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Economic and Technical Aspects of Embankments Reinforced with Fabric

Aspects techniques et économiques des remblais renforcés par le textile

From a comparison of estimated costs it is concluded that reinforcement is unlikely to be worthwhile for permanent road embankments unless fill has to be imported or space restrictions necessitate an embankment with a vertical face. However fabric may enable otherwise unsuitable cohesive soil to be used. The behaviour of fabrics in cohesive soils has therefore been investigated further. In shear box tests adhesion (at zero normal stress) was found to be small. At high normal stresses the fabric-soil shearing resistance approached the shear strength of the soil. In triaxial tests failure usually involved slipping of the fabric, but tensile failure occurredin some circumstances. Finally a computer program based on a slip circle method of analysis has been used to indicate the possible strengthening effect of geotextiles in earth dams and road embankments.

Normalement il ne vaut pas la peine des renforcements pour les remblais de route permanents, sauf dans le cas où il faut importer le sol ou il faut un remblai a pan vertical. Cependant, le textile on peu se servir d'un sol cohésif qui serait autrement péu convenable. On faisait donc des études au sujet du fonctionnement des textiles dans les sols cohésifs. Par suite des essais de cisaillement direct on trouvait que l'adhérence était faible. Aux contraintes normaleset hautes la résistance au cisaillement entre le sol et le textile approchait la force de cisaillement du sol. Dans les essais triaxials l'échec entraînait normalement un glissement du textile mais dans quelques états il y avait des échecs dans la résistance à la traction du textile. Finalement on se servait de la méthode d'analyse de la ligne de glissement circulaire pour indiquer l'effect de renforcement dans la construction des barrages de sol et les remblais de route.

INTRODUCTION

Horizontal layers of fabric may be incorporated in highway embankments and in earth dams to provide increased strength and/or better drainage. This paper is concerned with the strengthening function. The embankments considered are assumed to be constructed on a firm horizontal base.

COSTS OF CONSTRUCTION

To assess the value of fabric reinforcement in embankments with granular fill, estimates have been made of the costs of construction of a variety of reinforced and unreinforced embankments. Reinforcement should permit steeper side slopes to be used with a consequent reduction in the volume of fill and in the area of side slopes and land required. However additional costs are incurred in providing fabric and vertical facing units (if used).

The following cross-sections were compared:-

(a) an unreinforced embankment with $26\frac{1}{2}^{o}$ side slopes, i.e. 2 horizontal : 1 vertical

(b) a reinforced embankment with 45^{o} side slopes

(c) a reinforced embankment with vertical sides formed by turning back each layer of fabric(1)

(d) a reinforced embankment with vertical sides with special facing units similar to the glass reinforced cement units used in the York method of reinforced earth (2). (This is recommendedin preference to type (c) for permanent works).

Two widths of embankment were considered, 10m and 20m at the top, and a range of heights from 3m to 10m. The cost of having to import suitable fill was also evaluated.

The number of layers of reinforcement required for embankments with vertical sides was calculated from Rankine's theory of active earth pressures assuming $\phi = 30^{o}$ and $\gamma = 20kN/m^3$ for the soil, fabric tensile strength = 50kN/m and that a factor of safety of 3 had to be provided against failure of the fabric in tension. On the basis of some preliminary calculations embankments with 45^{o} side slopes were assumed to have two-thirds of the amount of reinforcement required for embankments with vertical sides.

It was assumed that the fabric extended across the full width of the embankment and that the unit costs of construction (1978 prices) were as follows:

Embankment fill from excavations	£0.52/m^3
Imported fill	£3.34/m^3
Soiling and sowing slopes	£0.55/m^2
Land	£0.25/m^2
Fabric	£0.40/m^2
Vertical facing units	£13.40/m^2

For embankments with a top width of 20m, the estimated costs of construction per metre length are shown in Fig.1.

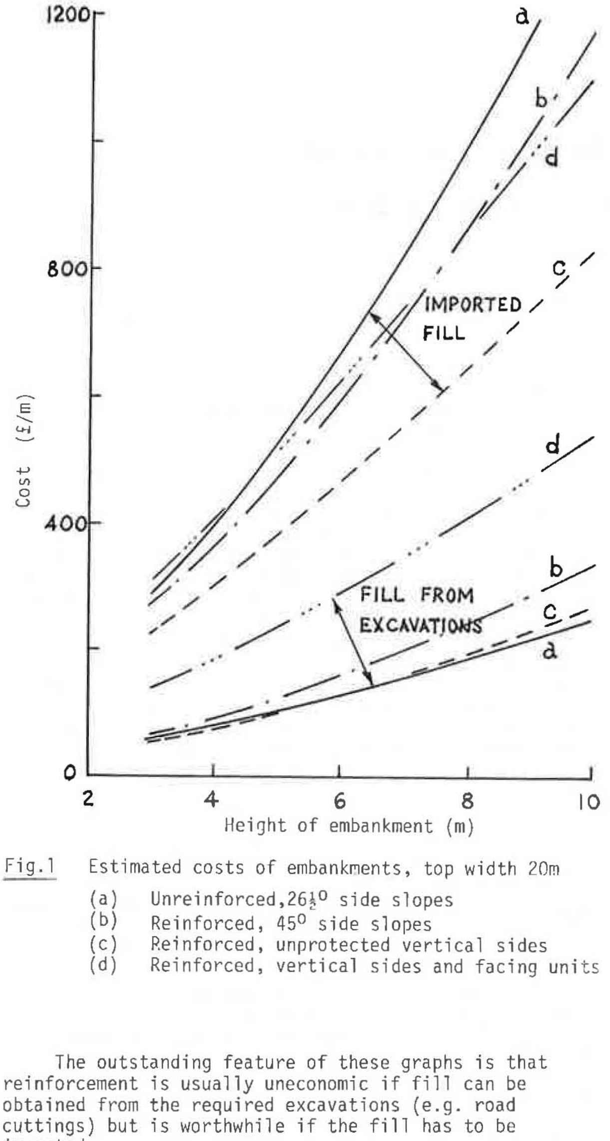

Fig.1 Estimated costs of embankments, top width 20m

(a) Unreinforced, $26\frac{1}{2}^{\circ}$ side slopes
(b) Reinforced, 45° side slopes
(c) Reinforced, unprotected vertical sides
(d) Reinforced, vertical sides and facing units

The outstanding feature of these graphs is that reinforcement is usually uneconomic if fill can be obtained from the required excavations (e.g. road cuttings) but is worthwhile if the fill has to be imported.

If the top width is reduced to 10m, type (c) reinforced embankments are cheaper than unreinforced embankments for both sources of fill but otherwise the conclusions are unchanged.

There is always a large difference in cost between an unreinforced embankment with imported fill and a reinforced embankment using material from the required excavations. Accordingly a significant saving would result if the addition of reinforcement made an otherwise unsuitable material from the excavations usable as fill. As some cohesive soils may be in this category the remainder of the paper is concerned with some aspects of the use of fabrics in conjunction with such soils.

SHEAR BOX TESTS

To obtain further information about the adhesion and skin friction which can be developed between fabrics and cohesive soils, the shear box tests described in a previous paper (3) have been extended to cover a wider range of soils, moisture contents and fabrics.

Soils included London clay (W_L = 69%, W_P = 29% Proctor optimum moisture content = 26%) tested at moisture contents from 24.0% to 31.7%, well-graded Edinburgh sandy clay (W_L = 28%, W_P = 17%, optimum moisture content = 14.7%) at moisture contents from 10.3% to 19.6%, and Peterhead clay (W_L = 51%, W_P = 25%) at a moisture content of 29.6%.

In addition to the three fabrics tested previously (A - woven polypropylene, B - spunbonded polypropylene - nylon, C - wire-reinforced jute scrim) the following (stronger) fabrics have been used:-

Fabric D : Knitted polyester, Terram RF/12, tested in direction of maximum tensile strength.

Fabric E : Woven polyester, Terram W/20-20

Fabric F : Woven polyester, Terram W/5.5-5.5

Fabric G : Woven tape polypropylene, Lotrak 56/46.

In general the soil-fabric shearing resistance was slightly higher for Fabric C because of its rough texture but otherwise differences between fabrics were insignificant.

With the sandy clay the soil-fabric angle of skin friction was approximately equal to the angle of shearing resistance of the soil. Both decreased slightly as the moisture content of the soil was increased. However, the influence of moisture content was less on soil-fabric adhesion (shearing resistance at zero normal stress) than on the cohesion of soil. Consequently the difference between the total soil-fabric shearing resistance and the shear strength of the soil was smaller at high moisture contents (Fig.2).

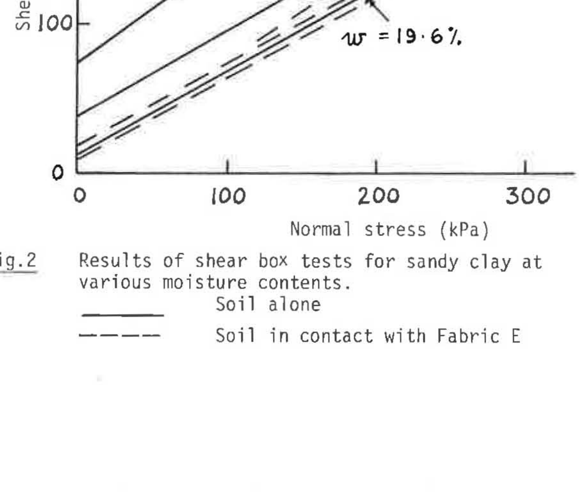

Fig.2 Results of shear box tests for sandy clay at various moisture contents.

——— Soil alone

- - - - Soil in contact with Fabric E

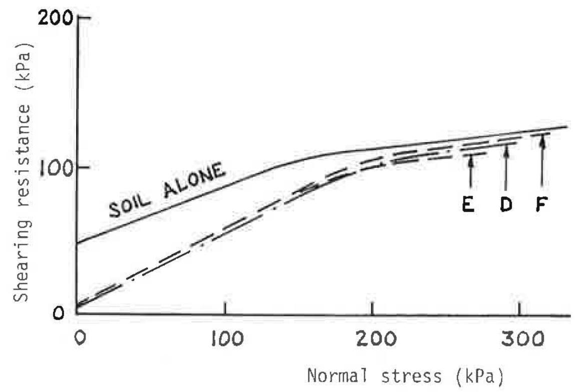

Fig.3 Shear box tests for London clay, alone and in contact with Fabrics D, E, and F. (w = 29.8%)

The highly plastic clays exhibited a non-linear relationship between shearing resistance and normal stress (see, for example, Fig.3). The angle of shearing resistance became small as the soil approached saturation at high normal stresses. Based on the initial part of such curves the cohesion and angle of shearing resistance of the soil decreased as the moisture content was increased. Over the same range of moisture content the soil-fabric adhesion and angle of skin friction remained fairly constant. In all cases the adhesion was much less than the cohesion of the soil. Consequently at low values of normal stress the total soil-fabric shearing resistance was less than the shear strength of the soil. However at high normal stresses the fabric developed almost the full shear strength of the soil. (At a normal stress of 300 kPa) the latter amounted to 270 kPa for specimens of London clay compacted at a moisture content of 24% and 88 kPa for moisture content = 31.7%)

TRIAXIAL COMPRESSION TESTS

The reinforcing effect of fabric layers in cohesive soils has been investigated by means of a series of triaxial compression tests on specimens 102mm in diameter and 203mm in height (4).

Specimens were made with either London clay or Edinburgh sandy clay at various moisture contents in the region of their Proctor optimum moisture contents. Both reinforced and unreinforced specimens were tested. In the former case, reinforcement was provided by Fabrics C, E and F at various height intervals.

For each reinforced specimen, soil was compacted in 6, 5 or 9 equal layers to suit the placing of 2, 4 or 8 discs of fabric respectively. The number of hammer blows was adjusted to give approximately the same amount of compaction per unit volume as in the standard Proctor compaction test. Each layer of fabric was placed horizontally and covered the full diameter of the specimen. Undrained triaxial tests were carried out at cell pressures of 128, 283 and 421 kPa. A constant rate of vertical deformation of 2mm/min was used.

During the application of the deviator stress it was observed that, although some bulging occurred between layers of fabric, overall barrelling of the specimen was prevented by the fabric. In all cases the deviator stress at failure (defined as the peak stress or as the stress corresponding to 20% vertical strain if no peak was reached earlier) was increased by the presence of fabric, increasingly so with more layers of fabric (Fig.4).

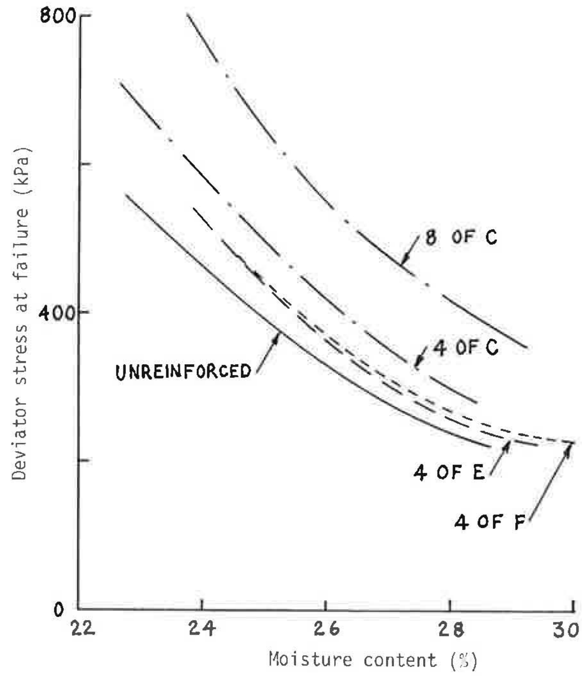

Fig.4 Effect of reinforcing discs on deviator stress at failure in triaxial tests on London clay (σ_3 = 283 kPa).

Failure almost always involved some slipping of the fabric. Exceptions to this occurred in tests with Fabric C in conjunction with Edinburgh sandy clay which had been compacted at moisture contents more than 2.5% below optimum. Under these conditions the soil-fabric shearing resistance was high and tensile failure of the fabric occurred centrally.

Mohr-Coulomb strength envelopes were constructed for both soils at various moisture contents with and without reinforcement. The shear strength parameters obtained from these graphs are given in Table 1.

TABLE 1 Undrained shear strength parameters for compacted soils with and without reinforcing discs of Fabric C.

Moisture content	Unreinforced		Reinforced with 4 discs		Reinforced with 8 discs	
	c	Ø	c	Ø	c	Ø
%	kPa	deg	kPa	deg	kPa	deg
London clay:						
24	185	5	245	5	295	6
26	125	5	160	5	220	6
28	110	2	130	2	135	8
Edinburgh sandy clay:						
11.5	170	18	405	20		
12.7	125	16	260	22		
14.7	110	6	145	16		
16.7	70	1	72	11		

These indicate that the inclusion of fabric in London clay led to an increase in apparent cohesion, especially with closely spaced reinforcement, but the angle of shearing resistance remained low.

With Edinburgh sandy clay compacted at 3.2% below optimum, c was greatly increased by the fabric but only a slight increase in Ø occurred. In this case failure was controlled by the strength of the reinforcement. On the other hand at 2% above optimum only Ø was increased.

While these tests demonstrate the reinforcing effect of fabric layers in cohesive soils, the parameters given in Table 1 are not directly applicable in design problems.

The tests involving tensile failure of the fabric have been analysed further in an attempt to relate the tensile strength of the fabric to an equivalent confining pressure.

Fig.5 shows an element of a horizontal reinforcing disc when this is subjected to a radial body force = R per unit volume. This produces stress resultants N_r and N_ψ at radius r. From conventional theory of circular plates (5) the equation of equilibrium is

$$r^2 \frac{d^2N_r}{dr^2} + 3r \frac{dN_r}{dr} + hR(4 + 2\nu) = 0 \qquad (1)$$

where h = half-thickness of the disc
and ν = Poisson's ratio.

The body force arises from transfer of stress by shear from the radially expanding soil to the restraining disc. As a first approximation it will be assumed that this is constant. In this case the solution to equation (1) is

$$N_r = \frac{hR}{3}(4 + 2\nu)(r_2 - r) \qquad (2)$$

also

$$N_\psi = \frac{hR}{3}(4 + 2\nu)(r_2 - r) + 2hrR \qquad (3)$$

where r_2 = outer radius of the disc.

From these equations the maximum stress resultant occurs at the centre and has a value of $hRr_2(4 + 2\nu)/3$. Failure occurs when this is equal to the tensile strength of the reinforcement, α_f.

i.e. when $R = 3\alpha_f/\{hr_2(4 + 2\nu)\}$

The total force transferred to the reinforcement is

$2hR\int_0^{r_2}\int_0^{2\pi} r\,d\psi\,dr$, i.e. $6\pi\, r_2\alpha_f/(4 + 2\nu)$ at failure.

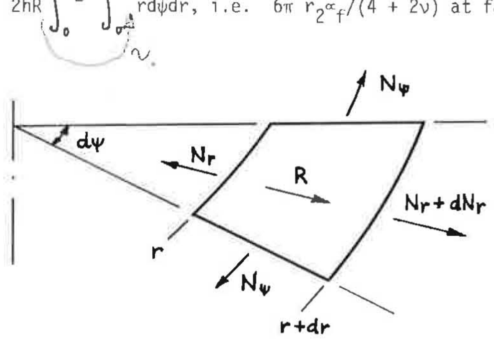

Fig.5 Element of disc subjected to radial body force R.

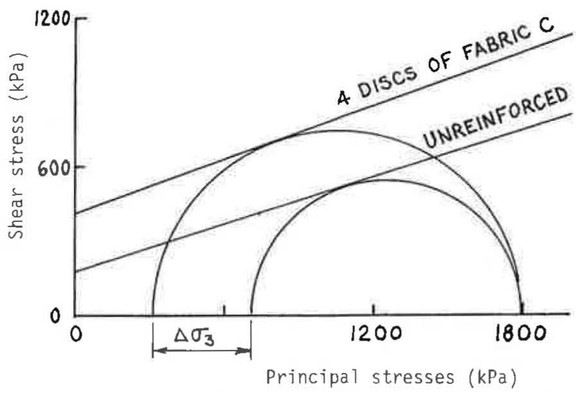

Fig. 6 Mohr-Coulomb strength envelopes for reinforced and unreinforced sandy clay (w = 11.5%)

In terms of the Mohr-Coulomb diagram the reinforcement has the effect of altering the value of cell pressure required for a particular value of maximum principal stress by $\Delta\sigma_3$ (6) as indicated in Fig.6. If the vertical spacing of the reinforcing discs is S_v the reduction in the confining force is $2\pi r_2 S_v \Delta\sigma_3$.

Equating this to the force transferred to the reinforcement gives

$$\Delta\sigma_3 = 3\alpha_f/\{(4 + 2\nu)S_v\} \qquad (4)$$

For specimens containing four layers of Fabric C, for which α_f = 27.5kN/m this gives $\Delta\sigma_3$ = 430 kPa whereas the observed value (Fig.6) is 400 kPa.

ANALYSIS OF EMBANKMENT STABILITY

A design procedure for horizontally reinforced embankments was given in an earlier paper (3). This included a slip circle method of analysis which is relevant to cohesive soils. Dividing the mass above an assumed circular slip surface into vertical slices the following approximate expression was obtained:-

$$F = \frac{\Sigma\{c'l + (W\cos\alpha - ul + Td\sin\alpha)\tan\emptyset' + Td\cos\alpha\}}{\Sigma W\sin\alpha} \qquad (5)$$

where F = factor of safety (assumed equal for shear failure of the soil and tensile failure of the reinforcement)

c', Ø' = shear strength parameters of the soil in terms of effective stresses

T = tensile strength of reinforcement per unit height

W = total weight of a slice

u = pore-water pressure on base of slice

l = length of base of slice

α = slope of base of slice

d = $l\sin\alpha$

In this equation T has units of stress. For example, if fabric having a tensile strength of 40kN/m is laid at vertical intervals of 0.5m, T = 80kPa.

If the lowest part of the slip circle is within rather than on the surface of the embankment the effect of reinforcement should be applied only where d is positive.

A computer program has been written to solve equation (5) for any number of assumed slip circles and hence obtain the critical value of F for a proposed design. For problems involving steady seepage conditions (for example, earth dams with reservoir full) pore-water pressures can be included by specifying a piezometric surface. Alternatively for large embankments during construction one or more pore-pressure ratios r_u can be specified where

r_u = u/total vertical stress.

The same program can be used for an analysis in terms of total stresses by putting u = 0 (artificially) and substituting total stress parameters c and Ø for c' and Ø'. This may be appropriate for smaller highway embankments which can be constructed rapidly and are almost undrained at the end of construction if the permeability of the fill is low.

The computer program has been used to analyse a range of embankment designs. The results provide a guide to the effectiveness of reinforcement under various conditions.
The following range of parameters was covered:-

Height of embankment (H)		10,20m
Angle of side slope		33.7^0,45^0
Tensile strength of reinforcement/m height		0-240kPa
Soil properties:	γ = 20 kN/m^3	
Total stress	c = 10 - 100kPa, Ø = 0	
Effective stress	c'= 0, Ø'= 25^0 - 40^0, r_u = 0 - 0.4	

For example, Fig.7 shows some results for a 20m high embankment with 45^0 side slopes. In this case a total stress analysis has been used with Ø = 0, representing a saturated clay under undrained conditions. For an unreinforced embankment F is proportional to c/γH. For a given cross-sectional geometry

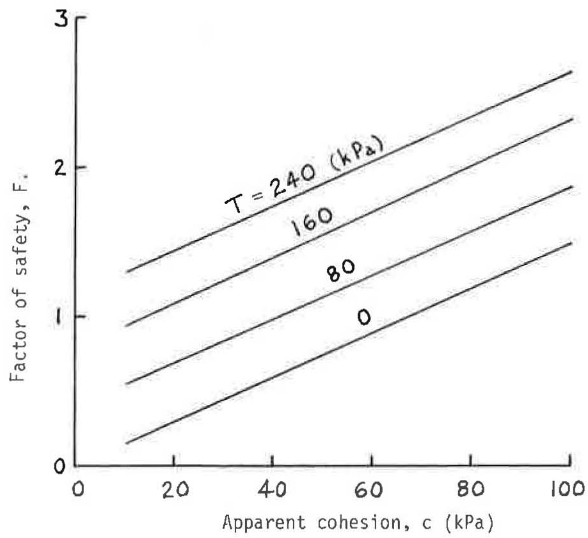

Fig.7 Effect of various amounts of reinforcement (T) on factor of safety of embankments with 45^0 side slopes (total stress analysis, Ø = 0).

the increase in F due to reinforcement is directly proportional to its strength. The effect of reinforcement can also be expressed as equivalent to an increase in c. Such an increase is also proportional to T and amounts to 0.32T. This equivalence is constant over the full range of embankments considered in terms of total stresses.

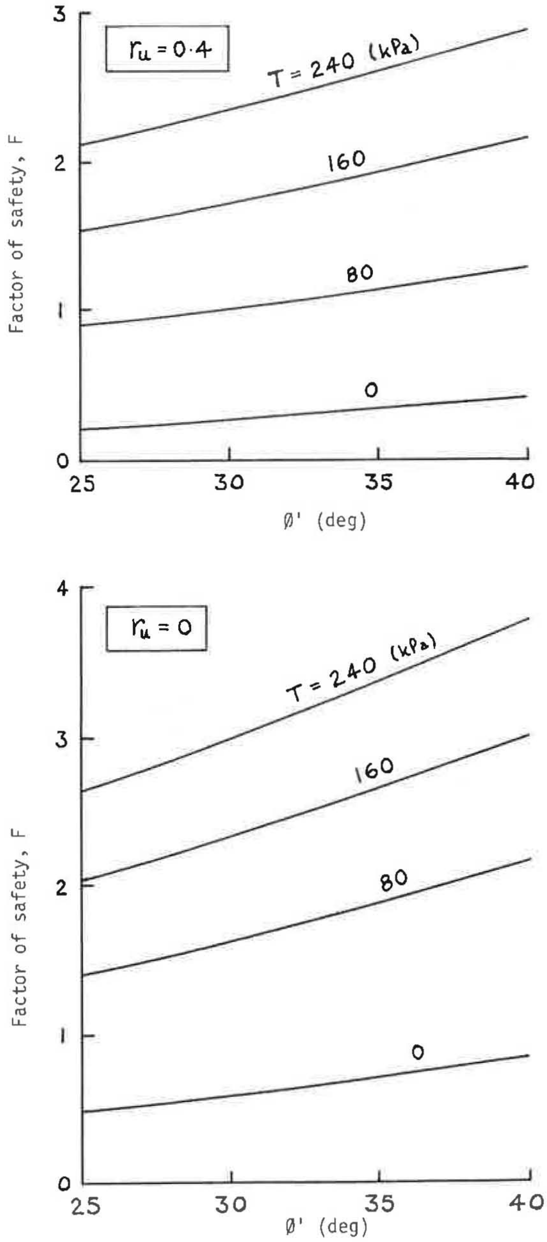

Fig.8 Effect of various amounts of reinforcement (T) on factor of safety of embankments with 45^0 side slopes (effective stress analysis, c' = 0).

Fig.8 shows some results based on effective stresses for embankments 20m in height with 45° side slopes. In the example considered c', which is often small in practice, has been neglected. The results shown are for fully-drained embankments ($r_u = 0$) and for embankments with a pore-pressure ratio of 0.4. For an unreinforced embankment there is a linear relationship between F and r_u (7). This applies also to the results for reinforced embankments. Consequently results for other values of r_u can be interpolated from Fig.8. Similar results were obtained for embankments with 33.7° side slopes, for which values of F were about 0.2 to 0.4 higher.

The relationship between the other variables, including height of embankment, is more complicated than in the total stress analysis. However in all cases the factor of safety against this mode of failure is substantially increased by the reinforcement.

In practice, design calculations must also cover the following possibilities:
(1) The shear box tests indicated that the shearing resistance between fabric and cohesive soils is usually less than the shear strength of the soil, especially at low normal stresses. The possibility of a non-circular slip surface passing partly along the interface between a layer of fabric and soil must therefore be considered.

(2) Unless the fabric extends across the full width of the embankment adequate bond length or anchorage must be provided beyond any likely slip surface. A factor of safety equal to the value considered to be acceptable in the slip circle calculations should exist when the pull-out force equals the tensile strength of the fabric.

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Erhöhung der Standsicherheit von Böschungen, Dämmen auf festem Untergrund

Bishop-Verfahren, erweitert mit horizontalen Zusatzkräften.

Verfahren zur Erhöhung der „zusätzlichen Kohäsion" durch Bewehrungseinlagen.

Ermittlung der Reibe- Haftfestigkeit

Verankerung und Berechnungsverfahren siehe Schlußbemerkung

Grenzgleichgewichtsmethode