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Evaluation of Geosynthetic-Reinforced Soil Wall Using Limit Equilibrium Analyses

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***Abstract*—Current FHWA design guidelines recommend the lateral earth pressure method for designing reinforced walls (face inclinations larger than 70°) and the limit equilibrium (LE) method for designing reinforced slopes (face inclinations less than 70°); however, this limitation is somewhat arbitrary and there is no clear reason why LE method could not be theoretically applicable to the design of reinforced walls. Therefore, this study evaluated the use of LE for predicting the failure of centrifuge geosynthetic-reinforced soil (GRS) wall models. The variables considered in the centrifuge testing program were the reinforcement types, lengths, spacing, and height of the wall models. The comparison results indicated that LE with a noncircular failure surface and centrifuge models had good agreement in locating failure surfaces. In-soil/confined ultimate tensile strengths T_{ult} of reinforcements were back-calculated from LE analyses at wall failure (FS=1.0) and consistent confined T_{ult} values were obtained for models with the same type of reinforcements. The consistent confined T_{ult} values imply that the LE can predict the maximum reinforcement loads at wall failure fairly well. Experimental results and the resulting discussion presented in this paper improve the understanding of LE analysis of geosynthetic-reinforced soil walls.**

***Keywords*—Geosynthetic-reinforced soil wall, Limit equilibrium analysis, Centrifuge model.**

I. Introduction

Geosynthetic-reinforced soil (GRS) walls have been well accepted in practice as alternatives to conventional retaining wall systems due to several benefits such as sound performance, aesthetics, cost and expediency of construction.

Current FHWA design guidelines (Berg *et al*. 2009) limit the use of limit equilibrium (LE) analysis to design reinforced slopes (face inclinations less than 70°) and lateral earth pressure method to design reinforced walls (face inclinations greater than 70°). However, this limitation is somewhat arbitrary and there is no theoretical reason why the limit equilibrium method could not be extended to design reinforced walls. In authors' opinion, this limitation of face inclinations should only be applied to lateral earth pressure method but not to LE analysis. That is because the lateral earth pressure method is theoretically-based and thus limited to relatively simple geometric structures with near vertical faces and difficult to extrapolate to structures with large face inclinations and with complex geometries such as narrow walls and multi-tiered walls. Compared to the LE analysis, the lateral earth pressure method also cannot evaluate global stability directly.

Allen *et al.* (2003) and Bathurst *et al.* (2008, 2005) investigated quantitatively the accuracy of reinforcement loads predicted by the earth pressure theory using careful interpretation of a database of 30 well-monitored full-scale walls on firm foundations and reinforced fills with no positive pore water pressures. By the comparison between the reinforcement loads (estimated from measured strains) in various instrumented GRS walls and the reinforcement loads predicted using the earth pressure theory, they concluded that loads predicted using earth pressure theory were excessively conservative. The predicted loads for GRS walls were *on average* three times greater than estimated values for full-scale instrumented walls. Furthermore, the distribution of reinforcement loads in the instrumented walls was seen to be generally trapezoidal (or uniform) in shape rather than linear with depth as assumed in the earth pressure theory for walls with uniform reinforcement spacing. This finding contradicts the basic assumption in the earth pressure method that the soil shear strength along the failure surface mobilizes equally and reaches peak shear strength simultaneously. Overall, the use of earth pressure method is limited to relatively simple geometric structures with near vertical faces and produces safe but conservative in terms of reinforcement strength for GRS structures.

Accordingly, the objective of this study is to validate the use of LE as basis for design of GRS walls. To achieve this aim, a series of LE analyses was performed for predicting the failure of centrifuge geosynthetic-reinforced soil (GRS) wall models. Experimental results and LE predictions were compared specifically for the failure surface locations. In-soil ultimate tensile strength of reinforcement, T_{ult}, back-calculated from the LE analyses at wall model failure (*i.e.*, FS=1.0), was evaluated and used to examine the LE prediction of the maximum reinforcement loads at wall failure.

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II. Centrifuge Tests and Limit Equilibrium Analyses

A. *Centrifuge Tests*

A series of centrifuge tests was conducted at the National Central University (NCU), Taiwan, to investigate performance and failure mechanisms in GRS walls (Hung 2008). A total of 12 centrifuge model tests were selected from the Hung's centrifuge testing program for the LE analyses in the current study. Centrifuge models were constructed in a rigid aluminum container with internal dimensions of 820 mm × 450 mm in plan × 580 mm in height. Figure 1 shows a schematic profile of the model wall. All models were built on firm foundation 150 mm thick. The height of the reinforced wall models were varied from 120 mm to 300 mm, and additional layer (equal to reinforcement spacing S_v) of soil was deposited on the top of the wall to cover the topmost reinforcement layer. Therefore, the wall models have an equivalent total height H varied from 125 mm to 320 mm, giving reinforcement spacing from 5 mm to 20 mm, and number of reinforcement layers from 16 to 25. Each reinforcement layer were folded back at the face of the wall models, forming a wrap-around facing and a secondary (overlapping) layer (Lo = 40% of reinforcement length for each wall). Table 1 summarizes the geometrical configuration, reinforcement length and spacing, and test results for the GRS wall models.

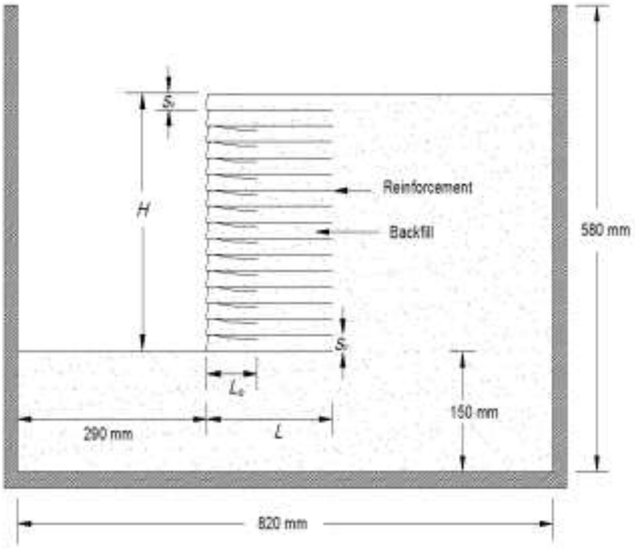

Figure 1. Schematic profile view of a centrifuge GRS wall model (L is the reinforcement length; L_o is the overlap length of reinforcement; S_v is Reinforcement vertical spacing)

In the centrifuge tests, all models were loaded by gradually increasing the g-level until failure. Table 1 summarizes the failure g-level, N_f, recorded for each model. Figure 2 shows the centrifuge model after wall failure observed in Test 5. Figure 3 shows a broken reinforcement carefully retrieved from the dismantled wall models after tests completed. The nearly horizontal breakage pattern in the reinforcement validates the plane strain condition in the centrifuge tests. The location of the critical failure surface was determined based on the observed tears (ruptures) in each layer of the reinforcement. The centrifuge testing program is discussed in further detail in Hung (2008).

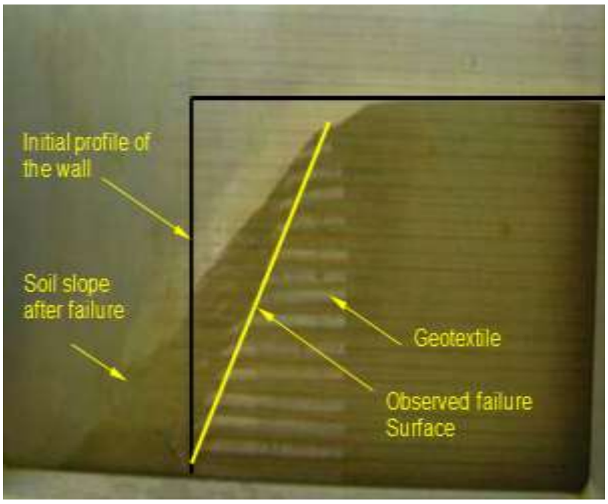

Figure 2. Photos of failure of centrifuge wall model Test 5

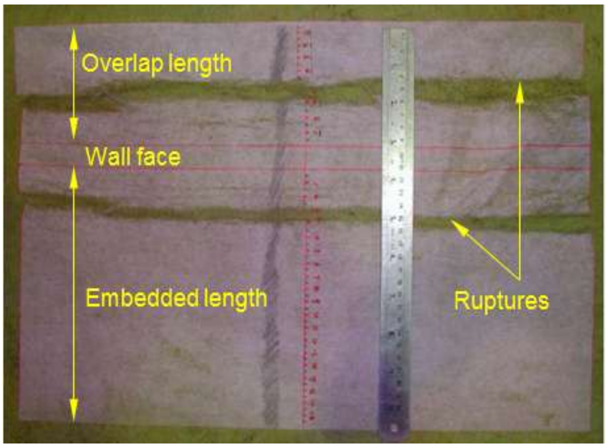

Figure 3. Breakage pattern in reinforcement material after wall failure

B. *Material Properties*

The soil used in the centrifuge test was clean and uniform Fulung beach sand, which is classified as poorly graded sand (SP) in the Unified Soil Classification System. The effective size D_{10}, uniformity coefficient C_u, and coefficient of curvature C_c for the sand are 0.17mm, 1.78, and 1.05, respectively. The sand was pluviated from a hopper to achieve a uniform and dense state. The backfill unit weight of sand and the friction angle obtained in a series of triaxial compression tests at the target relative density D_r of 70% were γ = 15 kN/m^3 and ϕ_{tx} = 39.5°, respectively. To characterize the shear strength of the test sand under the plane strain condition in the centrifuge model, the plane strain peak friction angle (ϕ_{ps} = 42.3°) was estimated using the correlation between the triaxial compression friction angle and the plane strain friction angle (Lade and Lee 1976):

$$\phi_{ps} = 1.5\phi_{tx} - 17 \qquad (1)$$

TABLE 1. Geometrical Configurations and Test Results of GRS Wall Models

Materials	Test No.	Wall geometry				Results	
		H (mm)	S_v (mm)	L (mm)	n	N_f (g)	*Back-calculated* T_{ult} (kN/m)
M1	1	250	10	170	25	35	0.089
	2	125	5	85	25	120	0.076
M2	3	320	20	210	16	34	0.231
	4	288	18	190	16	45	0.248
	5	256	16	168	16	56	0.244
	6	224	14	147	16	64	0.215
	7	192	12	125	16	85	0.210
M3	8	320	20	210	16	58	0.397
	9	288	18	190	16	72	0.397
	10	256	16	168	16	90	0.391
M4	11	320	20	210	16	65	0.444
	12	250	15	140	16	95	0.420

Note: M1 = Wood pulp fabric; M2 = Rayon fabric; M3 = Polyester, rayon fabric; M4 = Polypropylene fabric; H = Height of wall model; S_v = Reinforcement vertical spacing; L = Length of model reinforcement; n = Number of reinforcement layers ; N_f = Failure g-level of centrifuge model; T_{ult} = Back-calculated ultimate tensile strength of reinforcement

The geotextiles used in the centrifuge study were nonwoven wood pulp, rayon, polyester rayon, and polypropylene fabric, referred to as M1, M2, M3, and M4, respectively. A series of unconfined wide-width tensile tests (ASTM D4595) and zero-span tests with clamps 6 mm apart (Porbaha and Goodings 1996) were performed to evaluate the tensile strength properties of the geotextile materials. Table 2 summarizes the main reinforcement characteristics of the four different geotextile materials. The average T_{ult} for the geotextiles M1, M2, M3, and M4 were 0.06, 0.11, 0.17, 0.25 kN/m from wide-width tests and 0.1, 0.24, 0.37, and 0.40 kN/m from zero-span test, respectively. As the nonwoven geotextile tensile strengths were found to be affected by soil confinement and impregnation of geotextile by soil particles (Boyle *et al*. 1996), unconfined tensile tests like wide-with and zero-span tensile tests may not accurately represent in-soil tensile strength values. However, experimentally quantifying the in-soil mechanical properties of low strength nonwoven fabrics is difficult. This study therefore performed a back analysis to calculate the in-soil/confined ultimate tensile strengths T_{ult} of reinforcements. Figure 4 and Table 2 show the average back-calculated confined T_{ult} values. The back analyses used to obtain the values for confined T_{ult} and a comparison of the confined and unconfined T_{ult} values are discussed further in next sections.

C. *Limit equilibrium analyses*

Limit equilibrium analyses are typically used to analyze the stability of natural and reinforced slopes. A series of centrifuge tests of GRS slopes by Zornberg *et al*. (1998) showed that LE is effective for predicting failure in GRS slopes. In the current study, LE analyses were performed to predict the locations of failure surfaces in GRS wall models and to assess the confined ultimate tensile strength of reinforcements. The LE calculations were performed using Spencer's method with circular and noncircular critical failure surfaces as coded in the Slide v.6.0 program. The Spencer's method, which is sufficiently rigorous to satisfy all equilibrium conditions, assumes that all inter slice forces are parallel. The shear strength of the test sand in the centrifuge model was characterized by the plane strain friction angle. Centrifugal force was simulated by increasing the unit weight of backfill N_f times until it corresponded to the target g-level at failure. The critical failure surface was identified to initiate from the toe of the wall model.

The LE analyses in this study assumed a uniform distribution of reinforcement tensile forces with depth (Fig. 5), horizontal orientation of reinforcement forces, and overlapping geotextile layers modeled as additional reinforcements that increased stability in the wall. The tensile strength of reinforcement used as input in LE analysis was adjusted until a factor of safety was reached FS =1.0 in each centrifuge test model. The estimate accounted for the back-calculated confined ultimate tensile strength of the reinforcement and was expected to equal the average in-soil reinforcement tension at the moment of failure. Finally, reduction factors such as creep, installation damage and degradation were excluded because the centrifuge model tests were meticulously constructed to ensure that no installation damage occurred. The test duration was also kept sufficiently short to avoid long-term behavior such as creep or degradation.

III. Results and Discussions

A. *Location of Failure Surface*

Figure 6 compares the locations of failure surfaces obtained experimentally from centrifuge tests and the locations of critical failure surfaces predicted by LE analyses.

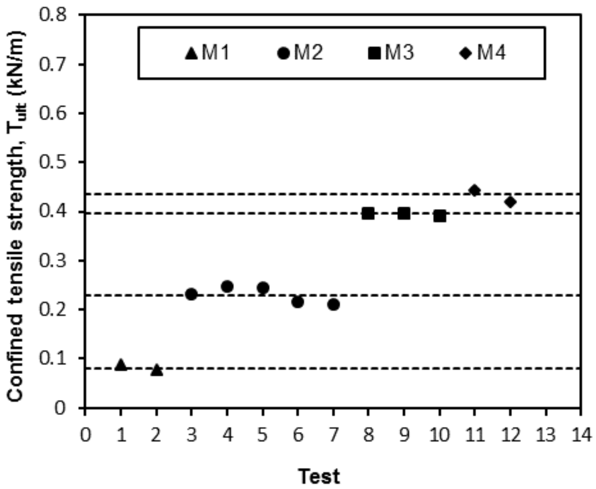

Figure 4. Back-calculated ultimate confined tensile strengths of the reinforcements

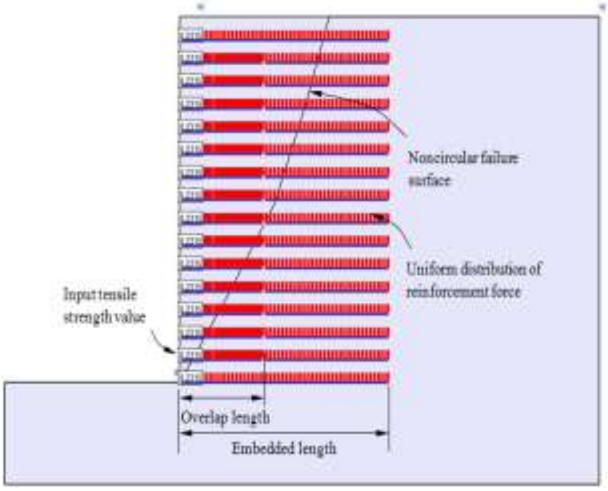

Figure 5. Reinforcement force distribution and failure surface used in LE analyses

TABLE 2. Geotextile Properties Used as Reinforcement in Model Tests

No.	Materials	Thickness (mm)	Ultimate tensile strength T_{ult} (kN/m)		
			Wide-width Test	*Zero-span Test*	*Average back-calculated*
M1	Wood pulp	0.07	0.06	0.1	0.083
M2	Rayon	0.13	0.11	0.24	0.230
M3	Polyester, Rayon	0.15	0.17	0.37	0.395
M4	Polypropylene	0.13	0.25	0.40	0.432

The failure surface of the centrifuge wall model, black triangles in Fig. 6, was identified by the tears (ruptures) observed in each reinforcement layer. The failure surface in LE analysis was identified by searching for both circular and noncircular critical surfaces. In Fig. 6, comparison results indicate a very good agreement between the critical noncircular failure surfaces predicted by the LE analyses and those actually observed in the experiments. Notably, the predicted critical circular failure surfaces slightly differ from the actual failure surfaces, in particular near the top of the wall. Figure 6 also shows comparison between experimental failure surfaces and the theoretical Rankine failure surfaces ($45 + \phi_{tx}/2$) recommended by FHWA design guidelines for a given triaxial compression friction angle of backfill. In most cases, the comparison results show that the theoretical Rankine failure surface can depict the locations of failure surfaces well, expect for Test 11 as shown in Fig. 6(d).

Overall, it can be concluded that the LE approach with a noncircular failure surface is competent of accurately predicting the failure surfaces in GRS wall models. Comparison results also support modeling assumptions (*e.g.*, use of the noncircular failure surface, uniform distribution of reinforcement forces with depth, and horizontal orientation of reinforcement forces). Finally, in design of GRS structures, reinforcement length that extends beyond the failure surface provides sufficient pullout resistance. Therefore, accurate identification of failure surface location by LE analysis confirms that it is effective for evaluating whether the internal stability of these structures is sufficient to withstand reinforcement pullout.

B. *In-Soil Geotextile Tensile Strength*

Ultimate tensile strength of reinforcement is the most important parameter when designing reinforced structures that resist reinforcement rupture. As mentioned, the ultimate tensile strength measured in the centrifuge test may differ from that measured in the standard unconfined tensile test due to soil confinement and impregnation of the geotextile by soil particles. One alternative is to evaluate in-soil geotextile strength by back-calculation from the centrifuge model results at failure.

Figure 4 and Table 2 show the calculated T_{ult} values which account for the average in-soil reinforcement tension at failure. As can be seen in Fig. 4, consistent confined T_{ult} values were obtained for models with the same type of the reinforcement. The consistent confined T_{ult} values are considered rational because the T_{ult} for the same type of reinforcement is expected to be similar, which also implies that the LE can predict the maximum reinforcement loads at wall failure fairly well. In addition, as shown in Table 2, the average confined T_{ult} values for all the reinforcements are larger than those obtained from the wide-width test and close to those obtained from the zero-span test. The reason of the confined T_{ult} values close to those from zero-span test is because the in-soil confinement of geotextiles restrains geotextile deformations in the direction perpendicular to loading which is similar to effect of preventing the geotextile necking in the zero-span test. These analytical results are consistent with previous studies (Christopher *et al.* 1986; Zornberg *et al.* 1998) demonstrated that the likely range for the in-soil tensile strength value of nonwoven geotextile can be defined using wide-width and zero-span tensile tests.

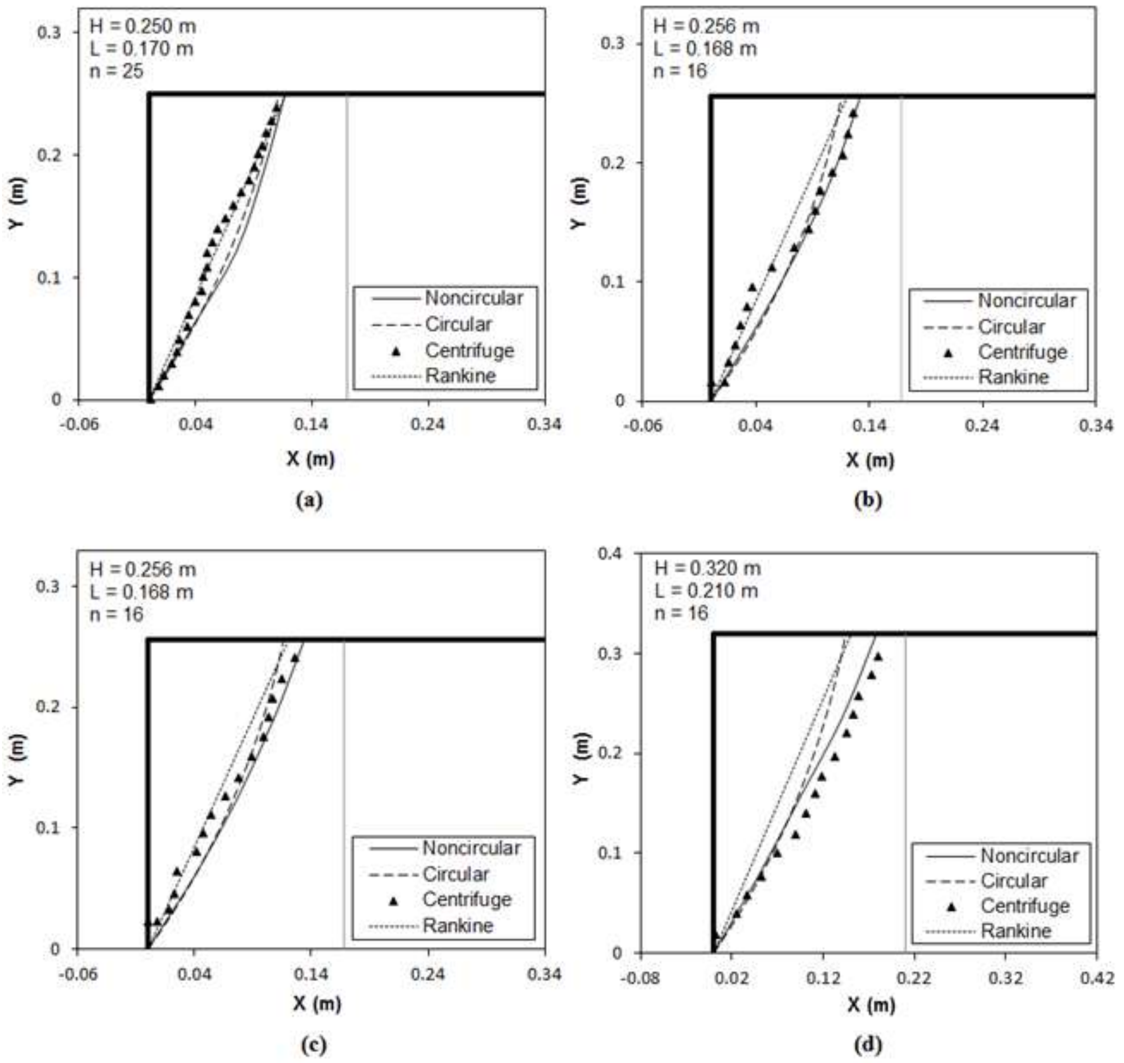

Figure 6. Predicted and measured locations of failure surfaces from centrifuge tests: (a) Test 1 (M1); (b) Test 5 (M2); (c) Test 10 (M3); (d) Test 11 (M4)

IV. Conclusions

This study conducted a series of LE analyses for centrifuge modeling of GRS walls with various reinforcement types and layouts and wall heights. This study demonstrated that LE can predict the failure (*i.e.*, location of failure surface and the confined ultimate tensile strength) of centrifuge geosynthetic-reinforced soil (GRS) wall models well. Specific conclusions drawn from this study are summarized below:

- The location of the critical noncircular failure surface predicted by LE analysis agrees well with the actual location of the critical failure surface obtained experimentally, which implies that the LE is capable of evaluating the required reinforcement length against pullout.

- Consistent confined T_{ult} values were obtained for models with the same type of the reinforcement, which implies that the LE can predict the maximum reinforcement loads at wall failure fairly well. The average confined T_{ult} values for all the reinforcements are larger than those obtained from the zero-span test.

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