to be dependent on the geometry and soil properties of the slope, the mechanical properties of geosynthetic reinforcements and geosynthetic/soil interface, and external loading conditions. Chalaturnyk et al. (1990) investigated stresses and deformations in unreinforced and reinforced slopes using a finite element method. Tensile strength and stiffness of geosynthetic reinforcements are two key mechanical properties. The tensile strength is considered in the calculation of the factor of safety using limit equilibrium methods. However, the tensile stiffness is one of the key factors influencing the deformation-related performance of geosynthetic-reinforced slopes. The tensile stiffness of geosynthetic reinforcement is defined as the tensile force divided by the corresponding tensile strain. Since geosynthetic reinforcements are man-made materials, they can have a wide range of tensile stiffness.

This paper presents a numerical study on the performance of reinforced slopes with different tensile stiffness of geosynthetic reinforcements. This study investigated the influence of tensile stiffness of geosynthetic reinforcements on horizontal and vertical displacements of slopes, maximum shear strains and their locations in the soil, and tensile force distributions in geosynthetic reinforcements.

2 NUMERICAL MODELING

The FLAC (Fast Lagrangian Analysis of Continua) program (Itasca Consulting Group, Inc., Version 4.0) was adopted for this numerical study. The geometry and soil properties of the slope were selected as shown in Figure 1. The stress-strain responses of all the soils are assumed to follow linear elastic-Mohr-Coulomb models. A firm clay layer was assumed for the foundation soil to ensure the potential failure could only develop above this clay layer and the deformation of this clay layer is negligible. A thin surficial soil layer with cohesion was added to the slope face to prevent the development of any local and/or surficial failures. Cable elements were used for modeling geosynthetic reinforcements. According to literature review (Bathurst & Hatami 1998, Lee et al. 1999, Varadarajan et al. 1999, Ling et al 2000), the tensile stiffness of geosynthetic reinforcements was selected in the range of 100 to 4000kN/m. In addition, the following parameters of geosynthetic reinforcements were used: the area of each cable element, A=0.002m^2, the perimeter of each cable element, L_p=2m, the allowable design strength of each cable element, T_a=20kN/m, and the friction angle and stiffness between each cable element and soil, δ=24.8^0 (tanδ=0.8tanϕ) and k_b=2x106kN/m/m, respectively. The bond cohesion of cable elements within the reinforced fill and the surficial soil layer cable was 0kPa and 16kPa, respectively. Longer geosynthetic reinforcements (L=7.5m) were designed to prevent possible pullout of the reinforcements. Although external loads are important for performance of geosynthetic-reinforced slopes, they were not included in this study for simplicity. In the numerical study, a number of runs were conducted by varying the stiffness of geosynthetic reinforcements and keeping all other parameters the same. Since the tensile stiffness of geosynthetic reinforcements is not included in limit equilibrium analysis, all the cases have the same factor of safety.

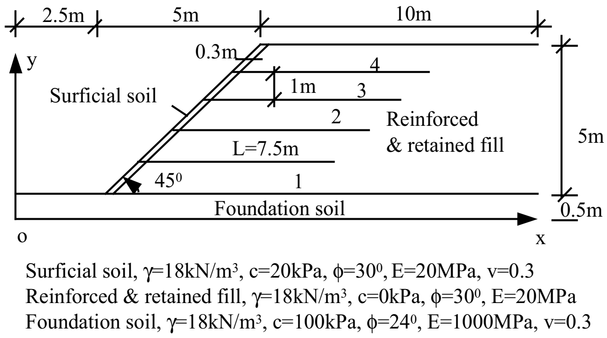


Figure1. Geometry and soil properties of the slope in this study

3 ANALYSIS OF RESULTS

3.1 *Factor of Safety*

Prior to the numerical analysis, limit equilibrium analyses were conducted to determine the factors of safety of the unreinforced and reinforced slopes. The simplified Bishop's method for an unreinforced slope was adopted for computing the resisting moment and driving moment from the soil, M_r and M_d. The resisting moment by geosynthetic reinforcements were calculated based on the allowable design strength and the vertical distance from the center of circular surface to each geosynthetic reinforcement. Then Equation 1 was used to calculate the factor of safety for the case shown in Figure 1. The computed factors of safety for the unreinforced (i.e. ignoring the existence of geosynthetic reinforcements) and reinforced cases were 0.89 and 1.56, respectively. The numerical program, FLAC, was also used to compute the factors of safety for the unreinforced and reinforced cases. Their results were 0.88 for the unreinforced case and 1.55 for the reinforced case. Therefore, the simplified Bishop's method and the numerical method basically yield the same results. In the numerical analysis, the soil strength and tensile strength or pullout resistance were divided by a factor of safety producing the limit equilibrium state. The method to derive the factor of safety using the numerical program (FLAC) can be found in the literature (Dawson et al., 1999).

3.2 *Maximum horizontal and vertical displacements*

The factor of safety calculated in the limit equilibrium analysis is dependent on the geometry and soil properties of the slope, the allowable design strength of the geosynthetic reinforcements, and external loading conditions. The factor of safety has nothing to do with the tensile stiffness of geosynthetic reinforcements. It is not uncommon in practice to consider slopes having the same factor of safety to yield equivalent performance. However, Figure 2 and Figure 3 clearly show that the maximum horizontal displacement (movement) and vertical displacement (settlement) of the slope are dependent on the stiffness of geosynthetic reinforcements, especially when the tensile stiffness of the geosynthetic reinforcement is less than 1000kN/m.

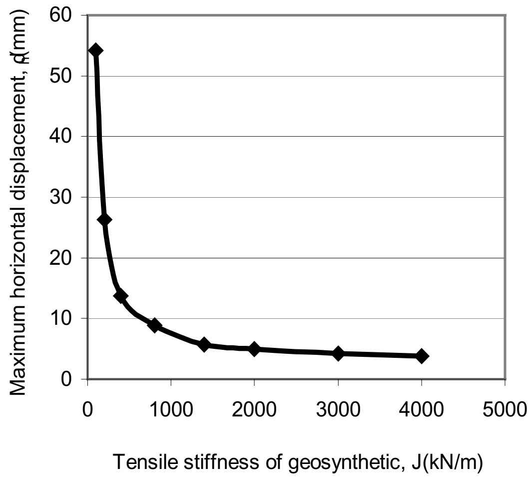


Figure 2. Influence of tensile stiffness of geosynthetic on the maximum horizontal displacement

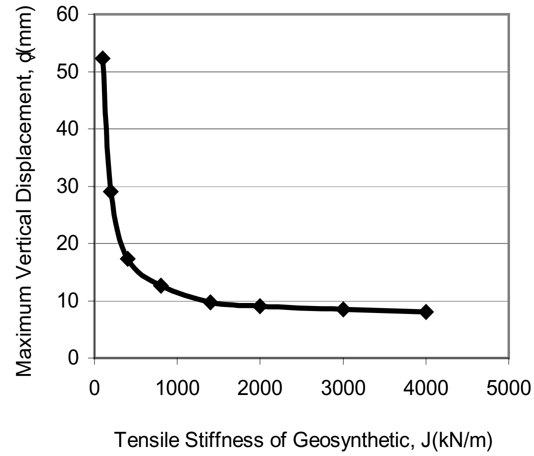
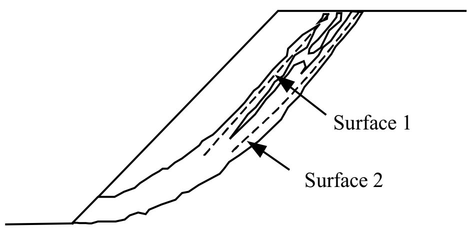


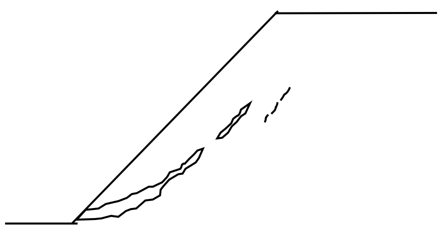
Figure 3. Influence of tensile stiffness of geosynthetic on the maximum vertical displacement

3.3 *Maximum shear strains and their locations*

The level of shear strain in the slope is an indicator of potential yielding of the soil since higher shear strain corresponds to a higher shear stress. The higher shear stress also indicates more shear strength being mobilized. As shown in Figure 4, the slope with a lower tensile stiffness (J=200kN/m) has a much wider area of soil reaching 1% shear strain than that with a relatively higher tensile stiffness (J=400kN/m). No shear strain greater than 1% exists in the slopes with the tensile stiffness, J≥800kN/m. It is shown in Figure 4(a) that there exist two potential slip surfaces in the slope. It is reasonable to conclude that slip surface will develop at an earlier stage in the slope with a lower tensile stiffness than in the higher tensile stiffness. In other words, the former case is closer to the limit equilibrium state than the latter case although they have an identical factor of safety based on the limit equilibrium method.



(a) J=200kN/m



(b) J=400kN/m

Figure 4. Contours with 1% shear strain developed in the slope

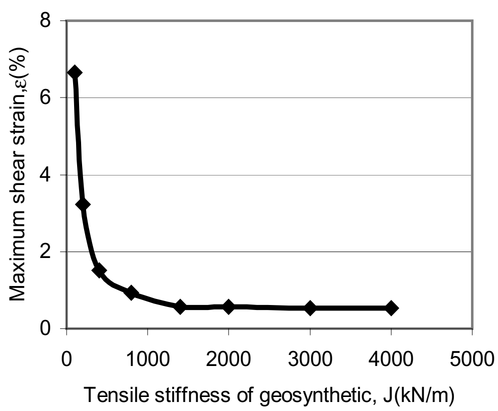


Figure 5. Influence of tensile stiffness of geosynthetic on the maximum shear strain

The variation of the maximum shear strain in the slope with the tensile stiffness of geosynthetic reinforcement is shown in Figure 5. It is clearly shown that the maximum shear strain decreases with an increase of the tensile stiffness especially when the value of the tensile stiffness is less than 1000kN/m.

In Figure 6, the two potential slip surfaces (Surface 1 and Surface 2) based on the higher shear strains are compared with the critical slip surfaces determined using the simplified Bishop's method. It is interesting to notice that the first potential slip surface is close to the critical slip surface for an unreinforced case while the second potential slip surface is close to the critical slip surface for a reinforced case. This phenomenon can be explained as follows: the first potential slip surface develops when the tensions in reinforcements have been rarely mobilized and then the surface shifts to the second potential slip surface when the reinforcements carry more loads. This phenomenon can also be seen in the cases with a higher tensile stiffness of geosynthetic reinforcement by analyzing the data. However, it is not that obvious because the geosynthetic reinforcements with a higher tensile stiffness pick up the force more quickly.

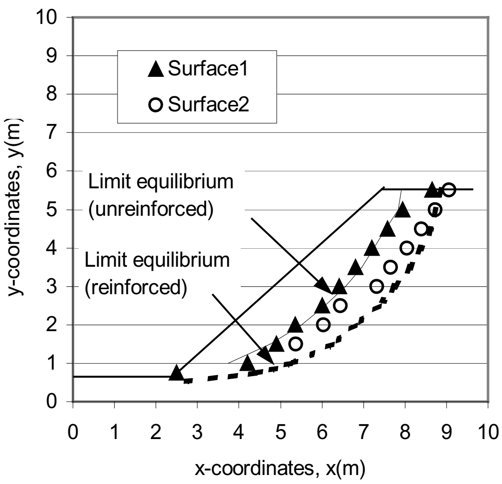


Figure 6. Potential failure surfaces from the numerical and limit equilibrium analyses (J=200kN/m)

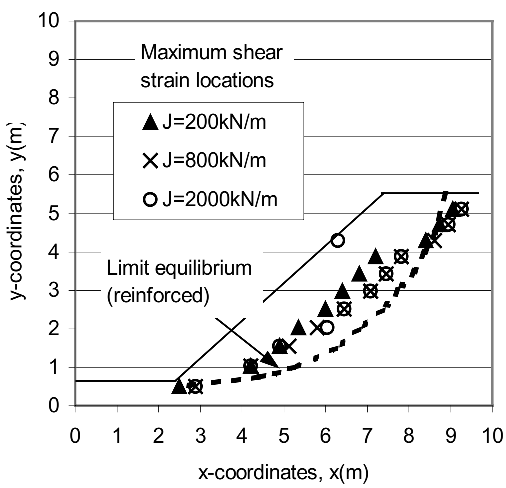
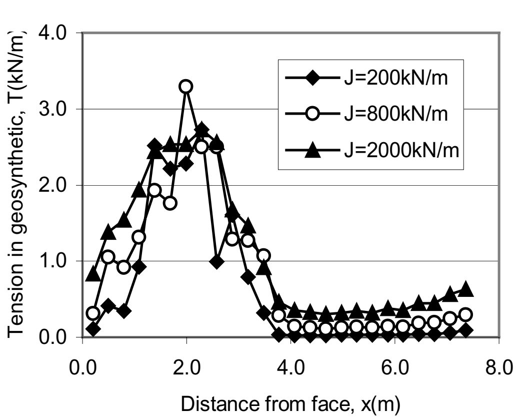
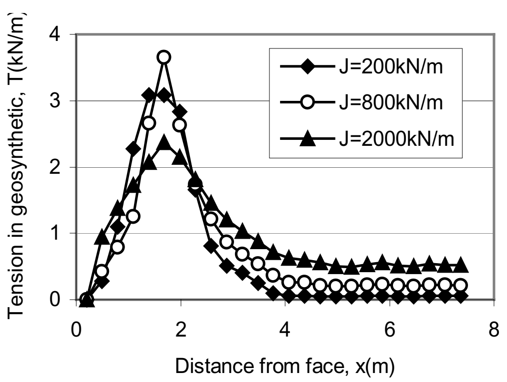


Figure 7. Locations of maximum shear strains

The positions of the maximum shear strains for three slopes with different tensile stiffness of geosynthetic reinforcements are presented in Figure 7. These locations are also plotted against the critical slip surface for the reinforced case determined by the simplified Bishop's method. It is shown that the two cases with J=800kN/m and J=2000kN/m basically have an identical potential slip surface. One point on the slope for the case with J=2000kN/m indicates the development of a localized high shear strain at the location of geosynthetic reinforcement. For a geosynthetic reinforcement with a higher stiffness, a tensile force is transferred farther along the reinforcement as discussed in the tensile force distribution section. Near the slope face, a certain magnitude of force can create a large shear strain due to the low confinement. The development of this localized high shear strain can also be contributed by the interface properties between soil and cable elements and properties of surficial clay and backfill material.



(a) Reinforcement 3



(b) Reinforcement 1

Figure 8. Tensile force (tension) distribution along geosynthetic reinforcements

3.4 *Tensile force distribution*

The tensile force distribution in geosynthetic reinforcements are presented in Figure 8. It is shown that the geosynthetic reinforcement with a medium tensile stiffness developed the highest tensile force while the geosynthetic reinforcement with a higher tensile force transferred the force toward the front and end of the reinforcement. Therefore, the reinforcement with a high tensile stiffness spreads the force widely. In addition, this reinforcement mobilizes the pullout resistance more quickly and uniformly.

If the factor of safety for reinforcement is defined as the tensile strength divided by the maximum tensile force, the three cases have factors of safety ranging from 5.5 to 8.0. They are much higher than the overall factor of safety for these slopes.

4. CONCLUSIONS

This paper has investigated the influence of tensile stiffness of geosynthetic reinforcement on the performance of reinforced slopes. The numerical study reveals that geosynthetic reinforcements with higher tensile stiffness can reduce horizontal and vertical displacements of the slope and minimize the maximum shear strains developed in the slope. The inclusion of geosynthetic reinforcements makes the potential slip surface shift from the critical slip surfaces for the unreinforced to the reinforced slope. The geosynthetic reinforcement with a higher tensile stiffness spreads the tensile force more widely and mobilizes the pullout resistance more quickly and uniformly.

The results indicate that there is a threshold value of stiffness (in this paper it is about J=1000kN/m), above which the effects of stiffness have been significantly reduced. In practice and for typical cohesionless backfill, one can use such a threshold to establish a minimum acceptable value of stiffness if performance is of concern.

It should be noted that the calculated displacements are relevant to slopes subjected to their own weight. In such a case, it is likely that these displacements will develop during construction. This would not be the case, however, if surcharge load, such as a bridge foundation, will be placed on the crest post construction.

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