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TECHNICAL NOTE

A procedure for the design and analysis of geosynthetic reinforced soil slopes

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Summary

A procedure for the stability analysis and design of geosynthetic reinforced soil slopes over a firm foundation is described. Firstly the unreinforced slope is analysed, and for this a circular failure method is used which allows a surcharge load to be taken into account. Any method of slip circle analysis could be used to identify the coordinates of the centre of the slip circle, its radius and the minimum factor of safety. In this study, both internal and external stability analysis of the reinforced slope is presented. Internal stability deals with the resistance to pullout failure within the reinforced soil zone resulting from the soil/reinforcement interaction. The external stability is considered by an extension of the bilinear wedge method which allows a slip plane to propagate horizontally along a reinforcing sheet. The results for total tensile force, internal and external stability are presented in the form of charts.

For given properties of soil and slope geometry, the required strength of the geosynthetic and the length of reinforcement at the top and bottom of the slope can be determined using these charts. The results are compared with the published design charts by Schmertmann *et al.* (1987).

Keywords: Geosynthetic, reinforced soil, slope stability.

Introduction

Geosynthetics are increasingly being used as reinforcing members in the construction of embankments. The use of geosynthetics permits construction of slopes at angles steeper than the angle of repose of the soil fill, thereby reducing land requirements for slope construction. Steep reinforced soil slopes frequently provide economic advantages over traditional design alternatives.

Chouery *et al.* (1989) presented methods of locating critical failure surfaces in reinforced slopes and a method of analysis for reinforced earth based on limit equilibrium was given by Koerner (1990) for a c–ϕ soil and cohesive soil. Leshchinsky and Reinschmidt (1985) have presented the results of both rotational and translational failure mechanisms. Leshchinsky and Boedeker (1989) presented an approach to the stability analysis of reinforced earth which involved internal and external stability. Internal stability was based on variational limiting equilibrium and external stability on an extension of the bilinear wedge method.

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Rowe (1984) considered the soil–reinforcement interaction, slip at the soil–fabric interface, plastic failure within the soil and large deformations in the analysis of reinforced embankments. Murray (1982) outlined a procedure which emphasized the effect of the layer spacing of reinforcement in the slope. Schneider and Holtz (1986) documented a design procedure for reinforced slopes with geotextiles and geogrids. Wallace and Fluet (1987) and Beech (1987) presented the concept of strain compatibility in design. Schmertmann *et al.* (1987) described the development of design charts for reinforced soil slopes. Verduin and Holtz (1989) presented a new procedure for geosynthetic reinforced slopes. Langston and Williams (1989), Fowler (1982) and Jewell (1982) presented a design method for reinforced embankments on soft foundations.

This paper presents a design procedure for slopes with geosynthetic reinforcement, modified and expanded from the work of Verduin and Holtz (1989). Some parts of the results obtained from the analysis are compared with the design charts published by Schmertmann *et al.* (1987).

The procedure described is used to produce design charts which allow the rapid evaluation of the reinforcement requirement for steep slope geometries. The design of the geosynthetic reinforcement involves determining:

(1) Additional tensile force required for overall stability.
(2) The tensile strength of the geosynthetic required for each layer.
(3) The reinforcement length required to resist pullout and
(4) The reinforcement length of the bottom layer of geosynthetic required to prevent sliding.

Geometry of the slope and the failure surface for analysis is shown in Fig. 1.

Factor of safety

Factor of safety (FS) for an unreinforced slope is defined as the ratio of resisting moment (M_R) to driving moment (M_D).

$$FS = \frac{\text{Resisting moment } (M_R)}{\text{Driving moment } (M_D)} \tag{1}$$

The resisting moment M_R, for an assumed circular failure, is the total resistance developed by the soil shear forces and the driving moment M_D is due to the total driving shear forces developed at the failure surface due to the weight of the failed soil mass.

After the addition of geosynthetics in the slope then the factor of safety of the reinforced soil slope (FS_R) becomes

$$FS_R = \frac{M_R + R\Sigma T}{M_D} \tag{2}$$

where R represents the radius of the slip circle and T represents the tensile forces in the reinforcement.

The tensile forces in the reinforcement is assumed to act tangentially to the slip circle as shown in Fig. 2.

The increase in Factor of Safety (FS') due to the geosynthetic is

$$FS' = FS_R - FS$$

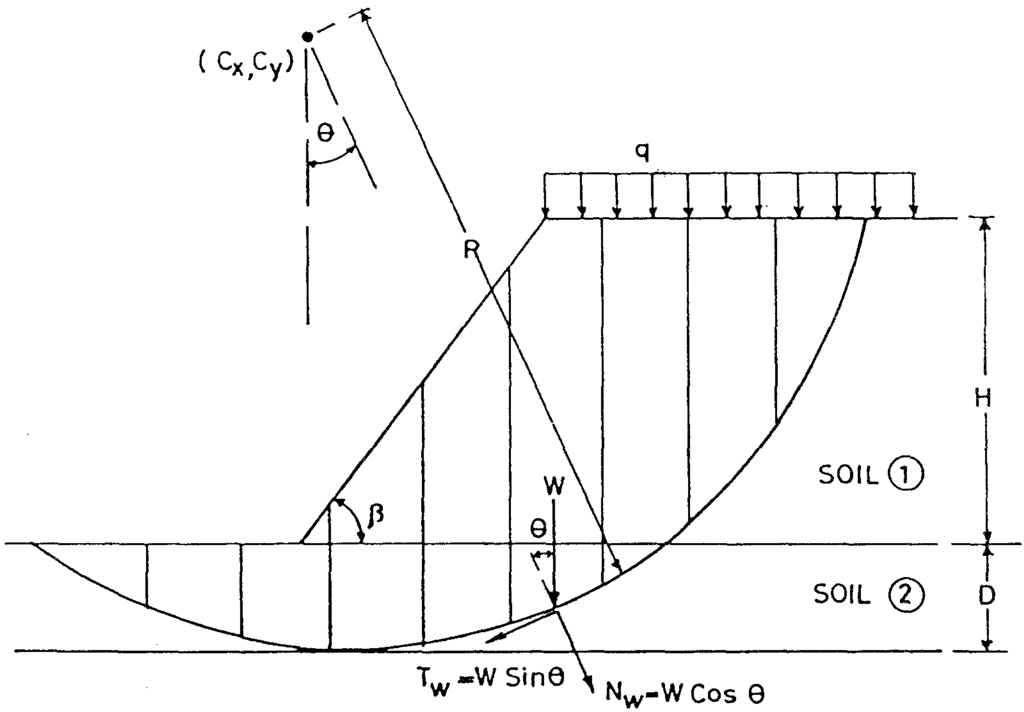


Fig. 1. Geometry and slip circle analysis of slope

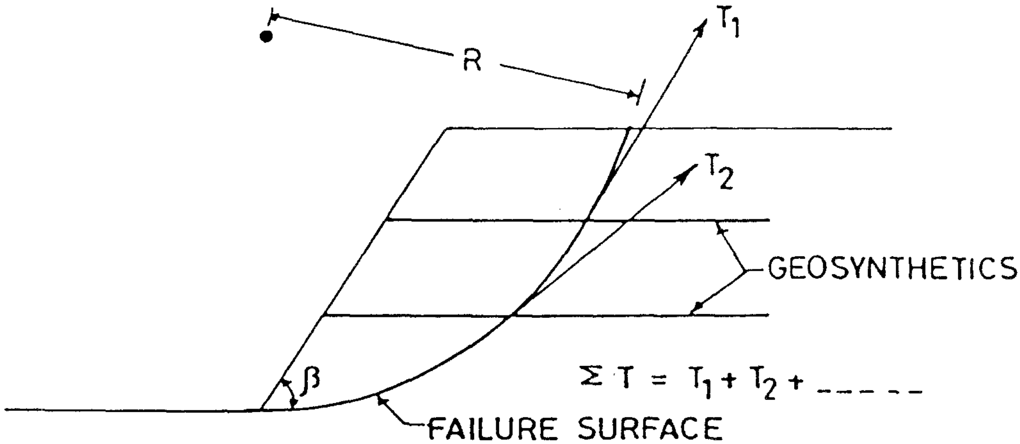


Fig. 2. Model for total tensile force

From Equations 1 and 2

$$FS' = \frac{M_R + R\Sigma T}{M_D} - \frac{M_R}{M_D}$$

$$FS' = \frac{R\Sigma T}{M_D}$$

$$\therefore \quad \Sigma T = \frac{FS' M_D}{R}$$

But from Equation 1:

$$M_D = \frac{M_R}{FS}$$

$$\therefore \quad \Sigma T = \frac{FS' M_R}{RFS} \tag{3}$$

Total tensile force

From Equation 3, total tensile force can be determined for the required factor of safety but this equation neglects any resistance the geosynthetic may provide normal to the shear surface. Fig. 3 shows the increase in normal force on the slip surface produced by the

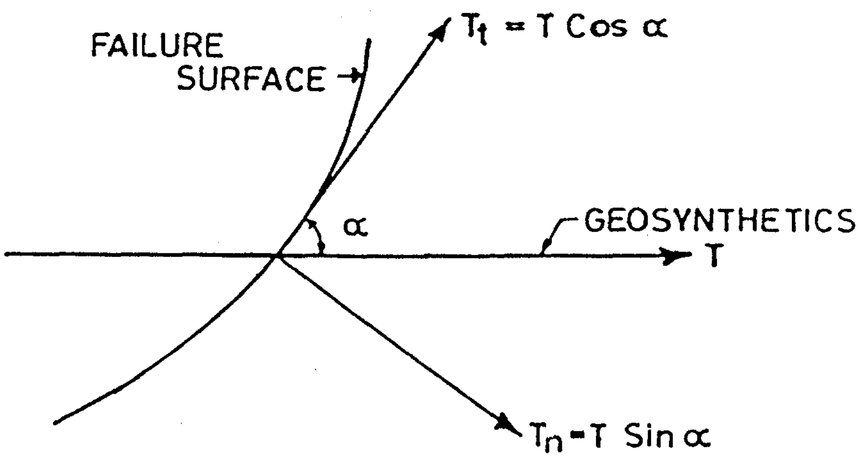


Fig. 3. Components of reinforcing force

geosynthetic to be $T \sin \alpha$ while the tangential force due to the reinforcement is $T \cos \alpha$. Here T is the tensile force in the reinforcement and α is the angle between the horizontal and the tangent to the slip surface.

To evaluate the effect of possible increase in normal stress on the potential slip surface, two extremes of geosynthetic force orientation are shown in Fig. 4; they range from tangential to

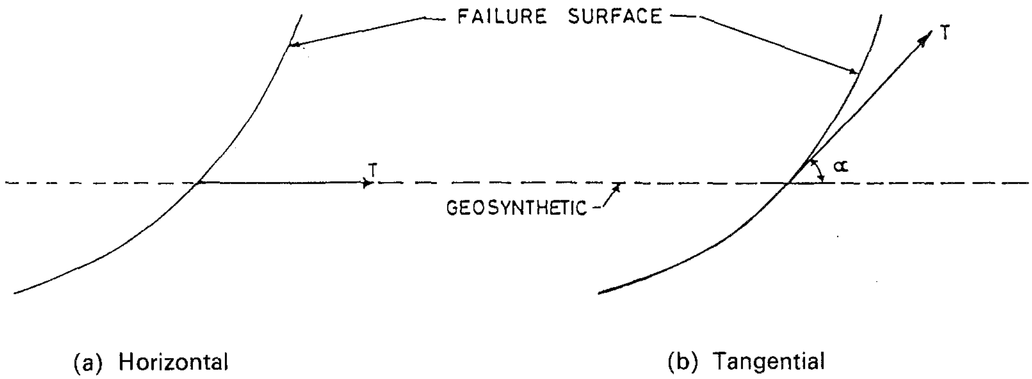


Fig. 4. Reinforcing force orientation

the slip surface ($\alpha > 0$) to horizontal ($\alpha = 0$). The assumption of a tangential geosynthetic force produces the lowest tensile force required for stability, while assuming the geosynthetic force to be horizontal will produce the highest force.

We assume the geosynthetic force to be horizontal and acting in the plane of the geosynthetic. To account for the increase in normal stress produced by the geosynthetic, the total tensile force in Equation 3 is modified for different ranges of α and modified total tensile force (ΣT^1) can be obtained from the following equations (Verduin and Holtz, 1989):

$$\text{for} \quad \alpha \geqslant 45^\circ \qquad \Sigma T^1 = \frac{\Sigma T}{1 + \tan\phi} \tag{4a}$$

$$\text{for} \quad 25^\circ < \alpha < 45^\circ \qquad \Sigma T^1 = \frac{\Sigma T}{1 + 0.5\tan\phi} \tag{4b}$$

$$\text{for} \quad \alpha < 25^\circ \qquad \Sigma T^1 = \frac{\Sigma T}{1 + 0.35\tan\phi} \tag{4c}$$

where ΣT^1 represents the modified total tensile force; ϕ is the angle of internal friction of soil; α is the angle between the horizontal and the tangent to the slip surface; and ΣT represents the total tensile force of reinforcement.

The actual value of α depends on the location of the critical surface and slope geometry. It is given by

$$\alpha = \cos^{-1}\left(\frac{Y_o - H/3}{R}\right)$$

where Y_o represents the vertical distance between the centre of the slip circle and the bottom of the slope (Fig. 5); R represents the radius of the slip circle; and H represents the height of the slope.

Geosynthetic tensile strength required per layer

After calculating the tensile force needed for slope stability, the individual strength of the geosynthetic layers can be determined. There may be different combinations of spacing and strength of reinforcement. Here two options are assumed. Option number 1 allocates the same spacing and same geosynthetic strength throughout the slope (Fig. 5). Option

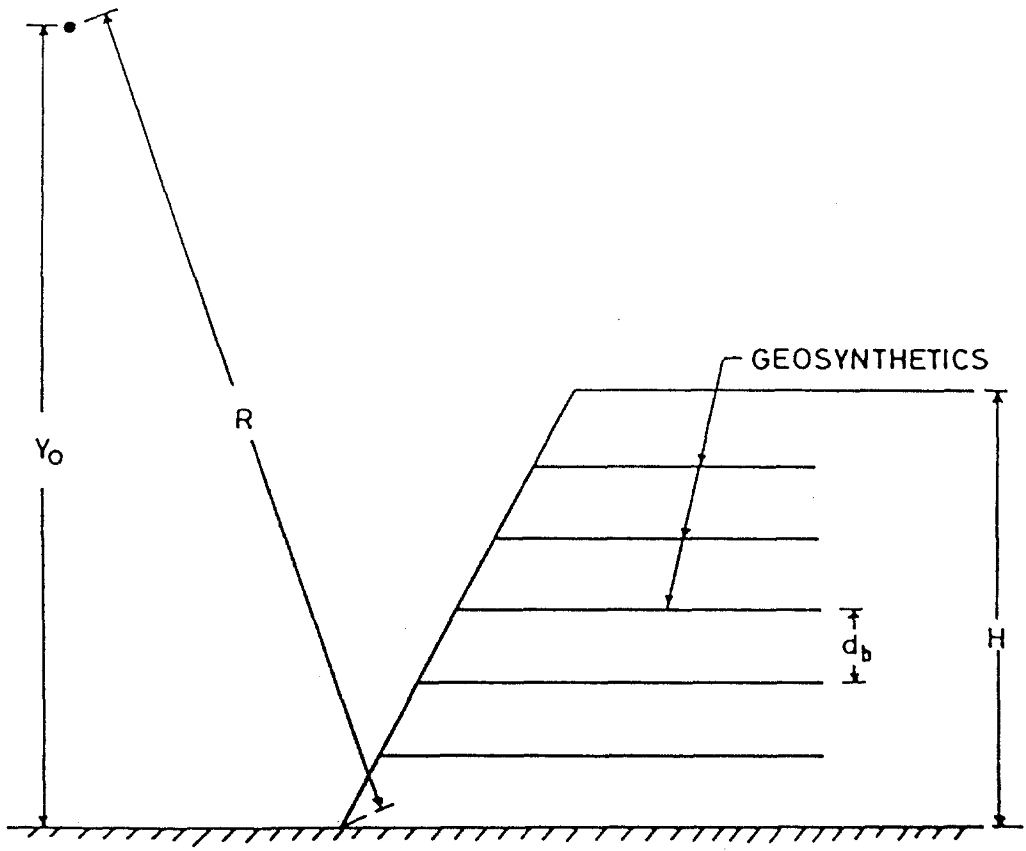


Fig. 5. Reinforcement arrangement for the same spacing throughout the slope

number 2 is for different geosynthetic strength and spacing in the upper and lower halves of the slope (Fig. 6).

The geosynthetic strength required in the upper layer (T_u) and lower layer (T_l) are determined by the following equations (Verduin and Holtz, 1989).

$$T_u = \frac{(1 - \text{Percent}/100)\,(\Sigma T^1)\,(R)}{nfl_t(Y_{ot}) - d_t[\Sigma(nfl_t)]} \tag{5}$$

$$T_l = \frac{(\text{Percent}/100)\,(\Sigma T^1)\,(R)}{nfl_b(Y_{ob}) - d_b[\Sigma(nfl_b)]} \tag{6}$$

where

$$\Sigma nfl_t = \frac{(nfl_t)\,(nfl_t + 1)}{2}$$

$$\Sigma nfl_b = \frac{(nfl_b)\,(nfl_b + 1)}{2}$$

$$Y_{ot} = Y_o - H/2$$

$$Y_{ob} = Y_o$$

Percent represents the percentage of force desired in the lower portion; H represents the height of slope; R represents the radius of slip circle; nfl_t represents the number of reinforcements in top layers; nfl_b represents the number of reinforcements in the bottom layer; Y_{ob}, Y_o represents the vertical distance between centre of slip circle and bottom of slope; Y_{ot} represents the vertical distance between centre of slip circle and half the height of slope; d_t represents the spacing in the top layer; and d_b represents the spacing in the bottom layer.

Option one: same spacing and strength

This is generally used for lower height embankments.

Equation 6 is used to calculate the forces using the following values:

$$\text{Percent} = 100$$

$$nfl_b = n_b - 1 \qquad \text{and}$$

$$n_b = \frac{H}{d_b}$$

where n_b represents the number of lifts; H represents the height of slope; and d_b represents the spacing of reinforcement.

Option two: different spacing and strength

If the slope is higher than 10 m, it is not possible to use geosynthetic of the same strength throughout. Hence usually two different geosynthetics and spacings are considered. Fig. 6 illustrates the reinforcement configuration for this option. For this option the values for input to Equations 5 and 6 are modified as follows:

$$R_n = \frac{d_t}{d_b} = \frac{n_b}{n_t}$$

$$n_t = \frac{H}{2(R_n)\, d_b}$$

$$nfl_b = n_b$$

$$nfl_t = n_t - 1$$

where R_n represents the ratio of the number of lifts in the bottom layer to the number in the top layer; n_t represents the number of lifts in the upper half of the slope; n_b represents the number of lifts in the lower half of the slope; d_b represents the spacing of reinforcement in the bottom half; d_t represents the spacing of reinforcement in the upper half; nfl_b represents the number of reinforcements in the lower half; and nfl_t represents the number of reinforcements in the upper half.

The percentage of total reinforcement in the bottom half should range from 60% to 80%. When only one type of reinforcing material is available, the percentage of reinforcement in the bottom is selected such that the strength in the upper layer (T_u) and the bottom

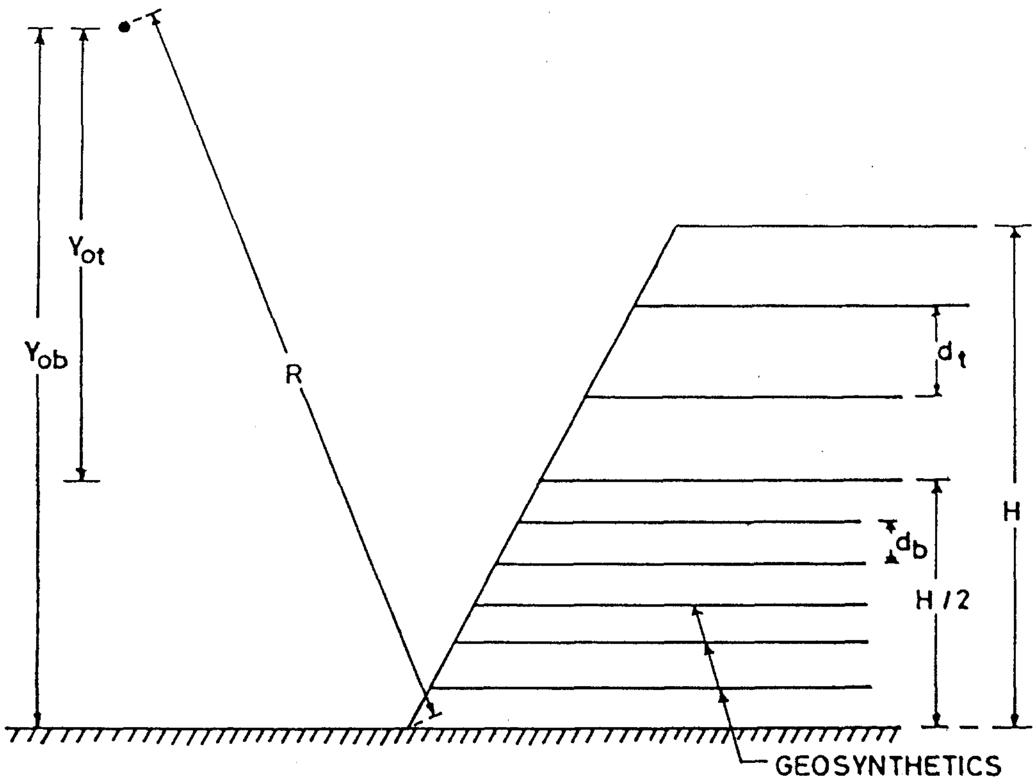


Fig. 6. Reinforcement arrangement for different spacings in the top and bottom of the slope

layer (T_l) will have similar values using Equations 5 and 6. The higher of the two strengths would be used for both layers.

Internal stability

To ensure the reinforcement has the capacity required to develop the prescribed design tensile strength, it must be embedded beyond the slip surface so that its pullout resistance will at least equal the design tensile strength.

It is important that the elongation of the geosynthetic is taken into account. Since the geosynthetic is extensible and confined, the magnitude of local movement at different points along the geosynthetic will probably never be the same. Therefore the shearing resistance will not be mobilized equally at all points along the reinforcement, as shown in Fig. 7 given by Beech (1987).

From Fig. 7 it is seen that the overall effect is a decrease in mobilized shear resistance with length along the surface of the geosynthetic reinforcement.

Figure 8 shows the model used for the internal stability to determine the embedded length, which is a generalization of the curve in Fig. 7. The mobilized shear resistance is taken to

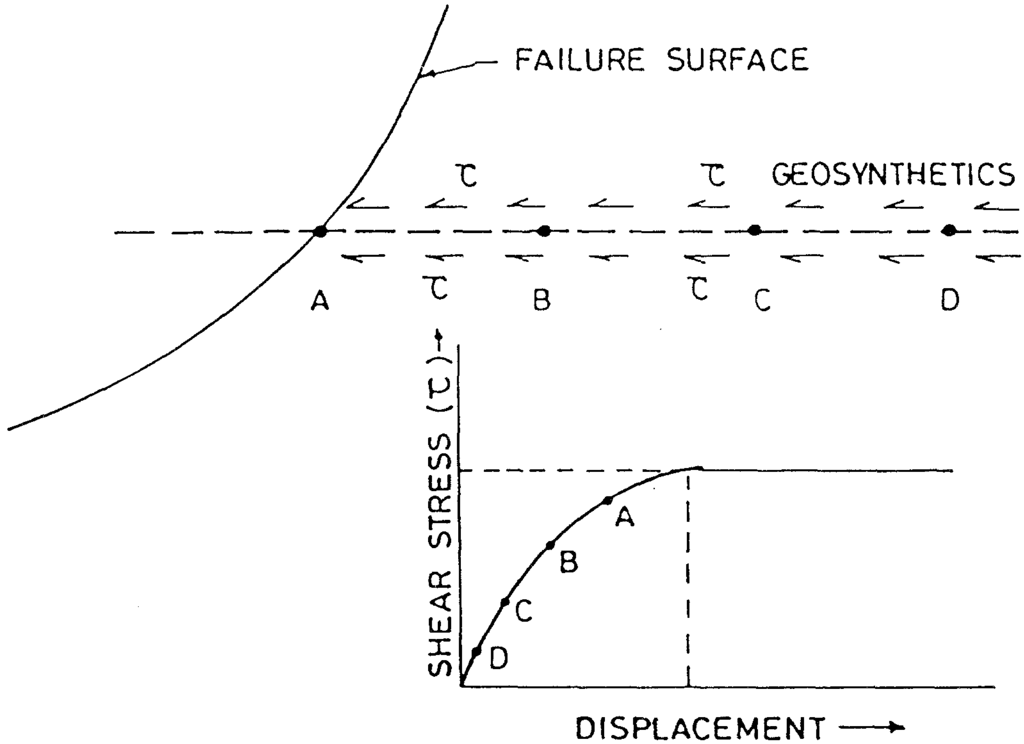


Fig. 7. Variation of shear stress along the reinforcement

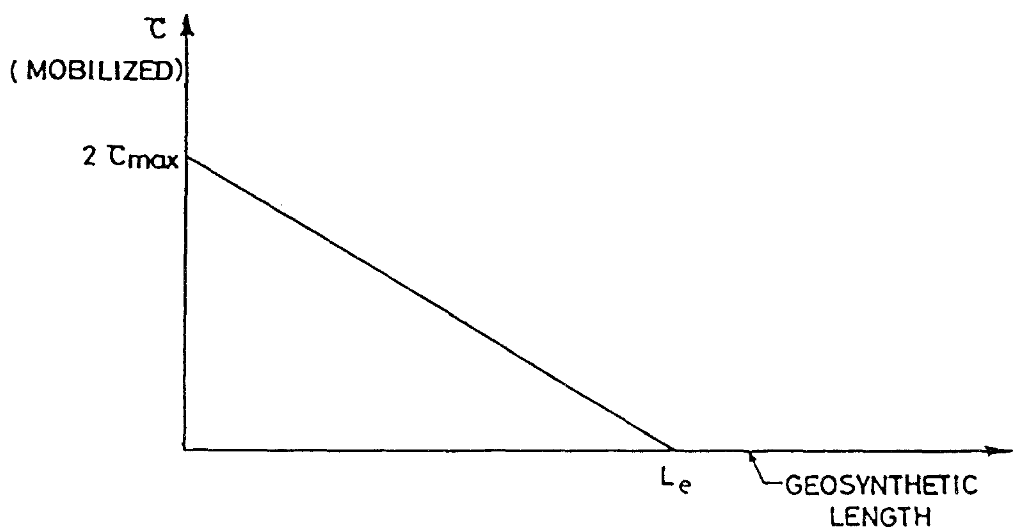


Fig. 8. Mobilized shear resistance model

attenuate linearly from a maximum ($2\tau_{max}$) at the critical surface to zero at the end of the geosynthetic length.

$$\text{Total mobilized shear resistance} = 2\tau_{max}\, \tfrac{1}{2} L_{\Phi}$$
$$= \tau_{max}\, L_{\Phi}$$

Total mobilized shear resistance should be equal to the individual design reinforcement strength.

$$T = \tau_{max}\, L_{\Phi}$$

Factor of safety (*FS*) against pullout is required because of uncertainty in the maximum mobilized shear strength.

Embedded length for a desired factor of safety against pullout is

$$L_{\Phi} = \frac{T}{\tau_{max}} FS \tag{7}$$

where T represents the individual reinforcement strength; τ_{max} represents the maximum mobilized shear strength $= \sigma_n \tan \phi_{sg}$; σ_n represents the overburden stress at the elevation of the reinforcement; and ϕ_{sg} represents the frictional angle of soil–reinforcement interface.

External stability

For external stability, the failure mechanism assumed is a bilinear planar surface extending outside the zone as shown in Fig. 9. The first block is an active wedge, which pushes against

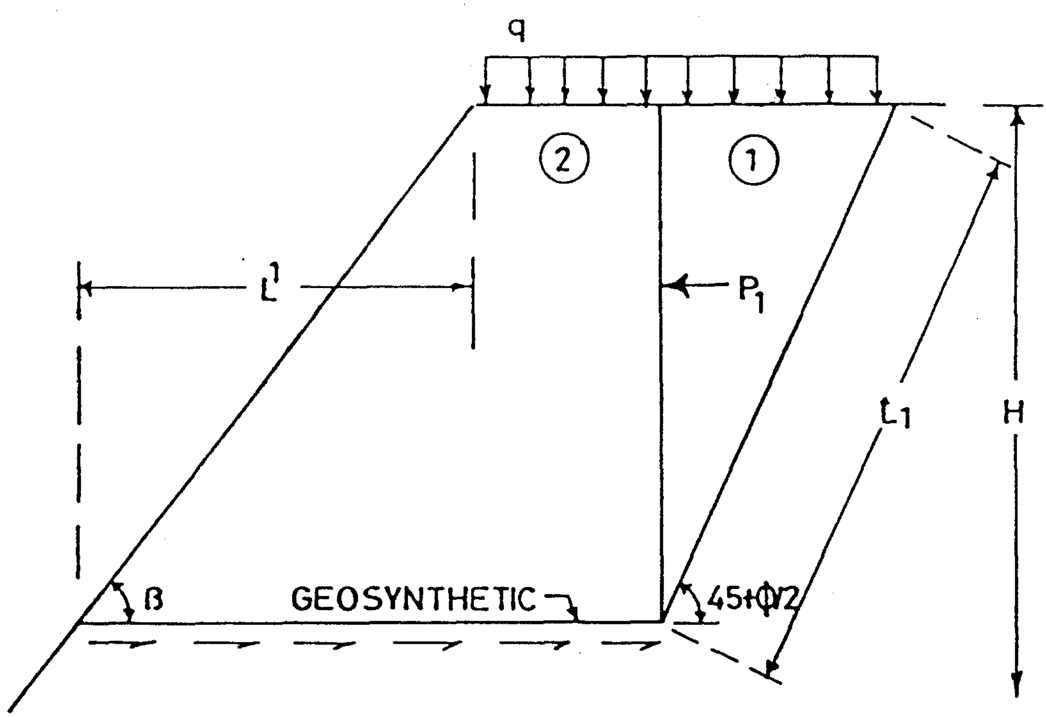


Fig. 9. Sliding block model

the second wedge which offers resistance in the form of friction at the soil geosynthetic interface. Geosynthetic length determination is computed using the following equations, taken from Verduin and Holtz (1989).

$$W_t = [\tfrac{1}{2}\gamma H^2 \tan(45° - \phi/2)][\tan(45° + \phi/2) - \tan\phi]$$

$$surch = q\left[H - \frac{H\tan\phi}{\tan(45° + \phi/2)}\right]$$

$$L_1 = \frac{H}{\sin(45° + \phi/2)}$$

$$coh = \frac{C \cdot L_1}{\cos(45° + \phi/2)}$$

$$P_1 = \frac{W_t + surch - coh}{1 + \tan\phi \tan(45° + \phi/2)}$$

$$L = \sqrt{\frac{2P_1\, FS}{\gamma \tan\beta \tan\phi_{sg}}} \tag{8a}$$

$$L_1 = \frac{H}{\tan\beta}$$

When the length of geosynthetic (L) calculated from Equation 8a is less than the horizontal distance between the toe and crest (L^1) then the following formula is used to calculate the length of geosynthetic (L) to resist sliding, i.e. if $L < L^1$

$$L = \frac{P_1\, FS}{H\gamma \tan\phi_{sg}} + \frac{L^1}{2} \tag{8b}$$

where γ represents the unit weight of soil; ϕ represents the angle of internal friction of soil; β represents the slope angle; ϕ_{sg} represents the angle of soil–reinforcement friction; H represents the height of slope; L represents the length of reinforcement to resist sliding resistance at the bottom; P_1 represents the horizontal active force; q represents the uniform surcharge; C represents the cohesion of soil; L_1 represents the length of the inclined failure surface of block (1) as shown in Fig. 9; W_t represents the weight of block (1); *surch* represents the weight of surcharge load acting on inclined failure surface; and *coh* represents the perpendicular force acting on the inclined failure surface of block (1).

Geosynthetic length in intermediate layers

The lengths of intermediate reinforcement layers are calculated by linearly interpolating between the length of the bottom-most layer (designed against sliding resistance) and the length of the top layer (designed against pullout resistance).

Overall rotational stability

After designing for reinforcement, the minimum factor of safety is determined of the reinforced soil slope to check the design. The method of analysis is the same as used for analysis of the unreinforced slope.

Salient features of the program

The computer program first determines the minimum factor of safety of the unreinforced soil slope. The program is operative on the CYBER 180/840 main frame system. If the minimum factor of safety is less than the required factor of safety then the program automatically proceeds to the design of reinforcement for the stability of the slope. The program can be used for various slope geometries, properties of soil and continuous uniform surcharge.

The program automatically generates the slope angle and height from geometric coordinates of the boundary of the slope given as input data (see Fig. 10). Provision is also

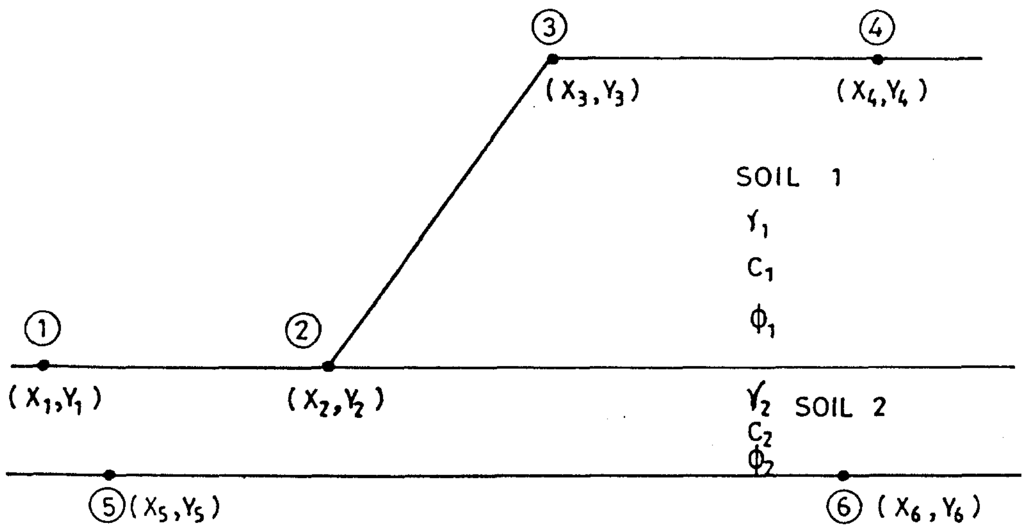


Fig. 10. Geometry and input data

made to calculate the directional angle from a separate subroutine for determination of the locus of slip circle centres. The program calculates the minimum factor of safety of unreinforced soil the radius and coordinates of the centre of the slip circle. It stores the resisting moments and calculates intersection points of the slip surface and boundary of the slope so that the failure surface can be plotted easily on a graph.

After calculating the minimum factor of safety of the unreinforced soil, and if it is less than the required factor of safety, the program calculates the total tensile force required for stability. A separate subroutine calculates the individual strength of reinforcement, embedded length of reinforcement in the top layer and the length of bottom reinforcement for a required factor of safety. It automatically calculates the intermediate length of reinforcement. It gives the position of reinforcement in each layer from the bottom of slope and the length for that particular layer.

Input data

The data for slope stability is the geometric data of the slope and material properties. The number of slices, required factor of safety, spacing in the lower portion and coefficient of friction at the soil/reinforcement interface are input. Input data has to be given as follows (see Fig. 10).

(1) Coordinates of the boundary of the slope as numbered (1) to (6) in Fig. 10 (X_1, Y_1), (X_2, Y_2), (X_3, Y_3), (X_4, Y_4), (X_5, Y_5), and (X_6, Y_6).
(2) Unit weight, cohesion and angle (ϕ) of soil fill (γ, C, ϕ) and height (H) for both soil(1) and soil(2), given in Fig. 10.
(3) Number of slices.
(4) Required factor of safety.
(5) Spacing of reinforcement in lower half.
(6) Coefficient of friction at the soil–reinforcement interface.

Output

Output of the Program is as follows:

(1) Height of slope.
(2) Angle of slope.
(3) Minimum factor of safety of unreinforced slope.
(4) Radius and centre point of slip circle.
(5) Length of reinforcement in top and bottom layers.
(6) Vertical position of all layers from the bottom and their corresponding lengths.
(7) Strength of reinforcing material.

The flow chart for the design of geosynthetic reinforced soil is given in Table 1.

Design procedure

For a given geometry of slope (slope angle and height), the unit weight of soil, cohesion of soil, internal angle of friction and uniform surcharge (γ, c, ϕ, q), the following procedure can be followed to utilize the charts given in Figs 11 to 22.

(1) Compute modified height (H') using the relation

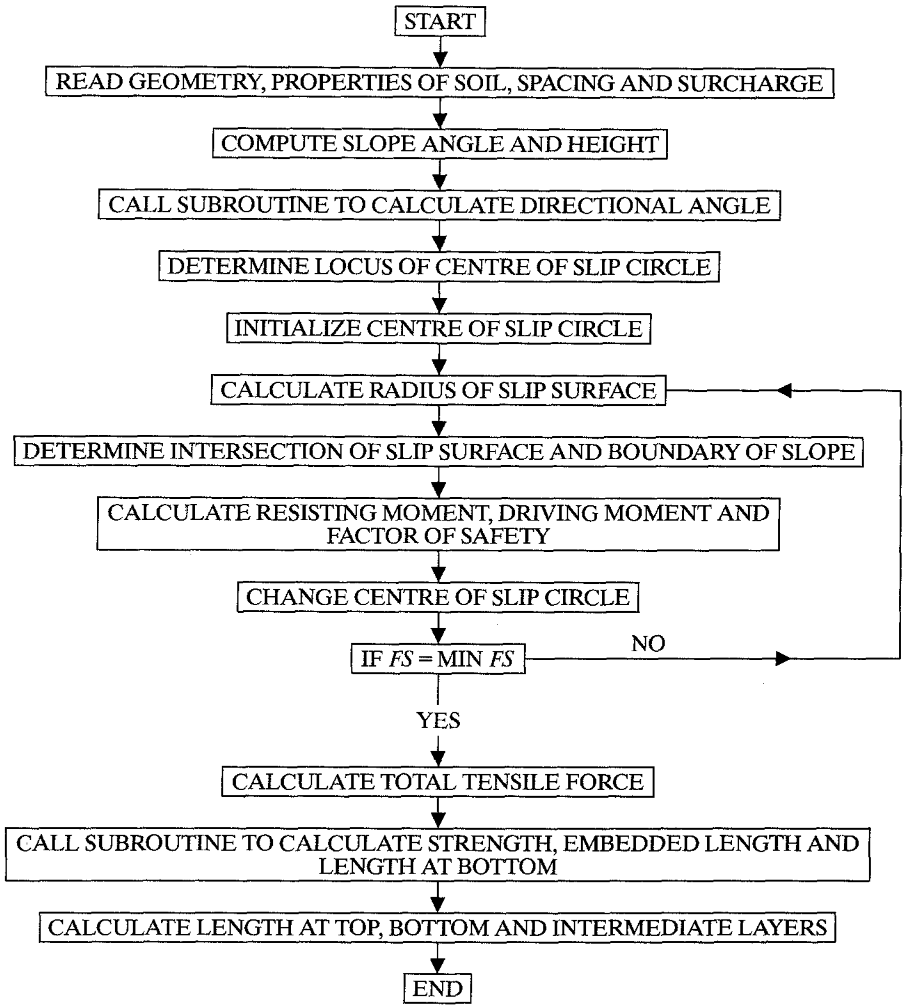
$$H' = H + q/\gamma$$

where H represents the height of slope; q represents the uniform surcharge; and γ represents the unit weight of soil.
(2) Calculate the value $C/\gamma H'$ to use all charts.
(3) Use the charts in Figs 11 to 14 to estimate ΣT for the given ϕ angle and slope angle. From the charts find out the approximate value of $\Sigma T/\gamma H'^2$ and calculate ΣT.
(4) Select the spacing of reinforcement in the bottom half. Calculate the number of reinforcements (*nfl*) and strength of geosynthetic (T).

$$T = \Sigma T/nfl$$

where *nfl* represents the number of reinforcement layers.
(5) Use the charts in Figs 15 to 18 to estimate the length at the top L_T.
(6) Use the charts in Figs 19 to 22 to estimate the length at the bottom L_B.
(7) Calculate the length of reinforcement at intermediate layers by linearly interpolating between the length at the bottom-most layer and the length at the top layer.

Table 1. Flow chart of geosynthetic stability of reinforced soil



Results and discussion

Total tensile force

The total tensile force, ΣT required is plotted on the vertical axis using the dimensionless parameter $\Sigma T/\gamma H'^2$ in Figs 11 to 14. These figures show the plot of total tensile force for different slope angles and values of ϕ. It has been observed that the total tensile force required increases with an increase in the slope angle. For steeper slopes, the required tensile strength is high. Considering the internal angle of friction of the soil ϕ, it is observed that as ϕ increases the total tensile force decreases for any slope angle. If considering variation of the unit weight of soil, total tensile force is affected, since by increasing or decreasing the unit

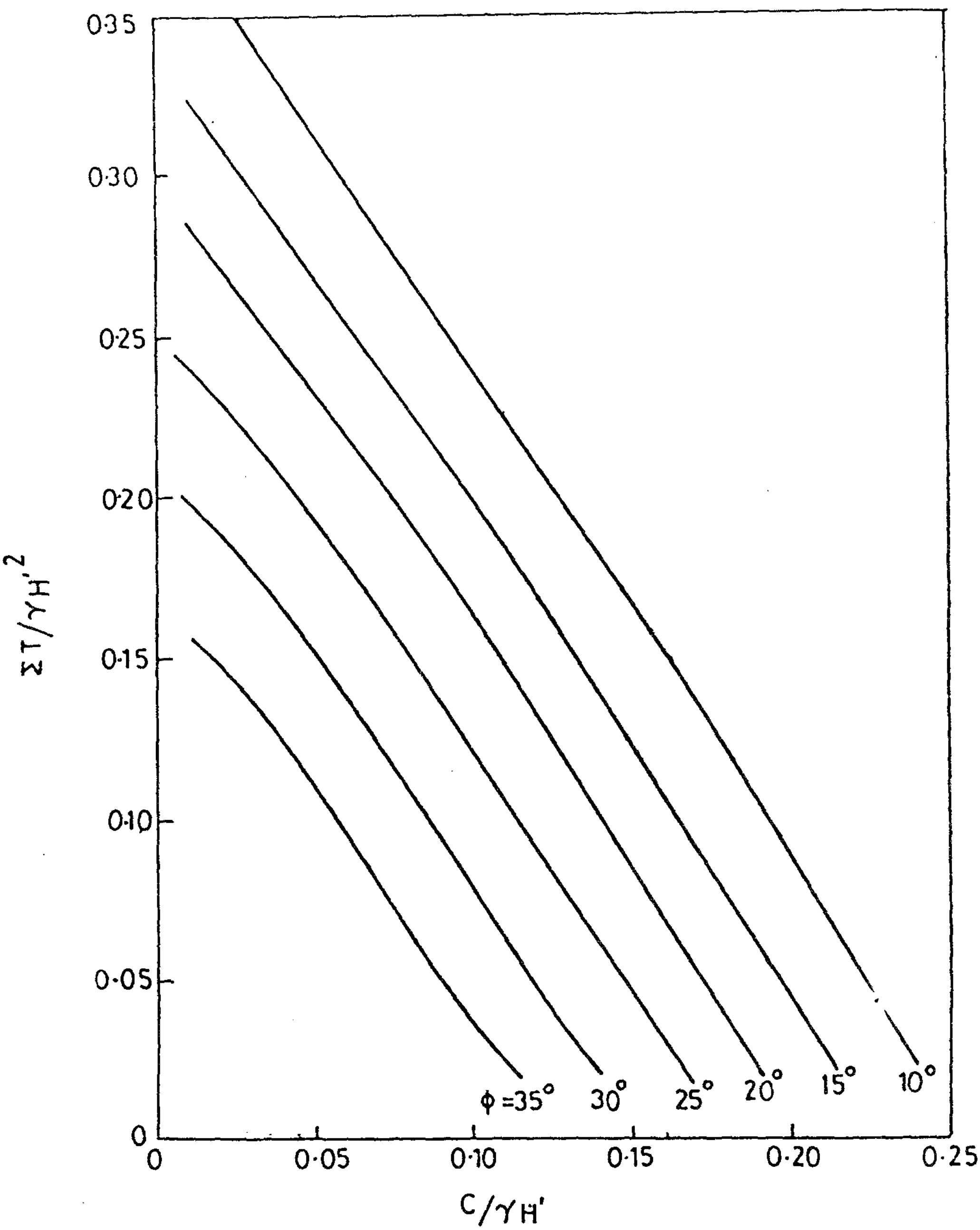


Fig. 11. Graph of total tensile force for slope 0.25:1 (76°)

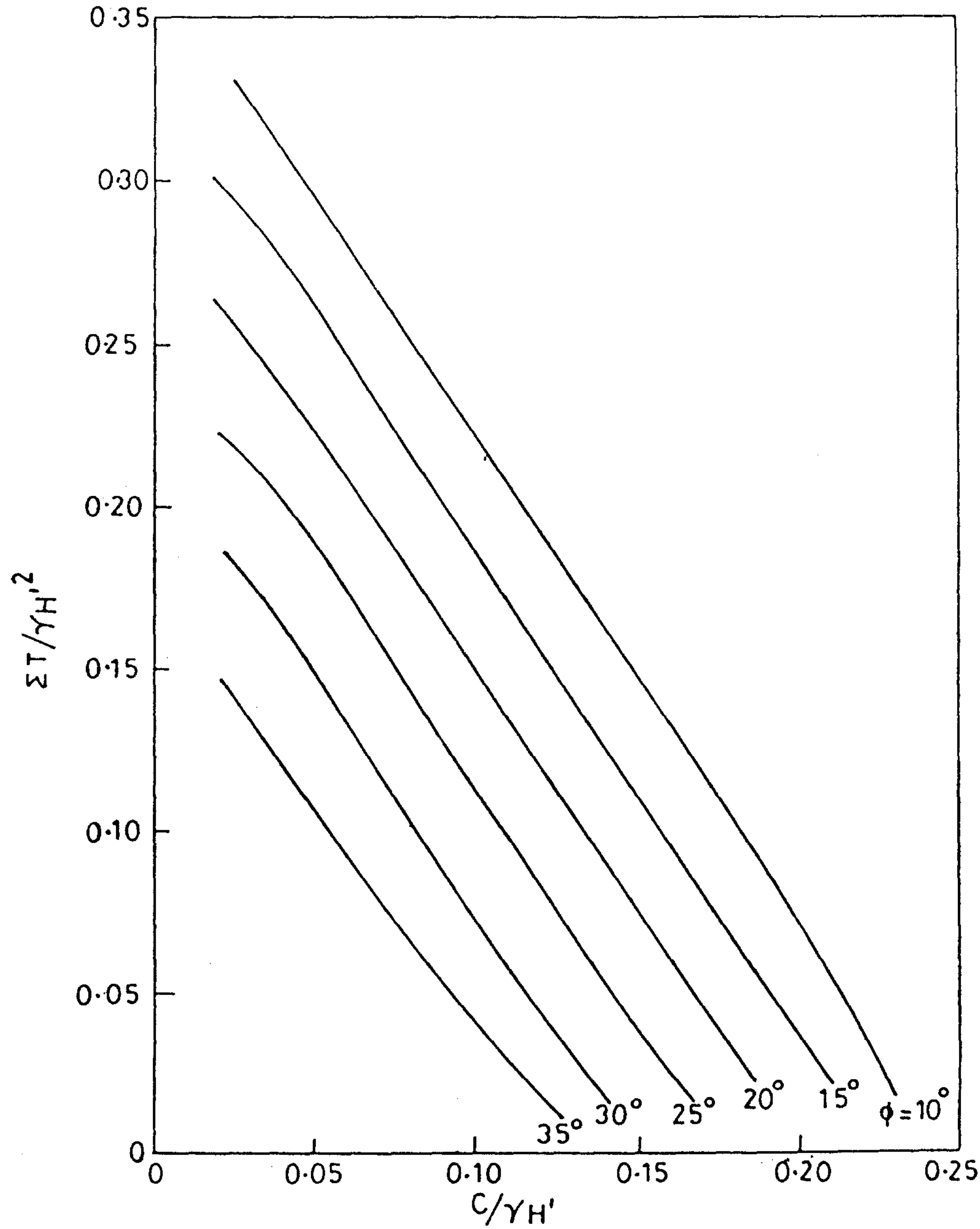


Fig. 12. Graph of total tensile force for slope 0.6:1 (59°)

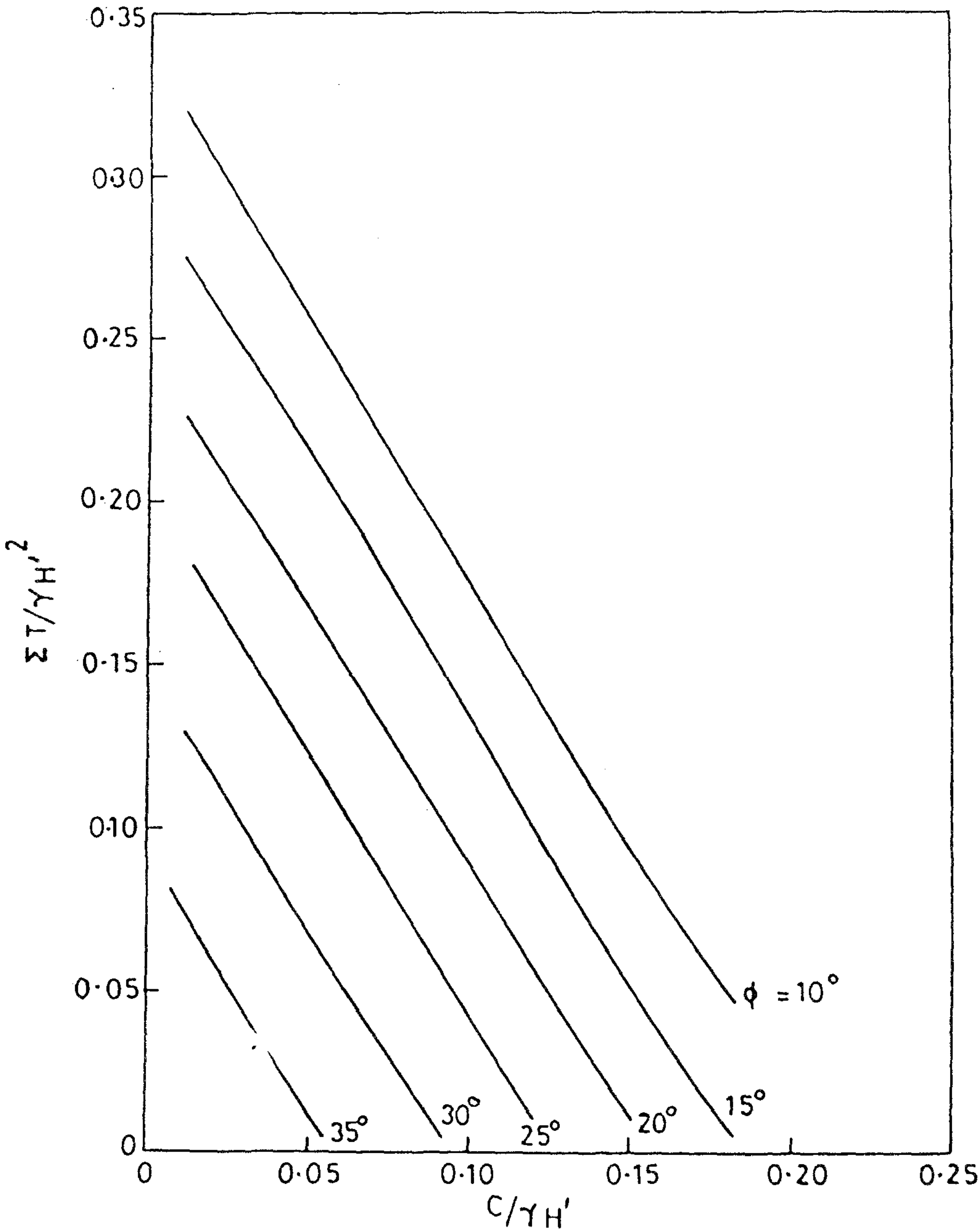


Fig. 13. Graph of total tensile force for slope 1:1 (45°)

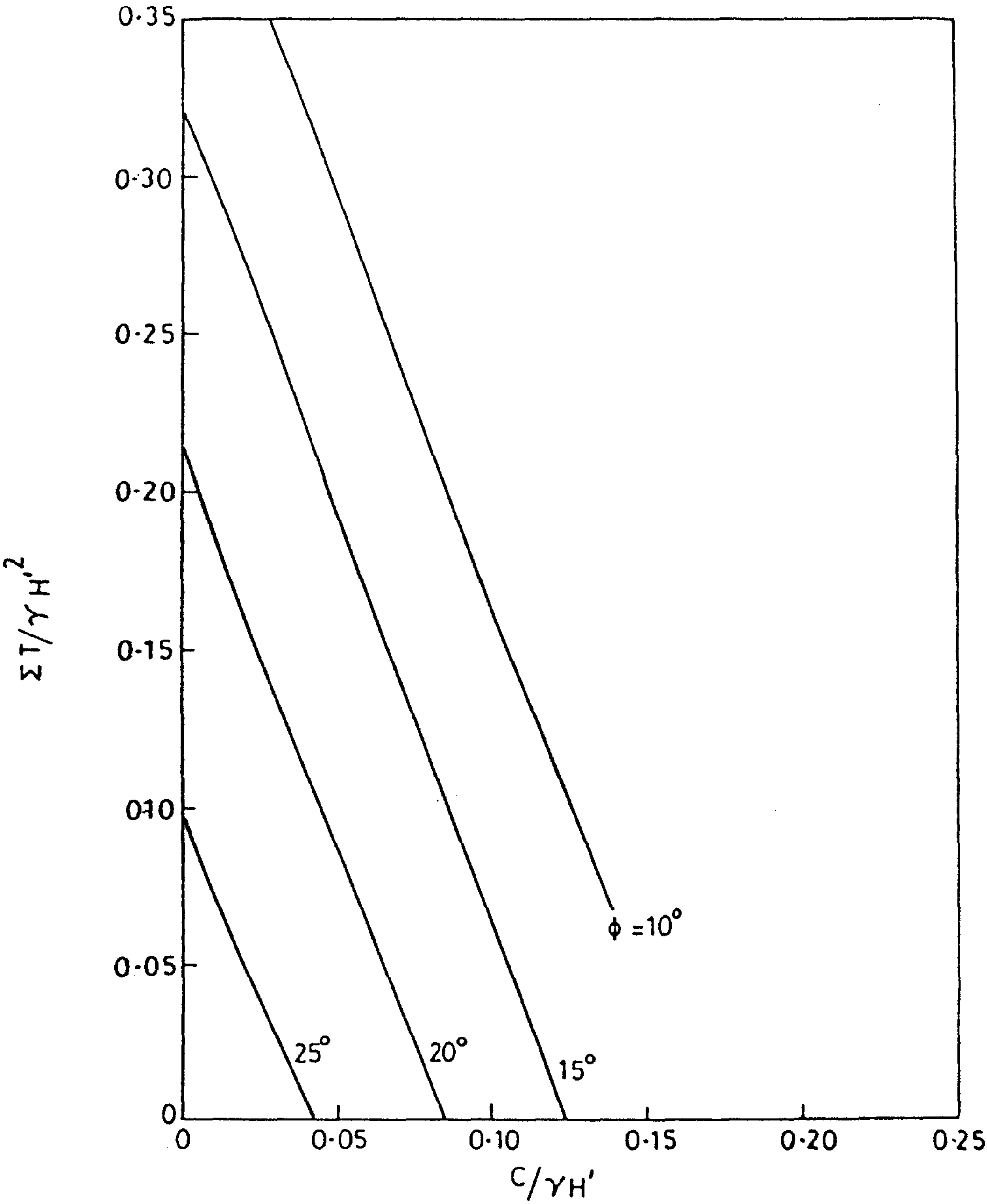


Fig. 14. Graph of total tensile force for slope 1.67:1 (31°)

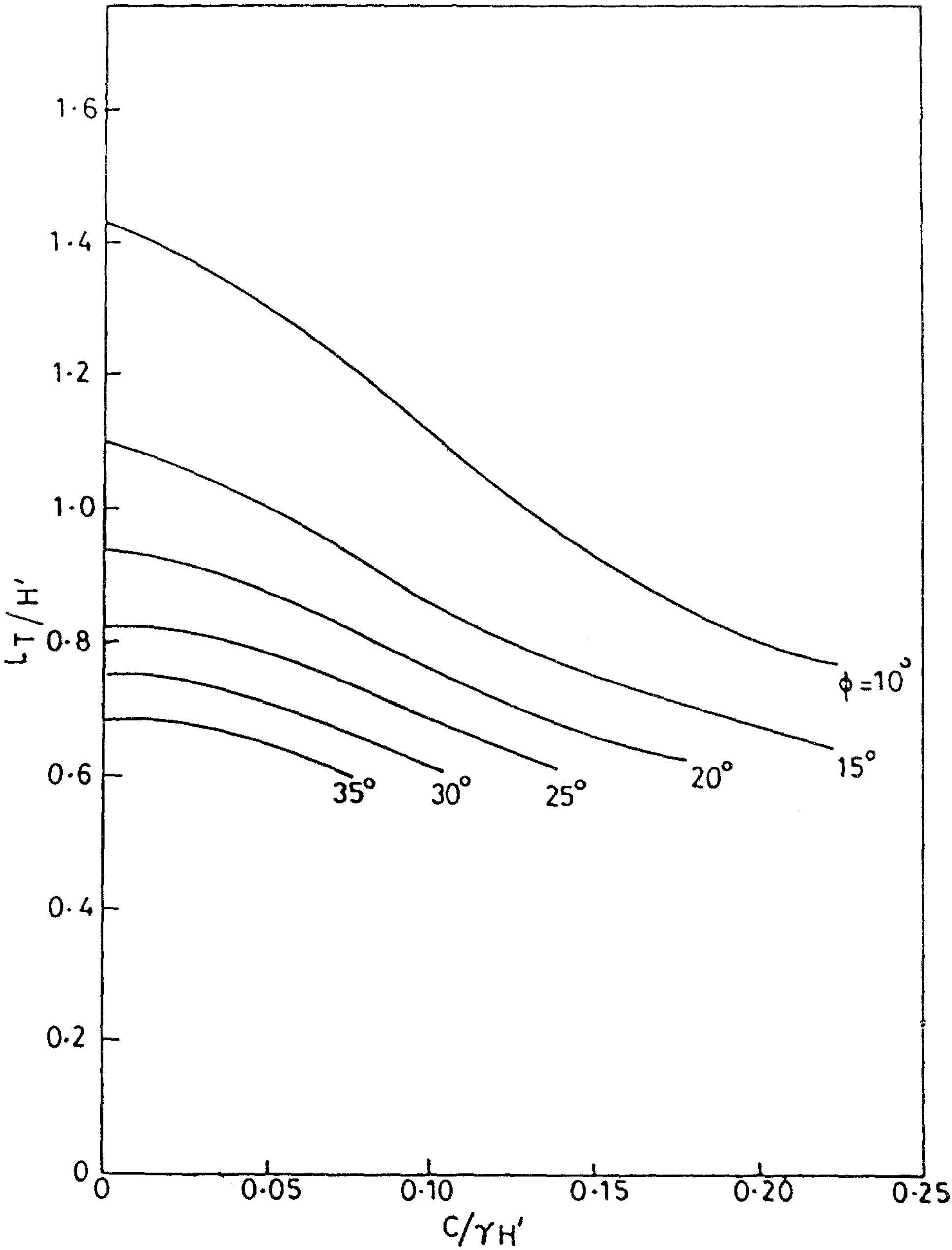


Fig. 15. Graph of length at the top layer for slope 0.25:1 (76°)

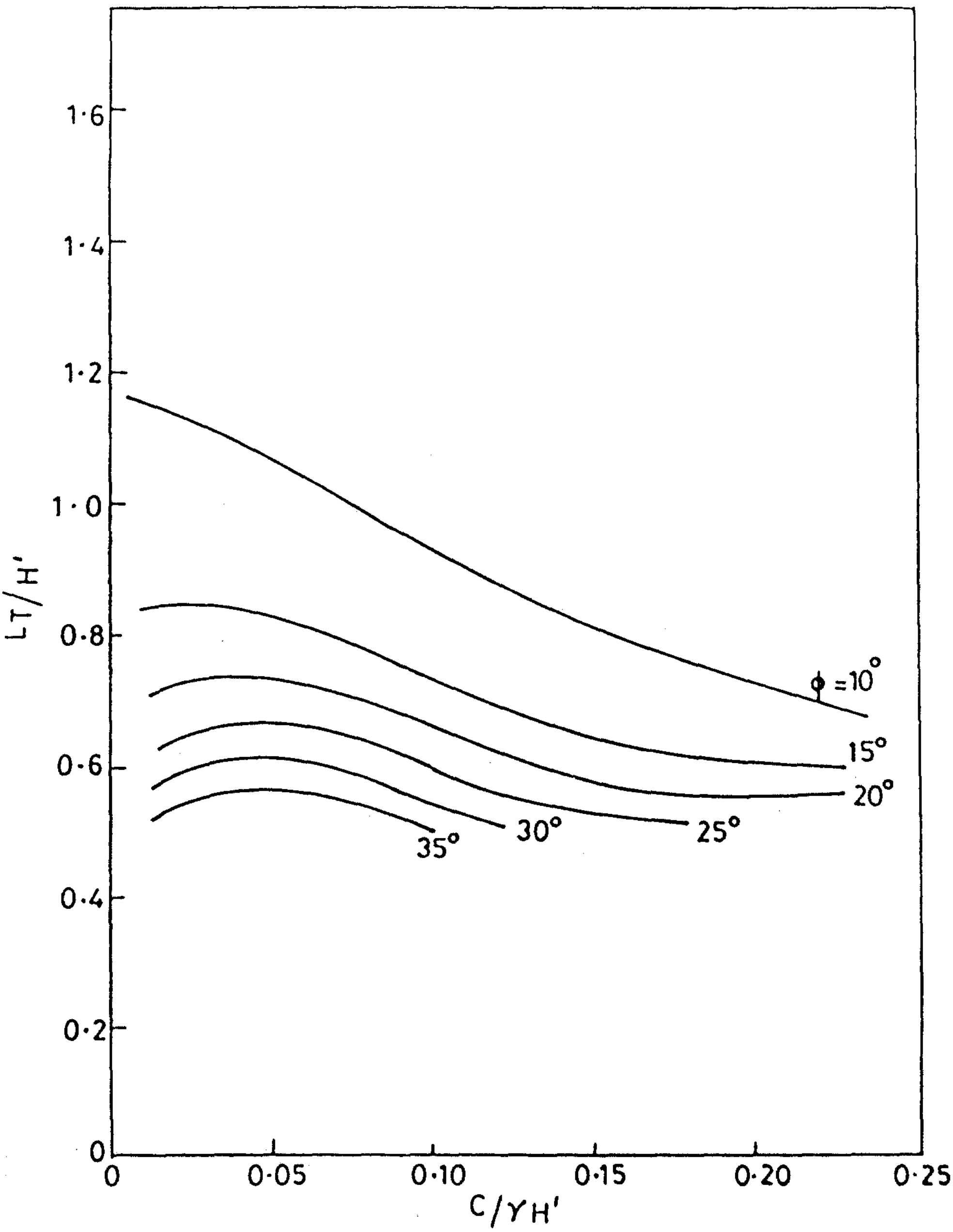


Fig. 16. Graph of length at the top layer for slope 0.6:1 (59°)

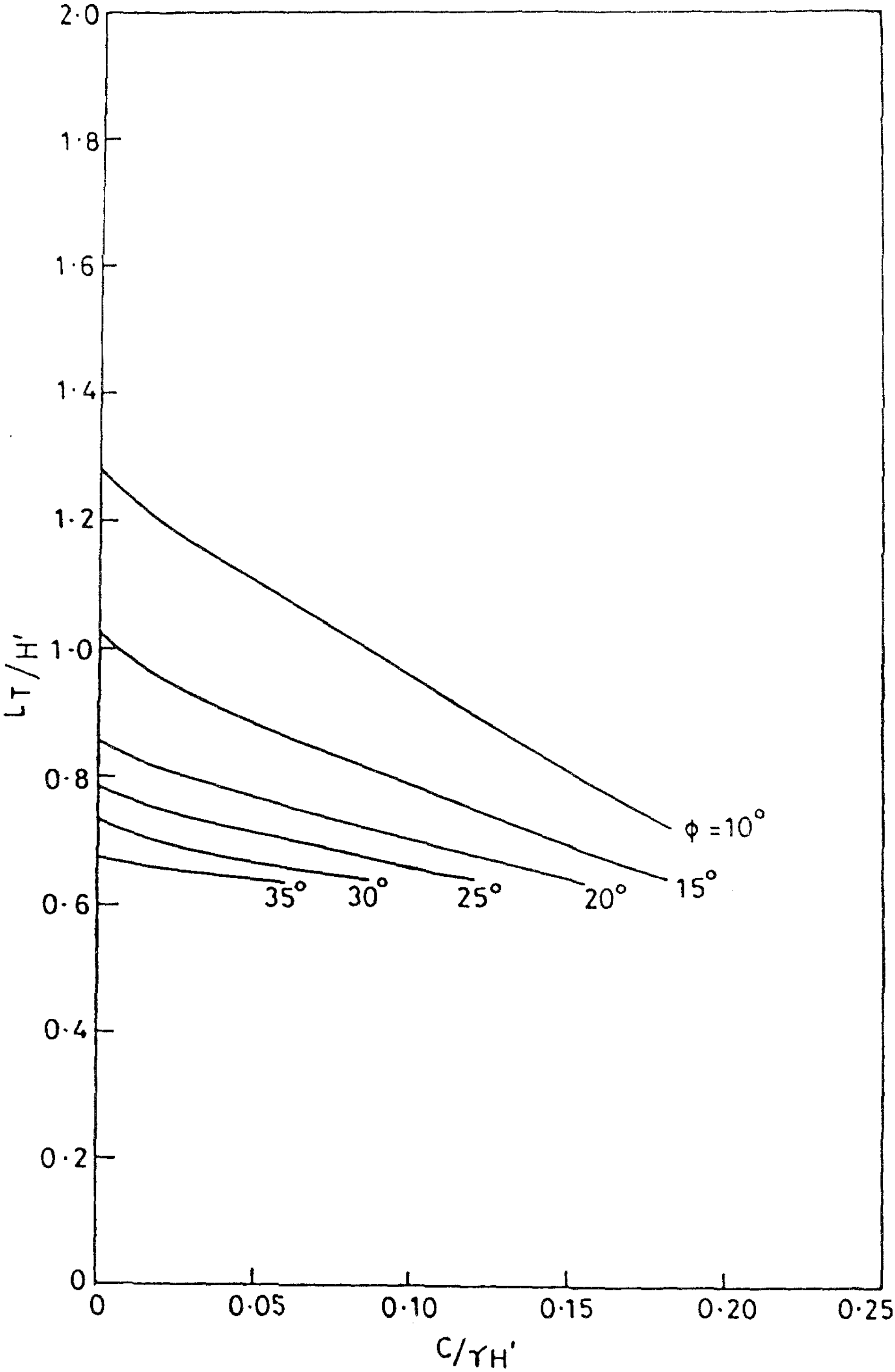


Fig. 17. Graph of length at the top layer for slope 1:1 (45°)

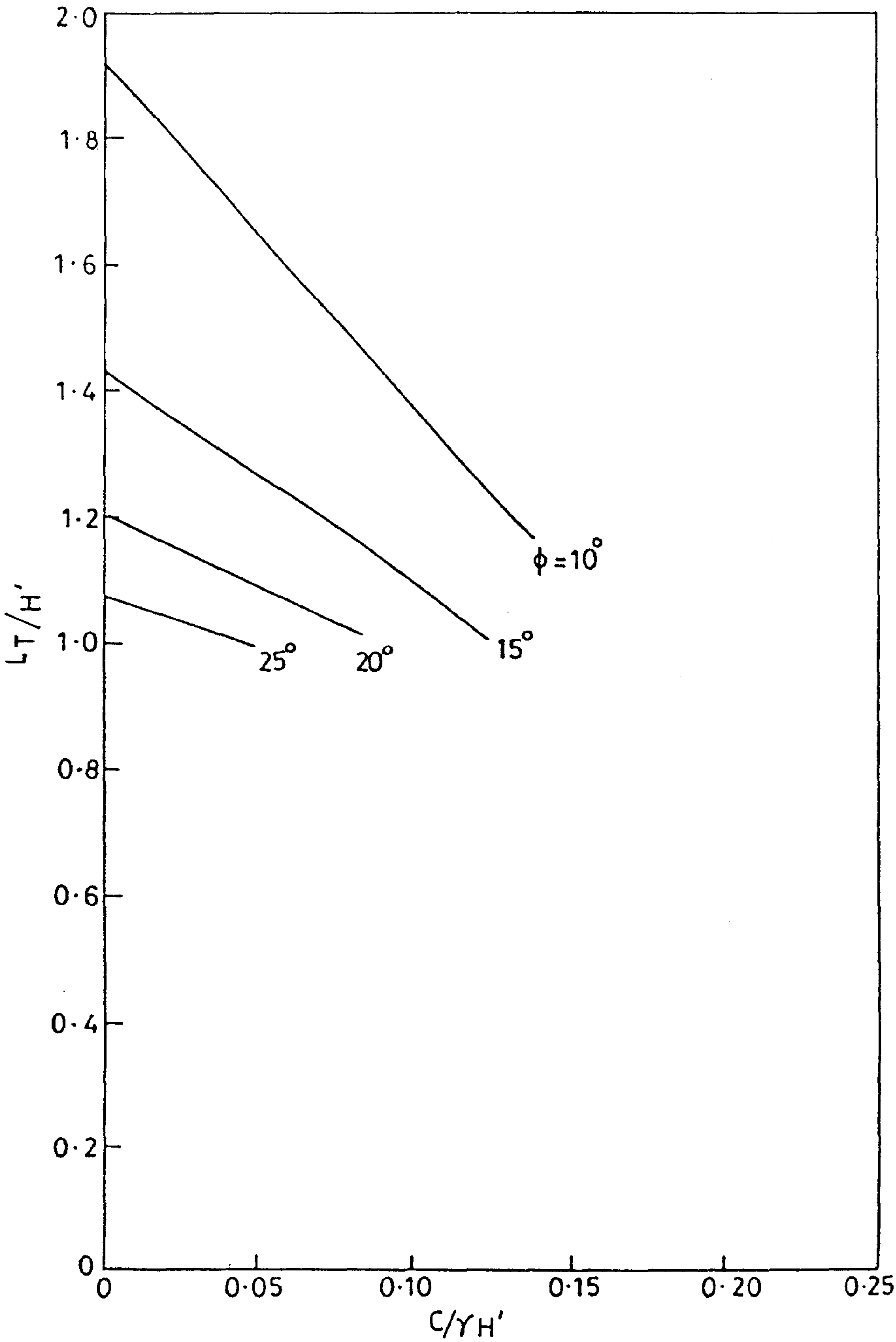


Fig. 18. Graph of length at the top layer for slope 1.67:1 (31°)

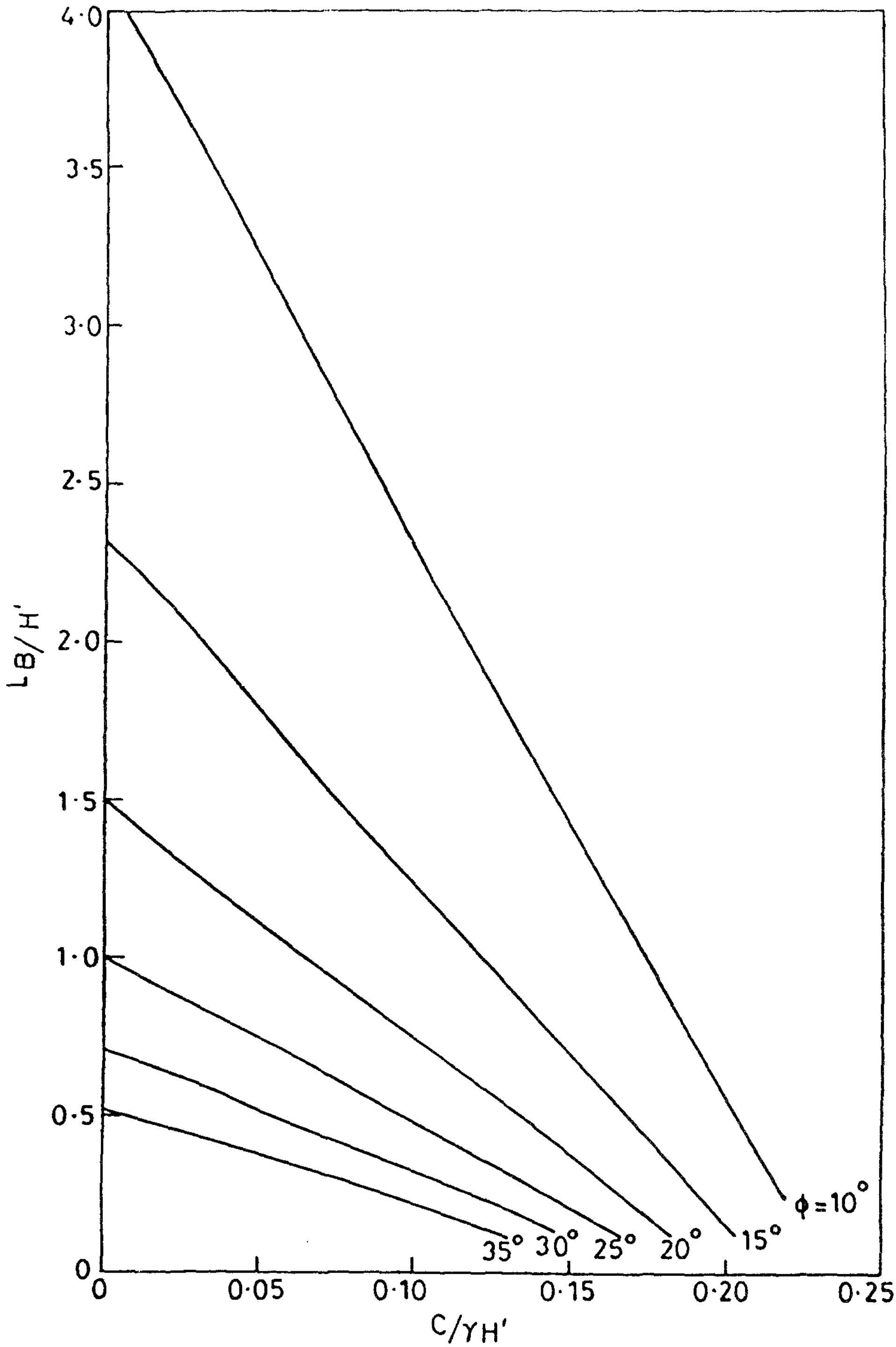


Fig. 19. Graph of length at the bottom for slope 0.25:1 (76°)

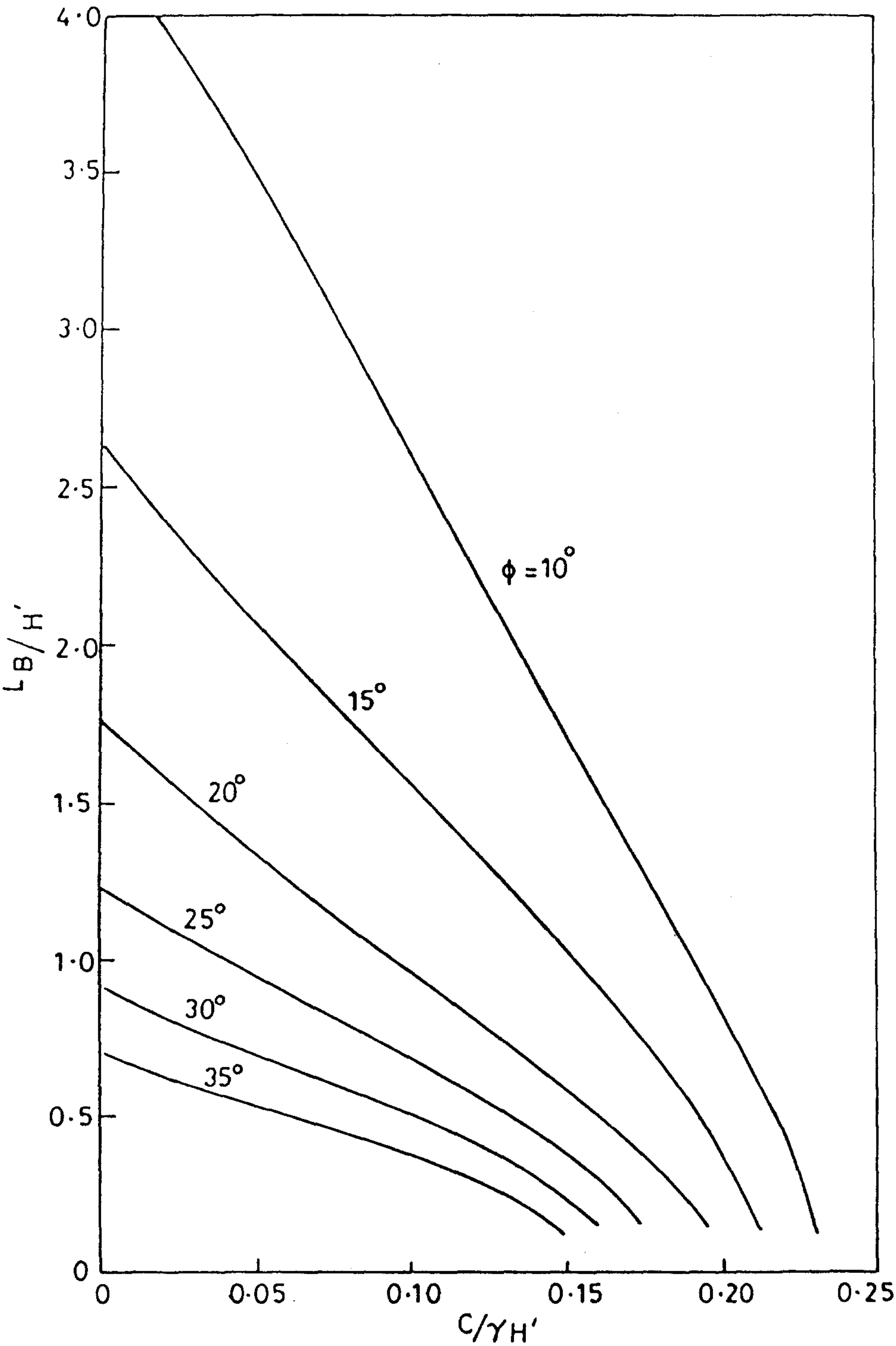


Fig. 20. Graph of length at the bottom for slope 0.6:1 (59°)

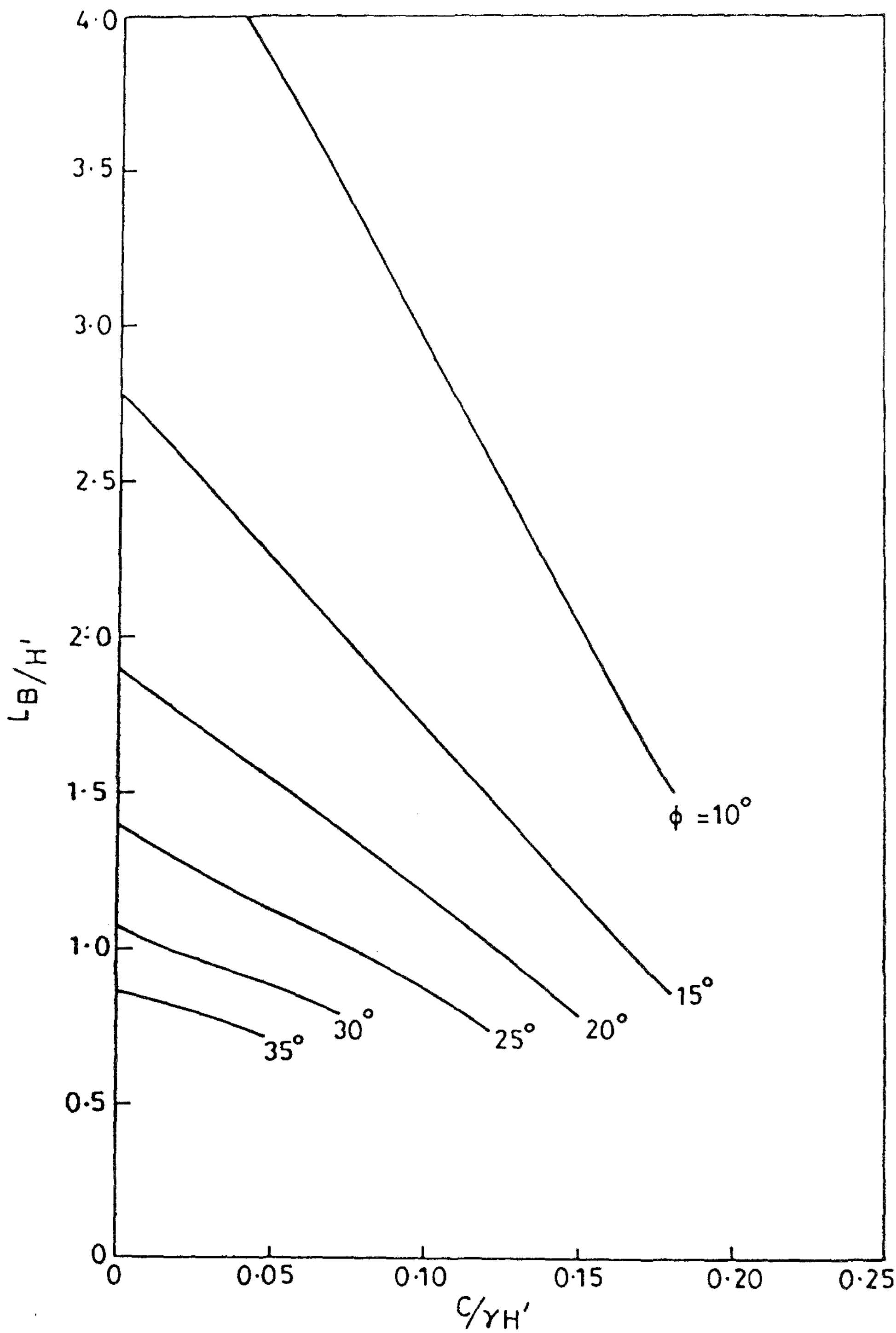


Fig. 21. Graph of length at the bottom for slope 1:1 (45°)

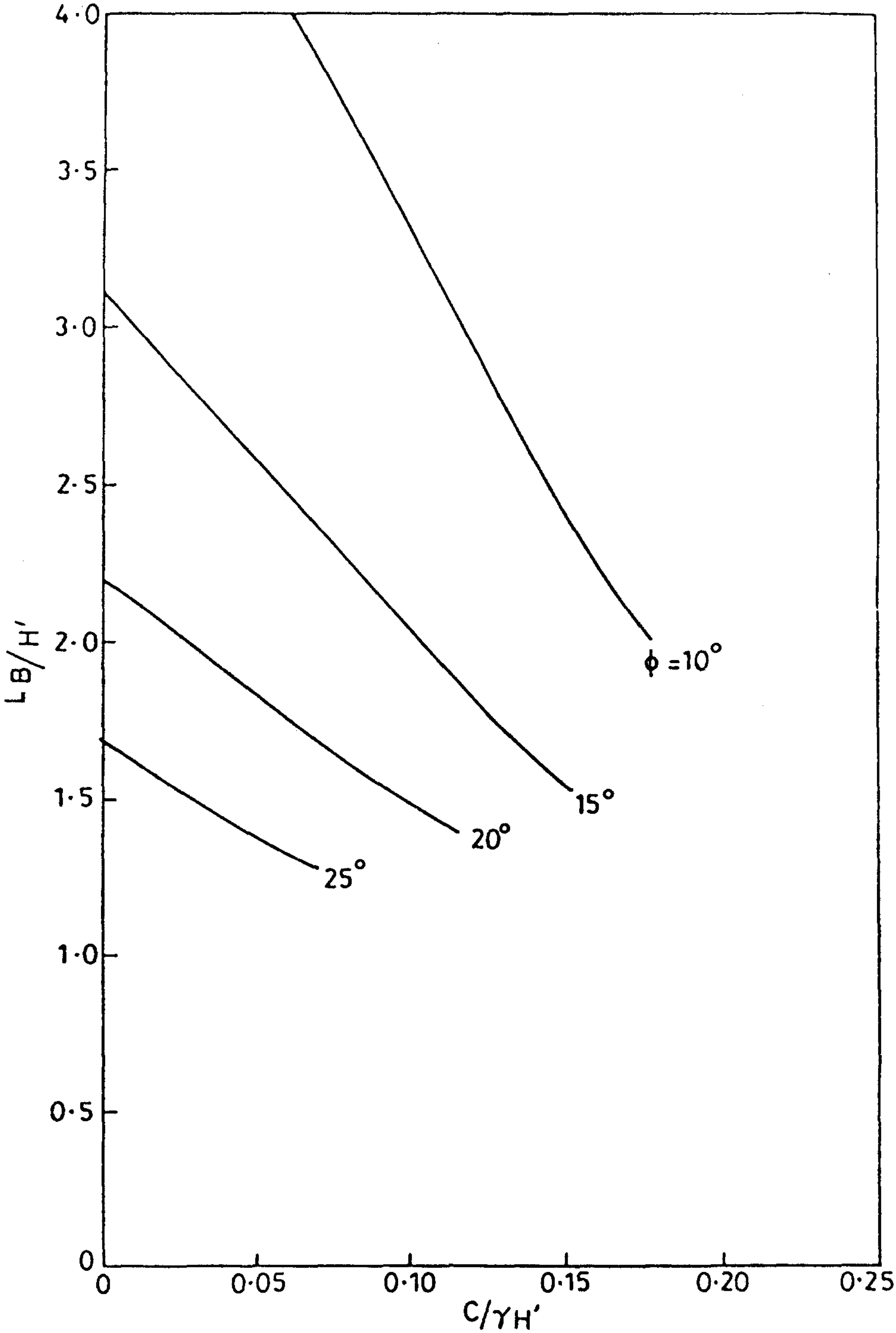


Fig. 22. Graph of length at the bottom for slope 1.67:1 (31°)

weight of soil, the dimensionless parameter on the x-axis will vary and accordingly produce a variation in the total tensile force required. For the cohesion of soil, as the cohesion decreases, the required total tensile force is increased. This means that the variation of the total tensile force required is inversely proportional to the strength of the soil. Again from the plots, it is observed that by increasing the height of the slope, the required total tensile force is increased.

Length of reinforcement at the top layer

The length of reinforcement at the top layer, L_T required is plotted on the vertical axis of Figs 15 to 18 using the dimensionless parameter L_T/H'. The figures show plots of length at the top layer for different slope angles and ϕ. It can be seen that the length of reinforcement of the top layer increases with an increase in slope angle. For steeper slopes, the required length at the top is high. It can also be seen that as ϕ increases the required length at the top decreases for any slope angle. Variation in unit weight causes variation in the dimensionless parameter on the x-axis and therefore variation of the length at the top occurs. Again for the cohesion of the soil, the length at the top increases with a decrease in cohesion. By increasing the height of slope, the required length at the top layer is increased.

Length of reinforcement at the bottom layer

Length of reinforcement at the bottom layer, L_B is plotted on the vertical axis using the dimensionless parameter L_B/H' in Figs 19 to 22, which show the length at the bottom layer for different slope angles and ϕ.

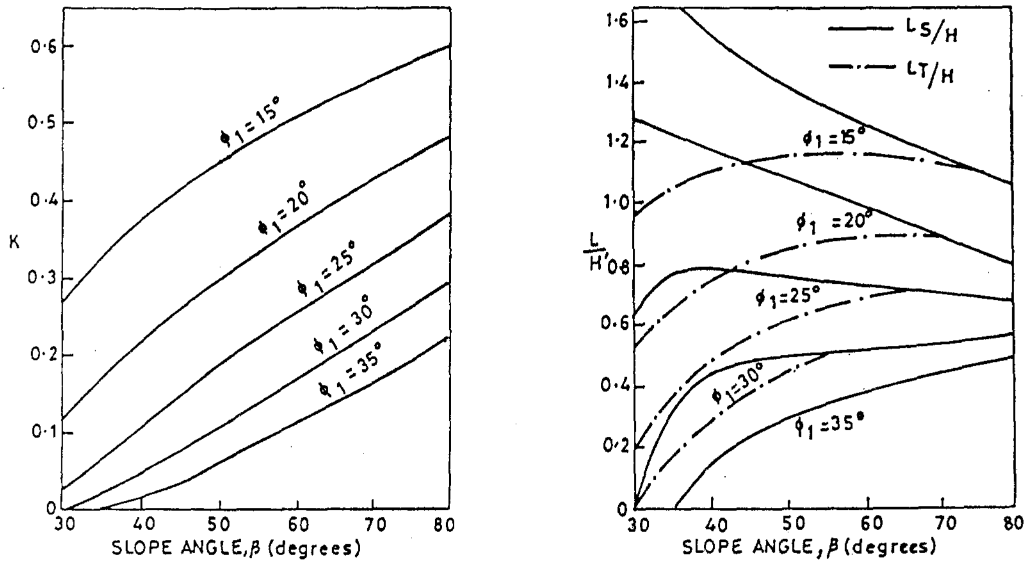
From Figs 19 to 22, it can be observed that the required length at the bottom layer decreases with an increase in slope angle. For steeper slopes, the required length at the bottom is less. For the angle of friction ϕ, it is observed that as ϕ increases, the required length at the bottom decreases for any slope angle. Changing the unit weight of soil means that the dimensionless parameter on the x-axis will vary and accordingly cause a variation of the length at the bottom. For the cohesion of the soil, if the cohesion increases then the required length at the bottom is increased. It means that variation of length at the bottom required is inversely proportionate to the soil strength. Again from the plot it is observed that by increasing the height of the slope the required length at the bottom is increased.

Comparison of results

The results presented here are compared with the results from the design chart in Fig. 23 which is taken from Schmertmann *et al.* (1987). They presented design charts for $c=0$. See Fig. 23.

Comparison is made with the results for a slope angle of 31° only, but for different angles of internal soil friction ϕ. The comparison is given in Table 2.

From Table 2, it is observed that the variation in $\Sigma T/\gamma H'^2$ is 10%, the variation in L_T/H' is 20% to 30% and the variation in L_B/H' is 10% to 15%. The variation in length at the top is high and the length at the bottom is also more than the variation in total tensile force because Schmertmann *et al.* (1987) used a simple bilinear wedge analysis. Also Schmertmann *et al.*



(a) Reinforcement force coefficient

(b) Reinforcement length ratio

Fig. 23. Design charts (Schemertmann *et al.*, 1987)

Table 2. Comparison of results with other published results

		Total tensile force $\Sigma T/\gamma H'^2$		L_T/H'		L_B/H'	
ϕ	Factored ϕ	Results	Design chart	Results	Design chart	Results	Design chart
25°	16.67°	0.1	0.095	1.07	0.8	1.87	1.6
22.5°	15°	0.15	0.14	1.13	0.97	1.9	2.0

(1987) considered a coefficient of soil–reinforcement interface of 0.9 and in the present results a value of 0.8 was used.

Conclusions

(1) Graphs are presented which can be used quickly to design a geosynthetic reinforced soil slope. They show the total tensile force in the geosynthetic reinforcement, and the length of reinforcement in the top and bottom halves of the slope for different soil parameters and different slope geometries.
(2) After comparing the results with design charts by Schmertmann *et al.* (1987) it is found that the variation in $\Sigma T/\gamma H'^2$ is 10%. The variation in L_T/H' is 20% to 30%. The variation in L_B/H' is 10% to 15%. The design and solution generated are conservative.

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