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Innovative use of geosynthetics for repair of slope failures along irrigation/drainage canals on soft ground

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ABSTRACT: Slope failures are so frequent along in irrigation canals on the soft clay foundation. The innovative use of dual function geotextile to solve this problem is presented in this paper. The dual function geotextiles not only act as earth reinforcements but also function as drainage paths to dissipate the excess pore pressure and hence increase in the strength of the soft foundation with time. The theoretical background for the analysis of slope stability as well as the interaction behavior between the geosynthetics and soil are examined. Based on the shear test results of the high strength geotextile reinforcement PEC200 embedded in the soft clay and weathered clay with different inclination angles, it is concluded that at a particular initial inclination angle, the resisting force due to geotextile is mainly controlled by the strength of the soil, regardless of the effective normal stress. The higher the soil strength, the greater the resisting force and the lower the limiting strain. The inclination factor, I_f, is only dependent upon soil strength, irrespectively of effective normal stress and initial inclination angle. Finally, the application of the high strength geotextile reinforcement for protection of the slope failure and the analysis are presented. There are two considerations for the slope stability analysis: A) with limitation of the foundation settlement and B) with the allowable large settlement.

1 INTRODUCTION

Chao Phraya Plain in Thailand is covered with soft clay deposits which causes many failures along the banks of irrigation canals. Research results in last two decades have proven that the geotextile reinforcements can improve the stability of the embankment on soft foundation with considerable savings (Bergado et al., 1994). It can also function as drainage paths to enhance the soil strength with time. The interaction behavior between soil and geotextile reinforcement has been investigated by many researchers (Fourier and Fabian, 1987; Buddhima et al., 1991; Long et al., 1997; and Bergado et al., 2000). However, the application of the dual function geosynthetic for slope protection has not been studied well. This dual function includes both reinforcement and drainage. An attempt to critically examine the theoretical aspects and interaction behavior between soil and geotextile is made in this paper. Direct shear test on remolded soft clay and weathered clay with geotextile reinforcements were performed to investigate the interaction behavior. The high strength geotextile, PEC200 is utilized in this study. Limit equilibrium method is finally used to predict the factor of safety of embankments reinforced by the high strength geotextile by employing the SLOPE/W Program.

2 THEORETICAL BACKGROUND

2.1 *Slope stability analysis*

Limit equilibrium analysis with a circular surface is commonly used in conventional design of geotextile reinforced embankment on soft ground. As shown in Fig. 1, the geotextile reinforcement in case that the reinforcement is fully anchored is calculated by following equation (Bonaparte and Christopher, 1987).

$$T_r = T(\cos\beta + \sin\beta\tan\phi') \qquad (1)$$

where T_r is the resisting force due to the geotextile reinforcement; T is the mobilized tensile force in the reinforcement; β is the angle between the direction of mobilized tension force and tangential direction; and ϕ' is the friction angle of the embankment fill.

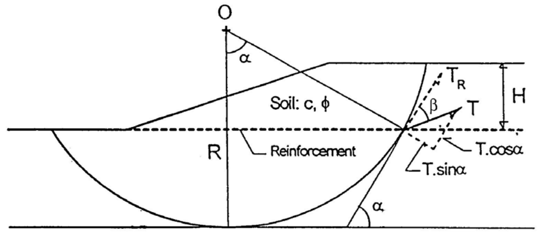

Figure 1. Assumptions on the behavior reinforcement force (Bonaparte and Christopher, 1987).

Selections of the mobilized tensile force and its direction, β are a key step for the calculation. The magnitude of this mobilized tensile force is dependent upon the limiting strain, ε_{lm}, which is controlled by the deformation of the embankment foundation system and the stress-strain behavior of the reinforcement. Long et al. (1997) have proposed an approach for determination of the limiting strain as follows:

$$\varepsilon_{lm} = \varepsilon_c + \varepsilon_{lc} \qquad (2)$$

where ε_c is the critical strain corresponding to the critical height (just prior to the primary failure or bearing failure of foundation soil), and ε_{lc} is the localized strain associated with the development of slip surface at the onset of failure caused by the reorientation (bending) of reinforcements. Based on full-scale test embankments with different types of geotextile reinforcement, it was demonstrated that the value of ε_c could be taken as 2.5% and 3.0%, irrespective of geotextile stiffness. The localized strain, ε_{lc} is determined by the following equations:

$$\varepsilon_{lc} = 225 I_f S^{-0.4} (\%) \qquad (3)$$

where S is the in-soil stiffness of geotextile determined as secant stiffness at 5% strain; and I_f is the inclination factor. This equation is derived from curve fitting method in which the ε_{lc} was calculated from FEM with variation of I_f and S.

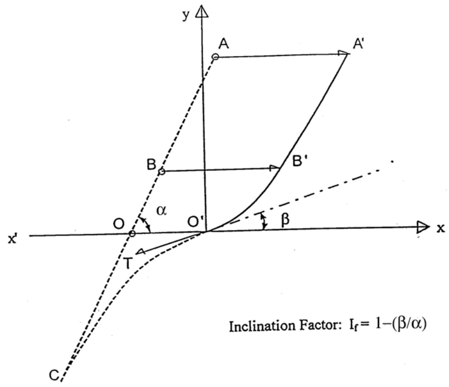

Figure 2. Schematic diagram for calculating the inclination factor of the mobilized tension force

$$I_f = 1 - \frac{\beta}{\alpha} \tag{4}$$

where α is the angle between the direction of the geotextile and tangential direction as shown in Fig. 2.

2.2 *Design consideration*

The design method for geotextile reinforced embankment on soft clay using circular slip analysis incorporating the compatible deformations between soil and geotextile is recommended as follows:

1. Design for the bonded length: as shown in Fig. 3, the reinforcement length should be long enough to prevent the pullout failure. The pullout force resistance due to the effective length, F using in the Limit equilibrium analysis is calculated as

$$F = \frac{L_e}{L} \times F_p \tag{5}$$

where L_e is the effective length, L is the bonded length, F_p is the pullout force resistance. Details of determination of the pullout resistance can be referred to Bergado et al., 2001.

2. Design for slope stability: based on Fig. 1 and Eq. 1, the slope stability analysis can be done by two considerations.

A) With limitation of foundation deformation, the mobilized tensile force in geotextile should be calculated with the limiting strain at $\varepsilon_{lm} = \varepsilon_c$, which is about 3%. The mobilized tensile force is in the horizontal direction ($I_f = 0$).

B) With allowable large settlement, the mobilized tensile force is calculated with the limiting strain at $\varepsilon_{lm} = \varepsilon_c + \varepsilon_{lc}$. The direction of the mobilized tensile force is governed by I_f.

The mobilized tensile force can be obtained from an in-air tension test of geotextile corresponding to the value of ε_{lm} which is in terms of I_f and S. The direct shear test of soil with geotextile is, thus, necessary to obtain these parameters.

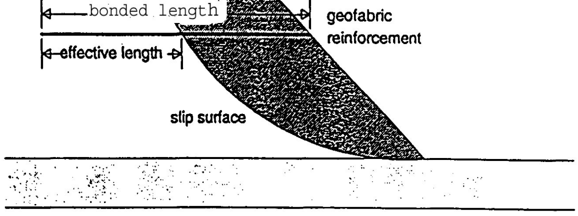

Figure 3. Modeling a geotextile reinforcement as a line load.

3 LABORATORY INVESTIGATION

3.1 *Sample preparation*

The soils used in this study are weathered clay and soft clay, which were obtained from the campus of Asian Institute of Technology. The weathered clay and soft clay were sampled from a depth of 0.5 to 1 m and 3.0 to 4.0 m, respectively. The disturbed samples were stored in plastic containers. The soil properties are presented in Table 1.

Table 1. Properties of soils used.

Properties	Weathered clay	Soft clay
Liquid limit	59%	103%
Plastic limit	49%	43%
Unit weight (kN/m^3)	-	14.3
Color	Reddish-brown	Dark gray
Activity	-	0.87
Sensitivity	-	7.3
Maximum dry density (kN/m^3)	15.9	-
OMC	24.8%	-

3.2 *Preparation of geotextile*

The geotextile used in this investigation was PEC200 whose mechanical properties are presented in Table 2. It was cut to obtain a dimension of 500 mm length and 300 mm width. Grid lines were drawn on the center of the geotextile and it was subsequently installed in the shear box at certain angle of orientation.

Table 2. Mechanical properties of high strength geotextile

Properties	Test standard	Values
Nominal mass	ASTM D 3776	700 g/m^2
Thickness (under 2 kPa)	ASTM D 1777	2.4 mm
Tensile strength	ASTM D 4595	200 kN/m
Secant stiffness at 5% strain	ASTM D 4595	1700 kN/m
Elongation at break	ASTM D 4595	12%
Vertical permeability (2 kPa)	-	2.5x10^{-3} m/s
In-plane permeability (2 kPa)		2.5x10^{-2} m/s

3.3 *Methodology of testing*

The geotextile PEC200 is installed inside the shear box after the required density and moisture contents of fill materials were achieved. Consequently, either the remolded clay or the weathered clay was placed under the geotextile corresponding to the desired inclination angle. The nonwoven geotextile reinforcement was used to cover the top surface of the fill materials to protect the fill materials going out from at the top boundary.

After the top cover was installed, the vertical load system of large direct shear apparatus was installed to apply the normal pressure. The vertical settlement was observed by dial gauges installed at the top cover of the apparatus. For the remolded clay, the sample was consolidated to reach 90% of the degree of consolidation. For the weathered clay, the soil was compacted to the 95% of maximum dry density obtained from the standard Proctor compaction test as shown in Table 1. Thereafter, the shearing process was conducted by moving the lower part of the large box at the shearing rate of 8 mm/min. The orientation of the geotextile was determined by measuring its elevations at the predeterminated positions along the geotextile reinforcement. The applied normal stresses were 50, 75 and 100 kPa for remolded clay and 25, 50 and 75 kPa for weathered clay. The direct shear tests were conducted at the inclination angles of 45°, 60° and 90°.

4 TEST RESULTS AND DISCUSSIONS

In order to clearly understand the role of the reinforcement in the soil, the typical relationship between undrained shear strength, S_u and normal stress, σ'_n is presented in Fig. 4 for remolded clay with and without reinforcement. It is found that $S_u = 0.11\sigma'_n$ for the remolded clay in the direct shear condition. It implies that the undrained shear strength of remolded clay only depends upon the effective vertical stress because of no cementation effect (Horpibulsuk, 2001). The undrained shear strength is enhanced by geotextile reinforcement.

The role of the initial inclination angle and the soil strength on the resisting force contributed from the geotextile reinforcement is next investigated. Figure 5 shows the typical shear strength and initial inclination angle relationship of the geotextile reinforced clay. It shows that the shear strength is dependent upon the initial inclination angle and effective normal stress. The effect of the effective normal stress is only to increase the soil strength, not to increase the strength contributed by the reinforcement as shown in Figs. 6 and 7. It is found that the shear strength due to the reinforcement is almost in the same order at a particular initial inclination angle for a given soil.

Based on Eq. 1 and test results, it is evident that the soil strength (ϕ') plays a great role on the development of the resisting force. The higher the soil strength, the greater the resisting force. The other dominant parameter controlling the resisting force is the initial inclination angle, which is reflected in the soil strength.

From test results, it is shown that the initial inclination angle providing the maximum resisting force is different between both soils. The soft clay yields higher value of the initial inclination angle providing the maximum resisting force, attributed to lower shear strength and stiffness. Table 3 summaries the values of inclination factors corresponding to the initial inclination angle. It is shown that the inclination factor is mainly controlled by the strength of the soil and practically the same even when the initial inclination angle alters. The lower the soil strength, the greater the I_f.

Table 3. Orientation of high strength getextile in direct shear test with different initial inclination angles in remolded and weathered clays.

Initial inclination angles, α (°)	Reorientation at shear displacement of 60 mm, β (°)	Inclination factor, I_f
Remolded soft clay		
45	12	0.73
60	15	0.75
90	20	0.78
Weathered clay		
45	22	0.51
60	25	0.58
90	30	0.67

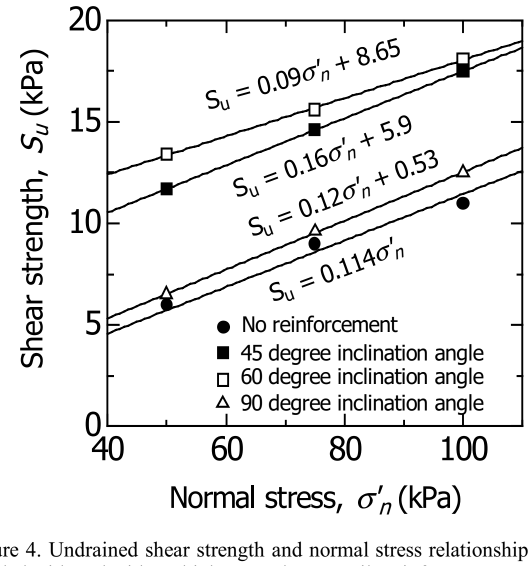

Figure 4. Undrained shear strength and normal stress relationship of remolded with and without high strength geotextile reinforcement.

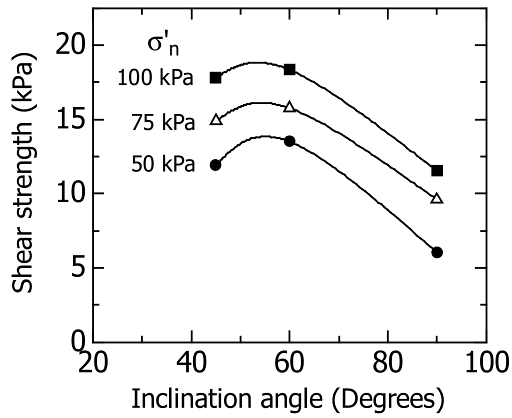

Figure 5. Relationship between shear strength and inclination angle of remolded clay with high strength geotextile reinforcement.

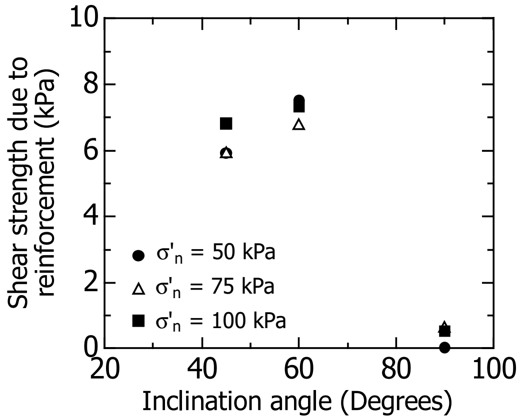

Figure 6. Shear strength due to the reinforcement versus inclination angle relationships of remolded clay with high strength geotextile reinforcement.

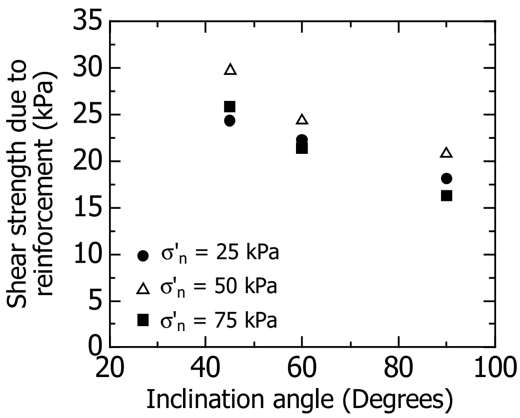

Figure 7. Shear strength due to the reinforcement versus inclination angle relationships of weathered clay with high strength geotextile reinforcement.

5 APPLICATION FOR SLOPE PROTECTION

Normally the slope protection along the irrigation canals on soft ground foundation was made employing the method of the improvement by in-situ deep mixing technique to effect the columnar inclusion. Another alternative method is to stabilize the slope by the high tensile strength geotextile, which can function as geodrain and reinforcement.

In Nakornnayok Province, Thailand at Klong 15, 29 and 31 areas, the slope failures are caused by drawdown of water in the canal. The soil profile and other information are obtained from the Royal Irrigation Department (RID). The former technique using soil-cement columns has been applied to stabilize the actual slope of irrigation canals. Soil-cement columns with a diameter of 0.6 m were installed down to 8 m depth from the surface as shown in Fig. 9. The design unconfined compressive strength of the columns is 500 kPa.

A detail of treatment of the slope failure by the geotextile PEC200 is shown in Fig. 10. The high strength geotextile was inserted in embankment and subsoil under the embankment. Soil parameters for the analysis is presented in Table 4. The analysis was divided into two cases: Case A with limitation of foundation deformation and Case B with allowable large settlement (*vide* Section 2.2) using SLOPE/W program. For case A, the ε_{lm} of 3.0% and T of 55 kN/m with $I_f = 0$ are taken for the analysis. By taking the average values of I_f, the ε_{lm} (ε_{lc} + 3%) values for case B are 11.6 and 9.8 percentage with corresponding T of 190 and 130 kN/m for soft clay and embankment, respectively. The factors of safety, FS, with regard to the two cases are tabulated in Table 5. It shows the effectiveness of using the high tensile strength geotextile for increasing the stability of the embankment on soft clay foundation. The calculation was done for the cases that geotextiles were inserted inside the embankment and soft clay foundation. The FS of the embankment stabilized by soil-cement columns is 1.972. It can compare with the case e) for the geotextile reinforcement. By the cost analysis, it is found that the geotextile reinforcement is cost effective about one-half cheaper than the in-situ deep mixing technique. The adhesion or interaction between the high strength geotextile reinforcement and the surrounding soft clay layer can be greatly improved if the geotextile reinforcement also functions as drains. Abiera et al. (1999) shows that the geotextile can function as drain when it is incorporated with the electric current so called electro-conductive drain.

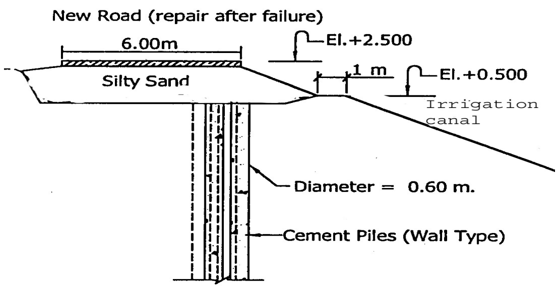

Figure 9. Use of soil-cement columns for the irrigation canal at Klong 15, 29, and 31 areas.

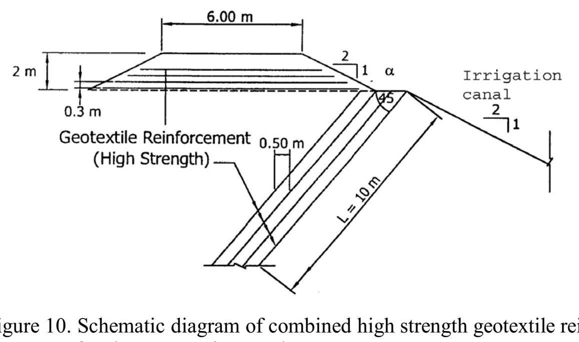

Figure 10. Schematic diagram of combined high strength geotextile reinforcement for slope protection at Klong 15, 29, 31 areas.

Table 4. Parameters for limit equilibrium analysis.

Soil condition	Depth (m)	γ_t (kPa)	S_u (kPa)	ϕ'(Degrees)
Silty sand (Embankment)		19.0	-	30
Weathered crust	0-2	17.5	25.0	-
Soft clay	2-16	15.0	12.5	-
Medium clay	16-22	16.0	25.0	-
Stiff clay	22-27	18.0	120.0	-

Table 5. Factors of safety calculated by SLOPE/W.

Description	FS of case A	FS of case B
Geotextile reinforcement		
a) Inside embankment (2 layers)	0.983	1.022
b) Inside embankment (4 layers)	1.022	1.260
c) Inside embankment (2 layers) and soft clay (2 layers)	1.388	1.578
d) Inside embankment (4 layers) and soft clay (2 layers)	1.662	2.020
e) Inside embankment (4 layers) and soft clay (3 layers)	1.810	2.449
Soil-cement columns	FS = 1.972	

6 CONCLUSIONS

This paper deals with the theoretical background, design method, and the application of the dual function high strength geotextile for protection of slope failure. The conclusions are drawn as follows.

1) The high tensile strength geotextile can be applied for the slope protection. It enhances the undrained shear strength to the soil. The resisting force due to the geotextile is mainly dependent upon the strength of the soil. At a particular initial inclination angle, the higher the soil strength, the greater the resisting force due to the geotextile, T_r and the lower the limiting strain. The resisting force, T_r is regardless of the effective normal pressure.

2) The initial inclination angle providing the maximum resisting force and the inclination factor, I_f, are principally governed by the soil strength. It is found that the inclination factor is irrespective of the effective normal stress and initial inclination angle.

3) There are two considerations for slope stability analysis: with limitation of the foundation deformation and with allowable large settlement. The selection is dependent upon the type of the structure.

4) Comparing between the application of soil-cement columns and geotextile reinforcement in terms of slope stability, the geotextile reinforcement is the cost effective method. The adhesion or interaction of the geotextile reinforcement with the surrounding clay can be greatly improved if the geotextile also functions as drains

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