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DESIGN AND CONSTRUCTION ASPECTS OF EMBANKMENT UNDERDRAINS

ASPECTS DU DIMENSIONNEMENT ET DE LA CONSTRUCTION DE REMBLAIS DRAINES

ASPEKTE DES ENTWURFS UND DER KONSTRUKTION DRAINIERTER DÄMME

As society becomes more aware of the visual intrusion and noise pollution caused by certain civil engineering works so there is more frequent use of environmental barrier embankments to abate these nuisances. Since these embankments are not paved they can suffer considerable surface water infiltration leading to the establishment of destabilising porewater pressure regimes within the embankment fill. This is particularly so for embankments constructed of intermediate permeability fill constructed over low permeability foundation soils. In these circumstances, the deleterious effects of water infiltration can be negated by the use of a basal underdrain. This paper considers uncertainties relating to the effective thickness of a conventional granular fill basal drainage layer and indicates how these can be reduced by the incorporation of a properly designed geotextile to protect the drain.

Je mehr sich die Gesellschaft der durch bestimmte Ingenieurbauten verursachten visuellen Intrusionen und Geräuschemissionen bewusst wird, umso häufiger werden die Umwelt schützende Sperraufschüttungen verwendet, um diese Ärgernisse zu verringern. Nachdem diese Erddämme nicht gepflastert sind, kann beträchtliches Einsickern von Tagwasser zu entstabilisierenden Porenwasserdrucksystemen innerhalb der Aufschüttung führen. Dieses tritt besonders bei Erddämmen auf, die aus einer Aufschüttung mittlerer Durchlässigkeit über Baugründen mit niedriger Durchlässigkeit bestehen. Unter diesen Umständen kann die schädliche Wirkung der Wasserinfiltration durch die Verwendung eines unterirdischen Basaldräns zunichtegemacht werden. Dieses Referat erwägt die Unklarheiten, die hinsichtlich der effektiven Stärke der Basaldränschicht bei einer herkömmlichen körnigen Aufschüttung herrschen, und zeigt, wie diese durch die Inkorporation zum Schutz des Dräns korrekt konstruierter Geotextilien reduziert werden können.

1. INTRODUCTION

In response to the need to reduce the environmental impact of certain civil engineering works increasing use is being made of large scale landscaping and environmental barriers. Environmental barriers, which may be used to abate noise or to screen unsightly industrial developments, are of particular concern since there is frequently a tendency at design stage to treat these as mere mounds of earth. Although these barriers serve no structural purpose, such as an embankment carrying a highway, they are nonetheless structures in their own right and should, therefore, be designed accordingly. Indeed compared to highway embankments, where much of the surface area is rendered "impermeable" by the pavement, environmental barriers can suffer considerably from the effects of surface water infiltration. Depending on height and slope geometry barriers particularly at risk are those constructed of intermediate permeability fill over low permeability foundation soils. For low permeability fill the majority of rainfall runs off the surface of the barrier with any filtration under gravitational flow ingressing at a velocity numerically equal to the permeability of the fill. In contrast high permeability fill, depending on topsoiling and seeding, can have an exceedingly high infiltration rate which is generally governed by the rate of rainfall rather than the potential infiltration rate of the fill. Even if significant volumes of water do enter the barrier these tend to set up vertical flow patterns. Water does not accummulate to any degree at the impermeable base since the fill permits lateral drainage at modest hydraulic gradients. Between these two extremes falls fill of intermediate permeability where without the benefit of a basal drainage layer, unfavourable porewater pressure regimes can be established. To illustrate this possibility an example is presented of a 13m high noise barrier constructed in southern England using intermediate permeability mudstone fill over an impermeable basal layer of Weald Clay.

2. EFFECTS OF INFILTRATION ON STABILITY

The geometry of the barrier is indicated in Figure 1 together with the long term shear strength parameters used for design. The fill material was won locally from a formation comprising Weald Clay over mudstone. Since the barrier was constructed as the fill was won the mudstone was placed above the low permeability clay used as a basal layer.

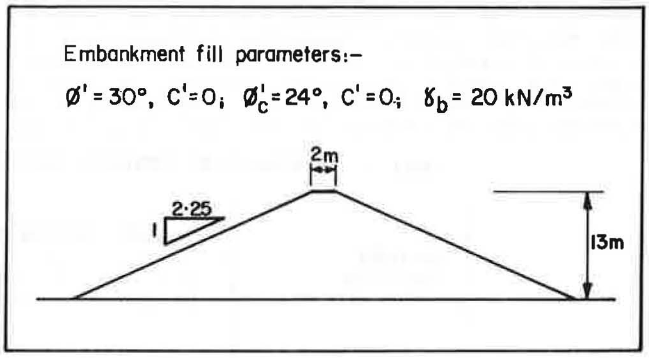

Figure 1 : BARRIER GEOMETRY

Before embarking on the design of an underdrain analyses were carried out to assess the effects of different seepage regimes on the stability of the barrier. Two conditions were considered, one with a basal drainage layer and one without. As can be seen from Figure 2, without a basal drainage layer sustained infiltration gives rise to an extremely unfavourable condition compared to Figure 3 showing the effects of an underdrain, which induces vertical gravitational flow.

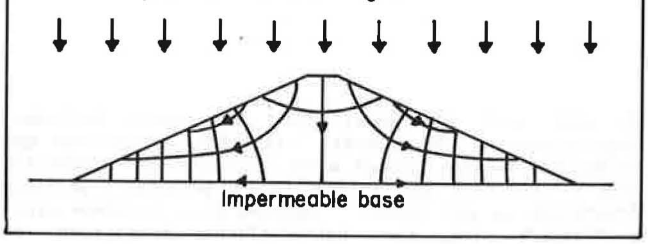

Figure 2 : INDICATIVE FLOW NET - IMPERMEABLE BASE

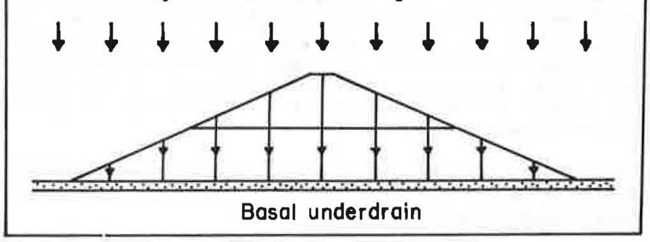

Figure 3 : INDICATIVE FLOW NET - BASAL UNDERDRAIN

The effects of the porewater regimes associated with these two conditions are mirrored in slope stability analyses carried out using both circular (1) and noncircular (2) analyses. Two different sets of shear strength parameters were used for the fill. In the first the peak angle of shearing resistance was taken from available laboratory test results neglecting any effective cohesion. Observation of intermediate term performance of other embankments constructed using the same material justified neglecting cohesion since the process of excavation, subsequent placement and compaction, and finally weathering substantially destroys effective cohesion. Since the rate of weathering of the mudstone under infiltration was not known, it was decided to carry out a second series of analyses using the critical state parameters quoted for Weald Clay by Schofield and Wroth (3).

The porewater pressure regimes for the condition of an impermeable base were determined from flow nets, Figure 2. In contrast the pervious base condition assumed the barrier to behave as though completely dry. The logic for this stems from Equation 1 where the subscripts e, b and w represent effective and bulk unit weights of the fill respectively with w representing the unit weight of water.

$$\gamma_e = \gamma_b - \gamma_w + i\gamma_w \qquad \ldots. 1$$

The hydraulic gradient i is positive downwards. If the bulk unit weight of the fill is assumed to be twice that of water and the hydraulic gradient is taken to be unity under the effects of vertical gravitational flow, Figure 3, then the effective unit weight defined by Equation 1 numerically equals the bulk unit weight of the fill. The results of the analyses are summarised in Table 1.

In considering the merit of using either peak or critical state soil parameters, it should be borne in mind that the critical state constitutes a lower bound strength below which the soil strength will never fall at low strains. Contrasting with this the peak strength constitutes an upper bound strength which is never fully mobilised at all points on a slip surface due to the phenomenon of progressive failure. In view of the uncertainty in the value of the peak parameters, it is prudent to check designs assuming critical state parameters and a low factor of safety. Since the critical state defines a lower bound strength which is unlikely to be ever reached at all points on a slip surface, it is permissible to base designs on a factor of safety marginally greater than unity. In this particular case a factor of 1.1 was adopted.

The low factor of safety of 0.46, Table 1, obtained assuming an impermeable base indicates that any build-up of porewater pressures in the barrier is likely to have serious consequences. To overcome this problem a basal drainage layer is necessary. Needless to say, the drainage layer must be designed to cope with the expected flow through the barrier and to remain fully effective throughout the required service life of the barrier.

3. DESIGN OF UNDERDRAIN

When rain falls on the barrier part of the fall infiltrates the embankment and seeps vertically down under gravity through the fill material to the basal drainage layer. The maximum infiltration rate through the compacted fill is numerically equal to its permeability k. The rate of flow of water into the basal drainage layer is then given by Darcy's equation q = kiA. In this case the hydraulic gradient, i, for vertical gravita-

TABLE 1. RESULTS OF STABILITY ANALYSES

DRAINAGE CONDITION	NON-CIRCULAR ANALYSIS		CIRCULAR ANALYSIS	
	Peak Parameters	Critical State Parameters	Peak Parameters	Critical State Parameters
Impermeable Base	0.67	0.52	0.59	0.46
Pervious Base	1.40	1.09	1.41	1.10

tional flow is unity so that the flow per unit length of the barrier over the half width L, Figure 4, is given by q = kL.

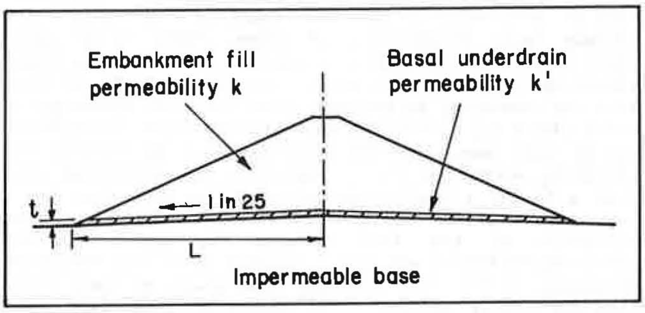

Figure 4 : DESIGN OF UNDERDRAIN

The flow rate that the drainage layer can cope with can also be assessed using the Darcy equation. In this case the hydraulic gradient is approximately equal to the cross fall in the drainage layer, 1 in 25, and the area of flow per linear metre of the barrier equals the drainage layer thickness t. Denoting the permeability of the drainage material k' the drain capacity is then given by q' = k't/25. By continuity of flow the drain capacity q' must at least equal the rate of flow of water, q, through the material of the barrier. This leads to the identity k' = 25 kL/t. For a barrier half width of 30m and a drainage layer thickness of 225mm, this identity leads directly to k' ≈ 3000 k.

Early laboratory permeability tests had been carried out on the fill compacted at moisture contents 2% to 3% wet of optimum and these indicated a permeability of some 10^{-10} m/s. In the event it was apparent that the mudstone fill would actually be placed some 5% to 10% dry of optimum and so obtain a density lower than that prevailing in the initial permeability tests. It was also apparent that the mudstone fill would be much more open structured than that used in initial testing. These two factors suggested that the field permeability was likely to be much higher than that initially assessed. Indeed subsequent falling head permeability tests both in the laboratory and later in the field, indicated a mudstone fill permeability of 3×10^{-6} m/s. Coupling this with the relationship derived between fill and drainage blanket material permeabilities indicated the need for a drainage material permeability of 10^{-2} m/s. The drainage blanket material finally specified was that complying to the requirements for Type B filter material to the Departments of Transport Specification for Roads and Bridge Works (4). As can be seen from the grading curve in Figure 5, the Type B material is quite coarse and uniformly graded. In consequence its permeability is high being typically 1 m/s. Theoretically, this is two orders of magnitude higher than the required permeability of 10^{-2} m/s and so allows some margin for any contamination of the drainage material during construction.

4. THE NEED FOR A GEOTEXTILE

The functions of a geotextile would be primarily filtration and separation with a secondary function of reinforcement of the drainage layer to reduce any rutting caused by illicit trafficking during the construction stage.

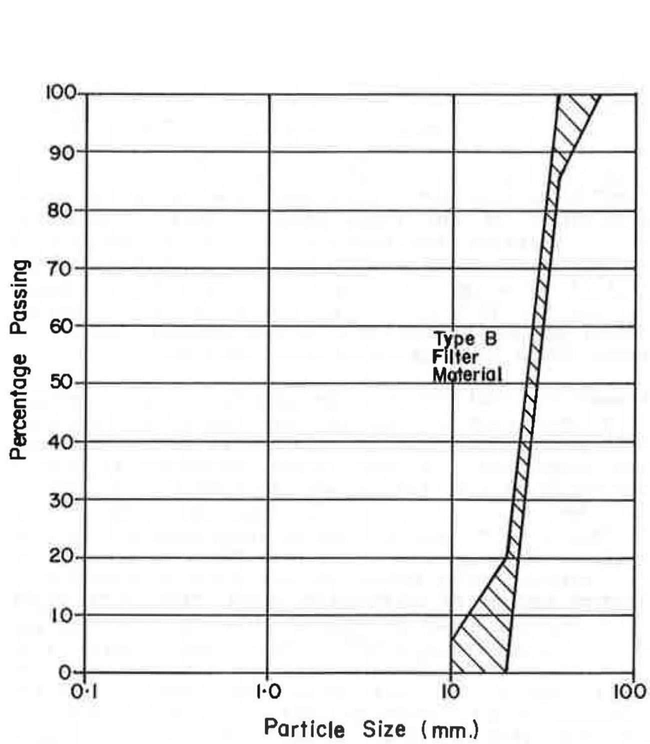

Figure 5 : TYPE B FILTER MATERIAL GRADINGS

The main purpose of filtration is to prevent ingress of fines into the drainage layer. Figure 6 gives an indication of the effects of fines contamination in the permeability of a granular sub-base material from which it can be seen that for a 5% increase in fines passing the No.200 (75μm) sieve, there is a drop in permeability of one order of magnitude. A similar effect might be anticipated for contamination of the Type B filter material which would reduce permeability to about 10^{-1} m/s. Even so, this is still one order of magnitude higher than that required for the drainage material to operate effectively.

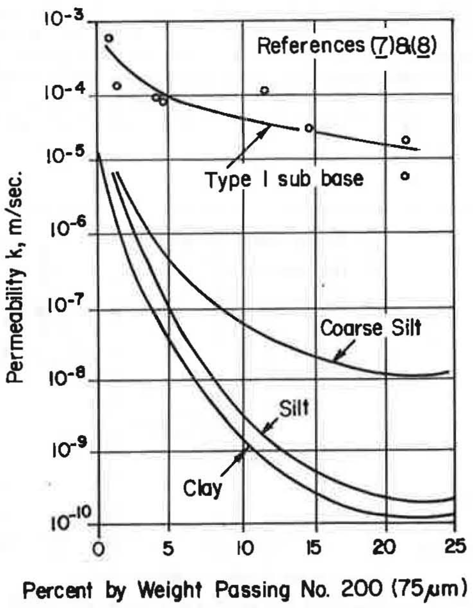

Figure 6 : EFFECT OF FINES CONTAMINATION ON PERMEABILITY

Regarding filter design it is difficult to be precise. Although there is no lack of filter criteria to apply it is difficult to obtain a meaningful grading for the mudstone fill since amongst other things this tends to break down during placement and compaction. Also it tends to be very much a gap graded material. In the event examination of the fines produced during compaction trials indicated fines particle sizes of typically 500 µm to 1000 µm. Based on these particle sizes and the fact that the flow velocity of water entering the fill would be low, say 10^{-6} m/s, it was concluded that a conventional geotextile with an effective opening size in the range 100 µm to 500 µm would prove adequate.

Remembering that the drainage material was to be placed on a basal layer of clay, and then covered with mudstone fill which breaks down to some degree during placement and compaction, it was deemed necessary to use a geotextile at both the top and the bottom of the drain. In view of this, one very important role of the geotextile is to separate the drainage material from the fill. If no geotextile is used there is a danger of fill material being forced into the drainage layer due to loading imposed by construction plant. This could result in a drainage layer of reduced effective thickness and hence reduced transmissivity. The drainage blanket is at high risk during the placement and compaction of the first layer of fill over the drainage blanket, since the compaction plant induces an additional vertical stress in the underlying fill given by Equation 2, based on Ingold (5):

$$\Delta\sigma v = 2p / \pi z \quad \ldots. \; 2$$

where $\Delta\sigma v$ is the vertical stress induced at a depth z by a roller inducing an equivalent line loading p kN/m. For a given layer thickness the line load induced by the compaction plant must be chosen to limit the induced vertical stress and so prevent extrusion of the fill through the geotextile into the drainage layer. The pressure, P, required to cause extrusion through a mesh is related to the undrained shear strength of the fill and the open area ratio of the mesh. A relation between extrusion pressure and open area ratio is shown in Figure 7 where test results are plotted for extrusion tests carried out on both metal and clay. For a suitable woven geotextile the open area ratio would be about 30%. With allowance for blockage of some of the pores by the drainage blanket material, the effective open area ratio is likely to be nearer 20 - 25%. Figure 7 shows a value of P/Cu of approximately 6 for this range of open area ratios.

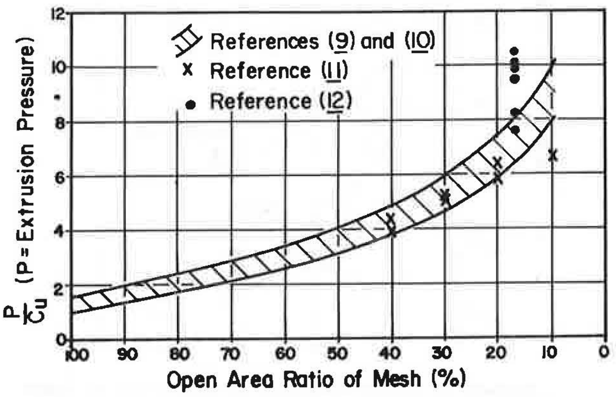

Figure 7 : RELATION BETWEEN EXTRUSION PRESSURE AND OPEN AREA RATIO

Earlier analyses of the barrier in terms of undrained shear strength indicated a minimum required value of undrained shear strength of 45 kPa to maintain short term stability. For a material of this strength extrusion would occur at pressures exceeding 275 kPa. Substitution of this value of $\Delta\sigma v$ into Equation 2 and assuming a minimum layer thickness z of 150mm, leads to an upper limit line load of 65 kN/m. Table 2 lists various towed vibrating rollers which exert line loads up to 65 kN/m with the vibrating mechanism turned off. The advantage of using vibrating rollers is that greater layer thicknesses may be used away from the drainage layer by turning the vibrating mechanism on. Typically the effective line load with the vibrating mechanism on is some four times that with vibrator switched off. In order to prevent extrusion of the fill through the geotextile the vibrating mechanism was not activated until the compacted thickness of the fill exceeded that given in Table 2 for each particular roller. It should be noted that the selection of compaction plant considered above related only to the problem of extrusion of fill into the drainage layer. The type of compaction plant, layer thickness and number of passes required to achieve the specified fill dry density were determined by trials held during the construction of an initial section of the barrier.

A secondary problem associated with the maintenance of the full thickness of the drainage layer is that of rutting of the clay fill beneath it due to illicit trafficking of the drainage material during construction. This problem is reduced to some degree through the geotextile, if sufficiently stiff, acting as a reinforcing membrane. Analyses were carried out based on the method proposed by Giroud and Noiray (6) and these suggested that in order to maintain an effective thickness of 225mm a drainage layer thickness of 300mm would be required for use with a geotextile rising to 500mm if no geotextile was used.

TABLE 2 : SPECIFICATIONS FOR TOWED VIBRATING ROLLERS

MODEL	LINE LOAD (kN/m) VIBRATING MECHANISM OFF	MINIMUM LAYER THICKNESS (mm)* VIBRATING MECHANISM ON
AMERICAN HOIST		
Bros-T-VP-15-D	32	210
BOMAG		
BW4	25	170
BW6	35	240
BW10	46	320
BW15	65	480
HYSTER		
C200B	23	180
C200Bsp	30	190
C210A	29	190
CLARK SCHEID		
CV40	22	200
CV60	31	260
CV70	34	270
CV120	54	460
STOTHERT & PITT		
T133	10	110
72T1C	22	220
T182B	33	250
T208	55	490
VIBROMAX		
W501	21	230
W651	30	340

* To limit induced vertical stress to 275 kPa at base of layer.

5. GEOTEXTILE SPECIFICATION

It became apparent during the design stage that there was a real need for a geotextile since without the protection afforded by a geotextile the drainage layer thickness would need to be increased significantly to ensure a minimum effective thickness was maintained after allowance for the various modes of contamination. The four prime requirements for the geotextile were defined as follows:-

i) Sufficiently small pore size to prevent infiltration of soil fines.

ii) Low open area ratio to prevent extrusion of fill during construction.

iii) Sufficiently high permeability to allow passage of water from fill into drainage blanket.

iv) Sufficiently high stiffness and friction to limit rutting caused by construction plant.

To a certain extent the first two requirements conflict with the third in as much as a smaller number of small pores would tend to give a low permeability normal to the plane of the fabric. It was necessary, therefore, to consider the relative importance of the four requirements.

It was thought that a thick felt with a pore size of approximately 100 µm might be better suited to preventing ingress of fines rather than an essentially planar woven geotextile which would need a comparatively large pore size of about 500 µm to ensure adequate permeability. However, it was considered that the quantity of soil particles free to move under action of water flow would be small and that, therefore, the problem of contamination of the drainage blanket due to inadequate filtration should be small. From this point of view there was little to choose between a nonwoven and a woven geotextile.

Major contamination of the drainage layer was thought more likely to result from extrusion of fill, particularly the basal clay fill, through the geotextile. A nonwoven, such as a thick felt, with a low open area ratio was thought likely to perform better than a woven. The woven in mind was a monofilament-on-monofilament since a woven tape fabric would fall short of the permeability requirement. It was considered doubtful, however, that the lower open area ratio offered by a felt was actually required since earlier calculations indicated that the higher open area ratio of a woven monofilament would be adequate to control extrusion. From this point of view there was little to choose between the two types of geotextile.

One vital aspect of the geotextile performance was the ability to maintain an adequately high permeability and indeed it was decided that the permeability of the geotextile finally selected would need to be at least one order of magnitude higher than that assumed in the design for the fill material. This indicated the need for a geotextile permeability better than 3×10^{-5} m/s. Such a figure was easily exceeded by the felts considered where permeability was typically 5×10^{-3} m/s at zero normal stress falling to typically 7×10^{-4} m/s when the geotextile was subjected to a normal stress of 260 kPa which represents the overburden pressure at the base of the barrier. Slightly higher permeability was attributed to the woven monofilament fabrics where permeability was typically 20×10^{-4} m/s. This was very nearly independent of normal stress level. There was a thought that the three dimensional structure of the thick felt might make it more prone to clogging and, therefore, on balance it was concluded that the woven monofilament fabric was more suitable to fulfill the permeability requirement.

Regarding the axial tensile stiffnesses of the various felt and woven monofilaments considered, the woven fabrics showed considerable advantages. This stemmed not so much from the higher tensile strength of the wovens but the fact that the failure strains of the wovens never exceeded 25%. In contrast failure strains of around 50% to 80% had been quoted for the nonwovens. Remembering that high stiffness is required to minimise rutting of the drainage blanket, it was concluded that the woven fabric would be preferable.

On technical grounds it was concluded that a woven monofilament-on-monofilament geotextile would be the most suitable material. The technical specification finally adopted called for a woven polyethylene or polypropylene monofilament fabric with a mass per unit area of not less than 250 g/m^2 and an effective pore size not greater than 500 µm. Permeability normal to the plane of the fabric should be greater than 10^{-4} m/s with warp and weft tensile strengths not less than 20 kN/m.

6. CONCLUSIONS

Environmental barriers and unpaved embankments constructed over a low permeability foundation soil can become unstable if rainfall infiltrates and establishes an unfavourable porewater pressure regime within the embankment fill. This problem can be eradicated using a properly designed underdrain installed at the base of the embankment fill. The prospect of such a drainage layer remaining serviceable throughout the design life of the barrier is enhanced by the use of a properly designed and installed geotextile which performs adequately as a filter, a separator and a reinforcing medium.

7. ACKNOWLEDGEMENTS

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