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PREDICTIVE EQUATION FOR THE STABILITY OF GEOTEXTILE REINFORCED EARTH STRUCTURE

EQUATION POUR LA PREDICTION DE LA STABILITE D'UNE STRUCTURE EN TERRE RENFORCEE PAR GEOTEXTILE

GLEICHUNG FÜR DIE VORHERSAGE DER STABILITÄT EINER GEOTEXTILVERSTÄRKTEN ERDSTÜTZKONSTRUKTION

The objectives of this paper are (1) to present a large amount of numerical results dealing with the stability of geotextile reinforced earth structures, and (2) to show the effect the inclination of the geotextiles' tensile force has on stability. The reinforced earth problem is formulated based on variational limit equilibrium. The results, obtained using a closed-form solution, satisfy all global equilibrium requirements for a sliding rigid mass. It was found that fitting the exact results into a third degree polynom enables an accurate, condensed and convenient presentation of a solution for many possible problems. Further, the inclination of the force in the geotextile at failure has relatively small effect on the stability of cohesionless structures; however, for cohesive soil the assumed inclination is significant.

Die Ziele dieses Beitrages sind es (1), eine grosse Anzahl numerischer Ergebnisse, die die Stabilität geotextil verstärkter irdener Strukturen behandeln, zu präsentieren und (2) zu zeigen welchen Einfluss die Inklination der geotextilen Zugkraft auf die Stabilität hat. Das Problem der verstärkten Erde ist formuliert basierend auf dem variationellen Grenzgleichgewicht. Die Ergebnisse, erstellt unter Benutzung einer Lösung geschlossener Form, erfüllen alle globalen Gleichgewichtsbedingungen für eine gleitende starre Masse. Es ergab sich, dass eine Anpassung der exakten Lösung an ein Polynom dritten Grades eine genaue, kondensierte und bequeme Präsentation einer Lösung für viele mögliche Probleme ermöglicht. Desweiteren hat die Inklination der Kraft im Geotextil beim Versagen einen relativ kleinen Einfluss auf die Stabilität von Strukturen ohne Kohäsion, für kohäsive Böden ist die angenommene Inklination jedoch signifikant.

INTRODUCTION

The term earth structure in this paper refers to walls and steep embankments where stability is enhanced by soil-reinforcement interaction. A major objective in analyzing such structure is to determine the effective increase in its internal stability. Clearly, achieving this objective enables one to carry out an economical and rational design.

There are numerous limit equilibrium methods developed to deal with stability of geotextile reinforced slopes (e.g., (5), (6), (7), (8), (17)). Essentially, in each method the failure mechanism is assumed and some of the limiting equilibrium requirements are satisfied.

The results presented here are based on the variational limit equilibrium as presented by Baker and Garber ((2), (3)). The mathematical details of the analysis are given elsewhere ((10), (19)). This variational analysis is rigorous in the sense that, for a sliding rigid mass, all limiting equilibrium equations are satisfied.

The purpose of this paper is to present a massive amount of information regarding the stability of geotextile reinforced earth structures in a condensed form. An additional objective is to present a comparative study showing the effect the inclination of the geotextiles' tensile force at the slip surface have on stability.

MECHANISM AND FORMULATION

To formulate the problem in accordance with the limiting equilibrium approach, the concept of mobilized resistance to global failure is used. It is assumed that the soil comprising the reinforced structure obeys Mohr-Coulomb's failure criterion and that each geotextile sheet can develop tensile resistance of known magnitude t_j. Thus, the mobilized strength of each component resisting failure in the composite structure is

$$\tau_m = (c + \sigma\psi)/FS = c_m + \sigma\psi_m \qquad (1a)$$

$$t_{m_j} = t_j/FS \qquad (1b)$$

where FS is the factor of safety, signifying the average margin of safety of the composite earth structure against collapse; c is the soil's apparent cohesion and ϕ is its friction angle; $\psi = \tan\phi$; σ and τ are the stresses normal and tangent to the potential slip surface shown in Fig. 1, respectively; t_j is the tensile resistance of each geotextile j; and the subscript m symbolizes a mobilized strength component.

It should be noted that typically t_j is controlled by the following: (1) Pull-out resistance developing over the geotextiles' restraining zone beyond the slip surface; (2) a prescribed elongation of the geotextile so as to minimize incompatibility with soil; and (3) a fraction of the geotextile's ultimate tensile strength so as to minimize creep. For design, therefore, one must select the least feasible value of the above criteria.

The objective is to determine the minimum value of FS for a given reinforced earth structure. To attain this objective, the failure mechanism as well as σ must be known. Using the variational extremization procedure, it can be shown (e.g., (3), (10)) that there are two possible failure modes in homogeneous soil: rotational or translational. The slip surface geometry corresponding to the first mode is log-spiral and to the second mode planar. The failure mechanism that is likely to develop is the one rendering the lowest factor of safety. Since the rotational failure in this paper was always critical, only the log-spiral surface is considered. It is expressed as

$$R = Ae^{-\psi_m \beta} \qquad (2)$$

where R is a nondimensional presentation of the potential slip surface defined relative to a polar coordinate system having its origin at an unknown point $X_c = x_c/H$ and $Y_c = y_c/H$ (see Fig. 1); A is an unknown constant; and β is the independent variable in the polar coordinate system.

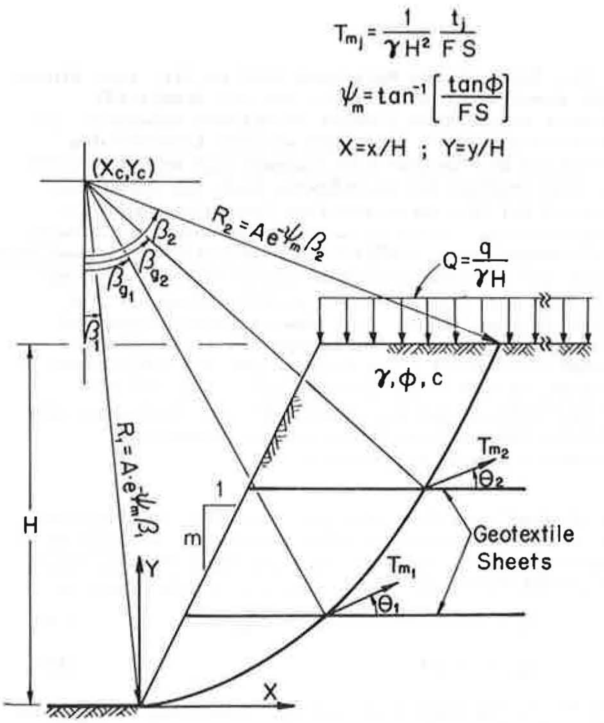

Fig. 1. Failure Mechanism and Definitions

To completely define the failure mechanism for the reinforced problem, one can assume that when the soil mass is at the verge of collapse, all geotextile sheets remain horizontal at their intersection with the slip surface (i.e., θ_j equals zero in Fig. 1). However, since it is likely that t_j is activated by soil differential movement, it is assumed that when failure of the composite structure occurs, t_j (or the geotextile) at the slip surface will be inclined so as to contribute its most resistance; i.e., be most effective. It can be verified (10) that in this case the geotextiles are orthogonal to the radius of the log-spiral at their intersection; i.e.,

$$\theta_j = \beta_{g_j} \qquad (3)$$

where β_{g_j} defines the intersection of geotextile j with the slip surface--see Fig. 1.

It is interesting to note that the collapse mechanism defined by Eqns. (2) and (3) is identical to the admissible mechanism used in the upper-bound theorem of plasticity where a rigid body is considered and the geotextiles' tensile force is opposing velocity. This equivalency has been shown by Leshchinsky et al. (12) for general variational slope stability problems, and it provides a physical interpretation for the variational extremization procedure. It should be stated that for unreinforced problems Baker (1) showed that these upper-bound results are identical to Taylor's (18).

To develop a closed-form solution and subsequently, a massive amount of information, a method was introduced relating any t_{m_j} to t_{m_1} where t_{m_1} is the mobilized tensile resistance of the geotextile at the lowest elevation. It is based on a virtual rotation of a rigid body, the geometry of the slip surface and an identical n geotextile sheets having an assumed linear load-elongation relationahip (up to t_{m_j}) which is independent of over-burden pressure. The following nondimensional expression was introduced

$$T_{m_j} = T_{m_1} e^{-\psi_m(\beta_{g_j} - \beta_{g_1})} \qquad (4)$$

where $T_{m_j} = T_{m_j}/(\gamma H^2)$ and γ is the soil's unit weight.

Notice from Eq. (4) that when cohesive soil is concerned (i.e., ϕ=0) all geotextile sheets are equally mobilized. Numerical results indicate that for granular soil and for a vertical cut, T_{m_j} will vary between about 0.9 T_{m_1} at the crest to 1.0 T_{m_1} at the toe. For slope face inclination of 1:2, however, T_{m_j} will be stressed to about 0.7 T_{m_1} at the crest. It is interesting to note that this distribution of tensile force is in good qualitative agreement with full scale test results reported by John et al. (9).

To obtain a statically determinate problem, the normal stress over the slip surface R is needed. This stress should render the minimum value of the safety factor FS and, simultaneously, satisfy the limiting equilibrium equation written for the potentially failing composite mass. It can be verified (e.g., (1), (2), (10)) that by using an extremization technique based on variational principles, the following nondimensional normal stress distribution is obtained

$$S = \frac{A}{1+9\psi_m^2}(\cos\beta + 3\psi_m \sin\beta)e^{-\psi_m\beta} - N_m \frac{1-e^{2\psi_m\beta}}{\psi_m} + Be^{2\psi_m\beta} \qquad (5)$$

where $S = \sigma/\gamma H$ = nondimensional normal stress distribution over $R(\beta)$; $N_m = c/(FS\gamma H)$ = stability number; and B is an unknown constant.

Following the procedure developed by Baker (1), one can assemble explicitly the three limiting equilibrium equations for the sliding mass defined by Eq. (2). An additional two equations are available by virtue of the geometrical boundary conditions: $Y(\beta_1) = 0$ and $Y(\beta_2) = 1$. It is assumed that there are n equally spaced geotextile sheets. Consequently, β_{g_j} for each geotextile can be determined yielding (n-1) times Eq. (4). Thus, there are now 5+(n-1) available equations. However, for a given slope, surcharge load $Q = q/\gamma H$, ψ_m, T_m, and n geotextiles' elevations (or β_{g_j}), the following unknowns exist: N_m, A, B, X_c, Y_c, β_1, β_2 and T_{m_j} (j = 2, 3, ...n); i.e., there are 7+(n-1) unknown parameters. Two additional equations are necessary to obtain a closed form solution.

Since only steep earth structrues are considered here, the following forced boundary condition seems to be reasonable

$$X_1 = 0 \qquad (6)$$

Equation (6) implies that the slip surface is forced to come through the toe (see Fig. 1 for definition of the cartesian coordinate system). The last equation results from extremization of $R(\beta)$ and $S(\beta)$ at the other boundary (i.e., transversality condition at $Y(\beta_2)=1$). The resulting equation is (19)

$$\{S(\beta)[\psi_m\cos\beta + \sin\beta]+N_m\cos\beta - Q\sin\beta\}_{\beta=\beta_2} = 0 \quad (7)$$

The number of non-linear equations now match the number of unknowns. Subsequently, for a given slope, Q, ψ_m, T_{m_1}, n and Y_{g_j} one can determine the required N_m.

RESULTS

It is convenient to define the following non-dimensional parameter (see also Ref. (14), (15))

$$T_m = n\ T_{m_1} \quad (8)$$

where T_m is defined as the equivalent geotextile tensile resistance and n is the total number of equally spaced geotextiles.

The results presented here are based on the analysis outlined in the previous section considering ten equally spaced geotextiles (i.e., n = 10). Volk (19), however, showed that the results are insensitive to n as long as T_m is constant and n is greater than 1.

Figure 2 is a typical design chart presenting N_m as function on ϕ_m, T_m, Q, and slope face inclination. This figure uses a mechanism where the geotextiles are orthogonal to their radius vector at the slip surface (i.e., see Eq. (3)). For a given problem one can determine FS using Fig. 2 (e.g., (13), (14), (15)). Alternatively, in a design procedure one can determine the required geotextiles' tensile resistance so that for given backfill properties a prescribed FS will be attained.

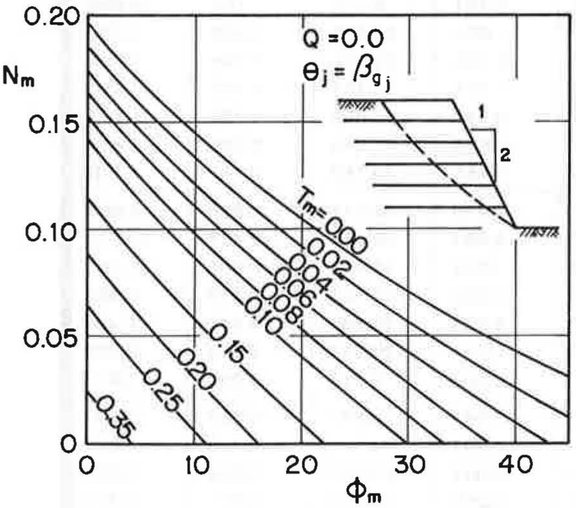

Fig. 2. A Typical Design Chart

Although Fig. 2 enables an easy visualization of the relationship among all parameters affecting stability in a reinforced earth structure, it is physically impossible to present a large number of such charts. It was found that a third degree polynom can represent the content of each design chart rather accurately. This polynomial representation is

$$N_m = D_o + D_1\ \phi_m + D_2\ \phi_m^2 + D_3\ T_m + D_4\ T_m^2 + D_5\ \phi_m\ T_m + D_6\ T_m\ \phi_m^2 + D_7\ \phi_m\ T_m^2 \quad (9)$$

where D_o, D_1, ...D_7 are coefficients; $N_m = c/(FS\gamma H)$; $\phi_m = \tan^{-1}[(\tan\phi)/FS]$ in degrees; and $T_m = nt_1/(FS\gamma H^2)$.

Table 1 presents the coefficient D for various slope face inclinations and uniform surcharge loads $Q = q/\gamma H$. To determine these coefficients, first N_m as a function of ϕ_m and T_m was computed at discrete points (ϕ_m in intervals of 2.5° at most and for T_m equals to 0, 0.02, 0.04, 0.06, 0.08, 0.10, 0.15, 0.20, 0.25, 0.35, 0.50, 0.75, 1.00, 1.25 and 1.50; the higher values of T_m were used only in conjunction with high surcharge loads). For this massive data the least-square curve fitting method was invoked yielding the polynomial coefficients presented in Table 1. A comparison of results revealed that the difference between N_m predicted by the fitted polynom and the exact N_m is typically less than 0.005, indicating that representing the results using Eq. (9) is practically as accurate as the design charts (e.g., Fig. 2). It should be emphasized, however, that Table 1 is equivalent to 42 such design charts.

Observing Eq. (9) one realizes that for a given problem (i.e., given γ, H, q, ϕ and c) and for a specified FS, the required T_m (and thus t_1; see previous section for the way t is selected) can be determined simply by solving a quadratic equation. For a given reinforced structure, on the other hand, the corresponding factor of safety can be computed by solving Eq. (9) using a trial and error approach. It is worthwhile to note that the numbers in Table 1 can be fed into a microcomputer, thus enabling instantaneous answers through direct computation or interpolation (depending on the given data).

DISCUSSION

The results indicate that when cohesionless unreinforced soil is considered, the maximum slope face inclination , i, equals ϕ and both the slip and slope surfaces coincide. When reinforced granular soil is considered, however, i is greater than the angle of repose (i.e., $i>\phi$) and the corresponding slip surface moves into the slope (e.g., see Figs. 3-4). This reinforced structure behavior is due to the nature of the analysis where a rotation of a rigid mass is considered. Consequently, when using these results, special attention must be paid to superficial potential failures.

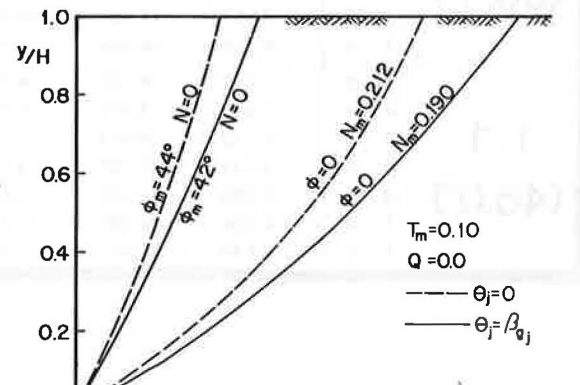

Fig. 3. Effect of Geotextiles Tensile Force Inclination on Slip Surface

Table 1. The Polynomial Coefficients

SLOPE	Q	$D_0\times10$	$D_1\times10^3$	$D_2\times10^5$	$D_3\times10$	$D_4\times10$	$D_5\times10^4$	$D_6\times10^4$	$D_7\times10^3$
1:∞ (90.0°)	0.0	2.601	- 4.302	2.016	- 7.578	4.035	- 7.002	- 1.857	- 18.988
	0.1	3.075	- 5.044	2.303	- 7.359	2.898	- 24.595	- 1.743	- 10.879
	0.2	3.563	- 5.869	2.734	- 7.395	2.786	- 21.006	- 1.845	- 10.423
	0.4	4.539	- 7.417	3.368	- 7.242	1.883	- 31.202	- 1.812	- 5.931
	0.7	6.013	- 9.751	4.322	- 7.162	1.251	- 38.048	- 1.790	- 3.182
	1.0	7.520	- 12.324	5.632	- 7.408	1.434	- 23.832	- 1.917	- 4.793
	1.5	10.000	- 16.316	7.372	- 7.335	1.019	- 30.245	- 1.850	- 3.088
1:6 (80.5°)	0.0	2.318	- 4.536	2.303	- 7.048	4.014	- 9.257	- 1.528	- 17.137
	0.1	2.721	- 5.277	2.599	- 6.791	2.874	- 27.221	- 1.374	- 9.504
	0.2	3.140	- 6.089	2.980	- 6.879	2.905	- 20.999	- 1.468	- 9.913
	0.4	3.985	- 7.744	3.821	- 6.914	2.507	- 17.005	- 1.495	- 8.742
	0.7	5.239	- 10.044	4.802	- 6.653	1.555	- 37.544	- 1.288	- 3.481
	1.0	6.513	- 12.475	5.964	- 6.663	1.295	- 34.942	- 1.345	- 3.014
	1.5	8.633	- 16.476	7.807	- 6.614	0.944	- 37.980	- 1.322	- 1.955
1:3 (71.6°)	0.0	2.108	- 4.852	2.807	- 6.510	3.621	- 9.468	- 1.323	- 12.965
	0.1	2.473	- 5.731	3.370	- 6.541	3.534	1.036	- 1.471	- 14.341
	0.2	2.825	- 6.420	3.580	- 6.253	2.562	- 25.967	- 1.141	- 6.041
	0.4	3.549	- 7.954	4.320	- 5.998	1.652	- 41.429	- 0.963	- 1.725
	0.7	4.660	- 10.378	5.603	- 5.967	1.319	- 41.048	- 0.962	- 1.137
	1.0	5.793	- 12.998	7.227	- 6.146	1.315	- 18.629	- 1.321	- 3.111
	1.5	7.643	- 16.977	9.289	- 6.013	0.900	- 26.827	- 1.243	- 1.476
1:2 (63.4°)	0.0	1.956	- 5.247	3.498	- 6.016	3.161	- 6.519	- 1.192	- 8.886
	0.1	2.264	- 5.977	3.846	- 5.598	1.803	- 34.863	- 0.869	0.203
	0.2	2.595	- 6.848	4.424	- 5.689	2.130	- 21.054	- 1.094	- 3.309
	0.4	3.238	- 8.363	5.198	- 5.342	1.131	- 43.151	- 0.792	1.860
	0.7	4.232	- 10.807	6.646	- 5.295	0.940	- 40.829	- 0.788	1.151
	1.0	5.223	- 13.196	8.027	- 5.175	0.624	- 45.950	- 0.730	1.943
	1.5	6.888	- 17.269	10.503	- 5.143	0.467	- 43.762	- 0.785	1.718
3:4 (53.1°)	0.0	1.800	- 5.928	4.789	- 5.337	2.410	- 5.013	- 0.896	- 4.392
	0.1	2.085	- 6.866	5.541	- 5.362	2.651	19.056	- 1.417	- 10.712
	0.2	2.359	- 7.605	5.943	- 4.988	1.604	- 15.032	- 0.866	- 1.103
	0.4	2.920	- 9.140	6.840	- 4.551	0.569	- 38.827	- 0.513	3.453
	0.7	3.797	- 11.617	8.482	- 4.513	0.538	- 34.299	- 0.540	2.338
	1.0	4.683	- 14.157	10.244	- 4.558	0.571	- 20.341	- 0.725	0.209
	1.5	6.172	- 18.448	13.346	- 4.667	0.560	0.519	- 1.042	- 1.376
1:1 (45.0°)	0.0	1.698	- 6.720	6.530	- 4.679	1.641	- 15.267	- 0.357	- 0.639
	0.1	1.940	- 7.564	7.192	- 4.244	0.601	- 41.386	0.108	5.373
	0.2	2.190	- 8.371	7.729	- 3.975	0.001	- 54.858	0.244	8.500
	0.4	2.717	- 10.103	9.006	- 3.940	0.295	- 42.251	0.061	3.709
	0.7	3.503	- 12.495	10.535	- 3.687	- 0.112	- 52.893	0.211	5.145
	1.0	4.304	- 14.962	12.219	- 3.694	0.060	- 43.319	0.114	2.507
	1.5	5.640	- 19.032	15.106	- 3.625	0.019	- 41.328	0.127	1.868

Figures 3-5 demonstrate the effect of the employed geotextile mechanism on the location of the slip surface. Two possible mechanisms are considered. In the first one, each geotextile sheet is assumed to be orthogonal to the radius vector defining its location at the slip surface (i.e., $\theta_j = \beta_{gj}$, as discussed in the analysis). In the second mechanism, each geotextile sheet is assumed to remain horizontal (i.e., $\theta_j = 0$ still using Eq. (4) but modifying the equilibrium equations accordingly). Observing the figures, notice that for cohesionless soil there is no significant difference in the location of the critical slip surfaces or in the required ϕ_m (for constant Q and T_m). The difference becomes more apparent when cohesive soil is considered. Notice from Fig. 5 that surcharge load Q decreases the difference. It is interesting to note that the potential slip surfaces are deeper when cohesive soil is considered.

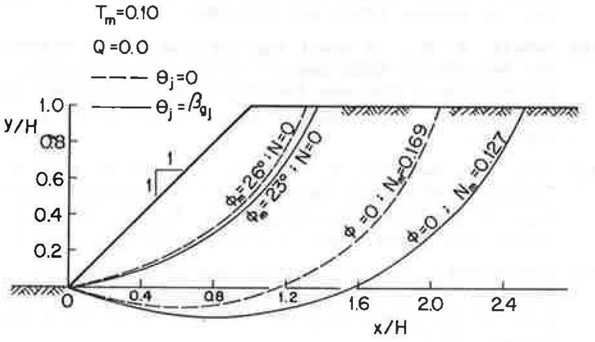

Fig. 4. Effect of Geotextiles Tensile Force Inclination on Slip Surface

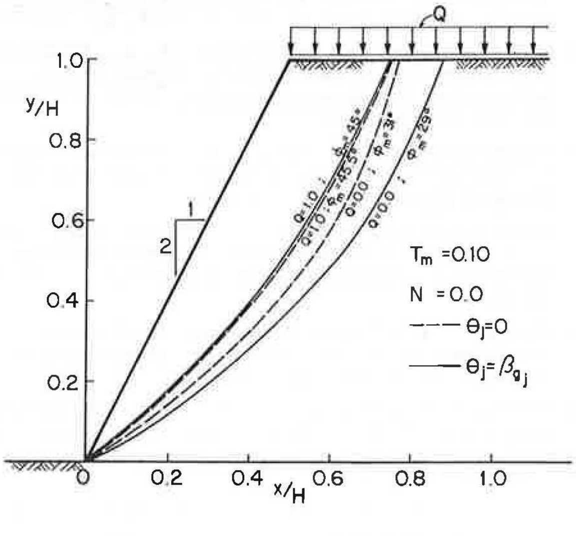

Fig. 5. Effects of Geotextiles Tensile Force Inclination and Surcharge Load on Slip Surface

Figures 6-9 show the effect these two mechanisms have on the factor of safety for a few specific problems. Notice that for cohesionless soil the difference in the predicted FS is rather small (i.e., typically less than 15% when a steep slope is considered). The differences in FS might be significant, however, when cohesive soil is considered.

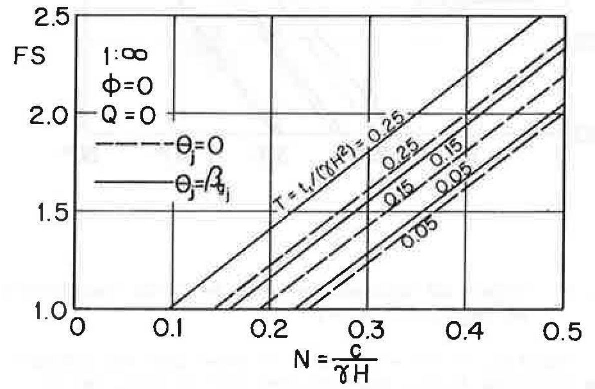

Fig. 6. Effect of Geotextiles Tensile Force Inclination on Factor of Safety

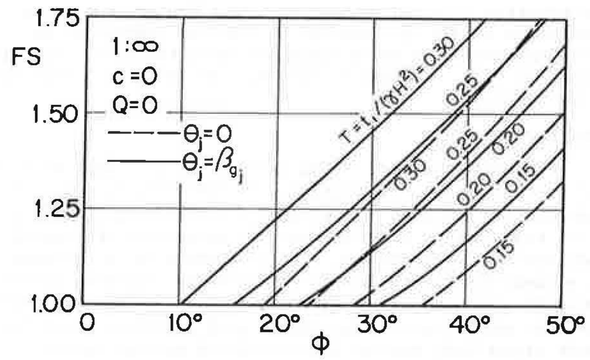

Fig. 7. Effect of Geotextiles Tensile Force Inclination on Factor of Safety

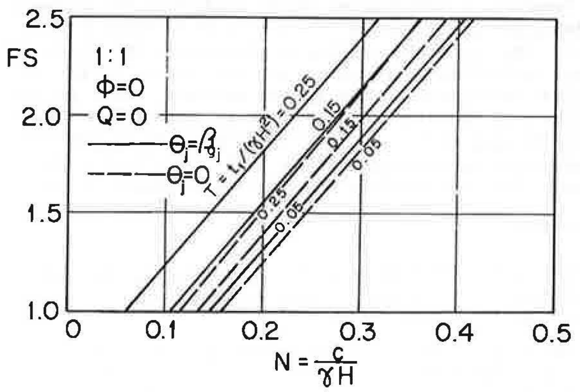

Fig. 8. Effect of Geotextiles Tensile Force Inclination on Factor of Safety

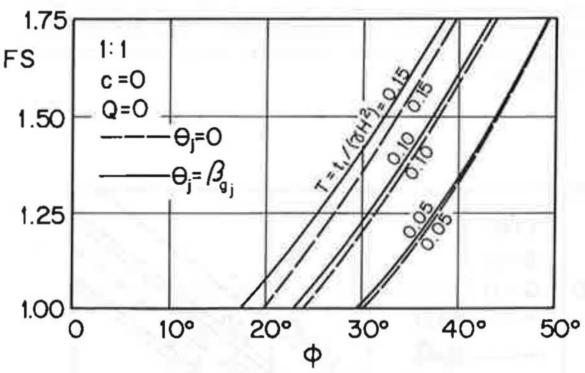

Fig. 9. Effect of Geotextiles Tensile Force Inclination on Factor of Safety

Finally, it is worthwhile to note that the predictive equation (i.e., the polynom) can be used, as an approximation, for a distribution of T_{m_j} different from the one expressed in Eq. (4). For cohesionless soil it is customary to assume the tensile resistance t_j to be proportional to the overburden pressure (e.g., (4), (16)). Thus, the tensile resistance distribution in this case is triangular. It can be verified (11) that for this distribution one can approximate the required tensile resistance of the geotextile at the toe elevation as twice the required value obtained from the previous distribution (i.e., it has to be $2t_1$, where t_1 is predicted by Eq. (9)).

CONCLUSION

Presented briefly is an analytical approach to predict the stability of reinforced earth structures. The analysis is based on variational limiting equilibrium. It is rigorous in a sense that it satisfies all global equilibrium requirements. The inclusion of any number of geotextile sheets in the analysis is obtained via a rational and consistent approach. The failure mechanisms, however, are identical to those used in limit analysis where rigid body motion is considered and an upper-bound solution is sought.

The results obtained from a closed-form solution are curve-fitted using a third degree polynom. Exhibiting the results in a format of polynomial coefficients enables a rather accurate and condensed presentation of many possible problems.

Finally, a comparative study regarding the assumed inclination of the geotextile sheets at failure is conducted. Two possible extreme inclinations are used; one is for horizontal geotextiles and the second is for geotextiles orthogonal to the radius defining their intersection with the slip surface. It is demonstrated that the difference in results due to geotextile mechanisms is most pronounced when cohesive soil is considered. However, for cohesionless soil this difference is small.

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