TECHNICAL RECOMMENDATIONS FOR HIGHWAYS

TRH 9

CONSTRUCTION OF ROAD EMBANKMENTS

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PREFACE

TECHNICAL RECOMMENDATIONS FOR HIGHWAYS (TRH) are written for the practising engineer and describe current, recommended practice in selected aspects of highway engineering. They are based on South African experience and the results of research and have the full support of the Committee of State Road Authorities (CSRA).

To confirm its validity in practice, the present TRH9 was circulated in draft form for a trial period before being submitted to the CSRA for final approval, which it has now obtained.

SYNOPSIS

This TRH gives guidance on methods of road embankment construction which have proved successful in South Africa. It is emphasized that a sound construction is the outcome of an investigation and design process which should have taken account of any special conditions at the site concerned. This, however, is not always possible or predictable and it is therefore essential that the construction agency should appreciate the problems which may have to be dealt with. A flexible approach is recommended and this document therefore deliberately avoids laying down specifications for construction.

SINOPSIS

In hierdie TRH word daar voorligting gegee oor metodes om padopvullings te bou wat reeds met sukses in Suid-Afrika gebruik is. Dit word beklemtoon dat 'n goeie konstruksie die gevolg is van 'n navorsing- en ontwerpproses waartydens enige besondere omstandighede by die betrokke plek in ag geneem is. Dit is egter nie altyd moontlik om hierdie omstandighede in ag te neem of te voorspel nie en dit is derhalwe noodsaaklik dat die instansie wat die bouwerk doen, 'n begrip moet hê van die probleme wat dalk teëgekom kan word. 'n Buigsame benadering word aanbeveel en derhalwe word daar opsetlik geen bouspesifikasies in hierdie stuk aangegee nie.

KEYWORDS
Clay, compaction, construction, drainage, embankment, maintenance, sand, slope.

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1 INTRODUCTION

Embankments can be considered in three separate phases: investigation, design and construction. It was the intention to publish three documents in the TRH series describing these three aspects. The first document has already been published as Draft TRH 10 (1). However, further consideration and discussion have led to the consensus that the two aspects of investigation and design are so closely interrelated that they should be dealt with in one document. It is accordingly now the intention to issue a new TRH 10 which will combine its earlier subject of design with additional discussion on investigation. The eventual intention is that all three aspects should be combined since it is believed that this combination will serve to emphasize the close interrelationship of, and interdependence between, the three phases (investigation, design and construction) which must be borne in mind in any successful civil engineering work.

The document on site investigation and design for embankments, which is currently being prepared and which will be published as TRH 10, provides a method whereby embankments may be divided into those for which a rule-of-thumb design is adequate, and those for which a more formal design procedure is required. The formal procedures will be described in general in TRH 10. The more problematic embankments frequently require unusual construction methods and more sophisticated construction controls. Because the necessary techniques may vary considerably for different situations, they should be individually specified for each situation and cannot be the subject of a generalized manual. The present document, on the construction of embankments, therefore deals primarily with the rule-of-thumb-designed embankments.

It should, however, be stressed that despite the most conscientious site investigations, unforeseen situations still frequently occur during construction and, what appears at first to be a routine embankment, may present problems. Alternatively, where problems are anticipated, these may not transpire in practice and a different set of problems may actually be encountered. In these cases, the construction team will be called upon to use its judgement and possibly to authorize departures from the specified design. If the reasons for using a particular design are fully understood, there can be no objection to changing it if the suppositions on which it was based cease to be valid. Unfortunately, the designs do not always reflect the realities of construction problems and may have to be altered to avoid uneconomical effort. It should be noted that where designs cannot, or should not, be strictly adhered to, this fact should be brought to the attention of the investigating and design staff, since it provides most valuable feedback which is unfortunately rare.

In general, this document adopts the approach that it is essential in engineering that the reasons why certain recommendations are made must be understood; only in this way can the implications of departure from specifications be appreciated, and the flexibility necessary to deal with the vagaries of nature be attained.

The document is set out in the chronological order in which embankments are usually constructed.

2 PREPARATION UNDER ENBANKMENTS

2.1 CLEARING

2.1.1 Removal of vegetation

The surface of the natural ground should be cleared of all artificial debris and natural vegetation, either growing or in decay, so that the embankment will form a continuous structure with its supporting subgrade. It is of course much easier to examine the subgrade after the vegetation has been cleared. Although the removal of tree stumps and crop roots is certainly good practice, they are sometimes left in place where the embankment height exceeds about 2 m in the case of stumps, and 1 m in the case of roots. In these circumstances, the stumps should be sawn off close to ground-level, and local experience should be used as a guide to the minimum effective cover needed over aggressive roots such as sugar-cane, sisal or kikuyu. Local experience sometimes dictates the use of weed or plant killers to treat the subgrade.

In the case of embankments over very soft subsoils it is sometimes advisable to take advantage of the tensile reinforcement provided by a root system since this may be sufficient to allow construction traffic to operate.

2.1.2 Restoration of the natural ground-surface

After the removal of roots and old foundations, the resultant cavities should be carefully filled and the filling compacted to the same density as the surrounding ground. If this is not done, particularly in the case of shallow embankments, localized depressions will probably show through in the completed work. If the cavities are numerous, it will not be practicable to fill and compact them individually and it will probably be necessary to rip and recompact all of the affected area.

2.2 REMOVAL OF TOPSOIL

'Topsoil' is generally understood to include all surface soils which have sufficient humus to support plant growth without resort to artificial fertilization.

Topsoil is the end product of many centuries of natural weathering and biological decay, and should be carefully preserved as an environmental asset. It is essential that the whole operation of topsoil removal be carefully planned in detail at the design stage, on the basis of field information as to the quality and depth of the topsoil. This is because the removal of topsoil has a significant effect on the measurement and balance of the earthworks and even on the programme of the job. There will, however, be some projects where the topsoil, for various reasons, is of little value; in these cases, it would obviously be futile to become involved in an expensive exercise to preserve it. The point to remember is that, to enable a rational decision to be taken, an evaluation of the topsoil has to be made and, of course, it may be necessary to step outside the engineering profession for advice on this.

Before placing an embankment, or starting an excavation, all the accessible and fertile topsoil, together with the natural root systems, should be removed to stock piles for later use on cut-and-fill slopes. The depth of excavation for topsoil stripping should be carefully controlled, on the basis of previously ascertained topsoil thickness, to avoid contamination with subsoils.

In some instances it has been found convenient to stockpile topsoil along the top of cuttings since the eventual use of the topsoil is to be on the cut slopes. Care should be taken if this method is adopted, since the surcharging of the slope may result in a stability failure.

It is generally accepted that undue compaction of topsoil is undesirable since aeration of the material is important to preserve life. Stockpiles should therefore be of limited height and, as far as possible, traffic over them should be avoided. On the other hand it is appreciated that working space is frequently at a premium and, to eliminate excessive handling costs, it may be necessary to stockpile topsoil higher than would normally be preferred.

2.3 ROADBED TREATMENT

2.3.1 General

No matter how low the embankment, the material upon which it is to be constructed must be assessed for its suitability as a foundation.

In the case of very high embankments the need for an investigation into the stability and settlement characteristics of the underlying soil is usually recognized, but it should be emphasized that even when the foundation problem is not immediately obvious, and the embankment height is not excessive, trouble is frequently to be expected.

It is, for instance, not generally appreciated that, although the contact pressures under an earth embankment may be much less than those under a structural foundation, the ground stresses caused by the embankment will, at a relatively shallow depth, exceed those caused by the structure. The reason for this is that the least dimension of the loaded area governs the rate at which the contact pressure decreases with increasing depth. It follows that if there is a considerable depth of compressible subsoil, then little difference will be made to the overall settlement of an embankment by compacting the top part of the subsoil. The reason for proper preparation is to provide an even platform for the embankment construction.

For reassurance on the foundation behaviour, the prudent designer will therefore look not only to the results of a site investigation, but also to the practical experience of his engineering colleagues in similar circumstances.

2.3.2 Geotechnical problems

Where the site investigation has found that special circumstances are likely to affect the performance of the embankment, the designer will usually have the benefit of a more sophisticated investigation and expert guidance as to the type of solution to be considered.

If a special problem is properly appreciated at the location stage, the first consideration is to decide whether it can be outflanked by relocating the road. If not, the adverse foundation conditions will have to be dealt with in place and the works will have to be designed to overcome the problems of settlement and stability, or peculiar problems such as subsidence or undermining.

2.3.2.1 Settlement

Road pavements can tolerate relatively large settlements in an embankment provided that the rate of settlement is slow, the differential settlement is small, and the pavement is flexible. Flexibility in this sense does not include only what are usually termed 'flexible' pavements, since a jointed or continuously reinforced concrete 'rigid' pavement will often make an equally accommodating adjustment. Settlement is a special problem where the predicted total settlement is excessive, where the rate of settlement is slow in relation to the construction programme, and where gross differential settlements can be foreseen on approach embankment to structures.

A number of techniques have been used in the past to overcome these settlement problems. These are briefly summarized as follows:

- removal or displacement of the unacceptable foundation materials;
- preconsolidation of the materials by vibration, vibroflotation, dropping weights or impact rollers;
- alteration of the consolidation characteristics of the subsoil by the injection of lime or chemical grouts;
- use of selected lightweight fill materials;
- acceleration of the rate of consolidation by artificial drainage in the form of sand blankets, subdrainage systems, vertical sand drains, or drainage wicks;
- acceleration of the effective rate of settlement by means of a surcharge on the embankment; and

?? interruption of the construction programme to allow a suitable time for settlement between the earthworks and paving stages.

Some of these techniques do nothing to lessen the amount of settlement and it is important to note that allowance has to be made for this settlement, both in the amount of material which will have to be added, and in the extra width of construction necessary, from ground-level upwards, to ensure that the design width and side slopes are adhered to.

Each technique has its merits, and the designer will have to select the best solution in any particular circumstance bearing in mind all the relevant considerations of soil mechanics, drainage, geometrics, construction programmes and costs.

2.3.2.2 Stability

Several types of failure can arise from inadequate shear strength in the embankment foundation - attention is often focused on the orthodox analysis of the critical slip circle, but a wary engineer should also assess the possibilities of slump, sliding and other types of shear failure. Note that it may be prudent to ignore or decrease the strength of the embankment material in stability analysis for the situation in which a brittle embankment overlies a comparatively yielding subsoil. This is because lateral strains may occur which will induce significant tension cracking in the embankment thereby reducing its strength. Extreme caution is required in selecting the correct soil parameters and ground-water conditions for design analysis, and in the construction phase both artificial and natural drainage systems should be monitored where there is any risk of excessive pore-water pressures.

Although it is not appropriate in this document to discuss in detail the philosophy of factors of safety for stability analyses, one or two remarks may be relevant. It must be appreciated that most geotechnical analyses are of a probabilistic rather than deterministic nature because one is dealing with variations in the disposition and strength of natural materials, with variations in construction and even with possible variations in weather. If one knows these with certainty, and is absolutely confident that the analytical method has faithfully modelled the real situation, then it may be argued that a factor of safety of slightly over 1,0 will be adequate. Since, in practice, one never has that confidence, some higher factor becomes necessary: the factor is then a reflection of the variability of the parameters. It is therefore not reasonable to talk of factors of safety in terms of set numbers.

What this means in terms of construction practice is that the construction supervisors must be aware of the suppositions made in the design, so that if these suppositions are discovered to be inappropriate, their significance will be appreciated. In some cases the design might not have had the benefit of geotechnical input, or the investigation which was carried out might have failed to reveal a problem which only became predictable during construction. The construction team should watch for indications of such problems.

Generally, on flat soft deposits the nature of the subsoil is sufficient indication of the potential instability, because the modes of distress are well defined. But for embankments on side slopes, or through gulleys, it is quite possible, particularly with those of modest height, to miss potential problems. Points to look for are signs of seepage or springs in the vicinity of the proposed embankment (i.e. not solely at the embankment position), hummocky ground or tension cracks which indicate previous movements, small terraces or terracets indicative of topsoil creep, abrupt changes in the direction of streams, adverse dip of the strata, discontinuities in the local geology through either faults or intrusions, and rough ground shown by broken contours. If any of these is observed, then an assessment should be made of its possible relevance to the stability of the proposed embankment.

With the modern speed of construction, long-term settlement and deformation are becoming far more problematic and, since the resulting cracks in the design layers of the pavement are serious, the causes deserve more attention than they usually get. Unfortunately there is not yet complete understanding of the causes of deformation in embankments due to their own weight and to built-in construction stresses from compaction. Finite-element analyses of embankments certainly indicate quite clearly that there can be significant tension zones which, depending on the material properties, could lead to cracking. It is clear from these analyses that more compaction is not the solution. There is a strong school of thought that it is the fast rate of construction which is at fault, the explanation being that at a moderate rate some form of stress relief takes place during the process so that by the end of the construction there is no accumulation of stresses; in other words some more gradual maturing process is desirable. It follows from this that embankments should be constructed as slowly as possible within the contract period. If the embankment is resting on a very compressible subsoil there could be a conflict of interests: on the one hand it is desirable to build the embankment as soon as possible, so that the subsoil can have maximum time to consolidate, but, on the other hand, it may seem desirable to slow the embankment construction so that the stresses within the embankment may be relieved. Since little is quantitatively known about the latter aspect, it seems reasonable to accept that if subsoil consolidation is expected to be significant, this consideration should prevail. However, if subsoil consolidation is not a problem then it is reasonable to give consideration to the possible advantage of a slow rate of construction.

2.3.2.3 Subsidence

In some places the designer is burdened with more deep-seated problems, and with more difficult responsibilities, as a result of the subterranean removal of structural support for the foundations - for example by chemical solution and the occurrence of sink-holes in dolomite and limestone formations, and by old mine workings. The use of specialist geotechnical advice and assistance in such circumstances is imperative.

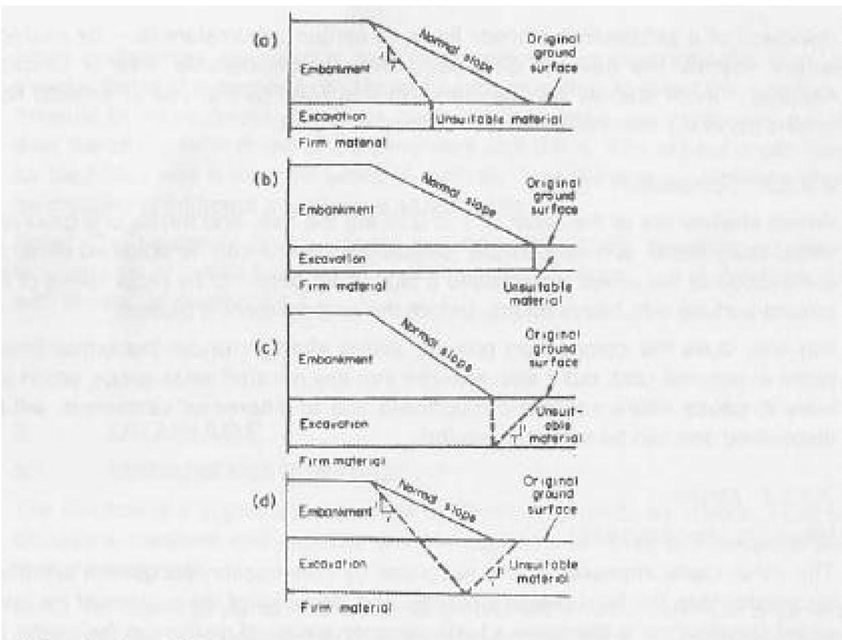
2.3.3 Routine problems

Even when a foundation is not so obviously poor as to excite academic interest in its settlement or stability, it may prove troublesome during construction.

The difficulties of construction which arise from the shortcomings of the natural ground - such as inadequate strength to support construction equipment - can normally be overcome by appropriate techniques. Serious construction difficulties are, however, often an early warning of performance problems to follow, and the designer is usually well-advised to meet with the construction forces and agree on a joint solution to any problem which is likely to prejudice the long-term serviceability of the embankment.

2.3.3.1 Removal and replacement

Wherever it is economically feasible, the unstable ground should be removed from beneath the embankment and preferably from the sides as well. Figure 1, which is taken from a Highway Research Board publication (2), shows some ways in which the extent of excavation may be defined. In general it is recommended that the most conservative solution, i.e. section (c), should be adopted. The feasibility of the operation should be carefully assessed in advance, by exploratory boring or trial pits, because there is little justification for the expense of partial removal if the unstable condition persists at the bottom of the excavation.



Note: Section (a) limited to unsuitable deposits that are less than 1,5 m in thickness.

FIGURE 1 Excavation of unsuitable subsoil

Similar problems can be expected if the replacement material is not chosen carefully. For backfilling below the water-table a granular material such as sand is desirable; a coarse granular material such as rock will contribute the added strength of aggregate interlock and is therefore to be preferred. For backfilling above the water-table, a good granular material is equally desirable, but local materials selected for their inherent strength will often prove satisfactory.

2.3.3.2 Bridging

Where the removal and replacement of unstable materials is not feasible, the embankment construction should be pioneered across the unstable area. A pioneer construction technique will usually involve:

- the removal of as much as possible of the natural ground-water, followed by
- the placing of a substantial fill layer, consisting preferably of coarsely graded material, in a single lift with a thickness of about 1 m.

The pioneer layer is normally placed by bull-dozing the material forward from loads dumped on the completed layer, and the correct thickness of the layer is that which will carry the construction equipment without undue deformation. Obviously the better the material, and the lighter the equipment, the less will be the thickness of a satisfactory pioneer layer. In certain circumstances - for example where shallow fills have to be placed over a considerable area of unstable material - initial stability can be markedly improved by the use of artificial fibre sheets generally followed by a layer of sand or gravel.

2.3.3.3 Compaction

Where shallow fills of the order of 1 to 2 m are the rule, and the natural ground is undesirably loose, soft, or variable, substantial benefit can be obtained either by compaction of the *in-situ* materials to a significant depth, or by proof rolling of the ground-surface with heavy rollers, before the embankment is placed.

Not only does the compaction provide added strength under the embankment prism at nominal cost, but it also ensures that any isolated weak areas, which are likely to cause future pavement roughness due to differential settlement, will be discovered and can be specially treated.

2.3.3.4 Pitfalls

Heaving (sponginess)

The initial loads imposed on the subgrade by construction equipment are often far greater than the final design loadings, and 'heaving' of the surface of the layer under construction is therefore a fairly common cause of distress in the wetter areas of the country. This distress occurs as a result of excess pore-water pressures induced by the equipment's loading, and can be overcome by reducing or spreading the loads, by draining the excess pore-water, or by delaying the work to allow sufficient time for the excess pressures to dissipate.

Frequently, however, the dissipation rate is too slow and the only practical solution may be to continue construction with the knowledge that as the embankment becomes higher so the heaving problems will decrease since the equipment-induced pressures on the subsoil will be reduced.

There are no generally accepted rules on this subject but a practical rule-of-thumb sometimes used is that provided heaving ceases before the embankment has been built to within 1 m of the bottom of the lowest pavement layer, the situation may be regarded as satisfactory. A further rule-of-thumb is that if the heaving has not stopped by the time the embankment is 2 m high, then one must view the situation seriously, since the supposed explanation may be incorrect. (It is of course always important to try to establish the cause of the distress.)

It has been found that a similar phenomenon can occur due to the moisture content and permeability characteristics of the fill material itself. In this case it would obviously be wishful thinking to hope that the problem will disappear as the embankment progresses, unless steps are taken to change the material itself.

Cut-fill transitions

The upper horizons of the soil profiles, which often have defined seepage zones, also have the least cover at the cut-to-fill transition. As a result pavement failures frequently occur in these areas. The inherent deficiencies are often exaggerated when undesirable geometrics carry sag vertical curvature into the cuts, and thereby flatten the drainage grades and seepage paths. To avoid this problem, all material in these zones should be removed to a generous depth, say not less than the total design depth of the pavement plus

0,5 m. The excess depth should be backfilled with a material which is naturally free draining, or drainage should be installed to intercept and remove all infiltration.

Note: The treatment of the natural ground by saw-tooth benching on side-hill locations, or at cut-fill transitions, is of major significance, and is therefore dealt with in detail in section 3.4.2.

3 DRAINAGE

3.1 SUBSURFACE DRAINAGE

The function of a subsurface drainage system is to provide a network of permeable layers, trenches and ducts for the interception and removal of seepage water from the subgrade.

Since the drainage paths in the natural ground are erratic, their flow is generally seasonal, and their occurrence is extremely variable, there is no standard type of drain, nor method of installation, which will satisfy all requirements.

However, the basic elements included in all subdrainage designs are firstly a permeable collector, such as sand or stone chips; secondly a suitable filter, such as fine sand or artificial membranes (geofabic); and thirdly a duct to provide a free flow-line through the collector.

Numerous designs have been developed, and some are illustrated in Figure 2. From this selection the designer should choose the type best-suited to the local considerations of cost, materials and personal preference.

In some solid profiles the seepage layers are easily recognized, but in others, in the dry season, it requires a very discerning eye to visualize the wet-season drainage paths.

The correct engineering solution, which will just balance the amount of subdrainage against the peak flow of ground-water, is extremely difficult to obtain.

Any serious shortcomings in the subdrainage are unpardonable because expensive pavement failures are the inevitable result. Conservative designs for subdrainage, well in excess of the apparent demand, should therefore be the general rule in the profession.

The value of engineering judgement based on local experience cannot be overemphasized - there is, in fact, far too little exchange of ideas, or banking of experience, on this vital aspect of earthwork construction. Subsurface drainage frequently contributes only fractionally to the cost of the work, but is highly significant to the performance.

Subsurface drainage will be treated further in TRH 15, which is still in preparation.

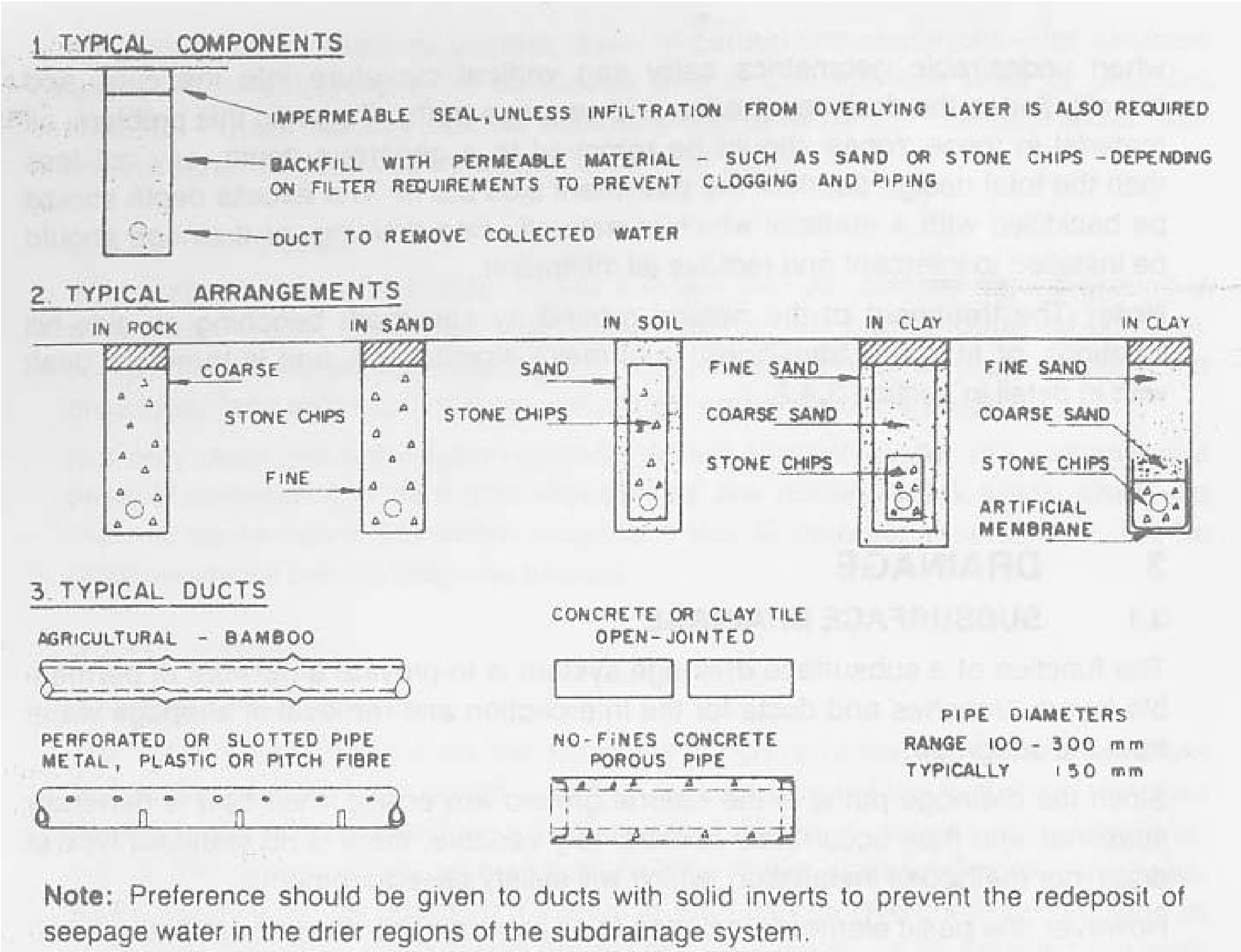


FIGURE 2 Subsoil drainage

3.2 SURFACE DRAINAGE

Surface drainage is installed to make effective provision for the disposal of stormwater which falls on, or is intercepted by, the embankment.

The fundamental requirements are that all the drainage installations - culverts, pipe culverts, channels and inlets - should have adequate capacities to deal with the design rainfall, and that they should also be designed to minimize erosion, ponding and infiltration into the road prism.

In cases where large settlements are anticipated, culvert capacities should obviously be calculated for the half-buried final condition.

The technical requirements of a satisfactory stormwater drainage system are well established, but there is room for improvement in the adaptation of these systems to rural situations. There is little point in rural road construction if defective drainage, resulting in silting and erosion, destroys the very environment that the facility sets out to serve.

Wherever possible, the natural ground-surfaces in and around the water-courses should be left undisturbed. Where stream diversions or stormwater concentrations make it essential to use artificial channels, these should be blended carefully into the surrounding topography and vegetation.

It is generally recommended, however, that one should only divert natural watercourses if it is absolutely essential, because it has been only too frequently observed that in times of flood these streams display a tendency to revert to their original courses.

Particular attention should be given to the transition from natural to artificial channels at the inlets and outlets of cross-drainage structures.

The appropriate design and construction of permanent surface drainage is an obvious necessity, but it is also of considerable importance to provide adequate temporary drainage during construction. This should be self-evident to anyone with experience of working in wet areas but, nevertheless, it is distressing to observe how frequently rain causes severe damage to embankments under construction, where no provision at all has been made for temporary drainage. Usually all that is required is some sensible shaping of the earthworks; or, if the period for which the embankment is to be exposed is fairly long, then some rolling or other sealing technique and the provision of temporary pipes may be called for.

Drainage design should not be restricted to the principles of hydraulics - road side aesthetics also need to be considered as a significant design objective, and engineering economics require that the capital costs should be weighed against the consequences of occasional floods.

3.3 EMBANKMENT DRAINAGE

3.3.1 Internal drainage

Even if an embankment is placed on a drained foundation and protected by surface drains and slope protection, surface cracking, sliding and slump failures may still occur as a result of:

?? inadequacies or failures in the surface or subsurface drainage works;
?? seasonal infiltration or evaporation;
?? gradual changes towards the equilibrium moisture content.

Embankments are particularly susceptible to these types of failure in high rainfall areas, and in large embankments the materials and their moisture contents should be judiciously chosen and placed so as to minimize the shrinkage and swelling movements which result from changes in the moisture régime.

Provision should also be made for the removal of excess moisture in critical situations, and the following are typical approaches (see Figure 3):

?? Sand blankets to intercept the movement of percolating or capillary water and to assist in internal drainage.
?? Rock-toe fills - possibly protected by graded filters or filter cloths - to relieve the high seepage pressures which can build up at the toe of an embankment. The provision of graded filters or fabric filters over rock toes is fairly expensive and careful consideration should be given to their use in any particular situation. The purpose of filters is to protect the rock from clogging and the surrounding material from piping. If the surrounding material is not susceptible to this internal erosion, and if no significant flow of water is expected across the interface being considered, then there can be no real justification for a complex filter system.
?? Permeable collectors in the form of columns, windrows or wafers of sand or granular materials which are placed to assist in the removal of excess water trapped in the layers during construction, and therefore to accelerate consolidation of the embankment itself.

It is impractical to expect that all embankments should be constructed with ideal, permeable, granular materials, but the use of inferior materials should at least be accompanied by sufficient forethought about the drainage to minimize the probable defects in the performance of the embankment.

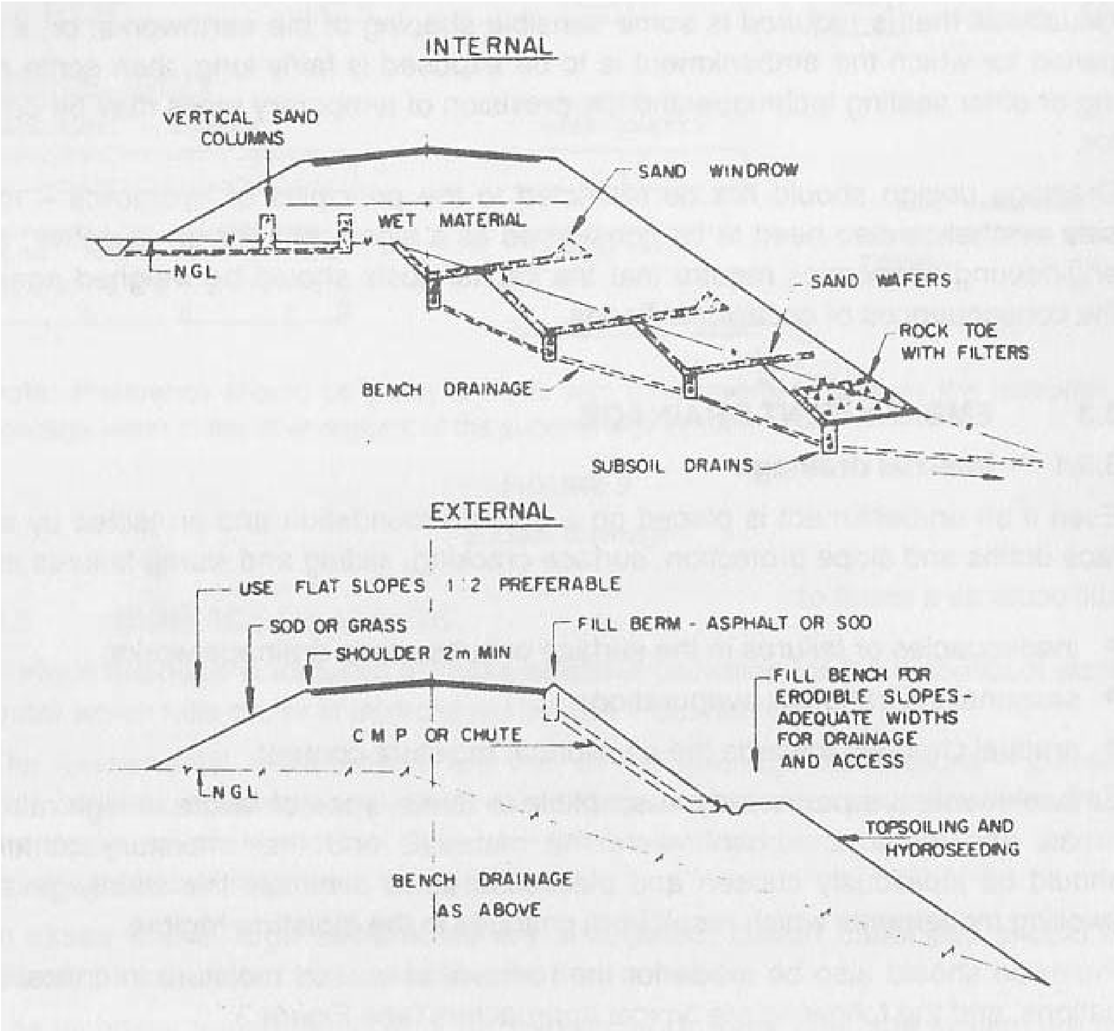


FIGURE 3 Embankment drainage

3.3.2 External drainage

Steep side-slopes and raw edges are characteristic of new embankments and unless the incidence of erosion at the edges is reduced by positive steps, the performance of the embankment in providing a uniform subgrade support will be affected by patchwork repairs. In high rainfall areas a continuous kerb or berm is necessary to control the surface runoff, and to discharge the collected flow down the face of the embankment in lined shutes. In some fortunate circumstances the embankment can be drained towards the median during construction. Some typical drainage arrangements are shown in Figure 3. In the case of high embankments where the runoff from the slope itself is sufficient to erode the materials, consideration should be given to using embankment benches. Benches reduce the length of runoff and thus the velocity of the runoff, but it is imperative that vegetation is established for optimum erosion control. Vegetation not only absorbs the impact force of rain, but also retards the velocity of the runoff.

3.4 BENCHES

3.4.1 Fill benches

These benches are horizontal or near-horizontal terraces built as part of the fill and normally slope inwards towards the centre line of the fill. They may serve a number of purposes. For high embankments they may be required to provide access to the side-slopes for maintenance, or they may be necessary for the control of surface drainage. For embankments on a subsoil which gives rise to possible stability problems, benches may be a means of providing a mass at the toe to counterbalance the forces tending to produce the instability. In these cases the benches are sometimes called berms and the width and height of these will be determined by stability considerations.

It is recommended that embankment benches be provided where long constant slopes are not suitable due to the characteristics of the embankment. The width of these benches may vary, but should be at least suitable for construction and maintenance plant, i.e. not less than about 4 m, excluding drainage requirements, and preferably 5 to 6 m.

The slope of the bench along the length of the embankment need not be the same as that of the road, but must be designed to allow free drainage, by properly constructed and maintained permanent drains, along the inner side of the bench with suitable and sufficient down-drains. The cross slope of benches should be inwards to minimize erosion. Undoubtedly arguments can be put forward in support of having the benches sloping outwards. The main argument is that one should conservatively assume that at some stage the drainage system will fail and, if the benches slope inwards, water will be directed into the embankment which may cause stability problems. The counter-argument is that if the benches slope outwards the same result will occur because the water flowing down from the slope above the bench still requires the drain which, if it fails, will almost certainly direct water into the embankment. The only real difference is that on the top bench only, the total flow to the drain will be less by the amount of rainfall falling onto that bench. Despite these arguments, it is strongly recommended that since prevention of erosion is the primary purpose of benches, then, in most circumstances, the cross slope of the benches should be inwards.

During construction, temporary drainage measures must be provided after completion up to bench height in order to lead off surface water and to prevent saturation or erosion of the complete works.

The safety of embankments is dependent on effective drainage, and provision must be made for maintenance plant to have access to the bench, to ensure that the whole drainage system is regularly inspected and maintained.

If the benches or berms are required in order to stabilize the embankment, there can be no question of omitting them to prevent drainage or erosion problems. If, on the other hand, benches are provided to reduce erosion problems, it is necessary to check that the material being used is not susceptible to erosion. In marginal cases, if adequate maintenance of the bench drains cannot be guaranteed, it may be advisable to dispense with the benches and, if possible, flatten the side-slope of the embankment. There is, of course, considerable merit in reducing the side-slopes in any case, and there is a growing point of view that slopes should generally not be steeper than 1 to 2, as opposed to the conventional 1 to 1½ , unless there are specific reasons for them to be steeper. Although the initial cost of construction will be higher, the overall cost in the design life of the road may be lower because of the much lower maintenance which will be required.

3.4.2 Cut benches

Cut benches are defined as near-horizontal steps, or ledges, excavated on and into steep side-slopes, both longitudinally and transversely, to form working platforms and bases on which the fill material may be placed in order to ensure stability of the embankment. These benches are generally recommended where the natural ground-slope exceeds 1 in 6 but, depending on the material, may be required for lesser slopes, e.g. where soil creep is taking place. In rock-slopes the direction of the dip is important and must be checked. Smooth rock-surfaces may be benched by blasting methods to prevent the possibility of sliding on an unfavourably inclined plane. Benches should be sloped inwards and, where required, suitable drainage must be provided on the inside to prevent water being trapped against the cut face. The inner cut face should be vertical or inclined inward for ease of placing fill material, and to facilitate the placing of a filter layer against the cut faces where the face shows free moisture.

Typical benches and drainage are shown in Figure 4. The width of the bench depends on the slope of the natural ground, but must be sufficient for construction plant to be able to place and compact the fill. Successive benches may be cut as embankment construction progresses and the excavated material, if of satisfactory quality, may be incorporated into the fill. Benches should be taken sufficiently far into natural ground to intercept any potential surface of sliding and any subsurface water. Generally, the construction of heavy earthworks takes place during dry weather, and seepage may not be immediately apparent. Indications of seepage, however, will almost certainly be clear to the experienced observer. One of the best pointers is the vegetation which, of course, must be noted before clearing operations; this is also quite often seen on air photographs. Other indications are zones of discolouration in the subsoil and isolated patches of marked weathering.

At transition sections from cut to fill the same considerations as for sidehill benches and for dealing with subsurface water apply.

Where new embankments are constructed against existing embankments such as in road widening, it is recommended that benches be cut into the existing fill slopes after the removal of topsoil, in order to key into, and provide a bond between, the old and new works. Such benches are normally narrow since they can be conveniently cut as the new embankment rises. Vertical steps of approximately 1 m are frequently used, but the height may vary considerably. The material from the steps may be incorporated into the new works, as previously described. Construction by end-tipping on slopes is unacceptable and must be avoided.

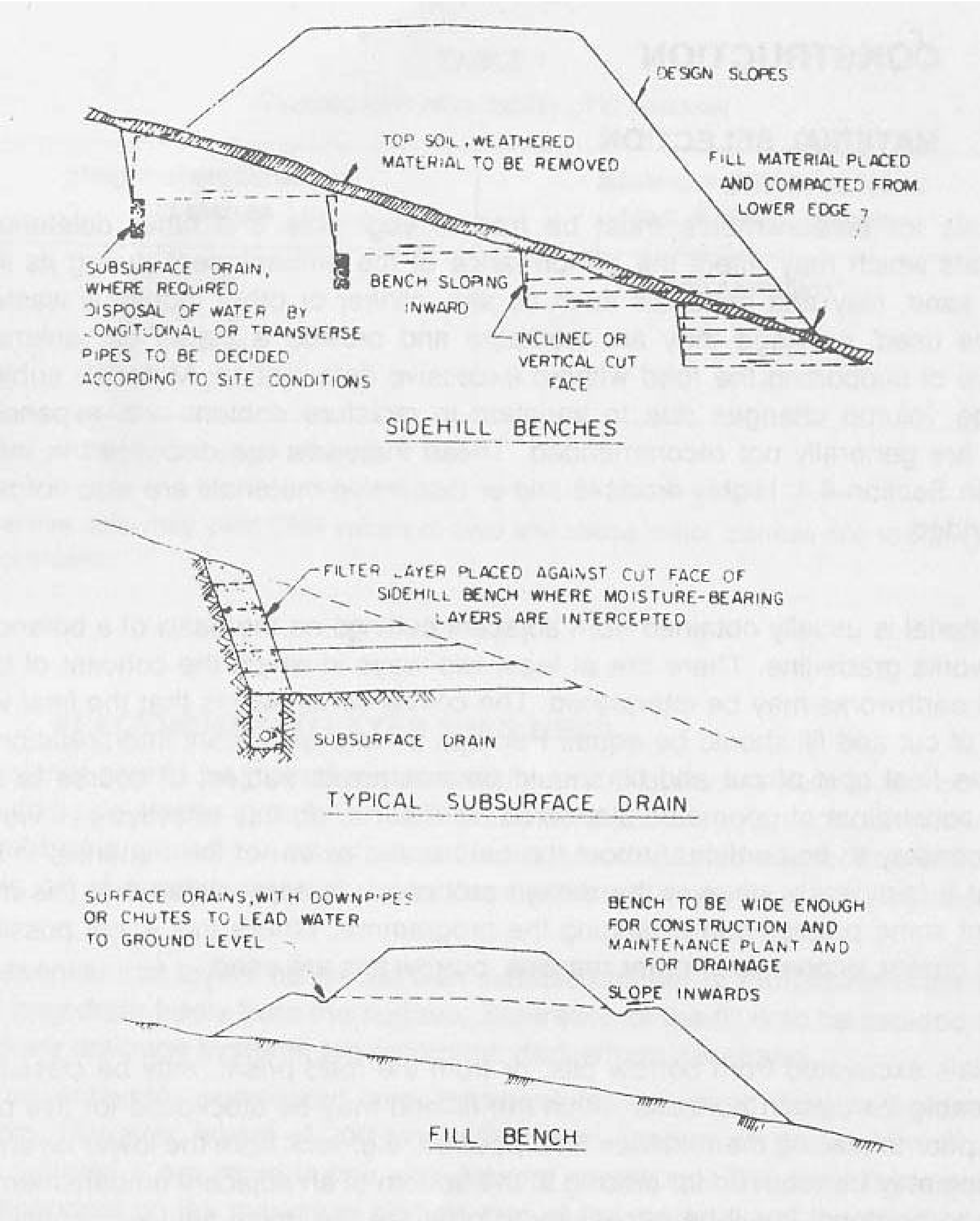


FIGURE 4 Typical benches

4 CONSTRUCTION

4.1 MATERIAL SELECTION

Materials for embankments must be free of vegetable and other deleterious materials which may affect the performance of the embankment during its life. Rock, sand, clay and materials such as ash, clinker or other industrial wastes, may be used, provided they are workable and provide a stable embankment capable of supporting the road without excessive deformation. Materials subject to large volume changes due to variation in moisture content, viz. expansive clays, are generally not recommended. These materials are discussed in more detail in Section 4.4. Highly erodible and/or dispersive materials are also not recommended.

Fill material is usually obtained from adjacent cuttings on the basis of a balanced earthworks grade-line. There are at least two ways in which the concept of balanced earthworks may be interpreted. The conventional way is that the final volumes of cut and fill should be equal. Perhaps a more significant interpretation is that the final cost of cut and fill should be minimized, subject of course to the same constraints of geometric standards. In order to do this effectively, it would be necessary to be confident about the nature and extent of the materials in the cuts at a fairly early stage in the design process; it is appreciated that this may present some problems in arranging the programme. Where this is not possible due to quality, economic or other reasons, borrow pits are used.

Materials excavated from borrow pits, or from the road prism, may be classified as suitable for certain horizons within the fill and may be stockpiled for this purpose, prior to placing them in their final position, e.g. rock from the lower layers of a cutting may be required for placing at the bottom of an adjacent embankment. If this is to be done, it will be necessary to organize the mass haul with considerable care to minimize double handling of the fill.

Although there is little definite information on the performance of embankments built with fill material showing poor load-bearing characteristics, as indicated by the normal test methods in use today, an indication of the common use of materials based on the CBR values is shown in Table 1. It must be stressed that the table should only be used as a preliminary guide. If any material is classified as unsuitable by this method, then that material should be tested by conventional shear strength testing methods before it is finally rejected.

Materials placed in the upper 1 m of the fill, measured from the bottom of the subbase level, should be selected to conform to the road design requirements; clayey materials are not generally recommended for use in this area, unless treated.

TABLE I Classification of suitability of fill material

Height of embankment in metres	Minimum CBR % at 100% Mod. AASHTO density
0 - 6	no restriction*
6 - 9	3
9 - 15	5
15+	7
Note – embankment slope taken as 1:1 ½	

* Dispersive soils may yield CBR values of zero and cause major distress due to piping and tunnel erosion.

4.2 PLACEMENT AND LAYER THICKNESS

Fill material should be placed systematically and in uniform layers to the correct width and side-slopes in order to facilitate control. Care is required to ensure that the material is placed correctly to avoid loose, uncompacted edges, clue either to blading off of surplus material, or to the addition of material due to insufficient width.

It is essential that layers be placed with suitable camber or crossfall in order that water may drain freely from the surface. Saturation of the fill is to be avoided and temporary drainage systems are recommended, where necessary.

The conventionally compacted layer thickness for soil, sand, clay and gravel is 150 mm. However, layers of 200 mm to 300 mm - and much thicker in rock and rocky material - are more in line with present conditions.

The layer thicknesses are dependent on the maximum particle size of the material and the efficiency of the compaction equipment. If layers thicker than conventional ones are being considered, it is recommended that proof rolling be done to establish the maximum satisfactory layer thickness for the site and material conditions.

4.3 ROCK FILLS

Rocky material should be placed in layers by spreading it evenly over the full width of the fill to the layer thickness specified. It is not usually considered necessary or advisable to attempt to construct to specified crossfalls or cambers; a flat surface is recommended. The rock should be spread by bulldozing to its correct position, to avoid arching within the dumped material. It is suggested that, in general, rock should not exceed a maximum dimension of two-thirds of the layer thickness. Although no criteria can rationally be given for angularity, there is little doubt that a cubical shape is to be preferred and it may be necessary to be specific to obtain this, bearing in mind that over-specification may result in high costs and also influence the choice of rock excavation technique.

Where the rocky material is placed with fine material - as quarried, or with the addition of fines - or where rocky materials which may weather rapidly, such as certain mudrocks and tillites, are used, the material must be placed to ensure minimum voids within the fill.

Materials which fracture easily or weather readily should be grid-rolled in order to break them down to satisfactory dimensions for the layer, since this may otherwise result in loose zones within the layer.

Solid, non-weathering rock, such as fresh igneous rocks and some sandstones, may lack sufficient finer material, after blasting, to fill the voids. This type of rock may be placed without the addition of finer material to fill the interstices. It is then recommended that a blanket of the smaller particle-sized materials be placed over the embankment area to a thickness of about 0,5 m.

Where the *in-situ* material is soft, it may be necessary to use a similar blanket, this time under the embankment, in order to prevent the penetration of the rock into the subsoil. As an alternative, it is possible to use artificial fibre mats for this purpose.

The upper 1 m of any coarse rock fill at the top of the subgrade immediately below the subbase layer must be placed with sufficient fine material to form a dense layer to prevent any loss of material into the interstices of the lower layers. Compaction by vibrating rollers and/or grid rolling is recommended, but slushing of the fines into the fill is not normally required.

4.4 SPECIAL PLACEMENT

If, for any reason, materials have to be used which do not conform to the usual design criteria, these may be placed within certain zones of the embankment.

Materials with a CBR less than 3 may be placed within the limits of 1 m and 6 m below the bottom of the subbase. It is also recommended that such poor materials be placed within the body of the embankment, not closer than 3 m to the outside, so that the effects of seasonal moisture variations are reduced to a minimum. Close moisture control with minimum variation is important for such materials to prevent unnecessary deformation of the embankment.

Large boulders are occasionally placed within the body of an embankment. This creates problems of compaction around them but is preferable to placing the boulders on the face of the embankment where, as well as creating difficulties in construction, future erosion problems and unsatisfactory aesthetics will result. It is sometimes possible, with a touch of imagination, to place the boulders in groups alongside the road and create a pleasing landscape feature. Should it be necessary to place large boulders within an embankment, they should be positioned so that the top of the boulder is not closer than about 1 m to the bottom of the pavement layers.

Placing of embankments through dams or other stretches of water may require special measures to prevent saturation or erosion of embankment slopes above normal water-level, due to flow or wave action. It is recommended that coarse granular material be used for such embankments below water-level, with side slopes not steeper than 1:2, suitably protected by a layer of rip-rap, rock in wire mesh, or flexible gabions. The placing of a suitable permeable layer over the full width of the embankment, above maximum water-level, is recommended to prevent saturation due to capillary action.

Artificial fibre mats (geofabric) may be used under embankments over areas of low bearing value.

The use of materials subject to swelling is considered in the following section.

4.5 EXPANSIVE CLAYS

Heaving, or swelling, may be described as the expansion of clayey soils, either *in situ*, or in an embankment, due to an increase in moisture content. Conversely, the same clays will shrink if the moisture content decreases.

All clays undergo the same process, albeit some more so that others, but clays in semi-arid areas may show an excessive volume change due to the large moisture variations which take place. In order to minimize the subsequent swelling of the *in-situ* material, its moisture content should be raised prior to placing the fill. The removal of plant growth and the placing of a 150 mm layer of permeable material, such as coarse sand, over the area - preferably exceeding the base width of the proposed embankment - is recommended; this should be done as far ahead as possible - preferably not less than twelve months before the construction of the embankment, to allow time for a moisture equilibrium to become established. If coarse sand is not available, any predominantly coarse-grained material may be used. It may be necessary to allow rain or irrigation water to pass through.

The removal and replacement of swelling clays may be considered where there is a shallow depth of the material. If removal of only some of the clay is to be carried out, then the exposed clay should be covered immediately to prevent loss of moisture. The fill placed over swelling clays will, by virtue of its weight, assist in counteracting the swell. A reduction in heave of about 30 per cent may be expected for each metre of embankment height.

Over areas of expansive clay, problems frequently occur at culverts. To minimize the difficulties, excavations should be kept covered to prevent evaporation, and possibly irrigated as well. Despite these precautions, deformations still occur because at culverts there is a maximum possibility of moisture increase in the subgrade and minimum overburden pressure to resist swell; it must be admitted that the problem has not been entirely solved satisfactorily. It quite often happens that the depth of expansive clay is not great and, in these circumstances, excavation of the material at the culvert position and replacement of it with a non-expansive material may well be economically justifiable. Considerable attention should be given to the prevention of leakage from the culvert into the soil beneath and of ponding at the inlets and outlets. An additional technique which can be most helpful is to arrange the work programme so that the maximum number of wet seasons will have occurred before the final pavement layers are constructed.

Generally the moisture content under the centre of an embankment reaches equilibrium after about five years. Heave under the centre will then cease. The subsoil at the edges of an embankment is, however, subjected to repeated cycles of wetting and drying. This results in the longitudinal cracks which are a feature of embankments over expansive clays. In order to prevent the cracks in the pavement, the embankment should be widened. This has the effect of moving the zone of fluctuating moisture further from the pavement. It is generally recommended that an extra width of say 3 or 4 m should be provided; with higher embankments it is not necessary to widen over the full height, but only at the toes. As far as possible longitudinal side drains at the toes should be avoided.

The cracks should now be expected in the side-slopes and, for at least the first few seasons, maintenance is required to fill these to prevent direct access of water to the subsoil. If this is not done, much of the purpose will have been defeated.

Materials which expand excessively should be avoided as fill material. Where it is unavoidable that such materials be used, it is recommended that they be placed at the base of, and contained within, the fill, not less than 3 m from the slope edge, so that the moisture variation is minimized.

Since moisture content is of the utmost importance when placing swelling clays, it is recommended that a moisture content of 2 or 3 per cent above the modified AASHTO optimum moisture content (i.e. approximately Standard Proctor) should be attained before compaction, as it has been found that this moisture content results in higher strength and cohesion properties, with reduced swell, when compared with results obtained using the lower optimum moisture contents with the modified AASHTO method. It is to be expected that construction problems will arise during compaction due to the higher moistures, which may necessitate the use of lighter equipment than is now usual for mass earthworks. Obtaining the specified densities may be difficult, and judgement will be required to allow possible deviations from the density requirement to ensure a satisfactory moisture content.

The swelling of clays may be reduced by lime-stabilization. This technique may be applied to both the *in-situ* material and to clay which has to be used within the embankment itself. There is little evidence in South Africa of the efficacy of this technique although there are many claims in international literature that it is successful. It has been reported that in Texas, for instance, there are cases of depths of 1,2 m being stabilized. Clearly it is expensive to stabilize to such depths but, on the other hand, it would be difficult to see the justification for stabilizing say only the top 100 mm of a 3 m thickness of expansive clay unless the purpose was simply to provide trafficability during wet weather.

In semi-arid areas the probability of swelling clays may be anticipated where:

- there is a high and active clay content;
- the water-table is low;
- the loss of soil moisture due to evaporation is much greater than the rainfall or where conditions of transpiration due to plant growth give raise to conditions of desiccation in the soil.

A preliminary estimate of the potential expansiveness of soils and the prediction of heave may be made using the method suggested by D.H. van der Merwe (3.4) or that suggested by Weston (5). These are described in Appendix 1. It should be noted that there has been, and continues to be, considerable argument about the methods of predicting heave. At present there appears to be general agreement that the van der Merwe method is conservative. Since the method is suggested as a preliminary indicator for roadworks, it is proper that it should be conservative. For the reasons explained in Appendix 1 the results should be viewed in a qualitative sense of high, medium and low heaves rather than as absolute quantitative predictions. As the Weston method is still relatively untried, it is recommended, as an interim measure, that both methods be used and the most conservative results be used.

Where soil engineering maps have been produced for a project, it is to be expected that areas of potentially expansive material will be shown. It is important that cognizance of these should be taken at an early stage so that a detailed investigation can be carried out. It is essential to realize that heaving is necessarily time-dependent and the construction programme must be planned to allow time for the various recommended techniques, such as prewetting, to take effect.

4.6 COLLAPSIBLE SANDS

Collapsible soils can be defined as dominantly sandy materials possessing *in-situ* dry densities of less than 85 per cent modified AASHTO, and oedometer-measured collapse potentials under future service stresses of greater than one per cent (6).

Problems associated with these materials are probably less widespread than those associated with expansive materials. As with the latter, however, the important step is to recognize the occurrence of the problem. Soil engineering mapping carried out by qualified and experienced people should delineate the affected areas. Generally, the problem can be satisfactorily dealt with during the construction programme since the collapse phenomenon is not strongly time-dependent. Collapse occurs due to wetting of the soil either with or without the addition of a load. The treatment is to induce the collapse before the placing of the embankment, and this is done by a process of compacting the *in-situ* material. At present this is done by wetting, rolling and observing the result, rather than by specifying any particular end-result criteria. With the current development of vibrating and impact rollers it seems likely that this approach is sufficient and that satisfactory results will be obtained by specifying a certain number of roller passes after some preliminary field trials.

This problem has recently been considered by Weston (6), who has recommended compaction of the upper 0,5 m of roadbed to 90 per cent modified AASHTO and of the next 0,5 m to 85 per cent.

Failures of embankments due to collapse of the compacted embankment soil itself can probably be prevented by compacting the embankment soil to more than both 85 per cent modified AASHTO and 1 650 kg/m^3 at a moisture content not less than Proctor optimum, which should be maintained at all points in the embankment throughout the period when the load is being increased (7).

4.7 COMPACTION

4.7.1 Introduction

Natural mixtures of soil and aggregate occur with a wide range of soil structures, varying from loose to dense, depending on the consolidation history of the deposit.

For any given soil used in an embankment, the solidity of its structure is generally measured in terms of its *dry density*, i.e. the weight of solids per unit volume in place.

The absolute value of the dry density is not, in itself, indicative of the state of the soil structure, because each soil will have a different maximum density depending mainly on the grading, shape and specific gravity of the soil particles.

Since the densification of embankment soils in earthworks is usually achieved by the application of a compactive effort using mechanical equipment, the relative density of the soil structure is referred to as the degree, or state, or percentage of compaction. To measure the relative density, the dry density of the layer in the field is compared with the maximum dry density that can be achieved in the laboratory, on the same soil, using a standard compactive effort. The resulting percentage compaction expresses the degree of solidity of the soil structure in the embankment.

There are at least three sound reasons why the compaction of embankment materials is a general requirement of good construction practice.

?? For all practical purposes the *shear strength* of the soil will be significantly increased by an increase in density.
?? Unless the embankment is satisfactorily compacted, subsequent loading may be sufficient to cause *deformation* of the finished formation.
?? Unless there is sufficient *uniformity* in the state of compaction in each embankment layer, variable strength and permeability characteristics may provide equally variable support to the pavement structure.

4.7.2 Considerations in compaction

A relatively high standard of compaction in an embankment, which is the objective of the designer, is not achieved without considerable effort and skill on the part of the construction forces.

The inherent variability of natural materials gives rise to a wide range of characteristics which are relevant to the compaction process. The significance of some of the more important factors in compaction is discussed in the following paragraphs.

4.7.2.1 Material characteristics

Since compaction is essentially a process of packing more solids into a given space, the physical features of the solids which assist or resist the packing process are of primary importance.

Grading
Well- or uniformly-graded materials, with sufficient fines to fill the air voids between the larger particles, can be fairly easily compacted, particularly if the fines have a sufficient degree of plasticity to lubricate the mixture.

Poorly-graded or single-sized materials, on the other hand, are generally difficult to work into the optimum particle arrangement required to meet high densities.

However, given the range of compaction equipment now available, it is generally possible to compact even the most erratically graded materials through the proper selection of plant and technique.

Shape and surface texture
Cubical aggregates pack into a dense formation fairly readily, but flaky aggregates require considerable work to achieve the necessary re-orientation.

Very flaky minerals, such as the micas, are difficult to compact, not only because of re-orientation problems, but also because of the elasticity they impart to the layer under compaction.

Rounded aggregates, unless they are exceptionally well-graded, are also difficult to compact, and some crushed aggregate is normally added to produce a workable material.

The surface texture of the particles governs the frictional resistance, and 'harsh' aggregates tend to resist the reshuffling forces of compaction equipment.

Plasticity of soil fines
Whereas a small clay fraction will materially assist compaction by providing interparticle lubrication, a material consisting predominantly of clay is usually troublesome, because of its high cohesion and low permeability, unless it is compacted very close to the optimum moisture content relevant to the material and equipment being used.

Soundness
Soft aggregates which pulverize under the compaction equipment or which readily disintegrate after weathering, should be handled with care. If subsequent volume changes in the embankment are to be avoided, the material should be artificially reduced, by rolling or accelerated weathering, to a condition as near to its final state as is practically possible.

Control problems also arise in the use of unsound aggregates because the material gradation on the road, after processing with heavy compaction equipment, is likely to be very different from the gradation obtained in the laboratory from which the control values were established. The Los Angeles Abrasion Test is recommended in defining these materials.

4.7.2.2 Moisture content

To achieve the maximum density in an embankment material with the minimum of effort, the material must be at the correct moisture content during compaction.

An approximation to this moisture content can be obtained in the laboratory by applying a standard compactive effort to a number of samples of the material, each with a different moisture content. The *optimum moisture content* in the laboratory is clearly the moisture content at which the standard effort produces the highest density.

Only experience in the field, with the material, equipment and techniques used in compaction, can determine the field moisture content at which a particular compactive effort is most effective. This *effective* moisture content in the field is often wrongly equated with the *optimum* moisture content in the laboratory, but one need only reflect on the difference between a laboratory compaction hammer and a massive, vibrating or tamping roller to conclude that they are but distant relatives.

Variations
Since the selection of the moisture content during compaction is mainly concerned with achieving the most economical compactive effort, it is normally left in the hands of the construction forces. In special cases, such as expansive clays, or materials with significant collapse potential, the moisture regime during construction has an important bearing on the future performance of the embankment, and in these cases it is appropriate to specify methods for moisture control.

Some overriding control over the upper limit of the moisture content during compaction should also remain with the designer, because with some materials it is possible to achieve design densities at moisture contents so high that the material is still plastic, and with most materials the strength in the finished layer is inversely proportional to the moisture content during compaction.

Difficulties
Fortunately for the construction forces, most embankment materials excavated by cut or borrow have a field moisture content which is not very different from the moisture content required for their effective compaction.

Adjustments are made in the field by the addition of water to the borrow material or the fill, or, with more difficulty and expense, by the aeration of the material to remove excess water.

Very close adjustments are necessary in the case of intractable materials, such as silty soils, and fairly close control is necessary in all cases if high densities are to be achieved with reasonable economy by the compactive effort.

In certain areas of the Republic the materials are so wet, and the climate so unfavourable, that effective control of the moisture content is just not practical. In such cases the designer must face the realities of the situation, and meet them with special provisions in the specification. The first option is to spoil the wet material. This option is of course usually not open because no convenient alternative source is available. If this is so then the basic design objective should be to achieve the best standard of compaction which is economically feasible, and to compensate for any deficiencies in the resulting embankment through supplementary design provisions, such as additional internal drainage, or planned stage construction. The practical assessment of what is 'economically feasible' is not easy, but essentially the selection and application of compaction equipment and techniques should be a matter for co-operation between designer and constructor, at least for a test period. It is quite irresponsible for the designer to insist on a result which is almost impossible to achieve and which even if it were to be achieved, would have an insignificant effect on the performance of the embankment. The assessment of results should look beyond the usual yardstick of dry density to include an appraisal of the uniformity and stiffness of the compacted layer, and to rate its acceptability on the basis of the remaining air voids.

4.7.2.3 Compactive effort

A considerable amount of work is required to compact embankment materials, and heavy construction equipment is used to apply the necessary forces in the form of static pressure, impact or vibration.

Plant

The range of equipment available has increased greatly over the past few years, and there are now few compaction problems which lack a piece of equipment tailored to meet the scale and complexity of the situation.

Pressures can be applied by steel-tyred, pneumatic-tyred, grid and tamping rollers; impact can be provided by impact rollers and high-amplitude vibrations; and vibration can be supplied, with mass, frequency and amplitude to order.

Every roller on the market is reputed to achieve design densities with fewer passes than its competitors and the availability of the plant is therefore no problem. However, the selection of the correct size and type of equipment for a given application requires construction experience and expertise.

Materials

Experience has shown that certain types of roller are best suited to certain materials; broadly speaking, cohesive materials can readily be compacted by the pressure of tamping rollers, and non-cohesive materials respond best to vibratory rollers.

The preceding discussion of the range of material characteristics which are relevant to compaction serves to indicate that an arbitrary distinction between cohesive and non-cohesive is a gross over-simplification. A glance at Table II, which tabulates equipment applications, shows that the selection of equipment for any given material has to be made in the rather complicated context of other considerations. The table, and particularly the layer thickness shown, is intended only as a guide. If in doubt, the results from the site must take precedence.

Limitations

There is little point in providing a substantial compactive effort unless the circumstances are conducive to good results, and the following practical considerations are perhaps given too little attention.

?? Unless the moisture content is reasonably within the range of the field optimum, the effort will be ineffective.

TABLE II Compaction equipment for various soil groups

Soil type	Rock fill	Soft rock	Sand and gravel	Silt and silty soil		Clay and clayey soils	
			Well-graded	Silty sand Silty gravel	Silt Sandy silt	Low or medium strength	High strength
Usual loose layer thickness	1 m	750 mm	250 mm	200 mm	200 mm	150 mm	150 mm
Type of compaction equipment							
Static smooth-wheel rollers 3-15 tons		?	?	?	?	?	
Vibrating smooth-wheel rollers 3-5 tons	?		?	?	?	?	
Vibrating smooth-wheel rollers 10-15 tons	?	?	?	?	?		
Impact rollers		?	?	?	?	?	?
Rubber-tyred rollers 10-15 tons		?	?	?	?	?	
Sheepsfoot rollers 5-30 tons		?			?	?	?
Tamping rollers 5-30 tons		?	?	?	?	?	?
Grid-type rollers	?	?	?	?	?	?	
Remarks	Not to be placed within 900 mm of formation level		Under O.M.C. use vibrating roller Over O.M.C. use pneumatic or tamping roller			Vary tyre pressures of pneumatic roller to achieve optimum result	

? Denotes suitable ? Denotes very suitable

?? Unless the underlying layer is sufficiently firm, the compaction forces will be spent in the production of elastic deformation and not in the densification of the layer under construction.

?? If the layer is too thick to be stressed to its full depth by the compaction equipment, the effort will give only superficial results.

On the other hand the forces applied to the layer under compaction should not be so great as to be destructive. The failure of structural elements, such as retaining walls, concrete box culverts and pipe culverts, is not unusual, and special precautions must be taken during the compaction work in the vicinity of such structures. It should be more generally appreciated that the preceding construction layer is also a structure - albeit an earth structure - and if it is subjected to compaction loads beyond its strength, it will be liable to failure. Disintegration under resonant vibration is a dramatic example of this type of failure, but damage to the completed work as a result of overstressing by construction equipment is becoming more and more common as the power of the equipment increases.

4.8 CONTROL OF MATERIAL QUALITY AND COMPACTION

The quality of the material is usually only monitored if the embankment design requires selective placing. This has been discussed under an earlier heading.

Typical specifications for material quality for embankments were given in the form of a table in section 4. 1.

If there is any doubt, it is obviously better to err on the conservative side, if material is available. Testing will, however, be required to ensure that the appropriate moisture-density relationship is being used for the material, so that the necessary density and moisture content can be specified for field compaction. All tests involved in the control of compaction and quality should conform to some accepted standard. It unfortunately happens all too frequently that it is not the quality of the material which is substandard, but the quality of the testing. The quality control systems recommended in TRH5 *Statistical concepts of quality assurance and their application in road construction* (8) clearly go a long way towards overcoming these problems, but it must be additionally stressed that the testing itself must be supervised and checked thoroughly if disputes are to be avoided. Another common problem is that after the material type has changed, an irrelevant moisture-density relationship continues to be used, with the result that either too little or too much compactive effort is asked for. It does not require great insight to appreciate the folly of delaying construction to wait for further laboratory results and yet this seems to happen fairly regularly. Obviously some occasions will arise when the laboratory cannot provide the required information timeously; it may then be necessary to rely on the judgement of the supervisor, who should be qualified by training and experience to make the decisions.

In order to ensure that there is suitable support for pavement layers, it is normally specified that the top layer, i.e. selected subgrade, should consist of a good-quality material. The requirements for this material are normally stated in the specifications in terms of Plasticity Index and CBR (typical > 12 % and < 10 % at 93 per cent mod. AASHTO density respectively).

A typical frequency of testing for fill material is given below, but it should be noted that different authorities may require quite different testing frequencies. The frequency should reflect the variability of the material at its source, and it could vary from say twice that given below to no testing at all.

(a) Indicator tests	
Embankment material	1 per 2 000 m^3
Selected subgrade	1 per 1 500 m^2
(b) CBR tests	
Selected subgrade	1 per 5 000 m^2
Fill material	1 per 5 000 m^3

4.8.1 Compliance with control requirements

The goal is to comply with specifications throughout the embankment construction. However, since tests generally only represent a minute portion of the fill, competent judgement must be exercised to ensure that the areas tested are as far as possible representative of the entire fill, unless some clearly substandard section can be seen and isolated. This requires continuous visual inspection to ensure that proper procedures and control requirements are being adhered to.

Specified requirements are normally regarded as minimum requirements. However, some road authorities, recognizing that there is variability in materials, construction processes and testing, have introduced statistical specifications which make allowance for the spread of test results normally obtained. Statistical specifications generally require that the mean value of a number of tests, or measurements, representing a particular lot, should exceed the design limit, plus a factor multiplied by the standard deviation of the test results. Consequently construction teams which are able to produce uniform work are allowed to work to a mean value lower than that required when the work is variable. The efficiency is thus rewarded directly, which is the intention of such methods of specification.

4.8.2 Control of dimensions

Both during construction and after completion of the fill, certain dimensional specifications are normally applied.

During construction of the fill, layer thicknesses (loose measure) are generally limited, as indicated earlier, depending on the material type and the compaction plant available.

Many specifications pay little attention to the required shape of an embankment during construction, other than to give permissible deviations from the final slope line, i.e. the levels of the surface are not stated. This is largely because the levels are thought to be the concern of the construction agencies only. However, it is generally accepted that good control of the surface shape reflects efficient working procedures and is very definitely to be encouraged.

Embankment slopes are normally trimmed to approximate the required lines and dimensions during the construction of an embankment. The final trimming is then carried out once the embankment has been constructed to its final height and prior to the slope -protection operations.

Embankments could be designed with slopes suitable for the particular material to be used. In practice this slope is usually taken as 1:1½ unless this is clearly unsuitable for the material although, as mentioned earlier, for protection against erosion and ease of maintenance, slopes no steeper than 1:2 are preferable. If the slopes are not trimmed to the correct lines and dimensions, it is possible that failure may occur due to a slope being steeper than was allowed for in the design. In general, however, the aesthetics and erosion control, rather than the mechanics of the slopes, are the main justification for insisting on careful trimming.

Cracking sometimes occurs due to failure to maintain the embankment at the correct slope during construction. This is because in order to keep to the specified widths, the last few lifts have to be placed at steeper slopes and are therefore unstable.

The stability of an embankment depends on the shear stresses developed in the material at the specified density. It is important for this density to be achieved right up to the edge of the embankment even if it means compacting the embankment to more than the specified final width and then trimming back to the correct line. If this procedure is to be adopted it must be explicitly stated in the construction documents. With very coarse materials it will not be possible to trim back in this way.

It is sometimes convenient to use excess cut material in an embankment; the embankment should then be properly constructed to the extra width at the specified density and the opportunity should be taken to construct the embankment with flatter side slopes, since this will almost certainly make erosion control easier.

In order to avoid an unsightly, ragged and broken surface, outside limits of 450 mm to either side of a mean slope, or a limit of 600 mm on the overall transverse width are commonly recommended.

In the case of rock fills these limits may be extended to 600 mm on either side or 900 mm on the overall transverse horizontal width.

4.9 SLOPE PROTECTION

4.9.1 General

Slope protection is required where the embankment slope surface may be damaged by either water or wind erosion; this applies to nearly all embankment slopes.

Water erosion may be due to the runoff from the road and slope surface, or to water flowing along the toe of the embankment, or to scour on approaches to structures such as bridges or culverts.

Erosion by wind is more of a problem in light soils or sands. Such soils, due to their low moisture-holding capacity, dry rapidly and are easily blown away by high-velocity winds. The use of a parabolic embankment cross-section, and other methods such as soil cladding or admixtures of straw, may help.

Heavier soils may also suffer wind erosion, but not to the same extent as the lighter soils. The heavier or clayey soils are, however, prone to erosion by water. Soils of high clay content are relatively impervious, thus the runoff will increase and, if not controlled, may cause severe erosion on the embankment slope. Clayey soils which lose their cohesion on immersion in water (slake) are particularly susceptible to erosion. Similarly, fine-sandy silts which possess very little natural cohesion are highly erodible.

4.9.2 Methods of slope protection

The method of slope protection used on embankments will depend on many factors, such as:

- the potential cause of damage necessitating slope protection;
- the climatic conditions such as regular high-velocity winds or high-intensity storms;
- the nature of the soil in the embankment, such as clayey soil, sandy soil or rock and gravel.

Some of the methods used to cope with the above conditions are outlined below.

4.9.2.1 Topsoil

Slope faces are often protected merely by spreading a layer of topsoil over the slope surface. Most topsoils contain sufficient grass roots, seeds or pioneer plants to establish eventually a growth of vegetation on the embankment slope.

Care should be taken, when spreading the topsoil, that it is not spread too thickly, as loose material is prone to sliding when wet. Conversely the layers should not be too thin, since they will not sustain plant growth for long periods. Topsoil in thin layers is also likely to erode more readily.

Common practice is to spread topsoil in layers varying from 75 mm to 100 mm, although thicknesses of up to 150 mm are sometimes specified.

Topsoil should be used as soon as possible after stripping, and the ideal would be to strip and spread it directly on the slope surfaces. This is, however, rarely convenient and stockpiling is usually necessary.

Where topsoil is spread on a rough surface, the necessary bond exists to prevent the topsoil from sliding down the slope. On smooth slope surfaces, however, measures such as tilling, to a depth of approximately 75 mm, or forming of chases may be necessary to prevent the topsoil from sliding. (See Figures 5 and 6.)

Other measures, such as a row of stakes with timber batters (Figure 6) or timber ledging, are sometimes used to anchor the topsoil to the slope surface. A recent substitute for logs is a bag made of open-weave artificial fibre, about one metre long and 100 to 150 mm in diameter, filled with a mixture of organic material, fertilizer and seed, and held in place by steel spikes and wire. There are numerous methods designed to overcome the problem of retaining topsoil. Unfortunately there is little firm evidence to support the claims of any of the proponents. It has frequently been found that the methods do not transplant readily from one area, soil type or weather pattern to another so the guiding principle must be to use the method that appears to be most successful in the relevant area. These measures are, however, seldom necessary on slopes flatter than 1:2, but are usually required on steeper slopes.

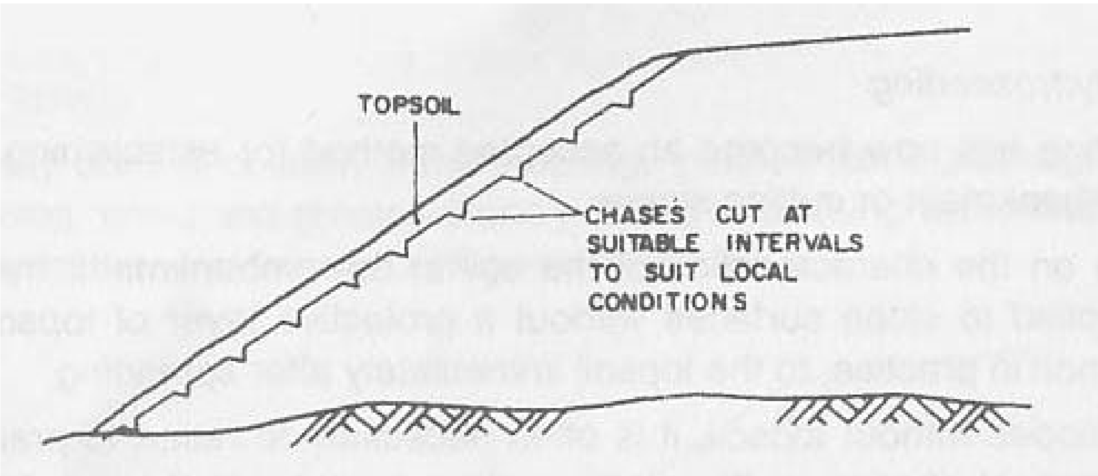


FIGURE 5 Protection of slopes: Chase method for topsoil

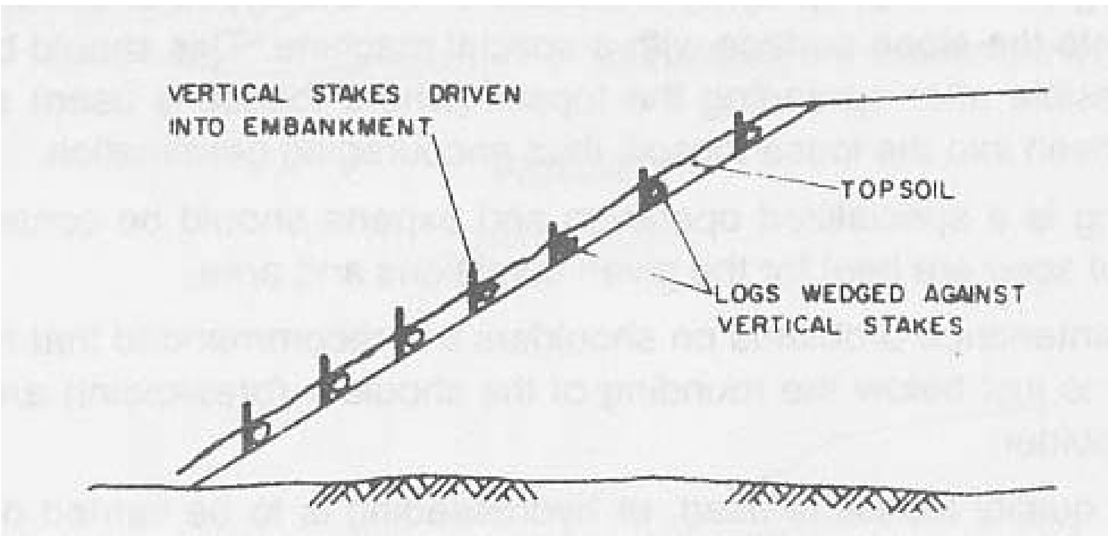


FIGURE 6 Protection of slopes: Stake and batter method

4.9.2.2 Mulch

This is normally used only where other covers, such as topsoil, are not available.

Mulch covers offer immediate protection, and wheat, straw or hay, when properly anchored, provides effective protection since it protects the soil from direct rain, increases water infiltration and decreases runoff.

Even where permanent vegetation is to be established, mulch can be applied either before, or after, seeding or planting, since it promotes conditions favourable to the germination and establishment of permanent plants.

Mulch is often anchored to the slopes, and methods such as a mulch-anchoring tool which pushes the mulch partly into the ground, mulch nets, application of asphalt emulsion to the mulch, or stakes, are often used, with mixed success.

4.9.2.3 Hydroseeding

Hydroseeding has now become an accepted method for establishing vegetation on road embankment or cutting slopes.

Depending on the characteristics of the soil in the embankment, hydroseeding can be applied to slope surfaces without a protective layer of topsoil or, as is more common in practice, to the topsoil immediately after spreading.

On steep slopes without topsoil, it is often necessary to resort to practices such as the cutting of chases in the slope surface to prevent the seed from being washed down the slope during rain. Chases also act as water traps which encourage the establishment of the grass. Revegetation of slopes steeper than 1:1 is seldom successful without the use of specialized measures.

Hydroseeding consists of spraying a mixture of various types of seed, in a cellulose pulp, onto the slope surface with a special machine. This should be done as soon as possible after spreading the topsoil (where topsoil is used) so that the seeds are driven into the loose topsoil, thus encouraging germination.

Hydroseeding is a specialized operation and experts should be consulted as to what types of seed are best for the given conditions and area.

To avoid maintenance problems on shoulders it is recommended that hydroseeding be done to just below the rounding of the shoulder (breakpoint) and not right up to the shoulder.

Where poor quality topsoil is used, or hydroseeding is to be carried out over an area without topsoil, it may be advisable to add a suitable fertilizer to the soil prior to hydroseeding.

4.9.2.4 Planting

Under certain circumstances hydroseeding may not be possible or advisable. In such cases it may be necessary to protect the slope surface by planting grass or other ground-cover plants.

Such cases may arise when for some specific reason tall grasses are not favoured, or a grass with a strong-spreading root system such as kikuyu or kweekgras is required. These two grasses require a fairly moist environment for successful propagation.

Ground-cover plants are used where deeper root systems are required, or sometimes for aesthetic reasons.

If ground-cover plants are used for slope protection, it is advisable to select plants that will create the most debris.

4.9.2.5 Rock or gravel protection

Where road embankments are constructed under conditions such that water may wash against the embankment, or where wind erosion may occur, the slopes may be protected by various methods.

A common and effective method is to cover the slope surface with a layer of rock or gravel. This is merely dumped and spread on the surface and no compaction or other finishing operation is required.

4.9.2.6 Pitching

Pitching may consist of plain stone pitching, grouted stone pitching, plain wirestone pitching, wired and grouted stone pitching or pitching with precast concrete blocks. Two of these are shown in Figures 7 and 8.

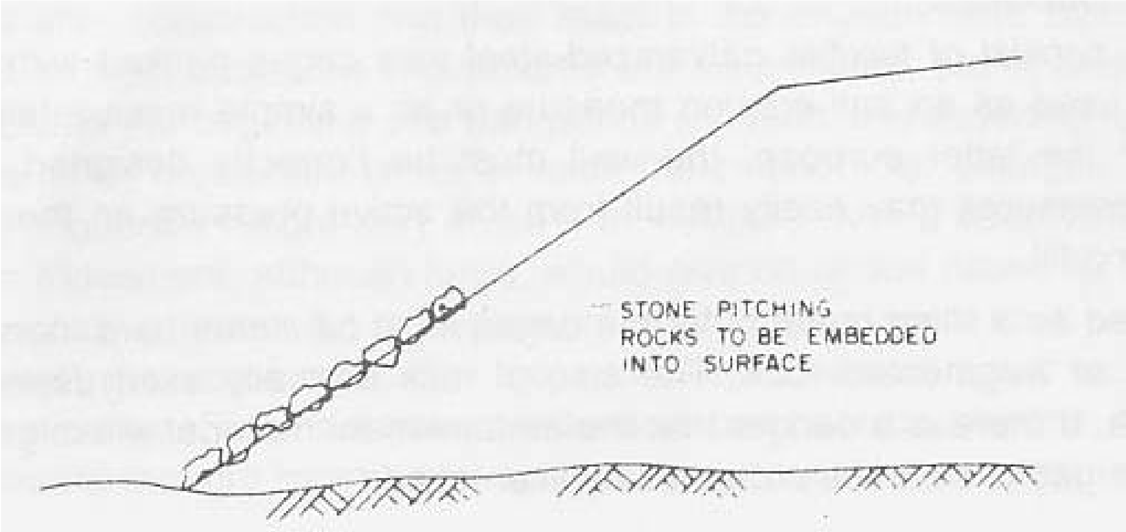


FIGURE 7 Stone pitching

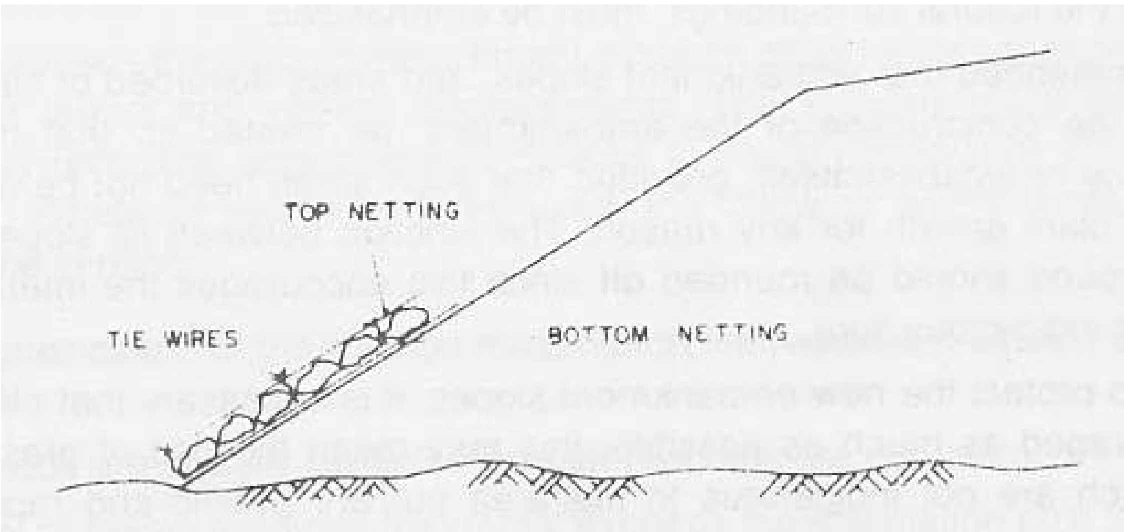


FIGURE 8 Wired stone pitching

Pitching is normally used where there is a possibility of damage to embankments such as at culvert inlets and outlets, and at bridges. The type of pitching to be constructed is determined by the degree of damage expected.

Stone for pitching must be sound and durable. The minimum size used in pitching is generally specified as about 200 to 225 mm. Smaller pieces, or spalls, however, may be used to fill the voids between the larger stones.

Before pitching commences, the slope surface must be compacted to ensure that no subsequent settlement occurs, and the stones used should be thoroughly embedded into the surface to be protected. It is recommended that a proper foundation should be laid along the toe of the embankment. There have been many cases where grouted pitching has concealed deformations in the slope beneath it by spanning across voids. It is therefore considered that this form of pitching should only be used if specifically justified.

A further form of pitching is the use of precast concrete blocks. These are easier to lay and have a neat appearance, although generally they are more expensive. They are often used at open abutment bridges and on embankment slopes in urban areas.

4.9.2.7 Gabions

Gabions consist of flexible galvanized-steel wire cages packed with rock. They may be used as an anti-erosion measure or as a simple mass-retaining wall. If used for the latter purpose, the wall must be correctly designed, since high ground-pressures may easily result from the active pressure on the wall due to the sloping fill.

Rock used as a filling material for the cages must be clean, hard, non-weathered boulders or fragmented rock. The size of rock normally used depends on the cage size. If there is a danger that the embankment material will migrate into the voids, the gabions can be protected by filter fabrics.

5 ENVIRONMENT

The preservation of the environment by confining the work to the essential work sites and avoiding unnecessary haul roads, clearing of bush and trees and disturbances of the natural surroundings, must be emphasized.

It is recommended that embankment slopes, and areas disturbed or cleared as a result of the construction of the embankment, be treated so that the normal growth may re-establish itself, provided that such areas need not be maintained free from plant growth for any reason. The junction between fill slopes and the natural ground should be rounded off since this encourages the inter-growth of exotic and indigenous flora.

In order to protect the new embankment slopes, it is necessary that plant growth be encouraged as much as possible; this may mean the use of grass or plant types which are not indigenous to the area but are prolific and rapid in their growth. It is useful to plant annual and perennial vegetation simultaneously. The annuals give rapid cover while the perennials establish themselves. Efforts should be made to encourage the growth of the indigenous plants as a matter of course, and it is recommended that this be done as part of normal maintenance of the road and embankment.

The construction areas adjacent to embankments should be cleared of any unsightly material which may have been dumped or discarded, and the areas treated so that they will blend in with the natural surroundings. Experience has shown that there are many advantages in keeping the work tidy as it progresses rather than leaving the tidying up until the end.

Borrow pits required for the fill should be chosen with care and be finished and levelled off properly, to present a neat appearance and where possible, treated to assist in the restoration of natural growth, as in the case of an embankment.

In order to achieve the best results all that is required is a real belief that it is an important part of civil engineering that the works should harmonize with nature as much as possible.

6 MONITORING AND MAINTENANCE

6.1 MONITORING

It was emphasized earlier that the successful production of a highway is a continuous process which ends only when the road is finally abandoned. All embankments move after construction and they react to the environment, both natural and artificial. In most cases the movements are insignificant, but in other cases they may indicate the beginning of a dangerous situation. It is essential to realize that the amount of movement is not in itself the criterion; for example, an embankment of moderate height may settle 1 m if placed over a deep soft alluvial deposit. This movement, although large, would give no undue cause for concern if it was expected, whereas 0,1 m settlement of an embankment on a side slope occurring after rain, some time after the end of construction, could be the first warning of a disaster. Since not all embankments can be instrumented, it is clear that considerable thought must be given to the purpose of the measurement of movements.

There are two purposes. The first is to monitor the embankment during and immediately after construction both to ensure that the behaviour is as anticipated, and to control the work programme. The second purpose of instrumentation is to serve as a long-term warning system.

For both purposes the usual measurement systems detect either changes in pore pressure or lateral and vertical displacements. The systems could range from continuously-recording pore pressure devices to visual observation of guardrails or culverts. Whatever system is to be used, the following points should be very clearly borne in mind:

?? The sophistication of the method must match the required precision of the output.

?? All methods are equally useless if regular readings are not taken.

?? The cost of taking readings frequently exceeds the installation cost in the long term.

?? The readings should be evaluated promptly and there must be some predetermined provisional plan of action should any reading indicate danger.

?? Since rainfall may have a considerable influence on the performance of an embankment, it is essential that rainfall measurements be made at the site or sufficiently close to it for data to be reliably extrapolated.

?? The provision of adequate bench marks or datums, which will not be destroyed, is usually more difficult than it appears.

?? The possibility of using culverts as indicators of vertical and lateral movements should always be considered; it is comparatively easy to measure by simple survey the settlement and extension of a culvert which is large enough to walk through.

?? Many organizations have maintenance check systems for major structures. The possibility of integrating the monitoring of embankments into these systems should be examined.

?? All field-measuring systems attract vandals. The small extra cost of making them at least partially vandal-proof is a vital insurance.

?? Once the purpose of the measurements has been achieved, no further readings should be taken; useless information, expensive to obtain, will merely clog the administrative system.

Various measuring systems are described in TRH10, 'Site investigation and design for road embankments'.

6.2 MAINTENANCE

To a large extent the successful performance of an embankment depends on adequate maintenance, particularly of the drainage. It is suggested that, ideally at least, every major embankment should have a preventative maintenance schedule formally specified and operated according to a chart to be completed on a regular basis. Items to which special attention should be paid during maintenance include the sealing of pavement cracks, drainage on benches, erosion damage, and culvert inspection, as well as the usual grass cutting. Notes must be kept about the sealing of pavement cracks since increasing need for this work may be an indication that serious deformation of the embankment is taking place. It is not sufficient merely to take notes; the system must also include reporting the findings to someone in authority who can decide whether action is required. It is not suggested that every embankment should have such a system, but it should be possible to list those which are strongly dependent on particular drainage assumptions for the design to be satisfactory. In these cases the monitoring of pore-pressure readings would be part of the maintenance schedule for a stated period - it would be foolish to expect such monitoring to continue indefinitely; if this proved to be necessary it would be an indication that the initial design was inadequate. In general, the purpose of the monitoring would be to confirm that the embankment is performing as designed; when this has been achieved, presumably after one or two rainy seasons, then sophisticated monitoring should stop.

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APPENDIX

PREDICTION OF HEAVE

1. VAN DER MERWE METHOD (3,4)

As already mentioned in the section on expansive clays, this method is widely accepted as giving conservative preliminary indications of heave potential, based on routine testing. If for any reason, more reliable predictions are required, then it will be necessary to use a method, such as one of the oedometer methods, which is much more time-consuming and expensive. It should be noted that even these apparently sophisticated methods have by no means been proved to be much more reliable as yet although there certainly appears to be more scientific basis for them provided they correctly model the real situation.

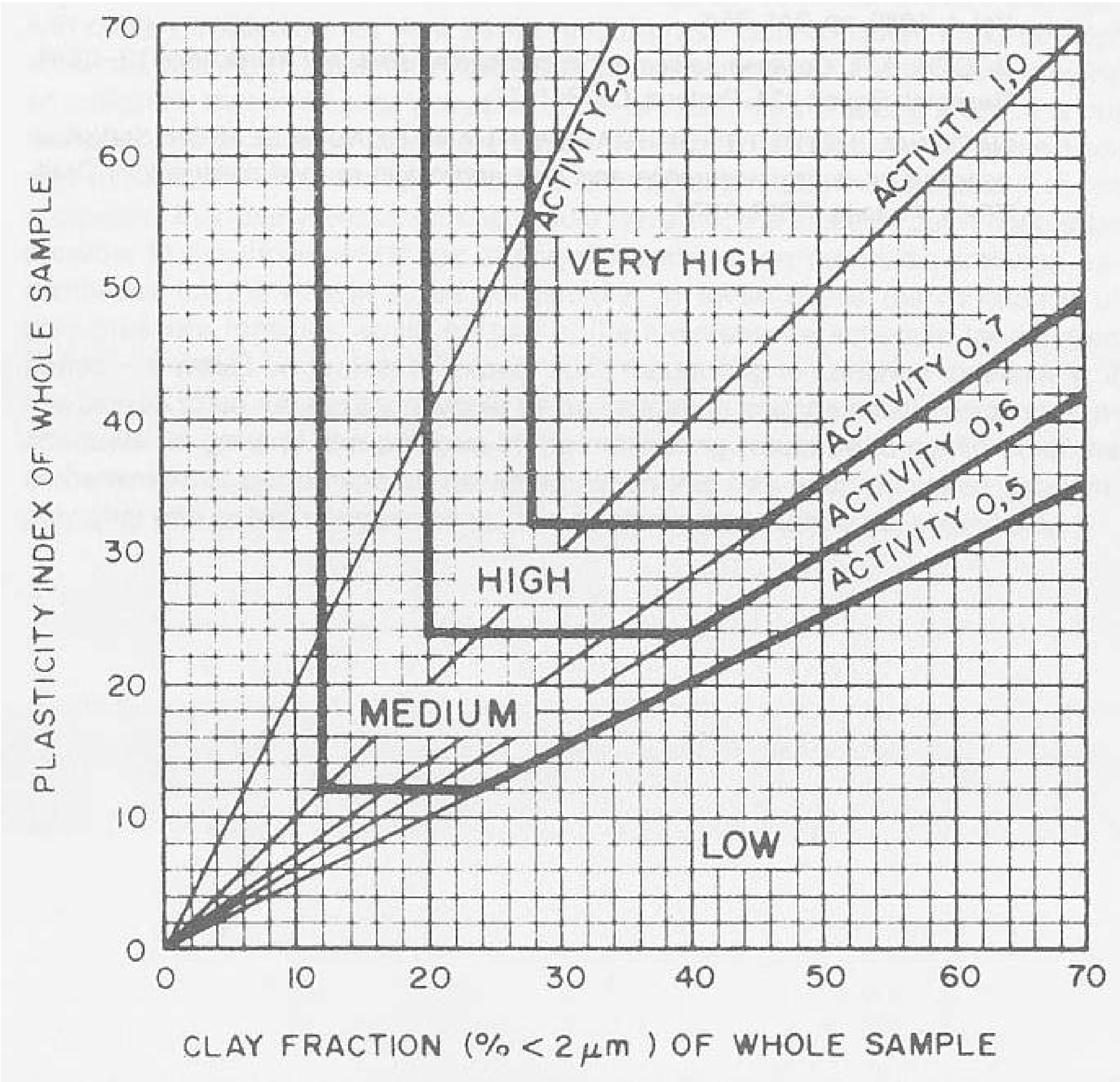

FIGURE 9 Relationship between Potential Expansiveness, Plasticity Index and clay fraction

The basis of the van der Merwe method is that expansive clay is classified into four grades of Potential Expansiveness (PE) by the relationship between the Plasticity Index (PI) and the clay fraction. Note that this fraction is defined as the percentage less than the 2 µm-size and therefore requires hydrometer testing; it should also be noted that it is the clay fraction of the whole sample, not only of that portion passing the 425 µm sieve, which means that the percentage less than 2 µm must be multiplied by the percentage less than 425 µm to obtain the clay fraction of the whole sample. This can make a considerable difference to the assessment of the heave potential.

The relationship between PI and clay fraction is shown in Figure 9. The amount of heave to be expected for each type is given in Table III below, and it is to be noted that this heave is that expected at the ground-surface.

TABLE III Grades of Potential Expansiveness

Classification	**Heave mm per m of profile**
Very high	80
High	40
Medium	20
Low	0

The potential heave, however, decreases with depth due to both the increase in overburden pressure and the probability of a decrease in moisture change. A depth factor (F) is therefore introduced to take account of this and a summarized version of this factor is given below.

TABLE IV Relationship between depth factor (F) and depth

Depth m	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9
Mean F	0,85	0,60	0,40	0,27	0,20	0,12	0,08	0,06	0,04

The total potential heave for any soil profile is then calculated as the sum of the Potential Expansiveness (modified by the depth factor) for each layer in the profile.

For example, if the profile consisted of three layers, each 1 m thick, with the following test data:

(a) Layer 1 : PI = 40; Clay fraction = 50 per cent

(b) Layer 2 : PI = 27; Clay fraction = 35 per cent

(c) Layer 3 : PI = 15; Clay fraction = 20 per cent

then the following calculation results from using Figure 9, Table III and Table IV.

Layer	Potential Expansiveness from Figure 9	PE mm/m Table I	F Depth factor	Heave mm = PE x F
1	Very high	80	0,85	68
2	High	40	0,60	24
3	Medium	20	0,40	8

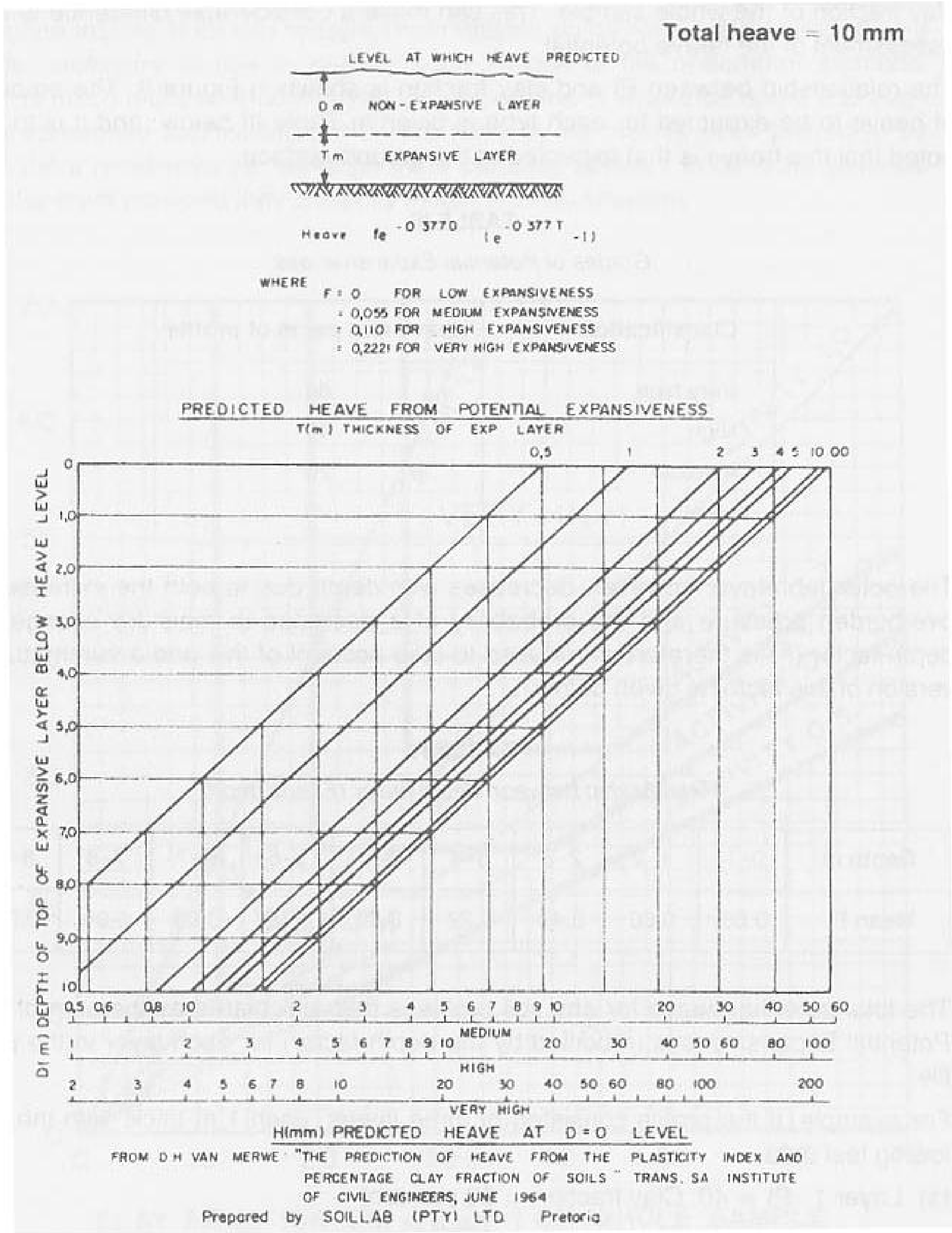

FIGURE 10 Chart for the prediction of heave Potential Expansiveness

This figure will then have to be modified further depending on the height of the embankment to be placed. It has been suggested that a reduction factor as high as 30 per cent for each metre of embankment height may be used. There is, however, not a great deal of evidence to support this and it may be prudent at this stage conservatively to ignore this height factor for the first metre of embankment and only to start the 30 per cent reduction above that level.

2. WESTON'S METHOD (5)

An alternative, though relatively untried, method which possesses the advantage of enabling the designer to consider the moisture changes that are likely to take place has been proposed by Weston (see Figure 11).

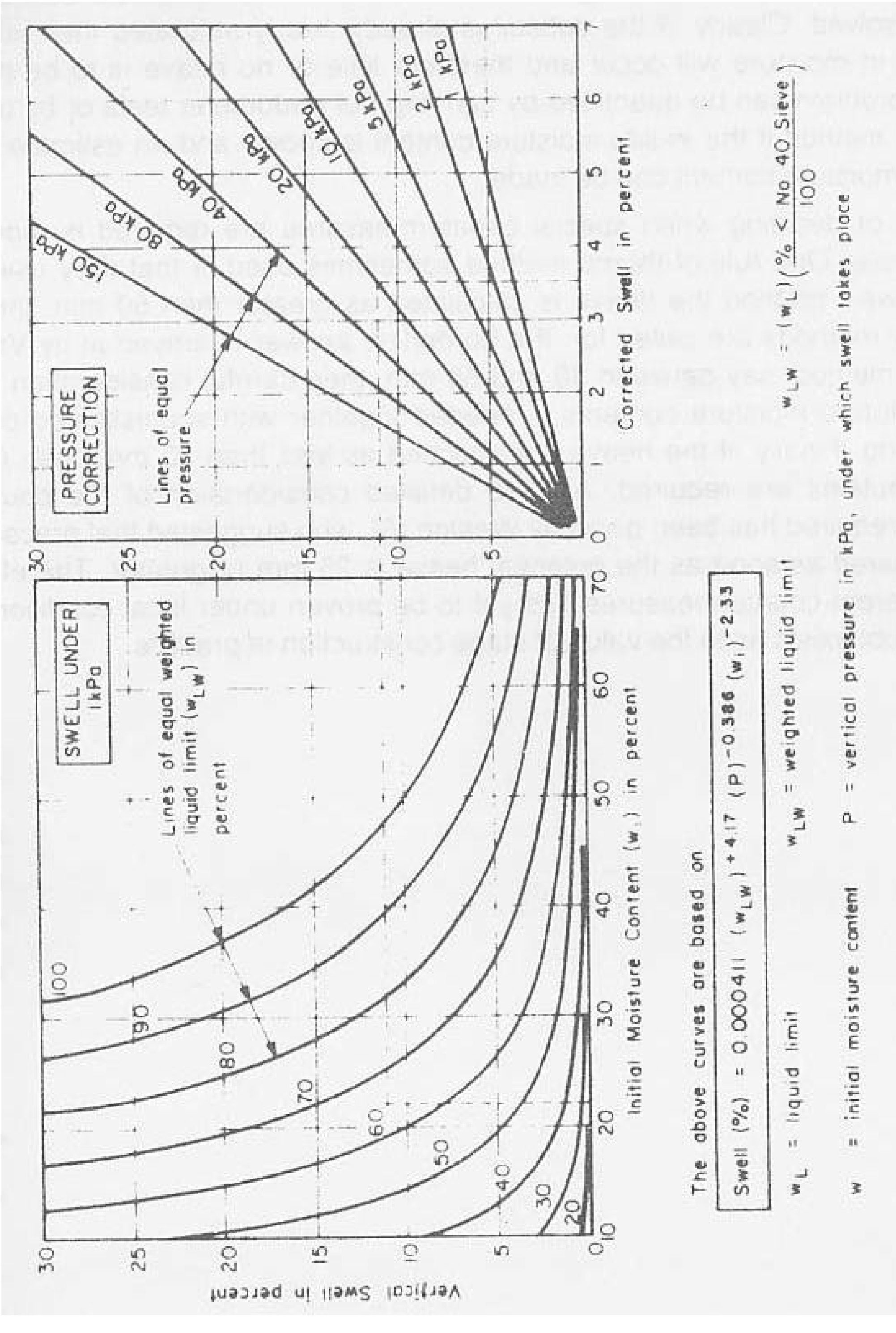

FIGURE 11 Swell prediction using w_L, w_{LW} and P
(1 kPa = 0,145 lb/in^2)

As in the Van der Merwe method, the total potential heave of the soil profile is calculated as the sum of potential expansiveness of each layer, with allowance for overburden stress (including construction layers). Although this method assumes saturation, an estimate of swell to a lower moisture content such as the equilibrium moisture content (7) could be made by making a second calculation taking this moisture content as the initial value and subtracting this value of swell from the first value. It is recommended that the Van der Merwe or oedometer method be used in addition to this method until more experience of it is gained.

3. INTERPRETATION OF RESULTS

Even after these calculations, the problems of what constitutes an acceptable amount of heave and of determining whether the potential heave will be realized, are still unresolved. Clearly, if the subsoil is already nearly saturated then very little build-up in moisture will occur and therefore little or no heave is to be expected; this problem can be quantified by carrying out oedometer tests or by using Weston's method if the *in-situ* moisture content is known and an estimate of the eventual moisture content can be made.

The problem of deciding when special countermeasures are required is, however, not simple. One rule-of-thumb method sometimes used is that if by using Van der Merwe's method the heave is calculated as greater than 50 mm, then precautionary methods are called for. If a borderline answer is arrived at by Van der Merwe's method, say between 30 and 50 mm, then careful consideration of present and future moisture contents is needed together with sophisticated oedometer testing. Finally, if the heave is calculated as less than 30 mm, then no special precautions are required. A more detailed consideration of the counter-measures required has been given by Weston (5), who suggested that precautions are required as soon as the potential heave is 25 mm or greater. The efficiency of different countermeasures has yet to be proven under local conditions and some doubt exists as to the value of stage construction in practice.