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Reliability analysis of internal stability of geosynthetic reinforced soil walls

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ABSTRACT: Traditionally factors of safety have been used in design of geosynthetic reinforced soil walls to compensate for uncertainties in loads and resistances due to spatial and temporal variability. Factors of safety are normally selected empirically, i.e., based on past experience or experience with similar engineering structures. There is not a formal relationship between the factor of safety and the probability of failure. The intrinsic empiricism in the factor of safety approach may lead to instability when uncertainties are greater than anticipated or conversely to over design when uncertainties are smaller than anticipated. In this paper a parametric study was conducted using Monte Carlo simulation to assess how uncertainty in design parameters affects the probability of internal failure of geosynthetic reinforced walls. The internal stability analyses carried out by Bishop‘s simplified method. Geo-Slope/w software was used to compute the factor of safety of geosynthetic reinforced soil wall. The results of the studies indicate that the mean and coefficient of variation of the backfill friction angle, mean unit weight of the backfill, mean and coefficient of variation of the tensile strength of geosynthetic, mean value of surcharge, mean geosynthetic vertical spacing, and mean geosynthetic length have a significant effect on the probability of internal failure of geosynthetic reinforced soil walls.

1 INTRODUCTION

Reinforced soil structures, such as mechanically stabilized earth and geosynthetic reinforced soil walls have been shown to be feasible alternatives to conventional earth retaining structures. Increased usage of these structures have seen in recent years and designs are becoming more aggressive with taller walls and wider variety of reinforcing and facing materials. Analysis method that balance moments or forces due to load and resistance are usually used for design of geosynthetic reinforced walls. Traditionally factor of safety have been used in design to compensate for uncertainties in loads and resistances due to spatial and temporal variability. Factors of safety are normally selected empirically, based on past experience with similar structures. A formal relationship does not exist between the probability of failure of the wall and the computed factor of safety (Christopher et al. 1994, Low and Tang 1997, Zornberg et al. 1998).

Reliability calculations provide a means of evaluating the combined effects of uncertainties and a means of distinguishing between conditions where uncertainties are particularly high or low. Christian et al. 1994, Tang et al. 1999, Duncan 2000 and others have described excellent examples of use of reliability in geotechnical engineering and clear exposition of the underlying theories. In this paper the spatial variability effects of reinforcement element properties and soil properties on internal stability of a typical geosynthetic reinforced wall were studied.

2 GEOSYNTHETIC REINFORCED WALL MODEL

In this study walls were simulated that had different height (H), length of reinforcement (L), vertical spacing of reinforcement elements (V_s), backfill unit weight (γ), backfill friction angle (ϕ), soil reinforcement interface friction angle (δ), surcharge (q) and tensile strength of geosynthetic (T). The reinforced geosynthetic wall that was modeled is shown schematically in Fig. 1. The wall height varies between 4 to 8 m, and the distance from retained soil to wall facing is set at 8 m. The reinforcement length to wall height ratio (L/H) was considered 0.7. This ratio is typical for all mechanically stabilized earth walls (AASHTO 1992). The backfill reinforced soil and retained soil were assumed to be same and cohesionless which have a mean friction angle (μ_ϕ) from 25 to 42 (deg.), mean unit weight (μ_γ) ranging from 15 to 22 kN/m^3 and mean reinforcement strength (μ_T), from 16 to 24 kN/m. Also a dense to very dense soil was assumed to be under the wall, so that failure would not occur trough the foundation. Rigidity of the wall facing was not considered in stability calculations because the facing rigidity reduces deformation of the wall and can increase the stability of reinforced soil structures (see Tatsuoka 1992). Thus the method of study described in this paper is more appropriate for reinforced earth wall using flexible facing such as wrap around system (Fig. 1).

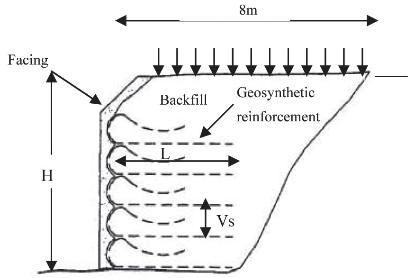

Figure 1. Geosynthetic reinforced wall with flexible facing.

In this study only planar reinforcement (geotextiles or geogrids) layers were considered and load transfer mechanism between soil and reinforcement was assumed to be frictional.

3 STABILITY ANALYSIS

The tie-back approach and slope stability approach are used most frequently among the limit equilibrium stability analysis. The tie-back approach is based on an analysis of horizontal forces due to lateral earth pressure. A planar failure surface is typically assumed, and reinforced that extend beyond the failure zone resists pullout (Claybourn and Wu 1991). The slope stability method for geosynthetic reinforced walls and reinforced steep slopes normally use a conventional method of slices with additional forces by reinforcement extending beyond the slip surface as resistance component. Among the slope stability methods, circular or log spiral failure surface is typically assumed as has been observed experimentally.

Bishop's simplified method by using circular failure surfaces, predicts the factor of safety as accurately as more rigorous methods such as Spencer, Morgenstern, Correia and Janbo that satisfy all conditions of equilibrium.

In this study the Geoslope/w software was used to calculate the stability of reinforced wall by using Bishop's simplified method. Resistance forces generated by geosynthetic layer were assumed to act horizontally. The mobilized resisting force due to the reinforcement (T_m) is set as smaller of force developed by the soilœreinforcement interface friction (F_{int}) as Eq. (1) and the allowable tensile strength of the geosynthetic (T_{allow}).

$$F_{int} = 2\sigma'_v L_e \tan(\delta) \quad (1)$$

where σ'_v = vertical effective stress, L_e = effective length behind the slip surface and δ = interface friction angle.

4 PROBABILISTIC ANALYSIS OF WALLS

Many source of uncertainty exist in geotechnical analysis ranging from the material parameters to the testing techniques and methodology of analysis. Probabilistic analyses were used to quantify the uncertainty due spatial variability in soil properties, geosynthetic properties, geometry of the wall and external surcharge loads. The process used in this study for probabilistic analysis of a geosynthetic reinforced wall is shown schematically in Fig. 2 (see Chalermyanont and Benson 2004).

The input parameters characterized as random variables that described uncertainties in the soil properties, geosynthetic properties, and loads of the wall, is used to calculate the internal stability of the wall.

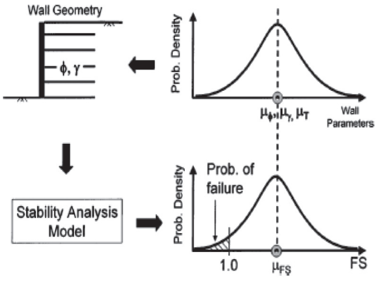

Figure 2. Probabilistic analysis of a geosynthetic reinforced wall.

The probability of failure (P_f) is then calculated as probability of the factor of safety being less than unity. The parametric study of probability of failure was calculated as the flowchart showing in Fig. 3. Reinforcement length, soil properties and vertical spacing for geosynthetic layers were randomly sampled from a normally distributed number generator and input to software to compute the factor of safety.

This process was repeated N_r times and probability of failure was calculated using Eq. 2.

$$P_f = P(FS < 1) = \frac{N_f}{N_r} \quad (2)$$

where N_f = number of realization where the FS < 1.

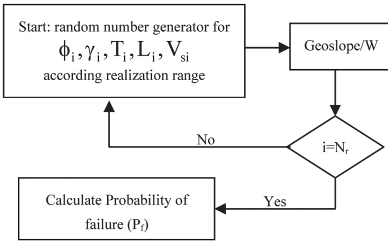

Figure 3. Flowchart for parametric study of P_f.

For base case study a set of simulations was conducted to clarify how P_f varies with N_r. The base case wall that used for parametric study had the following parameters: wall Height (H) = 5 m, length of reinforcement to height (L/H) = 0.7, mean of friction angle of backfill (μ_ϕ) = 32 deg., coefficient of variation of the friction angle (COV_ϕ) = 10%, mean unit weight (μ_γ) = 20 kN/m^3 and (COV_γ) = 5%, mean allowable tensile strength of geosynthetic (μ_T) = 18 kN/m and (COV_T) = 5% and $\delta/\phi = 0.75$. the vertical spacing of the geosynthetic (V_s) = 0.6 m, nine layers of reinforcement were used, and the first layer was installed 0.2 m above the bottom of the wall. The relationship between P_f and N_r for the base case is shown in Fig. 4.

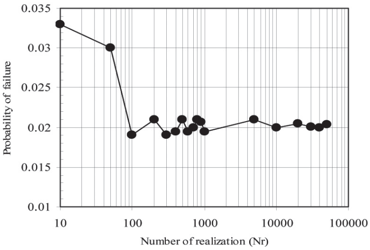

Figure 4. Probability of failure as function of the number of the realizations.

The P_f varies from 0.019 to 0.033 and is fairly constant about 0.021 when N_r is greater than 10000. Therefore for the base case wall study as a minimum 10000 realization are necessary to establish P_f. An initial parametric study was conducted to find out those variables that have considerable effect on the probability of failure of wall. In this study if the probability of failure changed by more than one order of the magnitude from the base case ($P_f = 0.021$), the parameter was considered to be significant.

5 PARAMETRIC STUDY OF WALLS

Design parameters were changed one at a time while the others parameters were kept constant at values corresponding to the base case study. The range of variation for each parameter was cited in section 2.

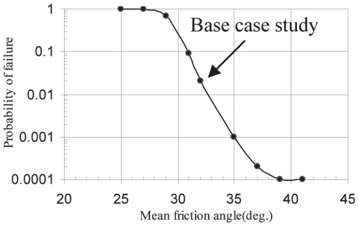

Figure 5. Sensivity of P_f to mean value of friction angle.

Results of the simulations are shown in Figs. 5 to 10 in terms of P_f.

5.1 *Effect of ϕ and γ of backfill soil*

As it was anticipated, results of simulation were shown that P_f decreases rapidly with increasing μ_ϕ. Accordingly μ_ϕ and COV ϕ are significant parameters affecting internal stability of walls (Figs. 5 and 8). Also P_f varies by more than three orders of magnitude as μ_γ is varied. Thus, μ_γ is significant variables because it has a global effect on the driving and resisting moment on the wall (Figs. 6 and 8).

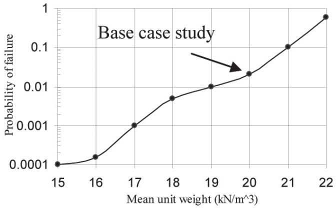

Figure 6. Sensivity of P_f to mean value of unit weight of backfill.

5.2 *Effect of tensile strength of geosynthetic*

The tensile strength of geosynthetic was varied from 8 to 25 kN/m and COV_T was set to 5%. As shown in Figs. 7 and 8 probability of failure varies by about four orders of magnitude with a small change in μ_T and two orders of magnitude with COV_T. It was shown that P_f is particularly sensitive to μ_T. Because the internal stability of geosynthetic reinforced wall relies on the average resisting force provided by the reinforcement layers. So μ_T is significant parameter.

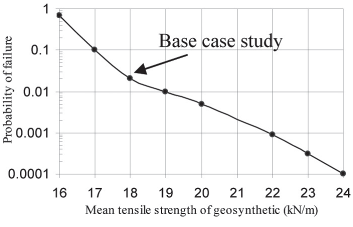

Figure 7. Sensivity of P_f to mean value of tensile strength of geosynthetic.

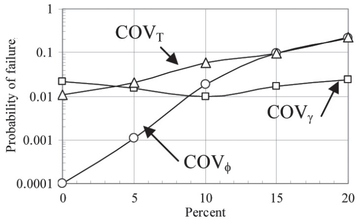

Figure 8. Sensivity of P_f to COVϕ, COVγ and COV$_T$.

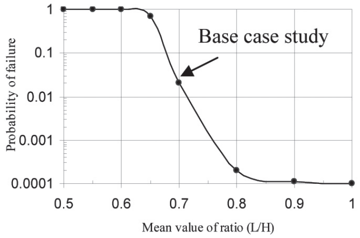

Figure 9. Sensivity of P_f to mean value of ratio (L/H).

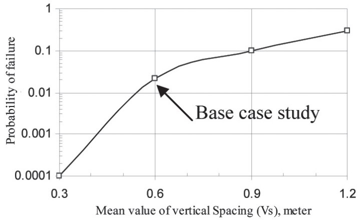

Figure 10. Sensivity of P_f to mean value of vertical spacing of reinforcement layers.

5.3 *Effect of reinforcement length and spacing*

Reinforcement length to height ratio (L/H) is conventionally equal to 0.7. In this parametric study the mean ratio ($\mu_{L/H}$) was varied 0.5 to 1 as shown in Fig. 9. It was shown that for ($\mu_{L/H}$) between 0.5 to 0.65 the P_f is near unity and then decreases rapidly as ($\mu_{L/H}$) is increased beyond 0.7. In this study P_f is not affected for ($\mu_{L/H}$) greater than 0.85 (Fig. 9).

Also result from simulations showing how mean value of vertical spacing (μ_{VS}) of reinforcing layers affect P_f, (see Fig. 10).When (μ_{VS}) become smaller, more reinforcing layers are added, so the resisting force increase and P_f decreases. Thus (μ_{VS}) is an important parameter.

6 CONCLUSIONS

In this paper a parametric study was conducted to determine which design parameters had a significant effect on the probability of wall failure. Results of the parametric study showed that the mean value of backfill friction angle and its coefficient of variation, the mean value of reinforcement tensile strength and its coefficient of variation, mean backfill unit weight and its coefficient of variation, mean reinforcement length to height and mean reinforcement vertical spacing effect on probability of internal failure of geosynthetic reinforced soil wall.

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