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Probabilistic analysis of reinforced slope

Analyse probabiliste d‘une pente renforcée

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ABSTRACT: The paper presents the results of simple geosynthetic reinforced soil slopes using the shear strength reduction technique in combination with the finite element method (FEM). Results indicate that large reductions in the probability of failure by adding geosynthetic reinforcement. Therefore, the effect of variability of the soil friction angle on probabilistic results for unreinforced and reinforced purely frictional soil slopes was investigated. Reinforced slopes with horizontal layers of geosynthetic reinforcement can have different mechanisms of failure. In this paper, two major mechanisms of failure of reinforced slopes are investigated. External mechanisms occur when the critical slip surface passes beyond the reinforced zone. Internal mechanisms are characterised by failure surfaces that intersect all of the reinforcement layers. Probabilistic slope stability analysis of these two mechanisms is carried out using Monte Carlo simulation with different purely frictional soils.

RÉSUMÉ: Ce document présente les résultats des pentes renforcées par géosynthétique en utilisant la technique de réduction de la résistance au cisaillement en combinaison avec la méthode des éléments finis (MEF).
Les résultats indiquent qu'il ya une réduction importante de la probabilité de rupture en ajoutant les géosynthétiques. Par conséquent, l'effet de la variabilité d'angle de frottement sur la probabilité de rupture pour des pentes frottantes renforcées et non renforcées a été étudié. Les pentes renforcées par des nappes horizontales de géosynthétique peuvent avoir différents mécanismes de rupture. Dans cet article, deux principaux mécanismes de rupture des pentes renforcées sont étudiés. Les mécanismes de rupture externes se produisent lorsque la surface de glissement critique passe au-delà de la zone renforcée. Les mécanismes de rupture internes sont caractérisés par des surfaces de rupture qui coupent toutes les nappes de renforcement. L'analyse probabiliste de la stabilité des pentes de ces deux mécanismes est réalisée en utilisant la simulation de Monte Carlo avec différents angles de frottement.

Keywords: reinforced slope; probability of failiure; spatail variability; failure mechanism.

1 INTRODUCTION

Geosynthetics are the main materials used for increasing the resistance and stability of geotechnical structures all around the world. The current methods of design for such reinforcement are deterministic based on the same limit equilibrium procedures that are used for design of conventional unreinforced slopes with their failure mechanisms described by a circular arc (Kitch.1994), log-spiral (Leshchinsky and Boedeker. 1989) and two-part wedge geometries (Jewell.1991; Bathurst and Jones. 2001).

(Ferreira et al. 2016) carried out probabilistic analysis of simple reinforced soil slopes using coupled limit equilibrium-based circular slip method of analyses and Monte Carlo simulation. However, the LEM approach used has the disadvantage that the type of critical failure surface must be assumed a priori and an assumption must be made regarding the magnitude and distribution of available stabilizing reinforcement tensile forces.

More recently, a probabilistic analysis technique called the Finite Element Method (FEM) has been used to carry out probabilistic failure analyses of simple unreinforced soil slopes (e.g. Griffiths and Fenton. 2004; among others) and simple reinforced soil slopes (Luo et al. 2016). Similar investigations using the finite-element method (FEM) have also shown the important influence of soil uncertainty on probability of failure for unreinforced slopes (e.g. Griffiths and Fenton. 2004; Huang et al. 2010) and reinforced slope (Luo at al. 2017). It is reasonable to assume that the uncertainty in soil properties will also influence estimates of probability of failure for reinforced soil structures. This line of investigation and the link between the conventional deterministic (factor of safety) estimates and probability of failure has attracted less attention. This paper is an attempt in this direction.

2 PROBLEM CHOSEN FOR ANALYSIS

The influence of spatial variability of soil properties for reinforced slope has been the topic of active research recently (Ferreira et al.2016; Luo et al.2016; Javankhoshdel and Bathurst .2016; Luo and Bathurst.2017).

In this study, probabilistic analyses of reinforced slopes (or embankments) were carried out using the random finite element method (RFEM) with adaptive remeshing (Tab.1) to investigate the influence of spatially variable soil strength (Friction angle) for reinforced and unreinforced slope. The slope has been studied by (Luo et al.2016) as seen from Fig.1. The slope has a height of 5 m and a slope angle of 45°, the slope consists of a single soil layer with a unit weight of 18 kN/m3 and the unfactored friction angle of the soil was assumed as 30°, C=1Kpa. This small value of cohesion has been interpreted by (Luo et al .2016) (to minimize computation time and prevent numerical instability during finite element analyses).

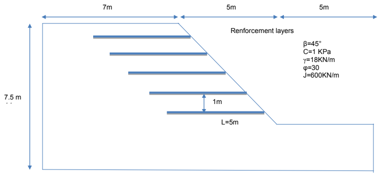

Figure 1. Reinforced slope model.

The type of geosynthetic used by (Luo et al.2016) is the a uniaxial geogrid with the factored reinforcement strength, length and spacing were selected using the deterministic LEM-based design charts by (Bathurst RJ.2001). However, the factored tensile strength (T_{ult}) of geogrid is T_{ult}= 72Kn/m (including the reduction factors due to installation damage, creep or degradation) and the axial stiffness (J) of the reinforcement is J= 600 KN/m. It is important to note that the SSR method used in this paper does not divide reinforcement loads by the strength reduction factor (factor of safety) in an analysis. The strength reduction factor is applied only to the strengths of slope materials, (Duncan and Wright.2005) prefer this approach.

Table 1 Control parameters for adaptive meshing

Parameter	
Initial number of elements	1000
Maximum number of elements	1000
Mesh refinement factor	0.25
Mesh coarsening factor	1.5
Number of adaptive iterations	3
Control variable for adaptive meshing	Shear dissipation

3 DETERMINISTIC ANALYSIS

The FEM was used to calculate deterministic factors of safety, using a range of soil friction angles (20°–50°). The tensile strength (72 kN/m) was used as the horizontal stabilizing force in all reinforcement layers. Figure .2 shows the results of deterministic analyses to investigate the influence of reinforcement on a factor of safety.

The plots show that the reinforced slope has a higher factor of safety. For example, in the case of an unreinforced slope with a friction angle of 30, the factor of safety is 0.78 which means the slope has failed. On the other hand, a reinforced slope with the same friction angle has a factor of safety of 1.35 which means the slope has stable. It is clear that results from the present study in a good agreement with those of (Luo et al. 2016).

However, In the FEM analyses with fixed tensile strength, the failure mechanism move from external type to internal type as the friction angle increases. Therefore, for a weak soil (low φ), the failure mechanism favored is an external failure mechanism Figure 3 however, for a strong soil (higher φ), the failure mechanism favored is an internal failure mechanism Figure 4.

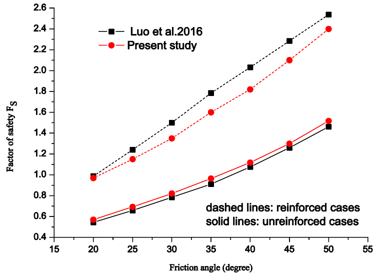

Figure 2. Factor of safety from deterministic analyses versus mean friction angle for unreinforced and reinforced soil slopes.

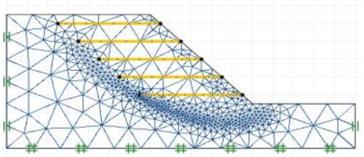

Figure 3. Example failure mechanism (external) for friction angle 25°(Fs=1.24)

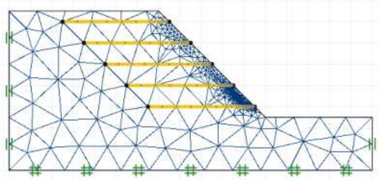

Figure 4. Example failure mechanism (internal) for friction angle 40°(Fs=1.82)

4 PROBABILISTIC ANALYSIS

Probabilistic slope stability analysis was carried out using the random finite element method (RFEM) which combines the strength reduction method with random fields that are generated using Monte Carlo simulation. Each random field of shear strength parameter was generated using the Karhunen-Loève Expansion.

In this section, the influence of spatial variability of soil friction angle on probabilistic outcomes for reinforced and unreinforced slopes is examined. According to the results of a literature review by (El-Ramly et al. 2003), the autocorrelation distance is within a range of 10–40 m in the horizontal direction, while in the vertical direction, it ranges from 1 to 3 m. As an illustration, an exponential autocorrelation structure with θ_h=30 m and θ_v=4 m is used. Figures 5 and 6 show the effect of spatial variability of friction angle on probability of failure for COV_φ=0.2 and 0.5 respectively. Two important observations can be made from these Figures. First, the reinforcement reduces the probability of failure by a large amount for weak soil (Low φ) than strong soil with spatial or random variability cases. For an unreinforced slope with a friction angle of 35° and a coefficient of variation COV_φ = 0.2, the probability of failure is 69%. For reinforcement slope, the probability of failure decreases to 12% for the spatial variability case (present study).

The second important observation made from these Figures is that, the spatial variability of friction angle has a very significant effect on probability of failure for reinforced slope than unreinforced slope. In which, for an unreinforced slope with a friction angle of 40° and a coefficient of variation COV_φ = 0.5, the probability of failure is 58%. For reinforcement slope, the probability of failure decreases to 42% for the spatial variability case. It can be seen that for the spatial variability of friction angle, the reinforcement becomes less effective in reducing the probability of failure when the coefficient of variation of friction angle increases. The same result found by (Luo et al.2016) for the random variabile case.

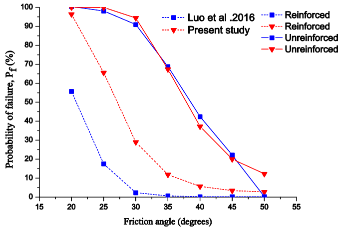

Figure 5. Probability of failure versus mean friction angle for cov_φ=0.2.

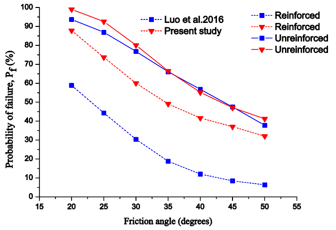

Figure 6. Probability of failure versus mean friction angle for cov_φ=0.5.

Figures 7 (a and b) show the heterogeneity of friction angle and the associated failure mechanisms with spatial random fields of friction angle for φ=20°, 45° and COV_φ=0.2. These figures show that the heterogeneity of friction angle varied between 13° to 24° for friction angle φ=20°. However, for friction angle φ=45°, its heterogeneity varied between 29° to 55°. It is clear that the heterogeneity of friction angle is larger for strong soil(φ=45°) than the weak soil (φ=20°). It can be seen that both the failure mechanisms were observed in deterministic analysis. Therefore, as a result, when a slope supports a weak soil (low friction angle), the failure mechanism obtained is an external failure mechanism however, for strong soil, the failure mechanism obtained is an internal failure mechanism.

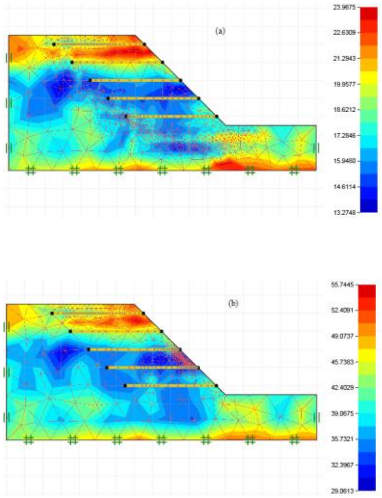

Figure 7. Typical realization of random fields of friction angle and corresponding critical failure surfaces (a) $\varphi=20°$, $COV_{\varphi}=0.2$, $\theta_v=4m$; $\theta_h=30m$ (b) $\varphi=45°$, $COV_{\varphi}=0.2$, $\theta_v=4m$; $\theta_h=30m$.

5 CONCLUSION

This paper considered the influence of spatial variability of friction angle on the slope reliability based on the random finite element method (RFEM) with adaptive remeshing, which combines the strength reduction method with random fields that are generated using Monte Carlo simulation. Each random field of strength parameters was generated using the Karhunen-Loève Expansion.

Based on the studies undertaken in this paper, the following concluding remarks can be made:

The reinforcement reduces the probability of failure by a large amount for weak soil (Low φ) than strong soil with spatial or random variability cases. Therefore, the reinforcement becomes less effective in reducing the probability of failure when the coefficient of variation of friction angle increases.

The spatial variability of friction angle has a very significant effect on probability of failure for reinforced slope than unreinforced slope.

As a result, when a slope supports a weak soil (low friction angle), the failure mechanism obtained is an external failure mechanism however, for strong soil the failure mechanism obtained is an internal failure mechanism.

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