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FE analyses of reinforced slopes using the shear strength reduction technique

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ABSTRACT: Geosynthetic reinforced soil is recently one of the most commonly used soil improvement techniques to increase the stability of unreinforced slopes. Limit equilibrium methods are widely used in design practice. However, it is often difficult to assess the accuracy of these solutions. This work is an attempt to model reinforced soil system using nonlinear finite element analyses to investigate the failure mechanisms of geosynthetic reinforced soil slopes and finding out the slip surface, the safety factor, and studying the effect of the wrap-back facings on reinforced soil slope. A 2-D elasto-plastic finite element program, considering the shear strength reduction concept, is used. The results showed that the slip surface could be determined accurately using the proposed method in this research. The safety factor could be obtained and in good agreement with experimental work. For reinforced embankments constructed with wrap-back type facings, the backed layers appear to be effective in sharing the load carried by the main layers of reinforcement, and finally, it appears that the shear strength reduction technique was successful and reasonable in predicting the overall behavior of reinforced embankments.

1 INTRODUCTION

The literature now contains numerous examples demonstrating the use of the finite element method (FEM) for predicting the performance of specific laboratory model tests or field prototypes. In this paper, the results of FEM are used for determination accurate slip surface of reinforced embankment with geotextile, safety factor, and effect of wrap-back type facings on the stability of the embankment. The materials typically used to reinforce soil are relatively light and flexible, and though extensible, possess a high tensile strength. As a result, various earth structures reinforced with geosynthetics are being constructed worldwide with increased frequency, even in permanent and critical applications.

Research and field studies have developed a solid basis for analysis and design of reinforced slopes and embankments and it is possible to design with confidence slopes and embankments that are reinforced with geotextiles, geogrids, and steel mesh. The principal function of reinforcement in the slopes and embankments is to provide stabilizing forces through friction between the reinforcement and the soil.

Modes of failure of reinforced slopes and embankments include tensile failure of the reinforcement, pullout of the reinforcement from the soil, excessive deformation of the reinforcement and also raveling of the soil from between layers of reinforcement at the face of steep slopes (Ingold 1982). Reinforced slopes are currently analyzed using modified versions of the classical limit equilibrium slope stability methods. All these methods try to fulfill the required criteria in order to secure the stability of the slope on an assumed failure surface that could be a circle or log spiral or two-wedge part. The main drawbacks of limit equilibrium analysis are its inability to deal with displacements and its limited representation of the interaction between dissimilar or incompatible materials comprising the slope. Typically, adequate selection of materials properties and safety factors should ensure acceptable displacements, including safe level of reinforcement deformation. One consequence of this is a perceived overconservatism in design.

2 EXTENSIBILITY OF REINFORCEMENTS

Most currently available geosynthetic reinforcing materials meet the criterion for extensible reinforcements in almost all practical applications. As the geotextile used to reinforce the slopes are extensible, the soil strength is expected to mobilize rapidly, reaching its peak strength before the reinforcements achieve their ultimate strength. This rationale led to the recommendation, particularly by European investigators and design guidelines, to adopt the critical state soil friction angle (instead of the peak friction angle) for the design of geosynthetic reinforced slopes (e.g., Jewell 1991). However, common practice in the United States has been the use of the peak friction angle for the design of geosynthetic-reinforced slopes. Experimental results indicate that the stability of the structures with extensible reinforcements is governed by the peak shear strength and not by the critical state shear strength of the backfill soil (Zornberg et al. 1998a).

3 THE IDEA APPLIED IN THE FE ANALYSIS

The main purpose of this work is to find out the slip surface of the reinforced embankment with geotextile, as it is difficult to predict the slip surface for reinforced embankment with geotextile exactly. The idea in this study is as follows: as the reinforced structure with geotextile is a composite structure and as the geotextile is extensible, in the finite element calculation with increasing the shear strength reduction factor the slip surface move towards inside the slope, although, the stress in the reinforcement layers exceeds the allowable stress. That means if the breakage of the geotextile is simulated, the slip surface will start at the point of the first break of the geotextile (i.e., the point that reach to its maximum stress). However, in this research it is not necessary to simulate the breakage of the geotextile. The benefit from that idea is applied in this research. Therefore, the slip surface will be the surface corresponding to the first layer of the reinforcement that reaches its maximum allowable stress. In this study the slip surface could be obtained and compared very well with the results of the centrifugal test done by Zornberg et al. (1998a) that prove the success of the idea in this research.

4 NUMERICAL MODELLING

The best approach to understanding the behavior of a system is through observation of a full-scale prototype. This may not only be expensive and time consuming but also in many cases failure is not attainable due to the large scale of the prototype. Therefore, modeling by either physical and/or numerical methods seems to be rational alternative approaches. Despite inherent limitations existing in these two techniques, the combinations of physical and numerical approaches to gain insight into the behavior of a system could be cost-effective option i.e., calibrating a finite element procedure and performing parametric studies to shed light on prototype behavior.

Finite element analyses have also been used to investigate failure mechanisms of reinforced soil structures (e.g., Hird et al. 1990). Standard finite element techniques are useful for analysis of structures under working stress conditions. However, the obtained results vary with different failure criteria assumed in the analysis.

A 2-dimensional numerical analysis based on the shear strength reduction technique (in the calculations the backfill shear strength parameters was reduced gradually using the shear strength reduction factor) was applied to analyze stability of geotextile-reinforced embankment failed under self-weight in the geotechnical centrifuge. In the calculations, the gravity-turn-on method is used and the actual embankments constructions were not modelled. The slopes of 1:2 (1H: 2V) were analysed. Reinforcement lengths were long enough not to slip. A plane strain finite element analysis was used. The soil was modelled by 8 node isoparametric elements and the reinforcements modelled by bar elements, the reinforcement was assumed to be bilinear elastic materials, the backfill was assumed to be an elastic-perfectly plastic material with Mohr-Coulomb failure criterion. The lateral boundaries of the meshes used in the FE analysis were assumed to be perfectly smooth, i.e., only vertical movements were allowed.

The analysed slopes consist of 6, 9 and 12 equally spaced reinforcement layers, the slopes heights were 4.8, 8.5, 13.75 meter respectively as obtained from the centrifugal test results (for more details about the centrifugal tests for example, actual heights and the lineal scale, see Zornberg et al. 1998 b). The used parameters in this study were as follows: the backfill friction angle 39.5° and the dry density of the backfill $\gamma_s = 15.64$ kN/m^3 (actual values) the Young's modulus of the backfill, E_s, 25.0 MPa, Poisson's ratio, ν, 0.35, the backfill cohesion value was assumed to be 1 kN/m^2 to avoid numerical stability problems (assumed values) the modulus of elasticity of the geotextile, $E_{GTX,}$ used in the analysis is 250000 kN/m, and 150000 kN/m, the ultimate tensile strength of the geotextile used was equal to that of the centrifugal test, and the area of each geotextile reinforcement layer was 0.003 m^2/m. The geotextile layers were wrapped (folded back) at the slope face into the soil to provide a flexible facing. Perfect adherence between soil and reinforcement was assumed. This means that there is no slip between the soil and the reinforcement; the soil and reinforcement strain are the same at this interface. According to Ehrlich & Mitchell (1994) and others perfect adherence is a reasonable hypothesis under working stress conditions. Other similar numerical study also assumed the hypothesis of perfect adherence. Therefore, no interface elements were utilized in the analyses.

5 RESULTS AND DISCUSSIONS

5.1 *Determination of the slip surface*

One of the main problems in the reinforced slopes is the determination of the slip surface accurately. However, in the previous researches the assumed slip surface depends on different assumptions that led to uncertainties of the results e.g. (Matsui et al. 1999). From the FE analysis results and by drawing the maximum shear strain distribution when the stresses in any reinforcement layer reach their maximum stress, the slip surfaces of all the analysed cases could be obtained. By comparing the analytical results with that of the experimental work done by Zornberg et al. (1998a), it is found that the slip surfaces are almost identical as shown in Figs 1, 2, and 3.

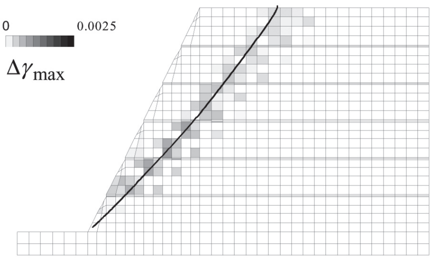

Figure 1. Slip surface indicated with maximum incremental shear strain ($\Delta\gamma_{max}$) for the case of 6 layers reinforced embankment.

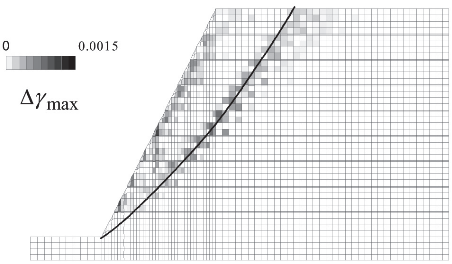

Figure 2. Slip surface indicated with maximum incremental shear strain ($\Delta\gamma_{max}$) for the case of 9 layers reinforced embankment.

The solid lines in these figures are the slip surfaces from the centrifugal test. From these figures it can be seen that the slip surface could be obtained accurately and it is very clear and in a very good agreement with the experimental results done by Zornberg et al. (1998a).

Failure of all models in this study was characterized by the development of a well-defined shear surface approximately through the toe of the slope. However, the calculation results show that the lower reinforcement layers were not the first to reach their

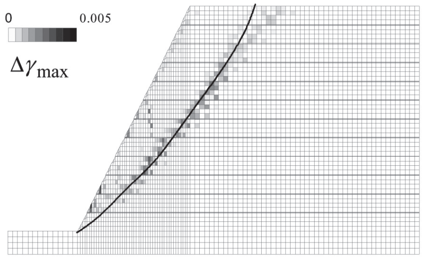

Figure 3. Slip surface indicated with maximum incremental shear strain ($\Delta\gamma_{max}$) for the case of 12 layers reinforced embankment.

tensile strength as is implied by current design methodologies, which assume a triangular reinforcement tension distribution with depth with a maximum tension at the base of the slope (the position of the layer that reach first to the maximum stress is not fixed, it depends on the geometry of the slope. In this study it was near the middle of the slope and it will moves down with increasing the slope until reaches the bottom reinforcement when the slope is 90 degrees i.e., vertical wall).

By comparing the FEM results with that of the experimental work, it can evaluate the success of the idea in this research.

5.2 *Safety factor of reinforced slopes*

From the results of an internally instrumented reinforced soil wall, Jaber and Mitchell (1990) noticed that stress redistribution occurred across the height of the wall before failure of the structure. In that investigation, even brittle aluminum reinforcement strips were deformable enough to redistribute the stresses across the whole height of the wall and, therefore, take advantage of the tensile strength of all reinforcement layers before failure.

As the geotextiles are more ductile reinforcements, at the moment of failure, the strain in the reinforcement will exceed the allowable strain. Therefore, there must be compromise between the stress and strain in the reinforcement and that can be satisfied using numerical analyses. For most routine slope projects, limiting the design value of the allowable reinforcement force so that the resulting deformation should not interfere with the appearance or function of the slope (Jewell 1991).

To detrmine the safety factor, the relations between the displacement and the shear strength reduction factor (F) have been plotted as shown in Figs 4 and 5 for the cases of 6 and 9 reinforcement layers respectively. As shown in these figures the safety factor can be determind and it is in very good agreement with the safety factor calculated by Zornberg et al. (1998a), while the difference in the safety factors is less than ±10%.

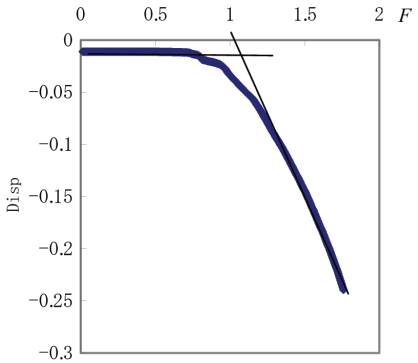

Figure 4. Displacement versus shear strength reduction factor for the case of 6 layers of reinforcement.

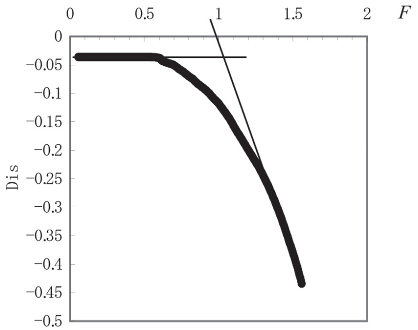

Figure 5. Displacement versus shear strength reduction factor (F) for the case of 9 layers of reinforcement.

6 EFFECT OF WRAP-BACK LAYERS

Current design of geosynthetic-reinforced slopes with wrap-back type facing does not take into account the contribution of reinforcement overlapping from the wrapped layers in the internal stability of the of the structure. As the function of the wrap back layers is generally considered to form the facing and to be for protecting the soil at the face from raveling.

In this study the overlaps were modeled as additional short reinforcement layers. The model of 9 primary reinforcement layers in the first set of analyses that did not consider the overlaps and a total of 18 reinforcements were used in a second set of analyses that modeled the overlapping layers. It is found that the geotextile overlaps contributed to the stability of the slope by reducing the stress in the main layers. However, disregarding the effect of overlaps may be a conservative assumption for design. These findings agrees with results of the centrifugal experimental done by Zornberg et al. (1998b) and may partly explain the conservatism of current analytical and design methods for this type of reinforced soil structure.

7 CONCLUSIONS

On the basis of the comparisons between numerical technique applied in this study and model tests, it appears that the shear strength reduction technique was successful and reasonable in predicting the overall behavior of unreinforced and reinforced embankments. From the above study the following points could be obtained:

The slip surface can be determined accurately in this research.

The FS of the reinforced slopes could be obtained reasonably.

Numerical methods must be used in this type of composite structure because there are some factors that cannot be considered using the limit equilibrium methods.

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