



Drainage of earthwork slopes: a review

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D M Farrar and K C Brady

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Executive Summary

Scope of the project

In many cases the stability of an earthwork is dictated by the prevailing pore water pressures in the soil, but there is a paucity of information regarding the long term pore water pressure regime. Without such information it is impossible to determine the effectiveness and efficiency of drainage measures, reinforced soil techniques (such as soil nailing) and maintenance operations. Pessimistic assumptions regarding the distribution of pore water pressures can give a substantial loss in economy whereas optimistic assumptions may lead to ineffective and inefficient construction and maintenance works.

The main objectives of this project are; (i) to review the methods used to measure soil suction in situ, (ii) to measure the distribution of pore water pressure in slopes, (iii) to compare the measured values of pore water pressure with those assumed in design and as predicted by numerical methods, and (iv) to provide a critique of current advice and specifications regarding the design and assessment of soil slopes.

To date the following work has been undertaken; (i) a literature search on the distribution of pore water pressures in soil slopes (this includes an assessment of the different methods and devices for measuring soil suctions in the field - a report is in preparation), (ii) a review of design rules and specifications for the depth, width and spacing of drains in slopes, and (iii) the measurement of pore water pressures at an embankment at the M23 Gatwick Spur and in a 14 metre deep cutting south of junction 4 on the M1.

Towards the end of the project the techniques for designing unreinforced and reinforced slopes will be reviewed and, where appropriate, recommendations for improving existing practice will be put forward.

Previous reports of the project

None

Summary of the report

This report reviews the information and advice available on the drainage of earthworks, identifies the limitations of current knowledge and provides recommendations on how these might be addressed.

The stability of highway embankments and cuttings is critically dependent on the magnitude and distribution of pore water pressures within the soils. The importance of drainage on stability is widely recognised, but there is comparatively little information on the subject in current design documents. There are references in a number of the documents that make up the Design Manual for Roads and Bridges (DMRB), but none deals specifically with the drainage of earthworks.

This report reviews those sections of the DMRB and the Manual of Contract Documents for Highway Works (MCHW) which deal with earthwork and pavement drainage. It also considers the functions of earthwork

drainage and its effect on the short and long term stability of cuttings and embankments. It concludes that there is much information available which could be usefully and readily made available through the publication of a new Advice Note on slope drainage. In addition, there is scope for expanding some of the clauses in the MCHW to cover the subject. A number of deficiencies in the present level of knowledge have also been identified which deserve further consideration.

Implementation

The findings of the project could be used to examine the reliability of current rules governing the design and assessment of earthworks (including the provision of drains to the side slopes and the design of soil nails) and the design of reinstated slopes provided with geosynthetic reinforcements. Thus the information would be disseminated, as appropriate, through revisions of current design standards, advice notes and the Specification for Highway Works. Publication of the project reports would draw attention to problems with the design, construction, assessment and maintenance of earthworks and also stimulate the use of cost-effective means for strengthening existing slopes and for repairing failed slopes.

1 Introduction

The stability of highway embankments and cuttings is critically dependent on the magnitude and distribution of pore water pressures within the soils. Drainage measures are therefore an important means of ensuring the long-term stability of earthworks. Although this is widely recognised, there is comparatively little information on the subject in current design documents. There are references in a number of the Advice Notes and Departmental Standards that make up the Design Manual for Roads and Bridges (DMRB), but none deals specifically with the drainage of earthworks. And although there is extensive literature elsewhere, there are gaps in current knowledge.

The design of a drainage system to a slope may be based largely on empiricism, or indeed entirely through the adoption of standard detail drawings. Whilst it is entirely appropriate that the design process for a drainage system should have some empirical input, because of the number of factors involved which cannot be determined particularly well, the application of some simple numerical analysis may help identify the more important factors at any one site, improve understanding and practice, and thereby improve efficiency and economy. Rarely, however, are experiments undertaken under controlled conditions on slope drains. Furthermore, the information available on the effectiveness of slope drains could be usefully augmented and disseminated more widely. In short, it is an important but neglected area of study.

This report reviews the advice given on drainage of earthworks, the limitations of current knowledge and provides recommendations on how these might be addressed.

2 Review of current DETR publications

2.1 Design Manual for Roads and Bridges

Volume 4 of the DMRB contains a number of Advice Notes and Departmental Standards concerned with geotechnics and with drainage. None is dedicated to the drainage of slopes, but many provide information on this topic. Details of the relevant text given in these documents, as extant in April 1999, are provided below. This follows the terminology used in the particular document, although this is not always consistent with the definitions used in later Sections of this Report and as given in Appendix A.

2.1.1 Contract documents

HA 44: Earthworks: design and preparation of contract documents (DMRB 4.1.1)

This document includes general advice on drainage matters that should be considered in the preparation of contract documents.

For cuttings, the possibility of shallow slope failures is emphasised. Because of restrictions on land-take it may not be feasible to form a cutting at a (long-term) stable angle; this is a particular problem with over-consolidated clays. In such cases the designer should consider (a) accepting some slope failures, and (b) drainage measures

which include the installation of:

- shallow stone-filled trenches cut normal to the slope (slope drains or rock ribs);
- deeper stone-filled trenches (counterfort drains) which buttress the slope as well as draining it to a considerable depth: however this is likely to be an expensive solution.

To reduce maintenance works the need for permanent drainage to a slope should be kept to a minimum. In side-long ground, i.e. sites where earthworks impinge on an existing and possibly unstable slope, particular care must be taken with design and construction, and adequate provision should be made for drainage.

Where stability cannot be maintained without drainage, consideration may be given to the installation of interceptor drains, counterfort drains, and a drainage blanket. Attention is drawn to the following:

- the importance of properly designed granular or geotextile filters;
- the possible need for a lined interceptor drain or ditch and the necessity to intercept existing field drains;
- the presence of drainage ditches near the top or bottom of a slope as these may create soft areas thereby reducing stability.

It is also emphasised that contractors must be made aware of (a) their responsibility for any temporary drainage works, and (b) that the permanent drainage works may not be adequate for de-watering earthworks to ensure the suitability of the soils. Where temporary drainage works are required it should be made clear in the contract documents.

For embankments, attention is drawn to the importance of the possible failure and settlement of the subsoils. Embankment slopes formed of over-consolidated clays are also liable to shallow slope failures: this may be dealt with by reinforcement of the surface layers, or substituting the surface layers with non-susceptible material. No reference is made in HA 44 to drainage measures for embankments.

For pavements, some of the advice given in HA 39 (see Section 2.1.2 below) is reproduced in HA 44.

HA 40: Determination of pipe and bedding combinations for drainage works (DMRB 4.2)

This Advice Note lists acceptable pipe and bedding combinations for drainage pipes. This document was written to accompany the Highway Construction Details (MCHW 3) and covers the piped drainage of surface water from the carriageway and sub-surface water from pavement foundations. Its scope could be extended to cover the drainage of earthwork slopes.

2.1.2 Drainage of highway pavements

Two publications deal with drainage of highway pavements. These are relevant because of the effect of highway drainage on adjacent slopes.

HA 39: Edge of pavement details (DMRB 4.2)

The Highway Construction Details (see Section 2.2.2 below) give a series of standard arrangements for pavement drainage: HA 39 provides additional information to them.

It is recommended that, wherever possible, surface and sub-surface drainage systems should be separate. The reasons given for this are to:

- avoid problems of stone scatter from the surface of combined drains;
- permit the hardening of central reserves;
- avoid problems associated with the introduction of large quantities of surface water into the road foundation;
- avoid the need for regular maintenance and replacement of filter materials;
- minimise the cost of importing suitable stone.

Nevertheless a combined surface and sub-surface drain may be appropriate for a limited range of situations, for example:

- where large groundwater flows are expected, particularly in cuttings;
- where the road has long lengths of near-zero gradient;
- for reconstruction work.

Where they are permitted, combined drains should be provided with a cover of topsoil or granular sub-base to reduce stone scatter. Care should be taken to deal with surface water running over the top of this less permeable surface. The drain will be filled with a filter material, possibly with a geotextile separator placed between the filter and surface cover.

Separate drains will normally be employed, with fin or narrow filter drains for sub-surface drainage, in accordance with design drawings and specification clauses.

Over the edge drainage (i.e. without any side drains) is permitted only in situations where it will not cause problems, e.g. for low height embankments with shallow side slopes formed from stable materials.

It is pointed out that the role of sub-surface drainage is to remove ground water from the pavement layers, the sub-base, and the capping layer if this is sufficiently permeable. In some circumstances, it may be possible for deep drains to increase the strength of the subgrade. The effect of drainage on the stability of verges is not mentioned in HA 39.

HD 33: Surface and sub-surface drainage systems for highways (DMRB 4.2.3)

This document reviews and in some respects complements the guidance given in the Advice Notes discussed above.

It points out that, while separate surface and sub-surface drains are desirable, combined drains can have the following benefits in cuttings:

- early installation and usage during the construction stage;
- removal of groundwater beneath the pavement to a greater depth than would be possible with fin or narrow filter drains;
- ease of construction;
- ease of inspection and maintenance;
- a facility to collect water from slope drains.

To minimise the passage of water into the subsoil from

combined drains in cuttings, pipes may be constructed with sealed joints and laid with perforations or slots uppermost. Trench bottoms may be lined with impermeable membranes. (It is implicit that combined drains will not be used on embankments).

Problems with stone scatter from combined drains may be reduced by:

- spraying the surface of filter material with bitumen;
- reinforcing the surface with geogrids;
- incorporating lightweight aggregate at the surface;
- placing bitumen-bonded filter material in the upper part of the trench.

With fin drains, problems of working in narrow trenches may be overcome through the use of automatic drain-laying equipment. Care must be taken when constructing drains around gully connections.

For narrow filter drains it may be difficult to achieve proper filtration for a drain provided with a filter sock ('Type 8' in the Highway Construction Details).

When designing and installing toe drainage and cut-off drains, the importance of existing land drainage and the requirements of the relevant water and drainage authorities are emphasised.

Cut-off drains may be desirable, but they may have to be installed some distance from the toe of an embankment.

Drainage works should be carried out at the earliest possible stage of construction. Slope drains should connect to an appropriate piped system, which in all probability will be separate from the edge of pavement drainage system.

2.1.3 Maintenance

HA 48: Maintenance of highway earthworks and drainage (DMRB 4.1.3)

This Advice Note recommends maintenance procedures for the drainage of highway earthworks, and discusses some of the problems which can arise from inadequate maintenance.

The majority of slips in embankments are shallow first-time failures, as reported by Perry (1989). These are associated with the ingress of water into the slope exacerbated by:

- shrinkage cracking;
- water draining from pavement layers through extended sub-bases;
- poor compaction at the edge of the embankment;
- unsatisfactory reinstatement after tree planting;
- trenching at top or bottom of slope;
- ingress through compaction planes;
- alternating compacted layers of different permeability;
- infiltration through pavements, central reserves, verges, and faulty drains.

There is also a possibility of long-term failure on side-long ground through pore water pressure equilibration, and the entry of water from springs.

Earthwork slopes and drains should be inspected regularly by trained personnel. The following should be noted:

- cut-off or slope drains may need to be installed where there is evidence of seepage;
- surface flows from higher ground should be dealt with;
- intercepting drains to deal with permeable surface layers should be sited where they will not initiate slope failures;
- the leakage from filter drains and ditches into slopes should be checked;
- vegetation on a slope should not be changed unless absolutely necessary;
- the drains at the top and bottom of a slope, horizontal drains and vertical drainage wells should be inspected for effectiveness.

Counterfort drains may be installed where a slope is becoming unstable, e.g. with surface movements of the order of 100 mm. During their installation, any slipped and softened material must be removed. The diversion of surface water may delay the onset of instability, as may the installation of slope drains and rock ribs. Appropriate vegetation may reduce the occurrence of shallow failures, but the roots must not block drains. Drainage and erosion protection may also be desirable in rock slopes.

2.1.4 Widening of highways

HA 43: Geotechnical considerations and techniques for widening highway earthworks (DMRB 4.1)

This Advice Note deals with geotechnical considerations for road widening schemes. Such schemes may involve moving the edge of a carriageway nearer the edge of a slope, widening an existing embankment, or steepening an existing cutting.

Prior to assessing the stability of the modified earthworks, consideration must be given to the stability of the existing earthworks and the functioning of the existing drainage. Where necessary, repair or strengthening measures including drainage must be evaluated. Care must be taken when incorporating the existing drainage into the new design, or when replacing the existing system.

The principles of slope drainage are set out, and the importance of temporary drainage measures during the works is stressed.

2.2 Manual of Contract Documents for Highway Works

2.2.1 Specification

This Manual contains the Specification for Highway Works (MCHW 1) and accompanying Notes for Guidance (MCHW 2). Only three clauses specifically deal with sub-soil drainage.

Clause 505: backfilling of trenches and filter drains

This Clause describes three classes of granular filter material:

- type A (well-graded fine grained) - this is a general purpose filter material, commercially available and suitable for coping with road detritus and for some but not all soils;

- type B (uniformly graded, free draining) - this is for use with a free draining backfill from which there could be a high flow: it would not act as a filter and retain soil particles;
- type C (grading to be specified) – this material is to be specified for a particular soil.

This Clause also describes compaction requirements for the materials – these are based on those given in Clause 612 for mass earthworks.

Clause 514: fin drains

This Clause covers the use of fin drains as edge of pavement sub-soil drains (in forthcoming European standards the preferred name for fin drains will be ‘geocomposite drains’). Because a full set of test standards is not yet available for geosynthetics, the accompanying Notes for Guidance include detailed descriptions of some test procedures.

Clause 515: narrow filter drains

This Clause covers the use of granular and geotextile filters for narrow filter drains employed for edge of pavement subsoil drainage: this is an alternative to the use of fin drains as covered in Clause 514 above.

The accompanying Notes for Guidance for Clauses 514 and 515 cover installation and design problems in some detail. Although these Clauses are intended for edge of pavement drainage, much of the information is also considered to be relevant for subsoil drainage of earthworks.

2.2.2 Contract drawings

The Highway Construction Details (MCHW 3) give standard drawings for construction, including drainage details. Some drawings which might be adapted for earthworks drainage are:

- F1 surface water drains;
- F2 filter drains (combined drains);
- F18-21 fin and narrow filter drains.

The Series B drawings (MCHW 3.1) show how the above are used for edge of pavement drainage.

3 Earthwork drainage

This Section describes the types of drainage systems available for earthworks, and the environment in which they operate.

3.1 Definitions

A list of definitions is given in Appendix A; these will be followed in the rest of this Report. Illustrations of some types of drain are given in Figure A1.

3.2 Highway pavements

Although highway drainage is not covered in this review, the objectives of such drainage are relevant to the stability of earthwork slopes; these are.

- i To rapidly remove surface water on the carriageway which might otherwise present a safety hazard.
- ii To remove sub-surface water in the pavement layers sufficiently rapidly to avoid any weakening of the pavement structure.
- iii To lower the water table in the underlying subgrade. However, as shown by Farrar (1994), this is often not practicable because there will be some seepage of water through the pavement, and also because of the depth of drain required to achieve any significant lowering.
- iv To lead surface and sub-surface water away from the site in a manner which will not adversely affect the stability of the pavement or adjacent earthworks.

For the above it is necessary to ensure that drain pipes and filters are designed correctly for a long life, and that adequate inspection and maintenance procedures are in place. The publications available to engineers, and described in Section 2 above, deal with all of the above points. It is reasonable to assume that a pavement built in accordance with modern recommendations will meet the above objectives, but an older pavement may not. For example it used to be recommended that water from the sub-base was led to the top of the embankment slope, as shown in Figure A1 (d). Furthermore, the drainage system may not have been constructed properly, see Samuel and Farrar (1988), and maintenance procedures may have been inadequate.

An additional and rarely considered effect of edge of pavement drainage is to improve the stability in the adjacent verges; again see Samuel and Farrar (ibid).

3.3 Design of subsoil drains

3.3.1 Granular filter materials

Clauses 505 and 515 of the MCHW give specifications for granular filter materials that could readily be adapted for slope drainage. Following Spalding (1970), the properties that need to be specified are:

- maximum particle size, to avoid impact damage to other components of the drain;
- the diameter of any hole or slot in the collector pipe, this must match the size of the coarser particles;
- the internal stability, expressed in terms of grading (Clause 505) or uniformity coefficient (Clause 515) (Kenney and Lau, 1985);
- the particle size of the finer fraction, to ensure stable filtration. The well-established Terzhagi rules are still considered applicable; see for example Spalding (1970), and Indratna and Vafai (1997);
- adequate permeability, specified either in terms of permeability or the particle size of the finer fraction (Kenney et al, 1984).

3.3.2 Geosynthetic filter materials

Numerous design rules are available for matching the pore size and flow rate of a geosynthetic filter to that of the adjacent soil, see for example Ingold (1993). The specification should cover:

- a method statement for installation;
- identification and, if possible, quality control requirements;
- durability, including resistance to the installation process;
- mechanical properties for short and long-term survival;
- pore size, and flow or permeability.

As well as their use for filtration, geosynthetics may be used as a geocomposite (fin) drain. In addition to the above such drains require the specification to cover:

- compressive creep characteristics;
- adequate in-plane flow.

Specification will become easier as further European Standards are published. The availability of Agrément certification is helpful. Clause 514 of the MCHW (see Section 2.2.1 above) can be used as the basis of a specification.

3.3.3 Collector pipes

The determination of the flow of water from the subsoil into the drain is uncertain, because it will reflect variations in the strata encountered. But provided surface water does not enter the system, flows are likely to be small. Care should be taken during construction to ensure that drains do not intercept potential drainage aquifers such as gravel cappings. HA 40 (see Section 2.1.1 above) could be adapted to deal with the structural design of carrier collector pipes.

3.3.4 Surface and base of drain

To control the ingress of surface water and detritus it is usually necessary to specify that the upper surface of the drain is covered with either compacted soil or a geosynthetic. It may also be desirable to cover the bottom of the drain trench with an impermeable membrane to prevent the percolation of ground water into the underlying soil.

3.4 Boundary conditions

3.4.1 Vegetation

Although not directly concerned with the placement of vegetation in the present context, the designer should be aware of its relevance to the moisture regime and stability of the earthwork.

The upper layers of a new earthwork slope will take some years to reach (long-term) equilibrium conditions. The following factors must be considered.

- i Initially the slope surface will be bare soil, and rainfall on the surface can permeate into the underlying soil, or erode away the surface. It is therefore essential to establish vegetation as soon as possible. If the soil is unsuitable for permanent vegetation, for example where the slope is too steep, other means of erosion control such as the use of geosynthetics must be considered.
- ii The vegetation will change as different species establish themselves: shrubs and trees take some years to grow to a reasonable size.

iii Seasonal effects (such as frost) and the establishment of a root structure lead to the development of a more permeable layer of soil near the surface.

Vegetation can play an important role in determining the moisture regime and stability of earthworks; see for example Coppin and Richards (1990) and Marsland et al (1998). Established vegetation will cover the soil surface, and root growth can penetrate to a depth of perhaps 1 m for grass and 5 m for trees; Marsland (1997) and Turner and Schuster (1996). Possible beneficial effects include.

- i Vegetation cover prevents erosion, and it may reduce the passage of water through the soil surface.
- ii Roots may have a beneficial effect in reinforcing the surface layers of soil; see for example Gray and Sotir (1995) and Marsland (1997). Turner and Schuster (1996) suggest that roots increase the cohesion of the soil and lists some values for this effect.
- iii Vegetation removes moisture from the soil, creating suctions equivalent to the wilting point of the plants in a dry spell. This may reduce the wetting up of the underlying soil in the wetter seasons.

Possible adverse effects include.

- i The roots break up the soil making it more permeable than the underlying ground (Farrar, 1990). This can lead to the development of a perched water table, which in turn can induce shallow slips, and it may allow water access to the underlying soils.
- ii The removal of water from clayey soils during periods of dry weather may induce cracking in such soils, again this can lead to an increase in infiltration and a rise in the pore water pressure (Gray, 1994).
- iii Root growth may damage drainage systems, particularly where these are not properly constructed or maintained.
- iv Planting holes dug for shrubs and trees contain organic matter which retains water. If the holes form a linear feature, this may trigger formation of the back scarp to a slip.

As part of any drainage scheme, the designer will need whatever advice can be given on the establishment and maintenance of appropriate vegetation. As further information becomes available it will be possible to improve this advice. It is worth noting that a five year research project investigating the bioengineering stabilisation of a clay slope on the M20 in Kent has recently been completed. This project, run by CIRIA and supported by the DETR, the TRL and the Highways Agency (HA), has shown that vegetation can be used to help stabilise a cut clay slope (Anon, 1998).

3.4.2 Groundwater regime

For all earthwork slopes, rainfall will enter the underlying soil through the surface, in quantities which depend on the soil type, topography, and vegetation cover. For a vegetated slope, water will be removed by transpiration.

For cuttings, water may enter the top of the slope from the adjacent ground. It may be necessary to install shallow drains to carry surface water and interceptor drains for sub-

surface water. A geomembrane may be incorporated at the base of such drains to prevent seepage into the underlying soil. Drains should not be placed at a location which could induce a tension crack in the soil. Surface and sub-surface water may pass from the bottom of the cutting into the edge of pavement drains; this is allowed in current specifications for such drains. Sub-surface water may also enter the cutting through permeable layers, springs, or drains intercepted by the cutting. Depending on the drainage details, ground or surface water flowing from adjacent areas may affect the performance of the road pavement.

For embankments, water may enter the soil from the pavement or edge of pavement drains, but the volume should be small if the pavement has been constructed and maintained to modern standards. This may not of course be the case during the construction or repair of the pavement.

The settlement and stability of the underlying ground, and the associated groundwater regime, pose separate questions outside the scope of this review; some information on these topics has been provided by O'Riordan and Seaman (1994).

3.5 Moisture equilibrium and movement

In a near-saturated soil, the steady state flow of water can be expressed by Darcy's law. In one dimension, this is:

$$v_x = -k_x \frac{\partial \phi}{\partial x} \quad (1)$$

where v_x is the water velocity in the x direction, k_x is the permeability in the x direction, and ϕ is the potential

For a uniform stratum this leads to:

$$k_x \frac{\partial^2 \phi}{\partial x^2} = 0 \quad (2)$$

Dynamic conditions can be expressed by the relation:

$$C \frac{\partial^2 \phi}{\partial x^2} = \frac{\partial \phi}{\partial t} \quad (3)$$

where C is a coefficient of consolidation or swelling.

These equations form the basis for a variety of techniques used to check or establish the pore water pressure distribution within a slope (and the effect of any drainage measures); assumptions of pore water pressure ratio; flownets; finite difference and finite element equations; and design charts. See for example Hutchinson (1977), Smart and Herbertson (1991), Bromhead (1992) and Abramson (1995).

In drier unsaturated soils, ϕ may have a large negative value (soil suction), and the values of k_x and C will vary widely with ϕ . The above equations are then replaced by a flow equation of the type:

$$\frac{\partial \theta}{\partial t} = \frac{\partial \left(k_x \frac{\partial \phi}{\partial x} \right)}{\partial x} + \frac{\partial k_x}{\partial x} \quad (4)$$

where θ is the volumetric water content.

The relations between k_x , θ and ϕ must be determined for the soil. It is known that this type of flow gives rise to a wetting front which advances into the drier soil, approximately according to the relation given by Philip (1957):

$$x = K\sqrt{t} \quad (5)$$

where x is the distance moved

t is the time, and

K is a constant for the soil and boundary condition.

There is now some understanding of how the parameters in Equations (4) and (5) might be evaluated (Huang et al, 1995; Parashar et al, 1995; Öberg and Sällfors, 1997).

There is at present probably no wholly adequate theoretical approach for expansive clays; see for example Vauclin and Angulo-Jaramillo (1995).

3.6 Counterfort drains

Counterfort drains, i.e. rock filled trench drains which penetrate to a depth below any potential slip surface, were widely used in railway earthworks (Gough, 1997). As well as functioning as drains they were considered to have a reinforcing effect due to the friction developed between the rock fill and the adjacent soil. It would be possible to carry out a stability analysis incorporating this effect, perhaps assuming that ' K_0 ' conditions existed at the sides of the drain. But the soil at these interfaces is disturbed both during excavation and by the subsequent passage of water and it is therefore likely that the available shear strength is much less than that of the intact soil. A more predictable reinforcing action can be obtained by other measures such as soil nailing.

3.7 Temporary drainage

The long-term stability of an earthwork can be compromised where the contractor either fails to provide an adequate drainage system for the construction phase, or damages the in-place permanent drainage system.

The importance of providing an adequate temporary system cannot be over-emphasised, and the advice already given in some documents of the DMRB should be cross-referenced or reproduced elsewhere and if necessary expanded.

3.8 Inspection and maintenance

Advice Note HA 48 (see Section 2.1.3 above) covers the inspection and maintenance procedures for earthworks, and should be referred to in any new advice note which dealt with slope drainage. The following points should be covered in any such advice note;

- access for inspection at the foot of any slope drain;
- in silty soils, means of checking that the filter is not clogged, e.g. by installing a standpipe piezometer;
- pipes in slope drains, and collector pipes, should be accessible for visual or CCTV inspection;
- preventing damage to the surface of slope drains by maintenance traffic;

- vegetation should be of the type anticipated in design, e.g. on a grassed slope ensure that trees do not establish themselves near drains;
- if there are any changes in boundary conditions, e.g. alteration in land use at the top of a cutting, the drainage system of the cutting may need to be modified.

4 The effect of drainage on stability

4.1 Near surface stability

Shallow planar slips, at a depth of 1 to 2 m, are common in embankments and cuttings through many soil types. Perry (1989) reports an extensive survey of their incidence on the UK highway network. The mechanism of these failures is understood in principle; it has been covered by Atkinson and Farrar (1985), Crabb and Atkinson (1991), Potts et al (1997), and involves the following:

- i Dynamic moisture movements near the soil surface associated with rainfall, and the development of a perched water table during wet seasons.
- ii The generation of lower soil strengths near the surface than at depth, due to a stress history of low all-round pressures and strain softening.

In the UK these slips do not normally impinge on the adjacent carriageway, but in many other countries the failures are serious. Field studies (Lim et al, 1996) meteorological analysis (Finlay et al, 1997), and pore pressure analyses (Fourie, 1996; Sugiyama et al, 1995; Ng and Shi, 1998; Anderson et al, 1997; Anderson et al, 1998) have been carried out to develop methods of predicting the onset of failure. Fourie (1998) concludes that although analytical methods provide useful approximations, it is difficult to make allowance for all the variables for a particular site.

At this time it is difficult to recommend a simple and general design method. Studies undertaken at TRL suggest that the critical time for instability is at the end of winter when the highest pore water pressures exist. The soil is then in a near-saturated condition, and either the steady state approach using Equations (1) or (2), or the dynamic approach using Equation (3), could be appropriate.

It would be instructive to apply both steady state and dynamic approaches to an instrumented site. Ideally it might be possible to formulate a simple steady-state approach, based on a depth of failure within a permeable upper layer and the residual strength of the soil. An example of such an approach is given in Appendix B.

In the UK the cost of repairing a shallow slip failure is not great and normally such failures do not impinge on the carriageway. Any substantial expenditure on site investigation is, therefore, probably not economically justified. The total cost of all the failures on the UK highway network is, however, substantial. The development of economic repair and preventive measures, based on simple design principles such as that in Appendix B, is therefore essential.

Johnson (1985) describes trials of a number of repair and preventive techniques. The costs (1985 prices) for a 7 m high embankment were:

- Repair techniques £170 - 420 per metre run of earthwork;
- Preventive techniques £110 - 170 per metre run of earthwork.

There may also be indirect costs associated with lane closures and traffic delays during repairs.

The cheapest preventive technique examined by Johnson was the installation of rock ribs. If the design principles in Appendix B prove valid, substantial savings in preventative and maintenance works may be possible. Data given by Langdon and Everest (1997) suggest that costs for simple techniques such as geocomposite or narrow filter drains could be as low as £25 per metre run of earthwork. In conjunction with the information from Perry's survey (1989), it should be possible to make an economic judgement of the merits of such preventive measures. It is therefore recommended that instrumented trials are undertaken to test out an approach such as given in Appendix B.

4.2 Long term stability of cuttings

4.2.1 Time to reach equilibrium

For cuttings in over-consolidated clays, due to stress relief, negative pore water pressures will develop at depth and will normally ensure short-term stability. Over a period which may be measured in decades, however, the soil will wet up and equilibrium pore water pressures will be approached or perhaps even attained. An estimate of the time to equilibrium may be derived from a knowledge of the geological formation; see for example Skempton (1977) for London Clay. The structure of such types of clay is complex, since it will in the mass have retained its undisturbed structure, but fissures may have opened up due to stress relief. It is not therefore certain whether saturated or unsaturated conditions prevail. A parametric study by Potts et al (1997) showed that an analysis based on saturated conditions can give plausible values for the time to equilibration. Given a knowledge of this time it is possible, in principle, to defer preventive drainage measures in clayey soils. However, in practice, access for such work is usually difficult following construction and so, where necessary, drainage systems are installed during construction.

4.2.2 Instability at depth

Unlike the shallow slips discussed in Section 4.1, deeper seated slips are circular or near-circular in shape. These failures have been well documented from experience with both road and railway construction; see for example Gough (1997) and Potts et al (1997). Pore water pressures within a cutting are determined in the long term by boundary conditions and permeability; i.e. Equations (1) and (2). Failures are usually analysed as 'brittle' failures by well established techniques; see for example Bromhead (1992) and Abramson (1995). Recent parametric studies by Potts et al (1997) and site studies by Cooper et al (1998) on clays have shown that failures of this type are associated with strain softening at the base of the cutting

and a non-circular slip surface. These authors conclude, however, that a 'brittle' analysis assuming a circular slip plane gives a reasonable value for the factor of safety.

Failures of this type are moderately expensive to repair, probably of the order of thousands of pounds per metre run, but more importantly they can impinge on the highway. It is therefore necessary to cut back a slope to an inclination known to be safe for the soil type. Where this is not possible, drainage or other measures must be included to improve stability. The site investigation prior to construction will provide a general indication of the strata to be encountered in the cutting, but may not provide sufficiently detailed information for example on the location of seepage layers. It is therefore important to identify these during construction and if necessary modify the drainage layout appropriately.

The technique used to predict the distribution of pore water pressure depends on the type of stability analysis being carried out, for example the use of an assumed pore water pressure ratio with stability charts. It is necessary to make reasonable assumptions about the boundary conditions, and about any marked anisotropy or variations in permeability. This presents the main difficulty in design in that the site investigation is unlikely to provide sufficient information on these points. Adequate information on winter water tables and on permeability would only be available by carrying out a level of testing not usually found in the UK - although this has been recommended overseas; see Anderson et al (1997). For the routine design of drainage works for cuttings, given the present state of knowledge, it is probably necessary to make the conservative assumptions that (a) without drainage the water table is at the surface and (b) the soil is isotropic.

In the UK, where drainage is required, it is provided by slope drains. These have the advantage that they intercept all the strata in the cutting, including any permeable strata that may have been missed in the site investigation. They are usually sealed at the surface, both to prevent ingress of surface water and to protect them against damage. Rock-filled rib drains are also used. Because of safety considerations, it is often not practicable to place a collector pipe at the base of the trench, and the trench may have to be dug sufficiently wide for the filter material to accommodate the anticipated flow. A number of drainage sites have been studied by TRL over an extended period and these have shown that properly designed drains do function effectively over extended periods: this work has been described by Farrar (1994).

Horizontal drains may be more appropriate, particularly on high and inaccessible slopes, to deal with well defined permeable seepage layers. Clearly their use depends on an appropriate site investigation to identify such layers, for example see Whiteside (1997).

Where drains are installed during the formation of a cutting as a long-term preventive measure, the time scale is unimportant. If they are installed to prevent an incipient failure, it is prudent to assume that the drains will not be effective during their first year; see Hutchinson (1977) and Farrar (1990, 1992).

An example of a simple calculation to determine the

spacing between slope drains is given in Appendix B. This shows that calculation is not difficult, but also that considerable economies might be possible if better site information were available. It would also seem possible to use more sophisticated design techniques.

If strain softening at the base of a cutting plays an important role in the failure mechanism, more attention should be paid to the role of edge of pavement drains in improving stability in their vicinity; no allowance for this is made in the simple stability analysis given in Appendix B.

4.3 Long term stability of embankments

Embankments constructed in the last half century have been built of thin layers of compacted fill, and so any fissures or structure in the natural soil will have been destroyed to a great extent. There may be compaction gradients through each layer of fill, and the properties of the fill may vary from layer to layer. Suitable fill will normally be sufficiently dry to develop soil suction on compaction. Occasionally, however, wet fill is employed with provision through drainage to dissipate excess positive pore water pressures; this is discussed in the next Section.

Modern road embankments therefore differ considerably from earlier road and rail earthworks which were constructed of poorly compacted fill. There is considerable uncertainty about long-term changes in the pore water pressures within a well compacted clay fill. Such fill is relatively impermeable and it is likely that negative pore water pressures are dissipated, if at all, over a very long time scale. It is recognised that, in the present state of knowledge, it is undesirable to introduce ground water which could induce instability at any depth within such fill, for example through drainage.

There are two possibilities for changes in the pore water pressure regime within compacted embankment fills that initially sustain negative pore water pressures:

- i That equilibrium is reached after a number of years, with any ingress of water from rainfall and other sources being balanced by summer transpiration from vegetation. There would then be no further wetting-up unless these conditions altered,
- ii That there will be a wetting-up in the very long-term, with consequences for the stability of the embankment.

Observations in London Clay and Gault Clay embankments reported by Farrar (1994) and Crabb et al (1987) showed that negative pore water pressures remained, at depth, for at least ten years after construction. The observations did not, however, identify which of the above mechanisms was operating. Some very limited work by Farrar (1983) suggests that the advance of any wetting front into compacted London Clay would be very slow.

Because the fill is unsaturated, moisture conditions are governed by equations such as Equation (4), which are difficult to apply without a detailed knowledge of soil moisture properties. Possible approaches are:

- i Field or laboratory studies to examine the factors determining the advance of a wetting front into a typical compacted fill, as described by Fard (1996).

- ii Examining the long-term moisture balance within an embankment. For this, the roles of seepage into and out of the earthwork, the effect of any drainage systems, and the role of vegetation would need to be determined.

Studies on these lines should contribute to a better understanding of the processes involved, in particular whether the establishment of appropriate vegetation will ensure long-term stability, or if long-term stability problems would still remain to be addressed.

4.4 Embankments constructed of wet fill

Where no particularly suitable fill is available on site, embankments have been constructed of fill at moisture contents higher than those usually specified. This is a particularly useful way of utilising what, otherwise, would have been unsuitable fill material – its economic importance has been increased substantially with the introduction of the land fill tax. Positive pore water pressures may thus be developed as overburden is placed over each layer. The critical period for stability is therefore during and immediately after construction. Horizontal drainage layers ('blankets') are placed at the base and, possibly, at intervals within the fill. The following precautions must be observed:

- i A stability analysis must take account of the possibility of a slip developing along the boundary between the drainage layer and the fill.
- ii The granular or geosynthetic materials in the drainage layer must be properly specified for pore size and flow capacity.
- iii Strict quality control must be exercised during installation.
- iv The quality and rate of placement of fill must be controlled.
- v Usually it is desirable to install piezometers to monitor excess pore water pressures; the results obtained must be reported.

4.5 Hillside slopes

Some hillside slopes, i.e. those on side-long ground, are actually or potentially unstable, and may contain relic landslips. If these are disturbed by highway construction there is the possibility of major slope failures which would be very expensive to repair.

Because such failures can have major consequences, it is essential that such sites are recognised. Therefore, usually it is appropriate to carry out a detailed site investigation and undertake site-specific preventive or remedial measures in which drainage plays a large part, see for example Garrett and Wale (1985), Leach and Thompson (1987), and Bromhead (1992). It would be possible to provide general advice on the recognition of such situations, and on whether there was a need to obtain specialised assistance.

4.6 Repaired and cut back slopes

Failures in earthwork slopes are often repaired by replacing the slipped material with imported granular material. This will introduce ground water at depth within the repaired slope, and appropriate measures must be taken to control

this in both the short and long term. A similar problem may arise if the slip is reinstated with lime-stabilised soil.

Drainage measures are an essential part of the design of a repaired slope. A variety of repair techniques are available, which usually allow the entry of ground water into the undisturbed part of the earthwork below the repair. In cuttings this will probably merely accelerate the rate of equilibration. In embankments, however, the introduction of ground water may alter or accelerate towards a long-term condition which is not well understood (see Section 4.3 above). Similar remarks apply to slopes which are cut back for road widening, see for example Russell (1996).

5 Recommendations and conclusions

This report reviews the advice that could be made available to designers concerned with the use of drainage systems for earthwork slopes. It is shown that much information is already published elsewhere, and could usefully and readily be made available through the publication of a new dedicated advice note on earthwork drainage. Furthermore there is scope for expanding the clauses in the SHW (MCHW1), the Notes for Guidance (MCHW2) and the Highway Construction Details (MCHW3) to include earthworks drainage; the standard drawings could be used to define terminology.

Amendments to the SHW (MCHW1) will be necessary to incorporate new test methodologies for geosynthetic filter drains.

There are a number of deficiencies in present knowledge which need to be addressed:

- i *Vegetation.* It is apparent that vegetation plays an important role in determining the moisture regime and stability of slopes. Designers concerned with drainage works should be made aware of this, and of any progress made through studies such as the jointly funded 5 year experiment managed by CIRIA (Anon, 1998).
- ii *Shallow planar slips.* Drainage can play a valuable role in preventing such failures. Further site studies are required to assess whether or not simple design rules can be used with confidence.
- iii *Deeper seated slips in cuttings.* The mechanism of this type of failure is well understood, and a number of design methods are available to determine the stabilising effect of drainage. But, because the site investigation information available is usually sparse, simple methods with conservative assumptions have to be employed. Consideration should be given to the economics of obtaining better site information. Recent research on the role of strain softening in slope failure may eventually lead to a different design approach.
- iv *Stability at depth within embankments.* The lack of reliable information on moisture movements within clay fill is a matter of concern. A combination of site and laboratory studies may throw more light on the mechanism and time scale of pore water pressure equilibration, and thereby make it possible to formulate recommendations for designers.

- v *Repaired slopes.* It would be useful to review the incidence of failures of repaired slopes. Any such failures need to be investigated to determine if there are any deficiencies in present procedures. A pilot-scale investigation of the trunk road network is recommended.
- vi *Field work.* It would seem worthwhile carrying out experimental studies looking at the effect of installing various types of slope drains on the pore water pressure regime within earthworks. This should be carried out both in a cutting and on an embankment because the effect is likely to differ between undisturbed and compacted soils. The buttressing effects of counterfort drains should be studied. In all this, it is important to cover both the short and long-term effect on stability.
- vii *Prediction of moisture movement in soils.* The results of the experimental work should be used to determine the reliability of the analytical methods put forward to predict the flow of water through slopes and its effect on stability.
- viii *Site investigations.* The requirements of a site investigation for drainage works should be revised in the light of progress in any of the above.

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Appendix A: Definitions

Combined drain. A drain intended to intercept and remove both surface and sub-surface water. Design flows are usually large, necessitating a permeable collector pipe at the base, see Figure A1 (a).

Counterfort drain. A trench drain which penetrates below a potential or actual slip plane. As well as providing drainage, it provides some strengthening effect: for this it is filled with stone or crushed rock, see Figure A1 (b).

Edge of pavement drain. Any drain designed to collect and remove surface and/or subsurface water from a road pavement, see Figure A1 (c) and (d).

Field drains. Drains installed at a shallow depth in fields; they usually comprise a permeable clayware or plastic pipe covered with soil. These are used to lower the water table for agricultural purposes, see Figure A1 (e).

Filter drain material. Granular material with a grading intended to act both as a filter material for the adjacent soil or aggregate, and to have sufficient permeability to allow the free passage of water.

Geocomposite drain ('Fin drain' in current specifications). A three-dimensional polymer core with a geotextile filter on one or both sides, placed vertically in a trench. Ground water passes through the filter(s), and drains through the core. The core must permit an adequate flow and also be sufficiently strong to resist lateral earth pressures. Usually, but not always, water passes through the core to a collector pipe at the bottom, as shown in Figure A1 (f).

Geotextile filter. A planar, permeable polymeric material used as a filter in contact with soil or aggregate.

Intercepting drain. Drain intercepting the flow of ground water at the top of a cutting. Flows may arise from a permeable surface deposit or from intercepted field drains, see Figure A1 (g).

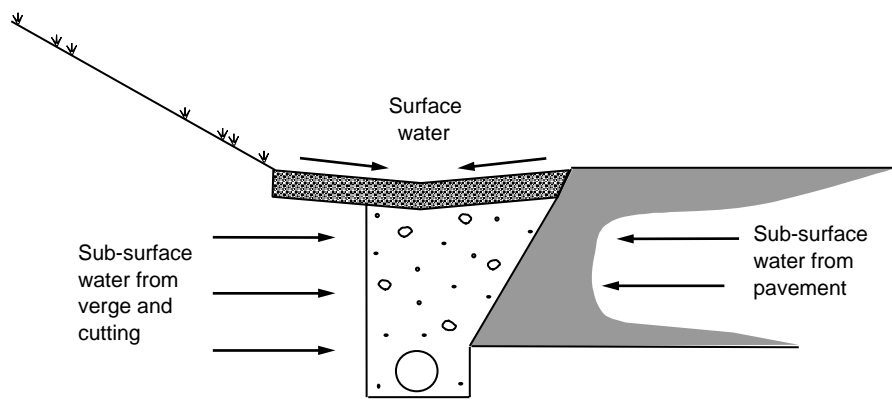
Rock rib drain. A rock-filled trench drain running up a slope face. The counterfort effect of such a drain may or may not be allowed for in design.

Shallow drain. A drain designed to intercept and remove surface water, and not specifically intended to have any effect on the soil at depth. It may be an open ditch, or it may be filled with permeable granular material, see Figure A1 (g).

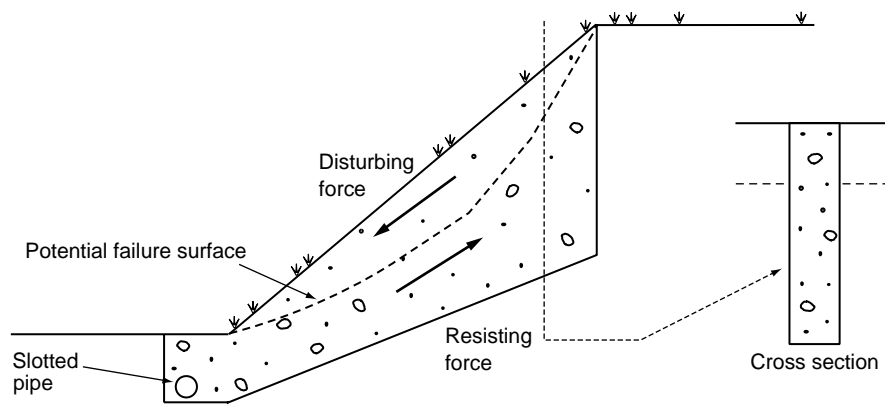
Slope drain. A trench drain running up the face of a slope, intended for sub-surface drainage only, see Figure A1 (h).

Slope drainage. Any form of drainage intended to remove water from a slope.

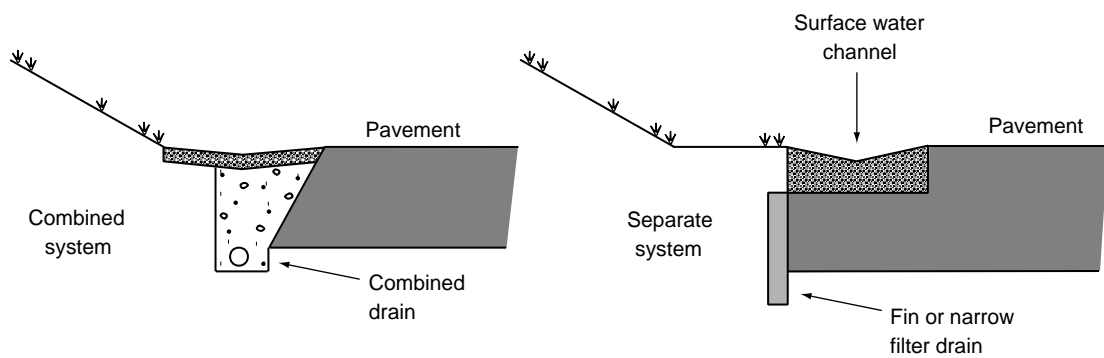
Trench drains. A trench installed in a soil to lower the water table by drainage. It may be filled with a granular filter material or a geosynthetic, and may incorporate a pipe. Examples of the types and application are shown in Figure A1.



(a) Combined drain

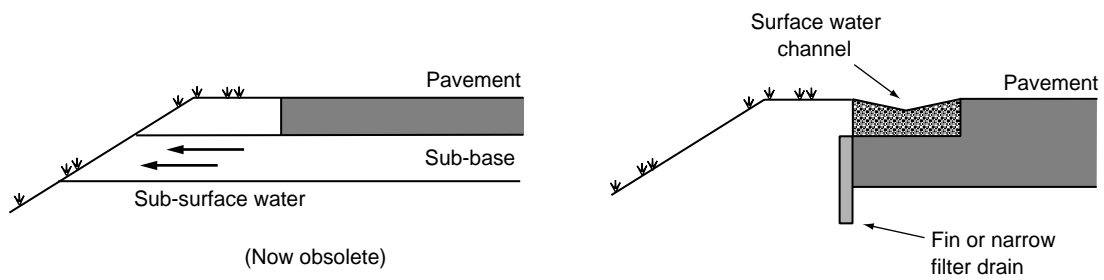


(b) Counterfort drain

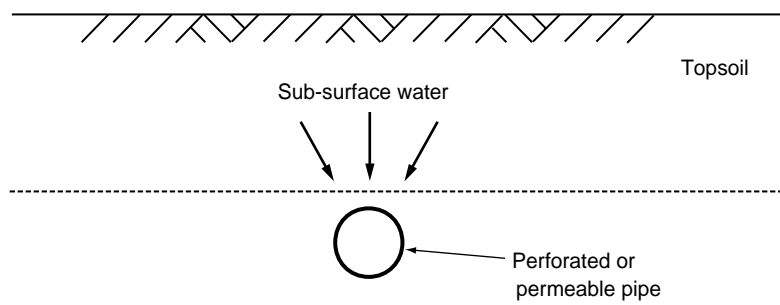


(c) Edge-of-pavement drains: cuttings

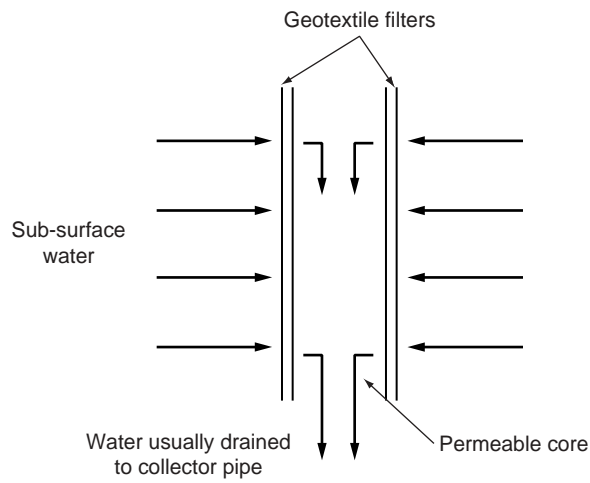
Figure A1 Examples of types of drain



(d) Edge-of-pavement drains: embankments

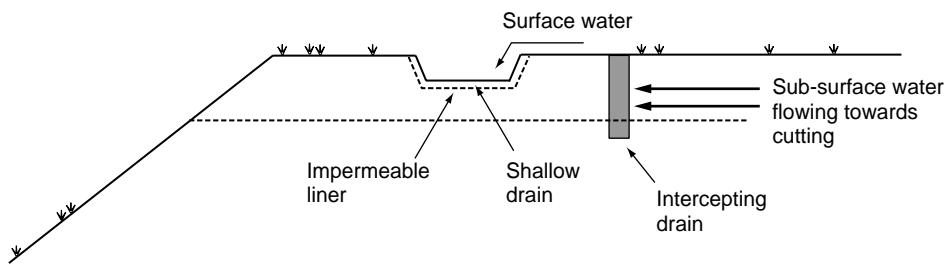


(e) Field drain

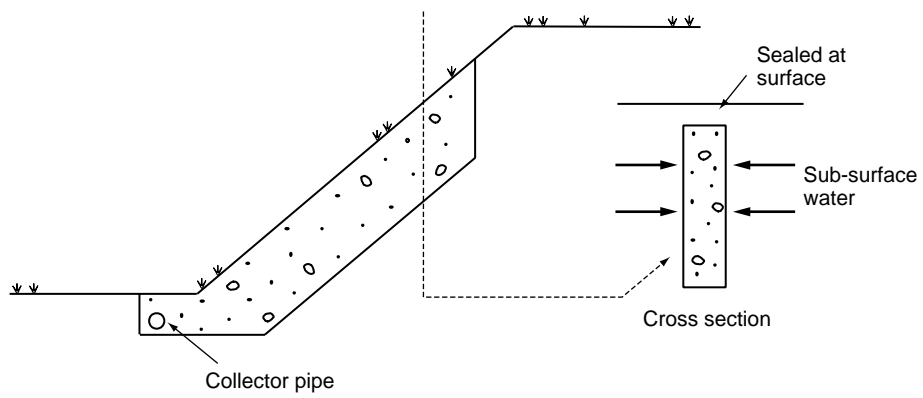


(f) Geocomposite drain ('Fin drain')

Figure A1 Examples of types of drain (continued)



(g) Shallow drain and intercepting drain



(h) Slope drain

Figure A1 Examples of types of drain (continued)

Appendix B: Example calculations

B1 Shallow slip

B1.1 Method

The following provides a simple calculation method for assessing the effect of drainage in stabilising a slope against shallow slips. It must be emphasised that it is uncertain whether or not the simplifications adopted in the method will always be justified.

This method assumes that, after a number of years, weathering and the establishment of vegetation lead to the situation, shown in Figure B1, of a permeable weathered zone to a depth (h) below the surface of a slope of inclination (α) with a relatively impermeable zone beneath. There will be a steady state seepage parallel to the surface, and the pore water pressure (u) at depth (h) is:

$$u = \gamma_w h \cos \alpha \quad (\text{B1})$$

where γ_w is the density of water

The factor of safety against a planar slip at depth (h) is:

$$F = \frac{(h\gamma \cos \alpha - u) \tan \phi' + c'}{\gamma \sin \alpha} \quad (\text{B2})$$

where γ is the soil density,

ϕ' is the effective angle of shearing resistance, and

c' is the effective cohesion.

The effect of slope drainage on pore water pressure may be determined by Hutchinson's (1977) charts, which have been reproduced by Bromhead (1992).

B1.2 Application

This example considers the upper layers of a London Clay slope, where a vegetative cover and roots are well established, and assumes steady flow conditions with a water table at the surface. It is further assumed that the soil beneath the weathered layer may be considered impermeable.

The values of the variables are:

Slope angle of 1:3.5	$\alpha = 16$ degs
Residual shear parameters, (no contribution from roots)	$\phi_r' = 13$ degs and $c_r' = 2$ kPa
Soil density	$\gamma = 20$ kN/m ³
Permeability (uniform and isotropic)	$k = 1 \times 10^{-7}$ m/sec
Depth to base of weathered layer (and of potential slip surface)	$h = 1.5$ m

Without drainage, the factor of safety is 0.97. If slope drains are installed at 2.5 m intervals, Hutchinson's charts show that the pore water pressure at a depth of 1.5 m is reduced from 14.4 to 6.1 kPa, and the factor of safety is increased to 1.32. Note that the permeability need not be known, although the ratio of horizontal to vertical permeability is relevant.

The flow through the soil into the drain is given sufficiently accurately by assuming unit hydraulic gradient. The total flow to each metre of the drain is therefore given by:

$$\text{Volume} = v_x \times \text{drain area} = -k_x \frac{\partial \phi}{\partial x} \times \text{drain area}$$

$$\text{Volume} = (1 \times 10^{-7}) \times 1 \times (1.5) \times (2) = 3 \times 10^{-7} \text{ m}^3/\text{sec}$$

(i.e. 3×10^{-4} litres/sec or 26 litres/day)

This is a very low flow, and the most suitable form of drain might well be a fin drain conforming to the requirements of Clause 514 of the Specification for Highway Works (MCHW1).

B2 Stability of cutting

B2.1 Method

The following provides an example calculation of the type commonly used for assessing the effect of drainage on the stability of a cutting slope where the failure surface is assumed to take the form of a circle, i.e. circular slip. Bishop and Morgenstern (1960) give design charts (which are reproduced in many standard texts) to determine factors of safety for a given slope angle, pore water pressure ratio (r_u), and soil strength parameters (ϕ' and c').

The value of r_u must be determined from considerations of steady state flow in the soil, possibly using a chart such as that given by Bromhead (1992). The effect of installing slope drains on r_u and hence stability may again be determined using Hutchinson's (1977) charts.

This simple approach would be adequate for much routine work, where site investigation data are limited. But for road widening, a more comprehensive approach would probably be appropriate. For such works the site would be accessible for a more comprehensive site investigation, and computer programs are readily available to determine flow patterns and the location of the critical slip surface.

B2.2 Application

The following values might be assumed for a cutting through glacial till:

Slope angle of cutting 1:2	$\alpha = 26.6$ degs
Height of cutting	$H = 6$ m
Peak shear parameters	$\phi' = 24$ degs and $c' = 6$ kPa
Soil density	$\gamma = 20$ kN/m ³
Soil permeability	$k = 1 \times 10^{-3}$ m/sec
Uniformity coefficient of soil	$C_u = 10$
Soil particle size (50% finer)	$D_{50} = 0.01$ mm
Soil particle size (85% finer)	$D_{85} = 0.03$ mm

In the absence of specific information, it must be assumed that the water table is at ground level behind the top of the cutting. The use of Bromhead's chart indicates an average r_u of about 0.4. It should also be assumed that

equilibrium conditions are reached fairly rapidly. Then using Bishop and Morgenstern's charts, for a $(c'/\gamma H)$ ratio of 0.05, gives a factor of safety of 1.10. Although above unity, this would not normally be regarded as acceptable, and remedial measures such as drainage are required at the time of construction.

(Note that if the water table behind the top of the cutting was at a depth of, say, 3m an acceptable factor of safety would be achieved without any remedial measures).

Consider slope drains installed at a depth of 1 m at the base of the cutting and 5 m at the top, with a spacing of 6 m. Hutchinson's charts show that this would reduce pore water pressures to below half their previous value, i.e. reduce r_u to 0.15. This in turn would increase the factor of safety to an acceptable value of 1.40.

(Note that if the soil was anisotropic, with a ratio of horizontal to vertical permeability of 4:1, the same improvement would be achieved with a drain spacing of 12 m).

The flow from the soil into each metre length of the drain would be:

$$Volume = v_x \times \text{drain area} = -k_x \frac{\partial \phi}{\partial x} \times \text{drain area}$$

$$Volume = (1 \times 10^{-3}) \times 1 \times (3) \times (2) = 0.006 \text{ m}^3/\text{sec} \\ (6 \text{ litres/sec})$$

where 3 m is the average depth of the drain

This is a substantial flow and, where a granular filter was to be used, the passing 15% particle size of the filter material ($D_{15 \text{ Filter}}$) should conform to Terzaghi's rule as given by Spalding (1970),

$$D_{15 \text{ Filter}} < 5 D_{85 \text{ Soil}} \text{ i.e. } 0.15 \text{ mm}$$

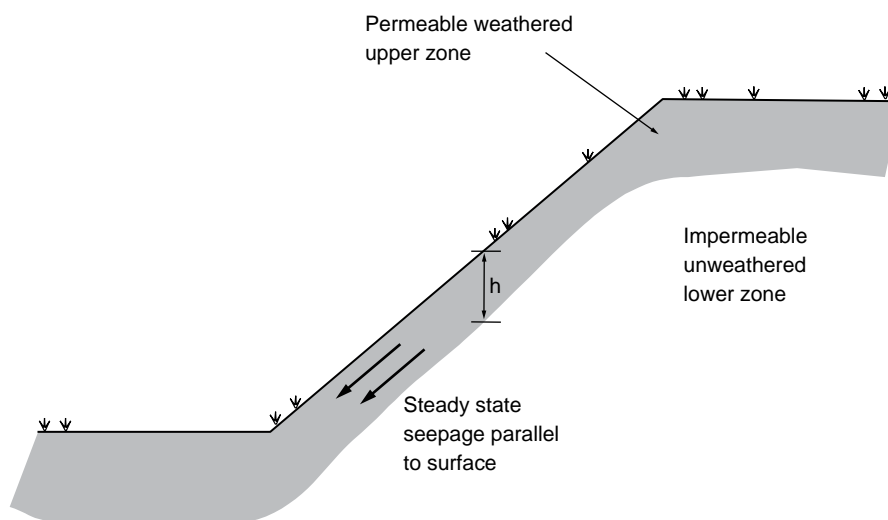


Figure B1 Depth of weathered zone

This is finer than some Type A filter drain materials specified in Clause 505 of the Specification for Highway Works (MCHW1), which would therefore be unlikely to have a high enough permeability for this slope drain. A better solution would be to place a geosynthetic filter, designed in accordance with Clause 514, against the soil in the drain, and fill the drain with permeable granular Type B filter drain material.

B3 References

Bishop A W and Morgenstern N (1960). *Stability coefficients for earth slopes.* Geotechnique, Vol 10, pp 129-150.

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Manual of Contract Documents for Highway Works. The Stationery Office, London.
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Spalding R (1970). *Selection of materials for sub-surface drainage.* Laboratory Report LR346. Transport Research Laboratory, Crowthorne.

Abstract

This report reviews the information and advice available on the drainage of earthworks, identifies the limitations of current knowledge and provides recommendations on how these might be addressed. The report concludes that there is much information available currently which could be usefully and readily made available through the publication of a new Advice Note on slope drainage. In addition, there is scope for expanding the clauses in the Manual of Contract Documents for Highway Works to cover the subject.

Related publications

- RR368 *Observations of slope drainage at Colchester, Essex* by D M Farrar. 1992 (price £25, code E)
- RR302 *Observations of slope drainage at Romford, Essex* by D M Farrar. 1991 (price £20, code B)
- RR199 *A survey of slope condition on motorway earthworks in England and Wales* by J Perry. 1989 (price £20, code C)
- CR341 *Highway embankments over soft compressible alluvial deposits: guidelines for design and construction* by N J O'Riordan and J W Seaman. 1994 (price £35, code J)
- CR61 *Field study of filter drains on Maidstone by-pass, Kent* by H R Samuel and D M Farrar. 1988 (price £20, code B)

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