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Fabric Reinforcement of Embankments and Cuttings

Renforcement des remblais et des déblais à l'aide de textiles

A method is described for enhancing the stability of cutting and embankment slopes employing fabric reinforcement. A feature of the method is that the load-extension properties of the fabric are linked in the design equations ensuring that the factor of safety in terms of serviceability is automatically satisfied.

The equations described have been applied to an example of an embankment constructed using a cohesive fill and also to the design of a motorway cutting reinstatement which recently failed in England. It was demonstrated that the repair of the cutting using reinforced soil reduced the costs by about 40 per cent when compared to conventional repair techniques.

L'auteur décrit une méthod d'amélioration de la stabilité des talus de déblai et de remblai par renforcement avec des textiles. Un aspect de cette méthod est que les caractéristiques d'extension du textile sous charge sont reliées entre elles dans les équations de dimensionnement, garantissant que le coéfficient de sécurité en termes de durée de service est automatiquement satisfait.

Les équations décrites ont été appliquées à un exemple de remblai en matériau cohérent et au dimensionnement de la réfection d'un déblai d'autoroute qui a récemment subi une rupture en Angleterre. On a démontré que la réparation du déblai avec de la terre armée réduit les coûts d'environ 40 % par comparaison avec les méthodes de réparation classiques.

INTRODUCTION

A major cost factor in the repair of slip failures in cuttings and embankments is associated with the haulage distances involved in the removal and importation of fill. In this paper a procedure is described which involved the re-use of the foundered soil by employing fabric layers to act as reinforcement. Such an approach can offer considerable savings when haulage distances are significant. Moreover, the calculation procedures described may also be utilised for designing fabric-reinforced embankments with steeper side slopes than would be possible for their unreinforced counterparts. Thus greater economies can be achieved by using locally available soils and by reducing the amount of fill and land required for constructing the embankment.

The method of calculation takes account of both adherence and tensile resistance of the fabric. The tensile resistance is based on a criterion of specified deformation rather than on the ultimate load characteristics of the fabric. An estimate of the deformations induced by construction plant can also be made.

The application of the method to the repair of a failed section of motorway cutting in England is briefly described.

Theoretical considerations

A simple bilineal slip plane is assumed to represent the failure surface (Fig 1). It is usually possible to make a reasonable representation of an actual failure surface by this approach. Two classes of problem are considered:

(i) Both failure surfaces emerge on the slope, representing most cutting situations.

(ii) The upper failure surface emerges on a horizontal plateau, as frequently occurs with embankment failures.

In a paper currently in press it was shown that resistance (R_T) against failure was given by:

$$R_T = \frac{1}{F} [\int(\gamma z \cos^2\beta (\tan\beta - \tan\theta)^2 - ru/\cos^2\theta\} \tan\phi^1 + c^1) dL + \Sigma T_z \sin\theta \tan\phi^1] \quad \ldots\ldots (1)$$

and that the total disturbance force (D_T) was given by:

$$D_T = \int\gamma z \sin\theta \cos\theta [1 + K \cos^2\beta \{\tan^2\beta - 1 + \frac{\tan\beta}{\tan\theta} (1 - \tan^2\theta)\}] dL - \Sigma T_z \cos\theta \quad \ldots\ldots (2)$$

The expressions under the integral signs $[\int]$ are taken along the full length of slip surface while the expressions under the summation sign (Σ) relates to the contributions made by the fabric layers in either tension or adherence. Clearly the lesser of these two conditions should be employed in the design. (The definitions of the symbols are provided in Appendix 1.)

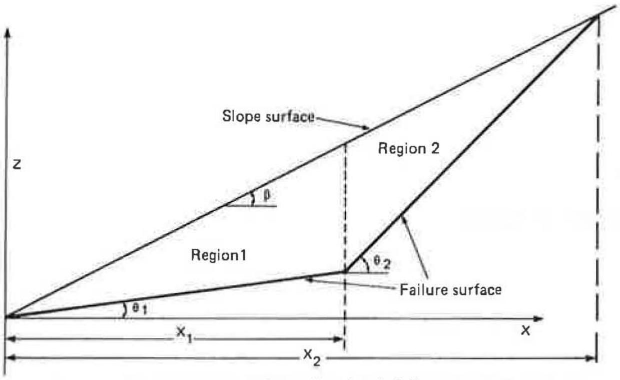

Fig. 1a Geometry of problem when both failure surfaces emerge on slope face

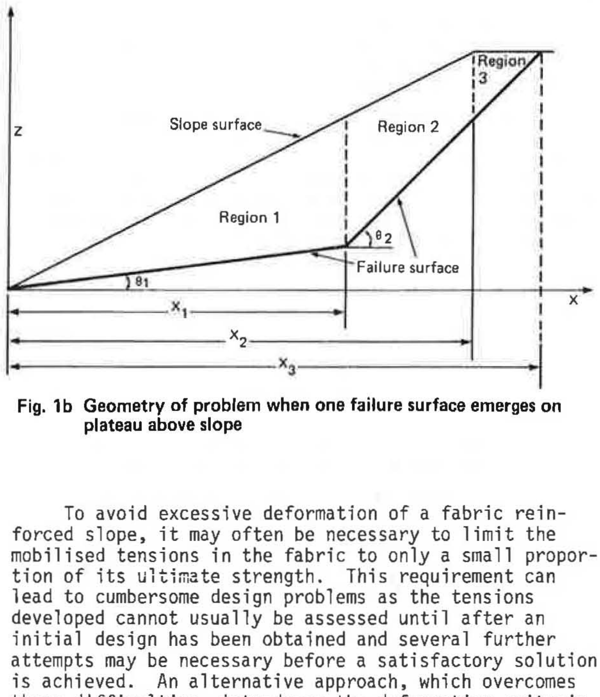

Fig. 1b Geometry of problem when one failure surface emerges on plateau above slope

To avoid excessive deformation of a fabric reinforced slope, it may often be necessary to limit the mobilised tensions in the fabric to only a small proportion of its ultimate strength. This requirement can lead to cumbersome design problems as the tensions developed cannot usually be assessed until after an initial design has been obtained and several further attempts may be necessary before a satisfactory solution is achieved. An alternative approach, which overcomes these difficulties, introduces the deformation criteria directly into the design formula, thus ensuring that the tension mobilised will be consistent with the deformation requirement. A further advantage is that the solution for both tension and adherence is obtained as a single computation.

It has been demonstrated (1) that the load-deformation characteristics of fabrics are often of hyperbolic form. The simplest hyperbolic expression relating load (T) to extension (e) is of the following form:

$$T = \frac{e}{me + c} \qquad \text{..... (3a)}$$

$$e = \frac{cT}{(1 - mT)} \qquad \text{..... (3b)}$$

These expressions imply that a linear relation will be obtained if e/T is plotted against e.

The analysis has been carried out on the basis of average values and no account has been taken of time-dependant creep strains. The horizontal stress (σ_x) acting on an element of soil adjacent to a slip surface (Fig 2) is given by:

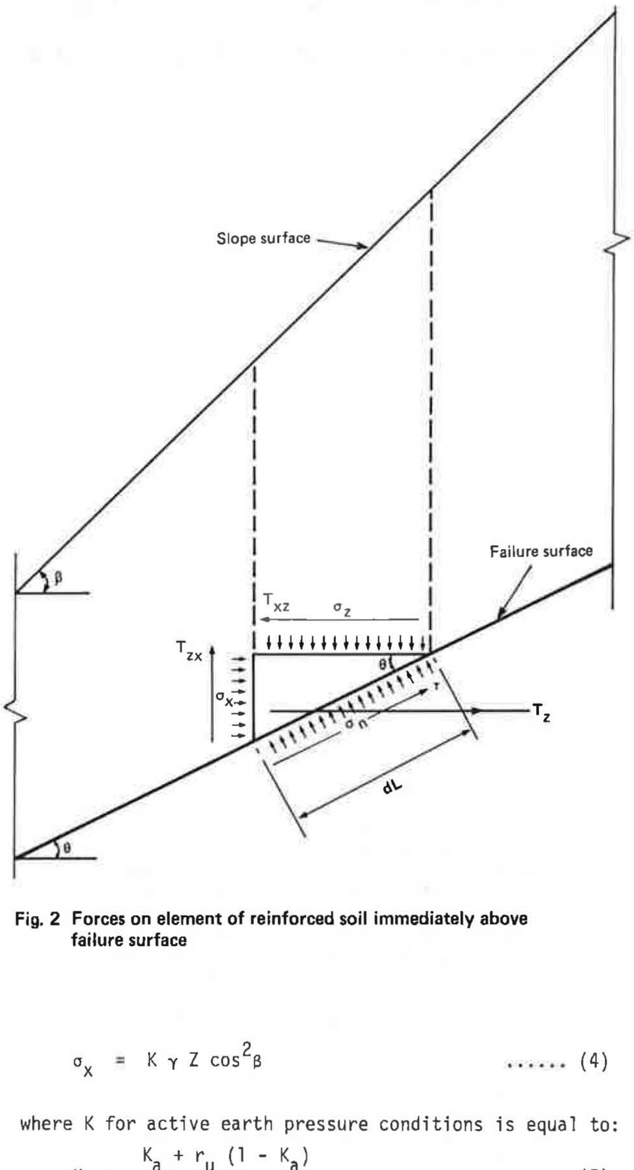

Fig. 2 Forces on element of reinforced soil immediately above failure surface

$$\sigma_x = K \gamma Z \cos^2\beta \qquad \text{...... (4)}$$

where K for active earth pressure conditions is equal to:

$$K = \frac{K_a + r_u (1 - K_a)}{(\cos^2\beta - K_a \sin^2\beta)} \qquad \text{...... (5)}$$

On the basis of a vertical spacing for the fabric layers of S_v, the maximum force developed in the fabric is given by:

$$T_M = S_v K \gamma Z \cos^2\beta \qquad \text{...... (6)}$$

The tension distribution in the fabric layer will probably vary from a maximum value near the potential failure surface to zero at the edge furthest from the slope. Assuming a linear variation of tension then the average value ($\bar{T}$) will be about half of that given by Equation (6). Substituting $\bar{T}$ in Equation (3a) enables the average vertical spacing (S_V) to be determined consistent with the specified extension (e).

$$\text{ie } S_v = \frac{2e}{(me + c)} \times \frac{1}{K.\gamma.\bar{Z}.\ \cos^2\beta} \qquad \ldots\ldots (7)$$

Integration of Equations (1) and (2) employing the above deformation criteria produces the equations, in terms of effective stress, shown in Table 1. The coefficients associated with these equations are defined in Table 2.

TABLE 1

Equations employed in assessing stability

Sector	Resistance Equation	
	Contribution from soil	Contribution from fabric
1	$R_{1S} = \left[\frac{A_1\ X_1^{\ 2}}{2}(M_\beta - M_1) + C_1^{\ 1}X_1\right]/\cos\theta_1$	$R_{1F} = \frac{B_1N_1}{2}\left[\frac{(N_1+1)(M_\beta-M_1)}{M_1}S_{v1} + M\beta L_1\right]$
2	$R_{2S} = \frac{(X_2-X_1)}{\cos\theta_2}\left[\frac{A_2}{2}\{X_2(M_\beta - M_2) + X_1(M_\beta + M_2 - 2M_1)\} + C_2^{\ 1}\right]$	$R_{2F} = \frac{B_2N_2}{2}\left[\frac{(N_2+1)(M_\beta-M_2)}{M_2}S_{v2} + 2X_1(M_\beta - M_1) + M_\beta L_2\right]$
3	$R_{3S} = \frac{(X_3-X_2)}{\cos\theta_2}\left[A_3\{M_\beta X_2 + X_1(M_2 - M_1) - \frac{M_2}{2}(X_3+X_2)\} + C_3^{\ 1}\right]$	$R_{3F} = \frac{B_3N_3}{2}\left[2\{X_2(M_\beta-M_X) + X_1(M_2-M_1)\} - \frac{(N_3+1)}{2}S_{v3}\right]$
Sector	**Disturbance Equation**	
	Contribution from soil	**Contribution from fabric**
1	$D_{1S} = \frac{E_1\ X_1^{\ 2}(M_\beta - M_1)}{2\cos\theta_1}$	$D_{1F} = -\frac{G_1N_1}{2}\left[\frac{(N_1+1)(M_\beta-M_1)}{M_1}S_{v1} + M_\beta L_1\right]$
2	$D_{2S} = \frac{E_2(X_2-X_1)}{2\cos\theta_2}\left[M_\beta(X_2+X_1) + X_1(M_2-2M_1) - M_2X_2\right]$	$D_{2F} = -\frac{G_2N_2}{2}\left[\frac{(N_2+1)(M_\beta-M_2)}{M_2}S_{v2} + 2X_1(M_\beta-M_1) + M_\beta L_2\right]$
3	$D_{3S} = \frac{E_3(X_3-X_2)}{\cos\theta_2}\left[M_\beta X_2 + X_1(M_2-M_1) - \frac{M_2}{2}(X_3+X_2)\right]$	$D_{3F} = -\frac{G_3N_3}{2}\left[2\{X_2(M_\beta-M_2) + X_1(M_2-M_1)\} - \frac{(N_3+1)}{M_2}S_{v3}\right]$

$$\text{Factor of safety (F)} = \frac{\sum_{i=1}^{i=3}(R_{is} + R_{iF} + F.D_{iF})}{\sum_{i=1}^{i=3} D_{is}}$$

TABLE 2

Coefficients employed in stability equations

Sector	Resistance Equation	
	Contribution from soil	Contribution from fabric
1	$A_1 = \gamma_1.\tan\phi_1^1.\cos^2\theta_1\left[1 + K_1\cos^2\beta(\tan\beta - \tan\theta_1)^2 - r_{u1}/\cos^2\theta_1\right]$	$B_1 = 2\mu_1L_1\gamma_1\ \sin\theta_1\ \tan\phi_1^1\ (1 + K_1\ \sin^2\beta - r_{u1}/\sin\theta_1\ \tan\phi_1^1)$
2	$A_2 = \gamma_2.\tan\phi_2^1.\cos^2\theta_2\left[1 + K_2\cos^2\theta(\tan\beta - \tan\theta_2)^2 - r_{u2}/\cos^2\theta_2\right]$	$B_2 = 2\mu_2L_2\gamma_2\ \sin\theta_2\ \tan\phi_2^1\ (1 + K_2\ \sin^2\beta - r_u/\sin\theta_2\ \tan\theta_2^1$
3	$A_3 = \gamma_3.\tan\phi_3^1.\cos^2\theta_2\left[1 - K_3\ \tan^2\theta_2 - r_{u3}/\cos^2\theta_2\right]$	$B_3 = 2\mu_3L_3\gamma_3\ \sin\theta_2.\tan\phi_3^1\ (1 - r_u/\sin\theta_2\ \tan\phi_3^1)$
Sector	**Disturbance Equation**	
	Contribution from soil	**Contribution from fabric**
1	$E_1 = \gamma_1.\sin\theta_1\ \cos\theta_1\left[1 + K_1\cos^2\beta\ \{\tan^2\beta-1 + \frac{\tan\beta}{\tan\theta_1}(1-\tan^2\theta_1)\}\right]$	$G_1 = 2\mu_1L_1\gamma_1\ \cos\theta_1\ (1 + K_1\ \sin^2\beta - r_u/\cos\theta_1)$
2	$E_2 = \gamma_2.\sin\theta_2\ \cos\theta_2\left[1 + K_2\cos^2\beta\ \{\tan^2\beta-1 + \frac{\tan\beta}{\tan\theta_2}(1-\tan^2\theta_2)\}\right]$	$G_2 = 2\mu_2L_2\gamma_2\ \cos\theta_2\ (1 + K_2\ \sin^2\beta - r_u/\cos\theta_2)$
3	$E_3 = \gamma_3\ \sin\theta_2\ \cos\theta_2\left[1 - K_3\right]$	$G_3 = 2\mu_3L_3\gamma_3\ \cos\theta_2\ (1 - r_u/\cos\theta_2)$

Influence of compaction on deformation

Construction plant is a further source of loading which can induce extension of the fabric. The mechanism involved may be as shown in Fig 3 where it is assumed that an effective bond exists between the fabric and soil particles. Compaction stresses induce local extension which is not fully recoverable because other particles interpose. Although compaction vibrations may result in some loss of contact stress, overall a net "locked-in" tension will result which prestrains the fabric and prevents further extension until the load induced by the fill creates tensions in excess of the "locked-in" values. Moreover, the pretension increases effective stress and improves the strength of the fill. The following analysis based on elasticity considerations permits fabric extension resulting from plant activity to be estimated.

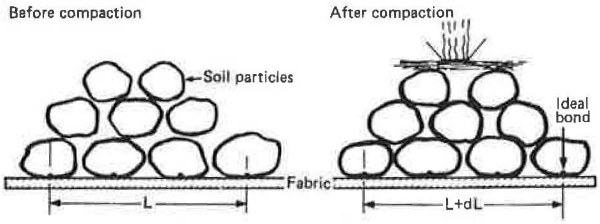

Fig. 3a Influence of compaction on pre-strain of soil

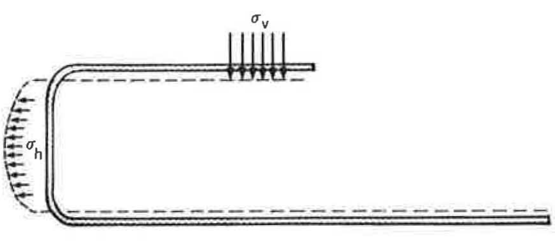

Fig. 3b Compaction stress inducing deformation at face of slope

Considering the force applied by the compaction roller as a surface line load acting normal to the slope face then the horizontal stress at a reflected boundary (Fig 3b) is obtained as follows (assuming Poisson's ratio for the soil is 0.5):

$$\sigma_h = \left[\frac{P}{\pi}\,\frac{x^3}{R^3}\right]_{X_B}^{X_A} \qquad \ldots\ldots (8)$$

The value of P has to be increased to allow for the effect of centrifugal force if vibrating plant is employed. A factor of two is normally used to account for this effect. Thus the force (F_C) developed at the slope face for a compacted layer of thickness t is obtained as follows:

$$F_c = \frac{P}{\pi}\int_0^t \left(\frac{X_A{}^3}{(X_A{}^2 + Z^2)^{3/2}} - \frac{X_B{}^3}{(X_B{}^2 + Z^2)^{3/2}}\right)\frac{dZ}{Z} \qquad \ldots\ldots (9a)$$

ie
$$F_c = \frac{P}{\pi}\left[\frac{X_A}{(X_A{}^2 + t^2)^{1/2}} - \ln\left\{\frac{X_A + (X_A{}^2 + t^2)^{1/2}}{t}\right\} - \frac{X_B}{(X_B{}^2 + t^2)^{1/2}} + \ln\left\{\frac{X_B + (X_B{}^2 + t^2)^{1/2}}{t}\right\}\right] . (9b)$$

Applying F_C in place of T in Equation (3b) permits an estimate of fabric extension at the slope face to be made. A similar analysis can be developed for regions remote from the slope face to obtain the following equation:

$$F_c = \frac{P}{\pi}\left[\ln\left\{\frac{W + (W^2 + t^2)^{1/2}}{t}\right\} - \frac{W}{(W^2 + t^2)^{1/2}}\right] . (9c)$$

An estimate of overall fabric extension induced by compaction plant can be obtained by applying the mean force determined from Equations (9b) and (9c) in Equation (3b).

Application of the technique to embankment and cutting slopes

The design calculations require data on the shear strength characteristics of the fill and the interface friction between soil and fabric. The former tests are best carried out in terms of effective stress using the triaxial apparatus. The latter values can be obtained from modified shear box tests. Load-extension tests also need to be carried out on the fabric and although several methods are available, McGown et al have pointed out the advantages of testing structural fabrics in a soil environment (2,3). An assessment of the likely pore pressure conditions will also be needed with cuttings, and embankments constructed from cohesive fill.

An example of the application of the technique to the design of a cohesive fill embankment is shown in Fig 4, which also lists the assumed properties of the soil and fabric. The safety factor for the slip surface shown (Fig 4a) was determined as 0.75. A subsequent analysis employing fabric reinforcement permitting up to one per cent extension produced the arrangement shown in Fig 4b. The factor of safety on the previous slip surface had been increased to 1.3. The permitted extension of the fabric would have produced deformation at the face of the slope of about 4 cm, however, assuming a 10 kN/m roller was used to compact the fill in 0.25 m thick layers, 25 per cent of the deformation would have been taken up by the compaction plant. The analysis has clearly produced a reasonably satisfactory design with regard to the original slip surface but it would now be necessary to check the stability of potentially deeper-seated failure surfaces behind the reinforced section.

Following a recent failure of a motorway cutting in London clay in Berkshire, England, reinstatement was undertaken by re-using the original soil reinforced by layers of fabric (Netlon CE131). Thic technique was adopted because of the high haulage costs which would have been incurred by the conventional method of removing the failed soils and replacing them with good quality material.

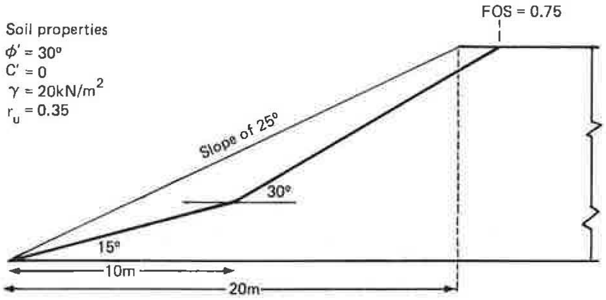

Fig. 4a Cohesive fill embankment unreinforced

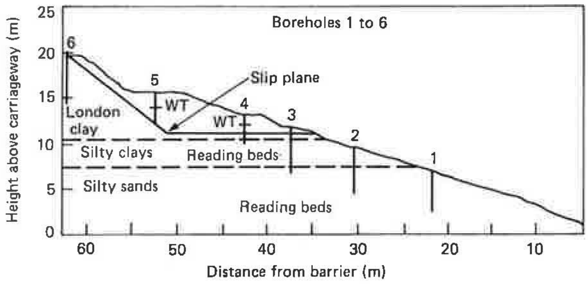

Fig. 5 Location of boreholes formed before remedial measures

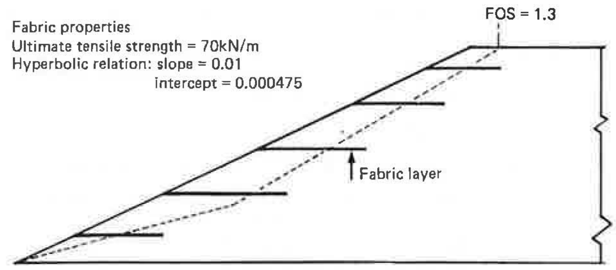

Fig. 4b Cohesive fill embankment reinforced by high strength fabric

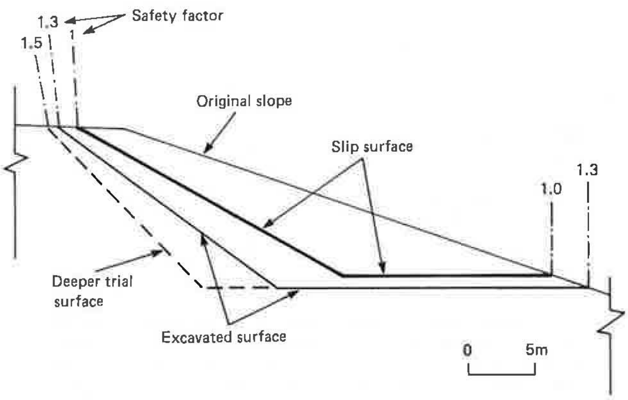

Fig. 6 Simplified profiles assumed for puposes of stability analysis

A cross-section of the failed cutting slope is shown in Fig 5. Triaxial tests produced a ϕ^1 value for the soil of about 25° and a value for r_u of 0.3 was obtained from standpipe piezometers. The results of the various analyses and the associated slip surfaces are presented in Table 3 and Fig 6 respectively. These indicate that the possibility of failure of the original slip surface has been removed as the minimum factor of safety was 1.3, even without the benefit of drainage measures and lime treatment.

The use of about one per cent by weight of quicklime at the scheme proved particularly advantageous as the construction plant was able to work effectively on the reinstated clay, even after wet weather, and further increased the safety factor (Table 3).

The cross-section of the reinstated cutting is shown in Fig 7. The vertical spacing of the reinforcement was 0.5 m in the bottom region which was increased to 1 m at higher levels.

The cost of the repair was estimated to be about 40 per cent less than that of the conventional method. These savings were related to the high haulage costs at the scheme and conditions would not always be as favourable.

Inclinometers installed in the slope for more than a year have shown no indication of movement.

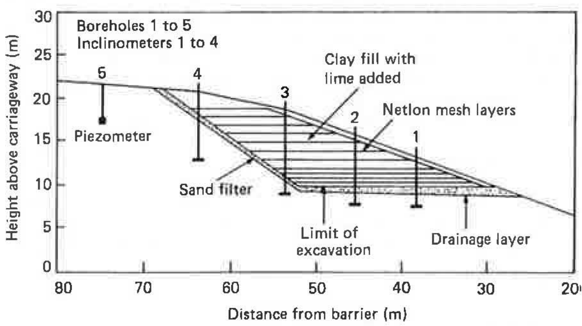

Fig. 7 Location of boreholes and inclinometers after remedial measures

TABLE 3

Factors of safety for various potential failure surfaces and conditions

Failure profile	Treatment	Sector	ϕ^1 degree	r_u	Safety factor
Original slip surface	None	1 2 3	25	0.3	1.0
	Fabric rein-statement	1 2 3	25	0.3	>10 (Adherence 1.6 (Tension at 4 per cent strain)
Excavated zone	None	1 2 3	28 25 25	0.3	1.3
	Drainage measures	1 2 3	28 25 25	0.2	1.5
	Drainage measures and lime treatment	1 2 3	35	0.2	2.0
Deeper trial zone	None	1 2 3	28 25 25	0.3	1.5
	Drainage measures	1 2 3	28 25 25	0.2	1.8
	Drainage measures and lime treatment	1 2 3	35	0.2	2.3

Conclusion

A description is provided of an analytical procedure for the design of cuttings and enbankments reinforced with fabric. The equations described are linked to deformation criteria so that conditions of serviceability are automatically satisfied.

An example of the application of the method to the design of a cohesive fill embankment is given showing how such an embankment may be constructed with steeper side slopes than would normally be possible and producing savings both in quantity of fill and land take. The repair of a failed section of motorway cutting in England using the method is also briefly described whereby the foundered soil was re-used in conjunction with fabric mesh reinforcement. It was estimated that the cost of the repair was reduced by 40 per cent when compared to the conventional approach of removing the failed soil and replacing with good quality granular fill.

Acknowledgements

The work described in this paper forms part of the programme of the Transport and Road Research Laboratory and the paper is published by permission of the Director.

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APPENDIX 1

List of symbols

A_i = coefft associated with soil resistance in sector i (Table 2)

B_i = coefft associated with fabric resistance in sector i (Table 2)

c = intercept of load-extension relation for fabric on hyperbolic plot

c^1 = cohesion intercept in terms of effective stress

D_T = total disturbing force

D_{is} = contribution to disturbance force offered by soil in sector i

D_{if} = contribution to disturbance force offered by fabric in sector i

e = extension of fabric in load-extension test

E_i = coefficient associated with disturbance force offered by soil in sector i (Table 2)

f = subscript relating to fabric

F = factor of safety

F_c = force applied horizontally be compaction plant

G_i = coefft associated with distrubance force offered by fabric in sector i (Table 2)

i = subscript relating to sector 1, 2 or 3

K_a = active earth pressure coefft

K_i = earth pressure coefft in sector i

L_i = length of fabric beyond slip surface in sector i

M = slope of load-extension relation for fabric on hyperbolic plot

M_β = tan (β)

M_1 = $\tan\theta_1$

M_2 = $\tan\theta_2$

N_i = number of fabric layers in sector i

P = line load per m applied by compaction roller

R = $\sqrt{X^2 + Z^2}$ in Equation (8)

R_T = total resisting force

R_{is} = contribution to resisting force offered by soil in sector i

R_{if} = contribution to resisting force offered by fabric in sector i

r_u = pore pressure ratio

t = thickness of compacted layer

T = load in fabric during load-extension test

T_Z = resistance at depth Z offered by fabric

W = half-width of compaction roller

X_A = distance from slope face to closest edge of compaction roller

X_B = distance from slope face to further edge of compaction roller

X_1 = length from origin to end of sector 1

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X_2 = length from origin to end of sector 2

X_3 = length from origin to end of sector 3

Z = depth to point under consideration

$\bar{Z}$ = average depth in sector being considered

β = angle of slope

γ = unit weight of soil

ϕ^1 = internal friction angle of soil in terms of effective stress

θ_i = angle of slip lane in sector 1, or 2

μ_i = interface coefficient of friction between soil and fabric in sector i

[illegible] einer bewehrten
Berechnung mit geraden
Gleitflächen