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The design of steep slopes constructed from cohesive fills and a geogrid

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ABSTRACT: The shear strength and consolidation properties of compacted cohesive fills are reviewed and are found to vary greatly between different soil types. Recent research on dissipating excess pore water pressure in steep slopes constructed from cohesive fill is also reviewed. A simple and practical design method for constructing steep slopes from cohesive fill is proposed. The design method estimates both the time to dissipate excess pore water pressures and the magnitude of the resultant settlements. It also estimated the required transmissivity required by the drainage elements. Guidance is also given on controlling seepage into the reinforced soil block.

1 INTRODUCTION

Free draining granular fill is conventionally used for the construction of steep reinforced slopes. Such fills have relatively high shear strength characteristics and their free draining properties minimise pore water pressures in the slope. Research (Zornberg & Mitchell, 1994, Kempton *et al.*, 2000) and long term case histories (Inada *et al.*, 1978 and Fukuoka, 1998) have shown, however, that finer grained and cohesive fills can be used to construct satisfactory steep reinforced slopes, as long as adequate drainage is provided within the slope.

The use of a cohesive fill in a reinforced slope would typically result in the generation of excess pore water pressures during construction. Such pore water pressure reduces the shearing resistance in the fill, and reduces the bond between the geogrid and the fill. Continuing deformation and settlement of the slope can result.

This paper reviews the strength and consolidation properties of cohesive fills as they relate to their potential use in reinforced slopes. Results from a laboratory research program (Kempton *et al.*, 2000) into the ability of a geogrid combining reinforcement and drainage functions to dissipate pore water pressures in clay soil are presented and analysed.

Based on the research program, a simple and practical design method is presented which deals with the excess pore water pressures and settlements that would develop at each stage of fill construction. The design method is considered to be applicable to both saturated and partially saturated cohesive fills. Recommendations are made on the interaction coefficients between cohesive fills and geogrid that may be used for design.

A design example is presented to illustrate the design method, and the range of strategies for construction. These range from relatively fast construction that results in higher construction pore water pressure, to relatively slow construction but with relatively little pore water pressure generated in the slope at any stage. Faster construction requires additional reinforcement compared with slower construction.

A related problem for a steep slope constructed from cohesive fill is the possible seepage of water into the reinforced block over the life of the structure from the unreinforced fill that is retained. Such seepage could cause an increase in pore water pressure in the reinforced fill, reducing stability and potentially causing deformation. Guidance is provided on how such seepage from around the reinforced block may be controlled.

2 THE PROPERTIES OF COHESIVE FILL

The shear strength and consolidation properties of compacted cohesive fill can vary greatly. The shear strength properties are a function of the plasticity index, mean effective stress and soil density, while the consolidation properties greatly depend on the grading of the fill.

Jewell (1996) provides guidance on the selection of appropriate strength parameters for cohesive fill. However, a simple and practical method to relate the state of a compacted cohesive fill with a peak angle of friction and dilation has not yet been developed. Typical values for the angle of friction of compacted cohesive fills from the literature are presented in Table 1. It should be noted that strength parameters can vary considerably between cohesive fill types.

The coefficient of consolidation, C_V can also vary greatly between fill types. Table 2 presents values of C_V for various cohesive fills determined in the laboratory (C_V Lab) and from site measurements (C_V *In situ*). It should be noted that the C_V values of marginal fills could be significantly higher than those of cohesive fills.

Table 1. Strength properties of compacted cohesive fills.

Soil Name	Plasticity Index %)	ϕ' (°)	c' (kPa)	Reference
Keupar Marl	19	27	-	Cox (1978)
Fort Creek Dam	31	23.5	20	Lieszkowszky (1978)
Leucate-le-Barcares	21	25	15	Thompson *et al.* (1978)

Table 2. Consolidation properties of compacted cohesive fill, after Vaughan *et al.* (1978).

Soil Name	Plasticity Index (%)	C_V Lab (m^2/ year)	C_V *In Situ* (m^2/ year)
UskFill	8	8.9	12.3
Selset	14	0.9 – 3.1	1.4 – 3.6
Llyn Brianne	10	15 – 20	-
Derwent	19 – 22	1.3	1 – 1.7

3 RESEARCH ON THE USE OF A COMBINED REINFORCEMENT DRAINAGE GEOGRID

Kempton *et al.* (2000) presented the results of a laboratory investigation into the ability of a new combined reinforcement drainage geogrid to dissipate excess pore water pressures in cohesive fills. The laboratory study used English China Clay (coefficient of consolidation 1.3 to 2.3 m^2/year). The main conclusions of that study are:

1 The new combined reinforcement drainage geogrid was seen to dissipate the excess pore water in the fill to 20 % of its initial value in 32 hours,
2 It was noted that the initial excess pore water pressure in the immediately vicinity of the new combined reinforcement drainage geogrid only reached 40 % of the applied stress,
3 Dissipation of excess pore water pressures occurred on both sides of the new combined reinforcement drainage geogrid even though the drainage channel was only on one side,
4 Increased pullout resistance was recorded both after full and partial dissipation of the excess pore water pressure,
5 Adequate transmissivity is provided to remove water from soil even at low hydraulic gradients,
6 No clogging or wash through of fines into the drain over the test period was noted.

4 OVERVIEW OF THE DESIGN OF STEEP SLOPES WITH COHESIVE FILLS

Codes of practice differ in their treatment of cohesive fills. Table 3 summarizes four codes widely used in design. While both UK coded allow for the use of cohesive fill the two US codes specify maximum values of fines. It should be noted that ever these requirements could be met by a wide range of slow draining or marginal fills.

Table 3. Approach to the use of cohesive fill adopted by codes of practice.

Code of Practice	Requirements
BS 8006 (1996) UK	Cohesive fill maybe used in conjunction with an appropriate reinforcement for reinstatement or new slopes.
HA 68/94 (1994) UK	No comment on cohesive fills but does not prohibit their use.
FHWA (1998) US	Allows soils with a gradation of up to 15 % passing No 200 sieve (0.075 mm).
NCMA (1997) US	Allows soils with a gradation of up to 35 % passing No 200 sieve (0.075 mm).

5 DESIGN METHOD

Based on the research presented by Kempton *et al.* (2000) a design method has been developed for constructing steep slopes from cohesive fills. The aim of the design method is to dissipate any excess pore water pressures present in the slope during the construction stage. This results in an increase in the shear strength of the fill and enhanced bond between the reinforcement and the fill. It also allows vertical and horizontal deflections to be controlled as construction proceeds.

The design method is shown diagrammatically in Figure 1.

5.1 *Dissipation of excess pore water pressure generated during construction*

Analyses of the dissipation test results (Kempton *et al.*, 2000) reveal that the dissipation of excess pore water pressures using the new combined reinforcement drainage geogrid can be reasonably modeled using the following equation:

$$T = \frac{F_{Diss} C}{C_V} \tag{1}$$

where, F_{Diss} = a factor of safety applied to the calcu-lated dissipation time, C = is a constant determined from Figure 2, C_V = the coefficient for consolidation (m^2/year) of the fill.

The factor of safety F_{DISS} is included to account for uncertainties in the determination of C_V, variability in the cohesive fill and extrapolation of

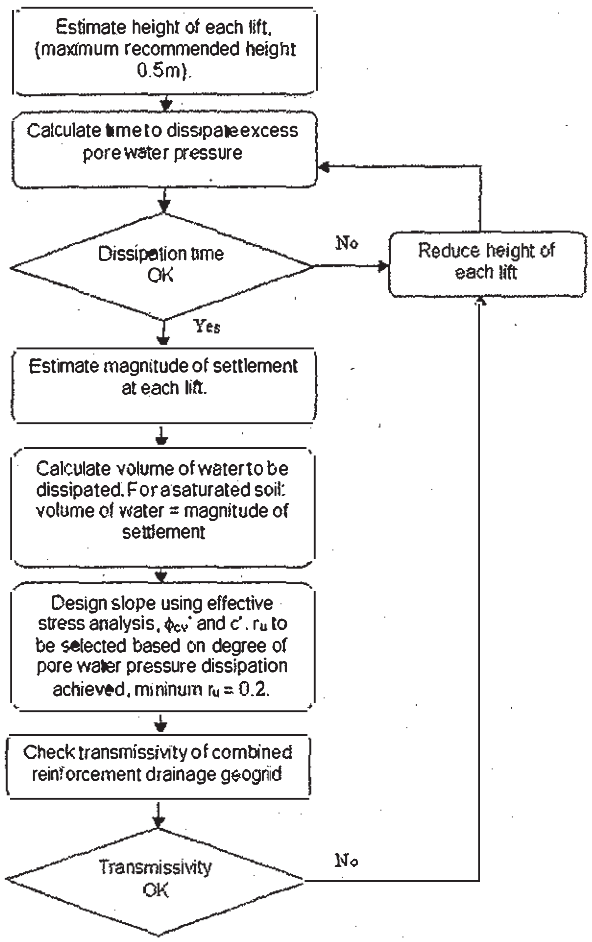

Figure 1. Flow chart of design method.

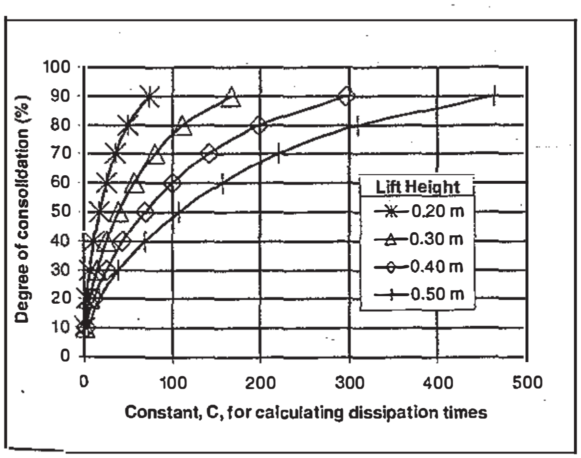

Figure 2. Constant C for various lift heights.

test data to field conditions. At present a value of F_{DISS} = 2.0 is recommended for use in design. It is also proposed to limit the lift height to a maximum of 0.5 m. An average degree of consolidation of 80 % is desirable at the end of constructing an individual layer.

When a new layer is constructed an excess pore water pressure will be generated in the previously constructed layers. The excess pore water pressure in any layer immediately after placing a new lift is:

$$\text{Epwp in layer i} = h\gamma + (n-1)[\gamma h r_{ui}] \qquad (2)$$

where, h = the height of each layer, γ = unit weight of the fill, n = number of layers constructed, r_{ui} = is the pore water pressure parameter in layer i.

5.2 *Calculation of vertical deflection and volume of water leaving each layer.*

Settlements in each layer of the slope will arise as dissipation of the excess pore water pressure proceeds. In practice the magnitude of the settlement will be small and will generally be corrected automatically as construction proceeds.

The magnitude of the settlement in each layer can be calculated from:

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where, δh = the settlement of the layer, h = the initial height of the layer, m_v = the coefficient of volume compressibility, $\Delta\sigma_v'$ = the change in the vertical effective stress and is equal to

$$\Delta\sigma_v' = \gamma h + q \qquad (4)$$

where, γ = is the bulk unit weight of the fill, h = the lift height, q = the surcharge due to construction traffic.

Where the degree of saturation of the fill is greater than 90 %, the volume of water leaving any soil layer can be determined from the magnitude of the vertical settlement per unit plan area:

$$V = \delta h * 1000 \qquad (5)$$

where, V = the volume of water, in litres, leaving a soil layer, δh = the settlement of the layer in metres.

5.3 *Designing the slope for the ultimate limit state*

Dissipation of the excess pore water pressure during the construction phase will increase the shear strength of the cohesive fill. An effective stress analysis, using the constant volume angle of friction, ϕ_{cv}', can therefore be used in designing for the ultimate limit state. A minimum r_u value of 0.2, corresponding to a degree of consolidation of 80 %, is recommended for all designs.

The coefficient of bond between reinforcement and the soil is directly proportional to the angle of friction of the soil. Values can be determined for a particular fill by carrying out shear box testing or alternatively for the new combined reinforcement and drainage geogrid the values in Table 4 can be used. The coefficient of direct sliding for the new combined reinforcement drainage geogrid is 0.7.

Table 4. Values for coefficient of bond for different ranges of ϕ'.

Angle of friction (ϕ')	Coefficient of bond
< 20	0.4
20 – 25	0.5
25 – 30	0.6
> 30	0.7

5.4 *Checking that the transmissivity of the geogrid is adequate*

The transmissivity of the new combined reinforcement drainage geogrid at different confining stresses and hydraulic gradients are presented in Kempton *et al.* (2000). When the volume of water leaving the soil and the time for consolidation to occur are both known, the required transmissivity can be calculated and compared with the transmissivity available. The transmissivity needs to be checked twice, firstly immediately after construction of a layer, when the hydraulic gradient is high but the confining stress is low and secondly at the end of construction when the hydraulic gradient is low but the confining pressure is high. If the transmissivity provided is inadequate then the lift height should be reduced.

6 A DESIGN EXAMPLE USING THE NEW DESIGN METHOD

A design example is presented to demonstrate the proposed design method. Figure 3 shows a 5 m high steep slope inclined at 70^0 to the horizontal. The bulk unit weight of the fill is 18 kN/m^3 and the consolidation properties are given in Table 5. It is

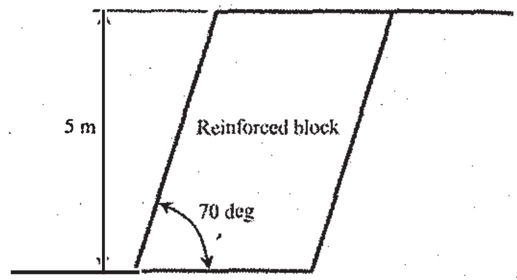

Figure 3. Slope used in design example.

Table 5. Consolidation properties of the fill.

Confining stress (kPa)	0 - 40	40 - 75	75 - 100
C_V (m^2/year)	10	8	6
m_v (m^2/MN)	0.5	0.4	0.3

proposed to construct the slope using vertical lifts of 0.5 m.

Using the proposed design method the dissipation time for each layer can be calculated, the resultant settlements estimated and the transmissivity checked. The above values have been determined for each layer after the construction of layer 10, the final layer in the slope and are presented in Table 6. The longest dissipation time is estimated at 103 hr (4.29 days) in the bottom two layers and the maximum vertical settlement of 2.25 mm occurs in layers 7 to 10 at the top of the slope. The total vertical settlement after constructing the final layer is 18.9 mm. The maximum transmissivity required after constructing this layer is 0.036 l/m.hr. The hydraulic gradient has been calculated in the body of the slope 4 m from the face.

In the design of steep slopes using this design method it is necessary to establish a balance between dissipating excess pore water pressures and arriving at a satisfactory construction time.

Figure 4 shows the excess pore water estimated at the base of the slope after construction of the first 3 lifts, 1.5 m high slope. While dissipation of excess pore water pressure to 70 % considerably reduces the construction time it results in a residual pore water pressure in the slope that may cause

Table 6. Dissipation times, vertical settlement and transmissivity after placing the final lift.

Layer	1	2	3	4	5	6	7	8	9	10
Height of slope (m)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Confining stress (kPa)	90	81	72	63	54	45	36	27	18	9
Dissipation time (hr)	103	103	77.6	77.6	77.6	77.6	62.1	62.1	62.1	62.1
Vertical settlement in each layer (mm)	1.35	1.35	1.8	1.8	1.8	1.8	2.25	2.25	2.25	2.25
Transmissivity (l/m.hr)	0.013	0.013	0.023	0.023	0.023	0.023	0.036	0.036	0.036	0.036
Hydraulic gradient after 1 hr						0.225				
Hydraulic gradient after 80 % dissipation						0.018				

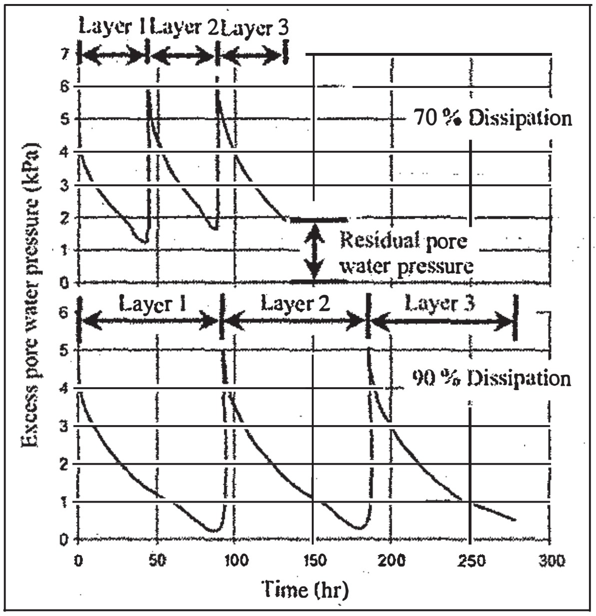

Figure 4. Excess pore water pressure at base of slope after constructing 3 layers (1.5 m).

short term instability. Dissipation to 90 % increases the construction time but reduces the residual pore water pressure in the slope. The effects of dissipating the excess pore water pressure to 70 and 90 % of the initial value are summarized in Table 7.

In the situation where a construction time of 135 hr and 90 % dissipation is required the height of each lift should be reduced to 0.24 m.

Table 7. Summary of dissipating excess pore water pressures to 70 and 90 % of initial value.

	70 % dissipation	90 % dissipation
Construction time (hr)	132.4	278.6
Average residual excess pore water pressure (kPa)	1.87	0.50
Average r_u value in layer 3 at end of construction	0.42	0.11

7 ASSOCIATED PROBLEM OF CONSTRUCTING STEEP SLOPES FROM COHESIVE FILLS

An additional problem associated with the construction of steep slopes from cohesive fill is the development of seepage pressures in the reinforced block, Figure 5. Seepage pressures can lead to a reduction of both the shear strength of the fill and the bond between the reinforcement and the fill.

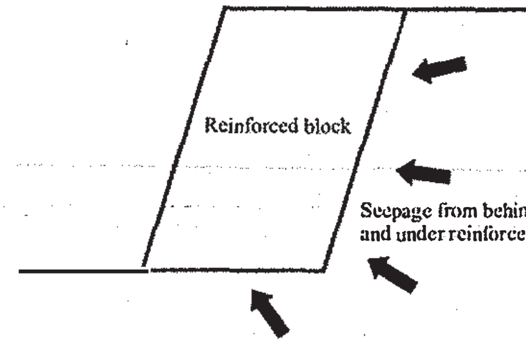

Figure 5. Development of seepage pressures inside the reinforced block.

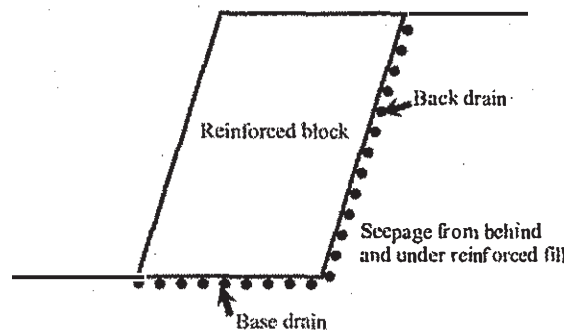

Figure 6. Control of seepage into reinforced block.

Constructing base and back drainage outside the reinforced block, Figure 6, can best control un wanted seepage. This method of construction has a number of advantages:

1 The base and back drainage can be independently designed to control any seepage conditions present.
2 The drainage component in the reinforcement block can be designed for a short design life, until the excess pore water pressure in the slope is dissipated. This will reduce the cost of the combined reinforcement drainage geogrid as one drainage configuration can be used to dissipate excess pore water pressures rather than having a range of drainage elements to meet particular site conditions.
3 Removal of the seepage water before it enters the reinforced block will remove any danger of piping channels developing which could have an adverse effect on the stability of the reinforced zone irrespective of the quantity of reinforcing or drainage elements present in this region.

It is recommended that suitable granular fill with adequate permeability wrapped in geotextile is used for both the back and base drain.

8 CONCLUSIONS

The properties of cohesive fills are presented and shown to have a wide range of shear strengths and generally low permeability leading to long pore pressure dissipation times.

Recent research has shown that a new combined reinforcement and drainage geogrid can dissipate excess pore water pressures during the construction period, resulting in an increase in the shear strength and enhanced reinforcement soil interaction.

A new simple and practical design method is presented which can be used to estimate the time to dissipate excess pore water pressures generated during construction. Methods of dealing with advancement of wetting fronts and seepage into the reinforced soil block are also presented.

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