TECHNICAL RECOMMENDATIONS FOR HIGHWAYS

TRH 18

THE INVESTIGATION, DESIGN, CONSTRUCTION AND MAINTENANCE OF ROAD CUTTINGS

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DIVISION OF ROADS AND TRANSPORT TECHNOLOGY
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THE INVESTIGATION, DESIGN, CONSTRUCTION AND MAINTENANCE OF ROAD CUTTINGS

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SYNOPSIS

This TRH is a guide to the investigation, design, construction and maintenance of road cuttings in southern Africa. It is not intended as an instruction manual, but is intended to inform the non-geotechnical engineer of the principles of cut design, construction and maintenance. Its main objective is to indicate when specialist advice is required. A simple flow diagram is provided indicating which cuts can reasonably be designed by the non-specialist and which require specialist input. Every cut, however, irrespective of its depth, is unique and should be regarded as such during the investigation, design and construction process.

SINOPSIS

Hierdie TRH is ’n riglyn vir die ondersoek, ontwerp, bou en instandhouding van paddeurgrawings in Suider-Afrika. Dit is nie ’n instruksiehandleiding nie, maar het as oogmerk om die nie-geotegniese ingenieur oor die beginsels van deurgrawingsontwerp, bou en instandhouding in te lig. Die hoof doelwit is om aan te dui wanneer spesialisadvies benodig word. ’n Eenvoudige vloeidiagram word voorsien waarin aangedui word watter deurgrawings deur die nie-spesialis ontwerp kan word en watter spesialisadvies benodig. Elke deurgrawing, ongeag sy diepte, is egter uniek en moet as sodanig tydens die ondersoek-en ontwerpproses beskou word.

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1 INTRODUCTION

The aim of this guideline document is to discuss the steps needed to design, construct and maintain safe and economical road cuttings. This document is not intended as a comprehensive manual on site investigation, stability analysis and construction procedures, but rather as a basic guide to the non-specialist engineer to indicate when specialist advice is required. A number of procedures are discussed to inform non-specialists of possible solutions that may be considered by the specialist.

As vertical and horizontal geometric standards for major roads and freeways become more stringent and the use and value of land increase, deeper cuts and higher fills are becoming more prevalent. Although the total cost (sum of construction, maintenance and road user costs) of minor and fairly lightly trafficked roads may indicate that geometric standards should be relaxed in preference to the construction of deeper cuttings, land availability or topographic conditions may often dictate that steep batters are necessary. Failure of these cuts and fills results in substantial maintenance and rehabilitation costs, possible danger to the public and often expropriation of further land for remedial work. This can often be prevented by better investigation and increased design expenditure prior to construction. The investigation, design and construction of fills is covered in TRH9[1] and Draft TRH10[2] and is not discussed in this document at all.

In the past, many cuts were "designed" on past experience and because many of the roads were secondary rural roads with minor earthworks, failures were not of major consequence. In many instances this practice can still be followed. This document has been compiled to assist in the evaluation of the extent to which the site should be investigated. The onus still rests upon the engineer to consider each cut on its merits and to decide on the investigation and design requirements. Optimally, a geotechnical specialist should be a part of the design team right from the start of a project. Every cut is unique and should be regarded as such.

It has been estimated that the average annual cost of landslides in southern Africa is about R40 million[3].

It must be noted that many slope failures are due to thin clay seams along joints or to steeply dipping joint sets, both of which are usually difficult to identify in the course of typical site investigations. Therefore, even the most detailed investigation may overlook factors that can lead to instability. However, identification of the geological material alone usually assists in decisions regarding the presence of these thin seams. It is also of cardinal importance to recognize the importance of ground water, whether temporary or permanent.

2 SLOPE MOVEMENTS

2.1 TYPES OF SLOPE MOVEMENT

During the early stages of an investigation it is important to have knowledge about the different types of slope movement that may occur. This aspect influences the investigation and design procedures to a major extent.

Slope movements can be classified in a number of ways. Table 1[4] shows a classification system based on the type of material and type of movement.

In this classification, materials are divided into rock and soil. Rock includes unweathered and weathered rock in which separation of the failed portion generally follows discontinuity planes. Soil is subdivided into predominantly coarse materials (debris) and fine materials (earth). Debris generally consists of colluvium or existing landslide deposits whereas earth consists of finer transported and residual soil. Failure in these materials is usually independent of the soil structure but may follow relic discontinuities preserved from the original material.

The various types of failure are defined as set out below (see Figure 1).

Falls: A mass of material of any size is detached from a steep slope, along a surface on which little or no horizontal shear displacement occurs. This material descends mostly through the air by free fall, bouncing or rolling.

Topples: Topples result from a rotation of the unit of material about a point below or low in the unit under the action of gravity, fluids, or forces exerted by adjacent units.

Slides: (Slips) Slides result from shear displacement along a plane or zone of inadequate shear strength. These surfaces may be concave (rotational failure resulting in a slump) or more or less planar (translational slide).

TABLE 1

Classification of slope movements (modified after Varnes[4])

TYPE OF MOVEMENT			TYPE OF MATERIAL		
			ROCK	SOIL	
				Predominantly coarse	Predominantly fine
Falls			Rock fall	Debris fall	Earth fall
Topples			Rock topple	Debris topple	Earth topple
Slides	Rotational		Rock slump	Debris slump	Earth slump
	Translational	Few units	Rock block slide (including wedge failure)	Debris block slide	Earth block slide
		Many units	Rock slide	Debris slide	Earth slide
Lateral spreads			Rock spread	Debris spread	Earth spread
Flows			Rock flow (deep creep)	Debris flow (soil creep)	Earth flow (soil creep)
Complex			Combination of two or more principal types of movement		

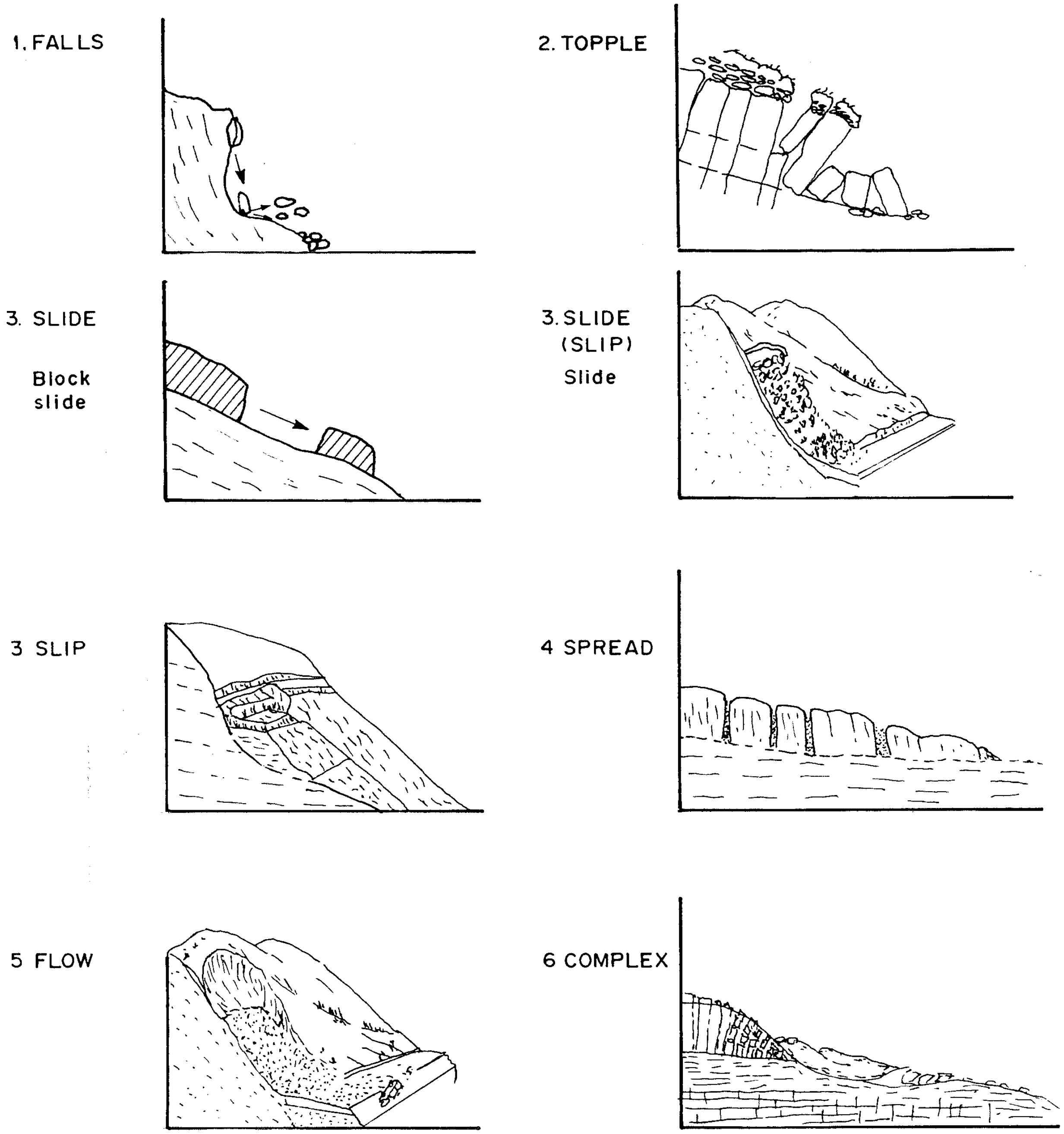

FIGURE 1

TYPES OF SLOPE MOVEMENT (Adapted from Varnes[4]*)*

Spreads: The dominant mode of failure in spreads is lateral extension accommodated by shear or tensile fractures.

Flows: In soils, both fast and slow flows are produced by a fluid-like movement of unconsolidated materials in either a wet or a dry state. Flow in rock is usually classified as creep, ie slow deformation under constant stress.

Complex: Slope movements often involve a combination of a number of these processes, either simultaneously or at different times during their development. These are complex movements.

It is important to identify types of possible failure at an early stage of the investigation. The design and interpretation of the investigation programme must be based on the possible type of failure, and the possible consequences of such a failure. The potential type of failure can usually be estimated at an early stage from a brief study of the geological material and structure, past history of instability and observation of local conditions.

2.2 CAUSES OF INSTABILITY IN CUTS

The main cause of instability in cuts is man's influence on the equilibrium of nature. Most natural slopes are in a state of geomorphological equilibrium under normal climatic conditions. However, the construction of a cut often results in the removal of lateral support and a change in natural ground-water conditions. The equilibrium is thus disturbed. Any outside influence (eg rainfall, earthquake, material weathering, blasting, external loading at the top of the slope, etc) can therefore trigger a slope movement. Interference by man with natural ground-water and surface-water regimes through dam construction, river diversion or even small-scale structures such as drains and soak pits, may result in unstable conditions in adjacent slopes and hillsides.

The main causes of instability can therefore be summarized as:

- unfavourable ground-water conditions and movements;
- unfavourable geological features, eg dip, joints, faults, dykes;
  oversteep slopes, ie removal of lateral support;
- unconsolidated loose material;
- unfavourable dip of strata;
- stress relief in deep cuts;
- destruction of vegetation;
- changes of material properties due to construction;
- undercutting by erosion;
- surcharge at the top of the slope and
- seismic forces.

It is important to understand the principal causes of instability by observation and investigation of cuts in different situations.

3 RECOGNITION OF POTENTIAL INSTABILITY

During this, the reconnaissance stage of the investigation, a general overview of the possible problem is obtained. This is the most important stage as it is during this process that the decision to carry out further investigation and the extent of this investigation is made. The reconnaissance stage is generally restricted to a desk study of all the available information followed by a general site visit where the surface topography, geology and water sources are examined, and the stable angles of natural and man-made slopes are noted.

3.1 TOPOGRAPHY

The first indication of possible instability problems can be obtained from a study of the topography. Topographic maps, aerial photographs and site reconnaissance all provide useful data on whether instability is likely to occur or has occurred in the past. Topographic maps, aerial photographs and orthophotos on various scales are readily available for most of the subcontinent. Evidence of past instability in the form of scars, terracetting, hummocky ground, bent trees, displaced fences and landslide debris is a good indicator of possible problems. An examination of existing cuts in the area often indicates possible problems and stable slope angles.

The incidence of instability is obviously likely to be greater in mountainous and rugged terrain than in rolling or gently undulating areas. However, areas with a rolling topography may have more deeply weathered, variable materials and poorer ground-water conditions.

Certain geomorphological features (land forms) are potentially less stable than others and cognizance should be taken of these (Table 2).

3.2 GEOLOGY

A thorough understanding of the local geology is necessary. Initially this involves the consultation of all available geological maps (both small- and large-scale), agricultural soil maps and soil engineering maps and reports. These data, when combined with the information from topographic maps and aerial photographs and an initial field reconnaissance, should provide adequate information to determine how much further investigation is warranted.

TABLE 2

Key to some land forms and their susceptibility to landslides
(after Rib and Liang[5])

Topography	Landform or geologic materials	Landslide potential*
I Level terrain		
A Not elevated	Floodplain	3
B Elevated		
1 Uniform surface	Terrace, lake bed	2
2 Surface irregularities, sharp cliff	Basaltic plateau	1
3 Interbedded - porous over impervious layers	Lake bed, coastal plain, sedimentary plateau	1
II Hilly terrain		
A Surface drainage not well integrated		
1 Disconnected drainage	Limestone	3
B Surface drainage well integrated		
1 Parallel ridges		
(a) Parallel drainage	Basaltic hills	1
(b) Trellis drainage, ridge-and-valley topography, banded hills	Tilted sedimentary rocks	1
(c) Pinnate drainage, vertical-sided gullies	Loess	2
2 Branching ridges, hilltops at common elevation		
(a) Pinnate drainage, vertical-sided gullies	Loess	2
(b) Dendritic drainage		
(i) Banding on slope	Flat-lying sedimentary rocks	2
(ii) No banding on slope		
• Moderately to highly dissected ridges, uniform slopes	Clay shale	1
• Low ridges, associated with coastal features	Dissected coastal plain	1
• Winding ridges connecting conical hills, sparse vegetation	Serpentinite	1
3 Random ridges or hills		
(a) Dendritic drainage		
(i) Low, rounded hills, meandering streams	Clay shale	1
(ii) Winding ridges connecting conical hills, sparse vegetation	Serpentinite	1
(iii) Massive, uniform, rounded to A-shaped hills	Granite	2
III Level to hilly, transitional terrain		
A Steep slopes	Talus, colluvium	1
B Moderate to flat slopes	Fan, delta	3
C Hummocky slopes with scarp at head	Old slide	1

*1 = susceptible to landslides; 2 = susceptible to landslides under certain conditions and 3 = not susceptible to landslides except in vulnerable locations

A summary of possible problems, associated with different rock and material types, is provided in Table 3[5]. Although this is fairly generalized, it will assist in the decision regarding the extent of further investigation (see 3.8).

3.3 WATER

Most landslides are triggered by water. Therefore the investigation for cuts in areas falling into the water-surplus zone of South Africa[6] (Figure 2) is of great importance.

Both surface water and ground water influence the stability of a slope and all available knowledge concerning water conditions should be collected. These data can be obtained from topographic, geological and engineering geological maps, aerial photographs, past experience and pedological maps or reports. Local farmers usually have a useful knowledge of run-off conditions, moist areas and ground-water depths.

It should be remembered that the rainfall in South Africa is subject to a wet/dry oscillation lasting about 18 years[7]. The incidence of instability during the wet cycle is significantly greater than during the dry cycles. It is important, therefore, to relate the prevailing conditions to the stage in the rainfall cycle, and if in the dry cycle to extrapolate the results to the future wet cycles. The present period (1990) is the beginning of a wet cycle which can be expected to continue until about 1998 after which a dry cycle can be expected until about 2008.

3.4 PAST EXPERIENCE

Relevant data on past instability in the same or similar materials can often be obtained from case histories (published and unpublished). These data will make it possible to assess critically the type, frequency and relevance of sampling and testing to be done.The observation of existing slopes is of the utmost importance. Any indication of slipping and scarring or rehabilitation works deserves due attention.

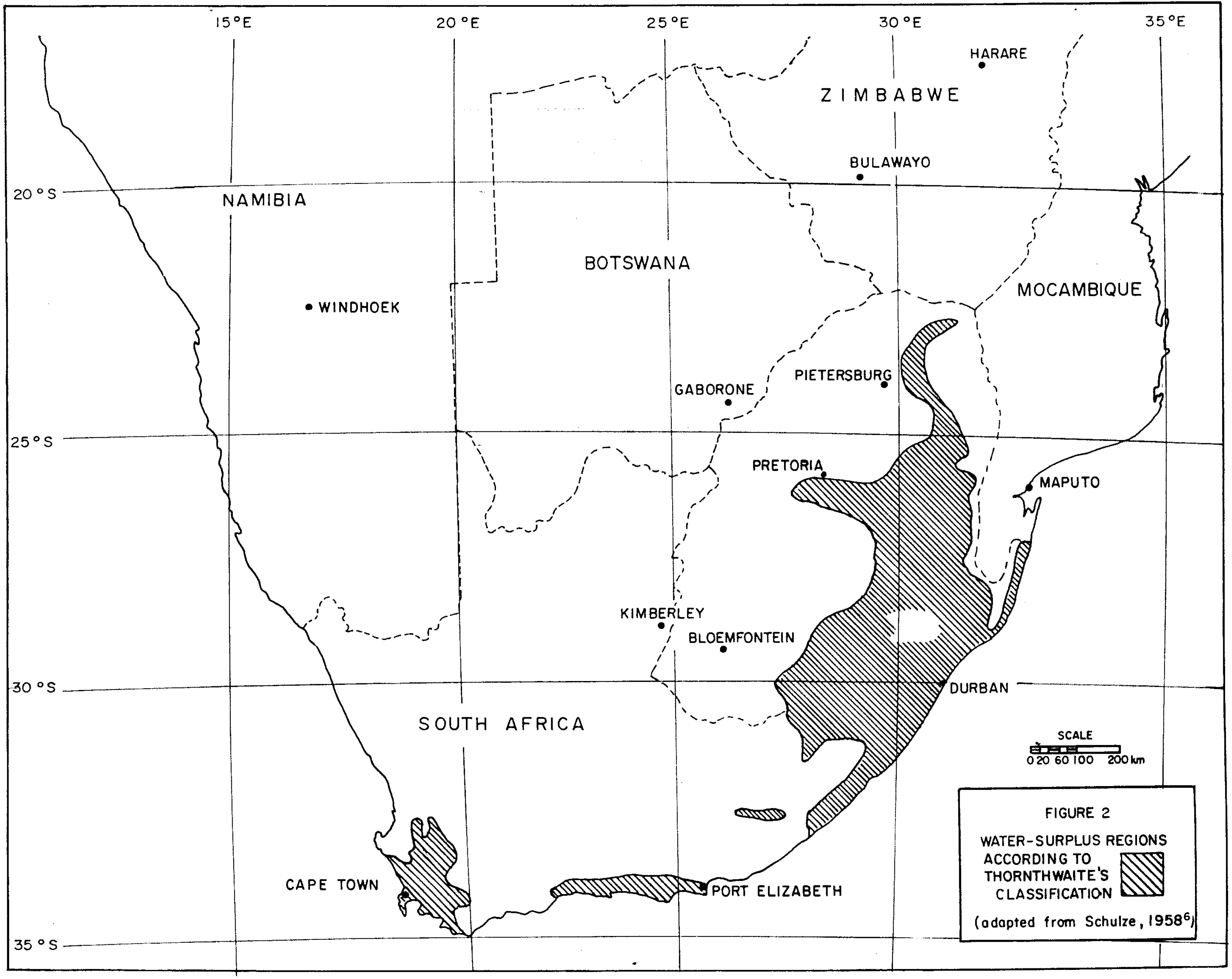

FIGURE 2

WATER-SURPLUS REGIONS ACCORDING TO THORNTHWAITE'S CLASSIFICATION ▨

(adapted from Schulze, 1958[6])

TABLE 3

Summary of rock types, weathering products and performance of cut slopes[43]

	Group	Main parent materials	Weathering products	Stability and possible types of failure*		
				Unweathered/ partly weathered	Weathered	Erodibility
1	Metamorphic rocks	Schist, phyllite, slate	Plastic clays, sands	Poor, rock topples, falls and slides, rock block slides along cleavage, joints etc	Good, if well-drained, earth slump or earth slides if not	Soils may be erodible
2	Acid igneous rocks	Granite, gneiss, syenite, felsite, granodiorite, rhyolite	Sandy to silty materials	Good, 2 or 3-dimensional rock block slides along joints and pseudo bedding	Good, if adequately drained, earth slides or slumps if not	Some decomposed granites are dispersive. Shallow angled cuts will often erode severely
3	Basic igneous rocks	Gabbro, norite, basalt, dolerite, andesite, pyroxenite	Expansive clays	Good, 2 or 3-dimensional rock block slides along joints	Good, if adequately drained, earth slides or slumps if not	Soil may be highly to slightly erodible. Certain rocks weather rapidly
4	Arenaceous and rudaceous rocks	Sandstone, quartzite, conglomerate, arkose	Sands and gravels	Influenced by dip, rock block slides common, wedge failures possible	Good, if adequately drained, rotational/ translational slump if not	Usually not erodible
5	Argillaceous rocks	Mudstone, shale, siltstone, marl	Clay and silt	Poor, rock block sliding along bedding common, small wedge, failures along joints	Earth slides or slumps if not adequately drained.	Usually not erodible but often rapidly slaking
6	Diamictites	Tillite	Silty clays and clayey sands	Poor when strata dips into cut, large block slides along clay filled bedding planes	Good, generally self-draining; possible earth slumping	Soils usually not erodible; some outcrops weather rapidly whereas others display a sort of "piping"
7	Carbonate rocks	Dolomite, limestone	Clay wad, sand and gravel	Stable, depending on attitude of jointing	Occasional earth flows or slumps when wad becomes saturated	Wad may be slightly erodible
8	Other sedimentary rocks	Banded ironstone, chert, pedocretes	Gravel - sands	Generally not very thick, stable	Probably stable; very few exposures	Usually not erodible
9	Residual materials	Clays, sands, silts	-	Unstable if water flow is not controlled (earth slumps)		Depends on parent materials; see above
10	Transported materials	Colluvium, sands	-	Unstable if water flow is not controlled (earth and debris slumps)		Minor problems with erosion
11	Complex areas	Intrusions, faults	Sands, silt, clay gravel	Often unstable, all types of failure, block slide, wedge slides, earth slumps, earth and debris flows etc		Variable

* The stability of any slope depends to a large extent on the ground-water conditions.

3.5 DIMENSIONS OF THE CUT

In deeper cuts, there is generally more interference with existing stability, material and groundwater conditions and the incidence of instability can be expected to be higher. However, it is important not to underestimate the interference with the stability caused by small cuts, especially if these occur at the foot of a higher natural slope (Figure 3). It is often these slopes which give problems. A small change in batter results in significantly increased excavation requirements and batters are therefore constructed as steep as possible.

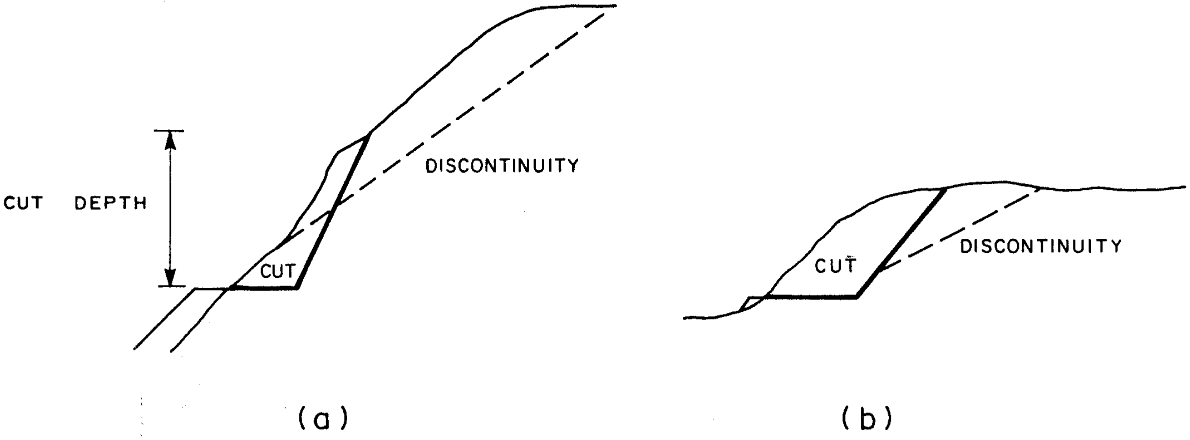

Figure 3
Undercutting of higher slopes

3.6 LANDSLIDE-SUSCEPTIBILITY

Should the topographic, geological, geomorphological and water conditions indicate possible problems, the engineer may decide whether to consult a geotechnical specialist. A generalized landslide-susceptibility map[8] (Figure 4) is included to assist with this decision. Areas of high susceptibility generally have an annual water surplus and are hilly to mountainous. Slopes in these areas are most critical and the probability of instability occurring is high if care is not taken during the design of the slope.

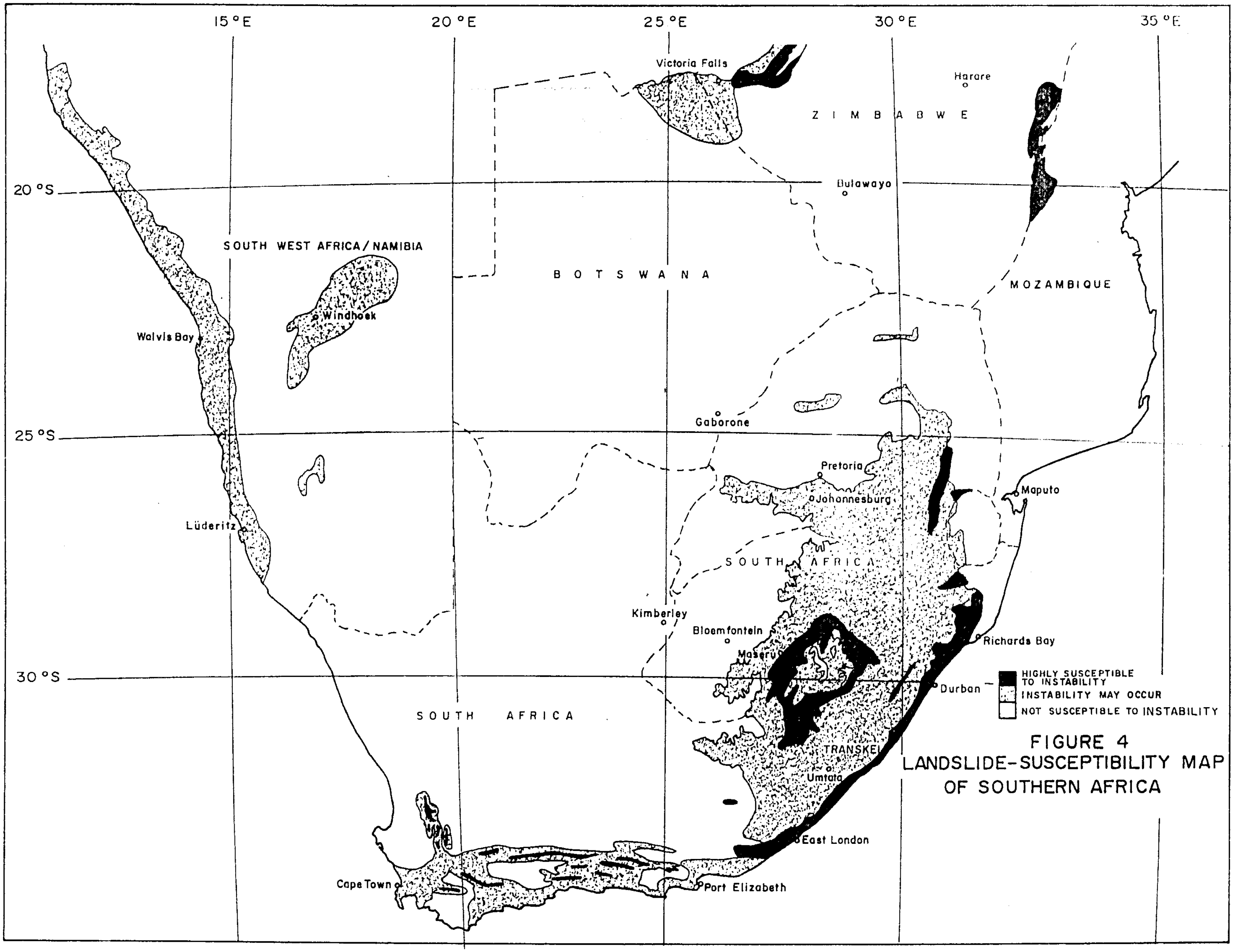

FIGURE 4
LANDSLIDE-SUSCEPTIBILITY MAP OF SOUTHERN AFRICA

Areas of low susceptibility tend to be the drier areas of the country and generally have a low relief. The probability of instability is low, although failure of slopes may occur under extreme conditions of rainfall or inadequate design. Moderately susceptible areas may have a combination of high relief and dry conditions or may have unfavourable geological structures eg steep dips which may result in instability. Localized areas of seepage or of steeply inclined geology which may lead to instability, are obviously not pin-pointed on a map of this sort. The map is only intended as an aid during the preliminary investigation stages for a road.

3.7 THE USE OF REMOTE SENSING TECHNIQUES

Remote sensing is a powerful technique for slope stability studies. This is a rapidly expanding field and has progressed from being restricted to the visible and near visible electromagnetic spectrum with frequencies of about 10^{14} to 10^{15} cycles/sec some years ago to cover almost the full spectrum from 10^{2} to 10^{20} cycles per second[5].

Conventional aerial photographs are the easiest to use and can be used with minimal experience to identify existing instability. The recognition of potential instability and other aspects such as seepage and geological structure require more experience but can be done rapidly by one experienced in aerial photographic interpretation. Colour infrared photographs are also extremely useful, particularly for moisture studies.

The best results can be obtained from multi-spectral scanning (MSS), where a number of wave lengths are recorded and computer enhancement of certain wavelengths and combination of these with other wave lengths results in extremely useful information. The production of MSS tapes is presently expensive but for many large projects it could prove highly cost-effective. Its use could be combined with construction materials location. MSS data in combination with topographic, hydrologic and geologic, engineering geologic and even cultural information which has been compiled into a geographic information system (GIS) can be extremely valuable in identifying potentially unstable areas, high risk areas and even probability of failure maps[9].

3.8 NECESSITY FOR FURTHER INVESTIGATION

At this stage of the investigation, the decision on whether any further investigation is required should be made. The optimum solution is for a specialist to be involved from the initial stages. At the end of the reconnaissance stage the specialist decides on the required investigation in consultation with the client with the objective of achieving an equitable balance between the cost of the investigation and the risk of not obtaining sufficient information. This is, however, generally impractical. However, the information obtained from the desk study, a reconnaissance site visit and the use of remote sensing techniques as discussed in this chapter provide all the information necessary to identify the necessity for further investigation.

Figure 5[10] shows this decision process which can be followed by the non-specialist. This allows the non-specialist to design simple cuts on past experience and it indicates when specialist advice is required ie in high risk areas. In many cases the specialist may decide that no further investigation is necessary and that the slope can be designed on past experience.

The flow diagram has been designed such that should specialist advice not be necessary and failure does occur, the consequences of failure are minimal. However, in a built up area or where life or high risk property is at stake, specialist advice should be obtained.

Should major instability be possible, it may at this stage be necessary to realign the route, avoiding problem areas.

3.9 MANAGERIAL CONSIDERATIONS

It is of vital importance that regular, close liaison is maintained between the client and the designer of cuttings. Aspects such as the consequences of failure of the cuttings should be clearly defined. The constraints and restrictions in terms of the scope and cost of the work, and time aspects should be fully understood but remain as flexible as possible. In this way, the investigation can be optimised as it proceeds to concentrate on certain aspects, curtail some of the investigation if necessary or be altered to ensure that the data collected is sufficient and appropriate to result in the correct decision.

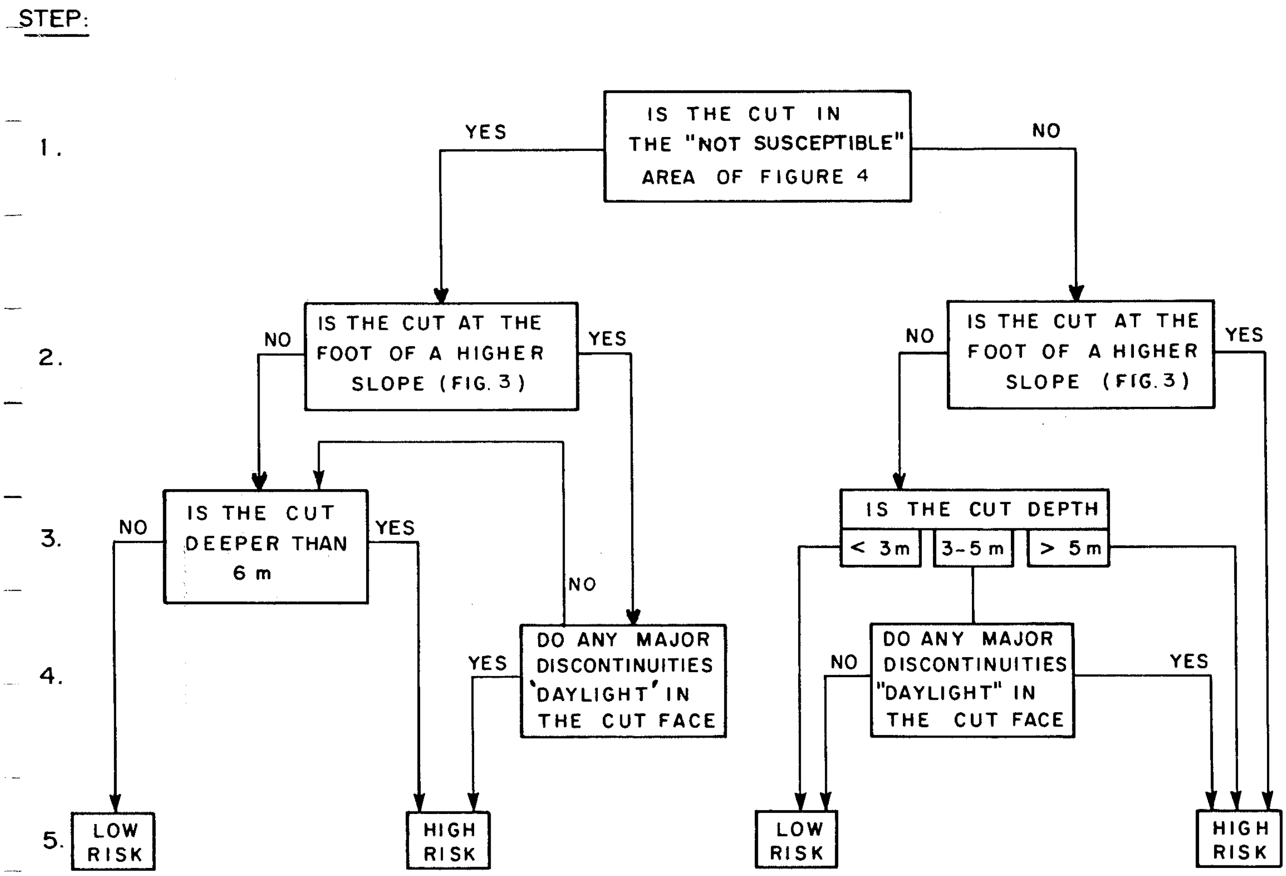

Figure 5

Flow diagram for risk assessment.

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Standard policies of the client should be defined. Aspects such as which standard practices are negotiable, where and for how long should samples be stored and where will materials cut to waste be dumped, etc should be clarified at an early stage in the negotiations.

The risk acceptability should be clearly defined. The traditional practice of specifying the factor of safety (FOS) results in a clear definition to the effect that failure will not occur when FOS is greater than unity unless either the material properties or water regime changes. A probability of failure approach on the other hand relates the stability to a finite value incorporating a certain identified risk. An acceptable value for this risk needs to be mutually decided on between the client and consultant.

4 INVESTIGATION

4.1 SITE INVESTIGATION

In the case of many cut slopes, successful design depends on a thorough site investigation. The site investigation should provide adequate information to:

- define fully the surface and subsurface geology over the area in which the cut will be constructed;
- define the ground-water regime in terms of flow paths, porewater pressures, permanent and temporary (perched) water tables and adjacent water sources under the worst possible expected conditions;
- define the geological and mechanical properties of the materials involved in the cut, regarding both the stability and excavation aspects;
- define the subsurface geological structure in order to identify possible planes of failure and
- assess the probable failure mechanisms, if any.

Figure 6 shows an idealized site investigation process[11]. Depending on the proportions and importance of the cut, this decision chart should be followed to a greater or lesser extent.

4.1.1 Geology

The surface geology should be mapped to a fairly large scale (1:1000 to 1:2500). Note should be taken of outcrops, different soil types and geological structure where exposures permit. From these data an estimate of the subsurface geology can be made. With this knowledge in mind, a subsurface exploration programme can be drawn up to confirm any assumptions in the initial estimate. It is often useful to excavate a trench or pit to get a direct view of the material and the geological structure.

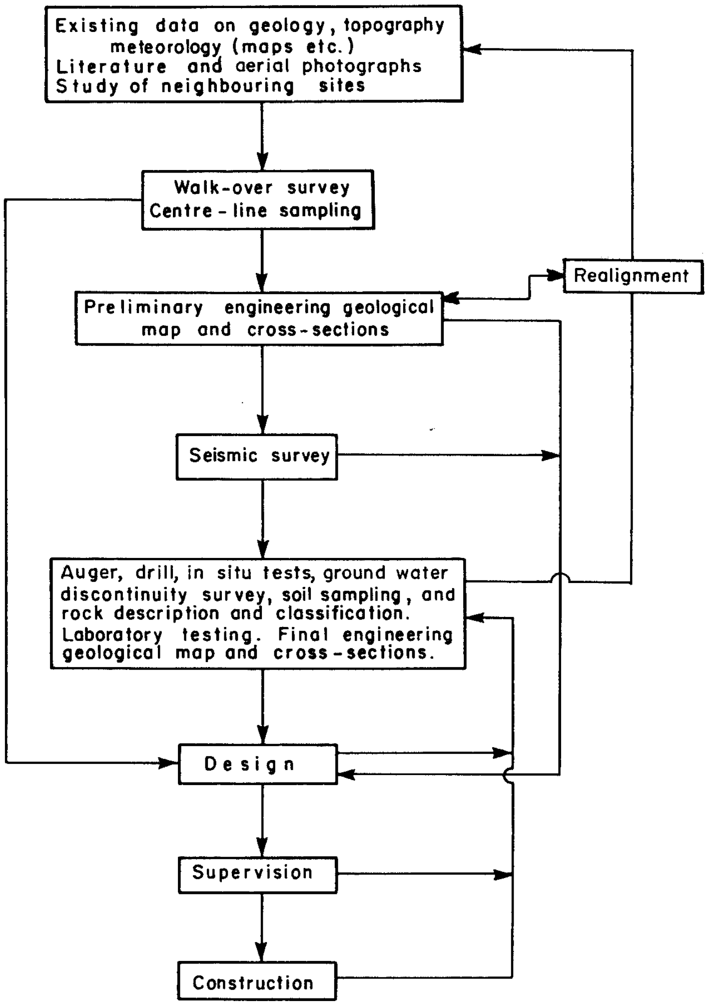


FIGURE 6

SITE INVESTIGATION: FLOW DIAGRAM FOR CUT SLOPES

A seismic refraction survey can be used to delineate the soil/rock or soft rock/hard rock boundaries. It is useful as a rough indicator of excavation properties when combined with geological input[12] (eg Figure 7 for a D9 type ripper[13]) but is of little use in stability estimates other than defining material boundaries. However, a seismic survey is of invaluable assistance in the design of the boring or drilling programme as unexpected variations in the soil/rock contact can be investigated directly. **It is always necessary to confirm seismic refraction data by means of drilling.**

The success of the drilling programme is related not only to the number of boreholes, but also to the quality of the samples extracted and the drilling record. The use of inclined boreholes to intersect steeply dipping discontinuities should be considered. Numerous boring and core-drilling techniques are available. These range from augers to double and triple-barrel and wireline rotary drilling. Integral core sampling[14] is a highly specialized technique for obtaining complete, oriented cores. The final choice of equipment will depend on the material type, accessibility of the site, availability of equipment and available funds.

The layout and spacing of the borings will depend on the anticipated subsurface geology, the configuration and dimensions of possible unstable areas and the anticipated mechanism of failure. The practice of specifying a minimum number of boreholes per unit length of cut is both undesirable and uneconomical. The drilling programme should be designed on a sound geotechnical basis, and may be done in two stages: a few holes initially followed by a more detailed programme later.

Usually it is not economical to carry out a site investigation so thoroughly that the possibility of unforeseen factors being discovered during the actual investigation for the cut is completely eliminated. Both the designer and the supervisory staff should be aware of this. **The actual excavation of the cut should therefore be regarded as the final phase of the site investigation.**

4.1.2 Water

Surface-water conditions should be surveyed. This will involve an investigation of possible water sources, of the channelling of water into the slope and of ponding or seepage, which

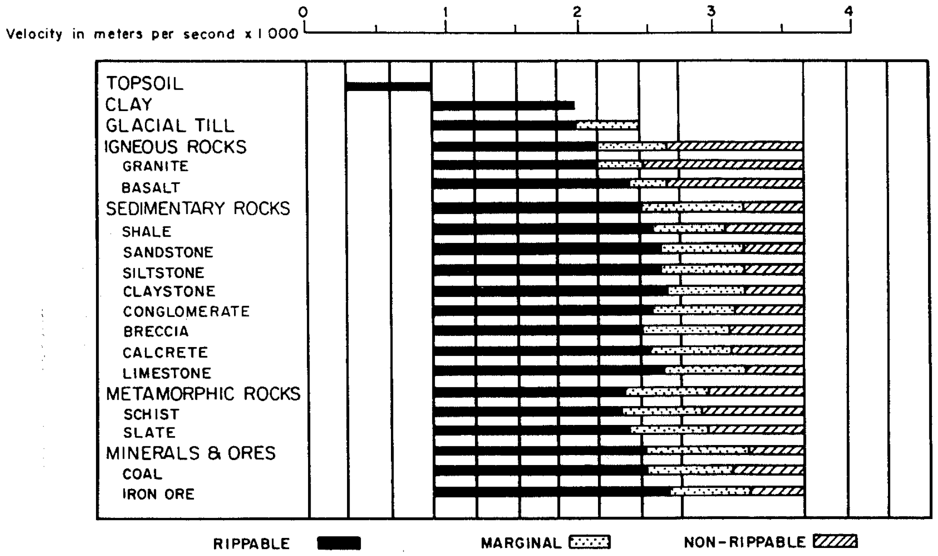


FIGURE 7

RIPPER PERFORMANCE RELATIVE TO SEISMIC WAVE VELOCITY THROUGH SOME SOILS AND ROCKS (D9 TYPE RIPPER)

(Adapted from Weaver, 1975)

may affect the slope. Note should be taken of any flora or fauna normally associated with moisture, eg reeds, rushes, frogs and crabs.

A preliminary indication of subsurface water conditions can be obtained from the detailed drilling records which indicate permeable soil or rock layers, zones of water loss and standing water levels. However, **it must usually be specified in the drilling contract that this information is to be recorded**.

Should any of these conditions indicate a possible excess of water, further hydrologic observations should be carried out.

It is useful to monitor standing water levels in the boreholes drilled during the site investigation for as long as possible; if only to obtain an indication of probable water table levels and seasonal fluctuations, especially if drilling was done during the dry season. The stage in the long-term wet/dry cycle[7] should always be borne in mind. It should be remembered that infiltration in clay soils may be very slow and standing water levels may not be representative. Standpipes or other appropriate piezometers should be installed in boreholes in softer materials. Should unexpected water conditions be encountered, a decision as to what form of further investigation is required or whether geotechnical specialists should be consulted, must be made.

4.2 FIELD TESTING

Once the subsurface geology and geometry have been defined, the mechanical properties of the soils, rock and discontinuities must be determined for design purposes. A number of techniques for quantifying these properties in situ are available, but these usually require sophisticated equipment and testing procedures. In addition, considerable experience is necessary to interpret the output in terms of field relationships. It is therefore recommended that field testing, other than simple water level monitoring, be left to the geotechnical specialist who has the necessary equipment and experience to interpret the results.

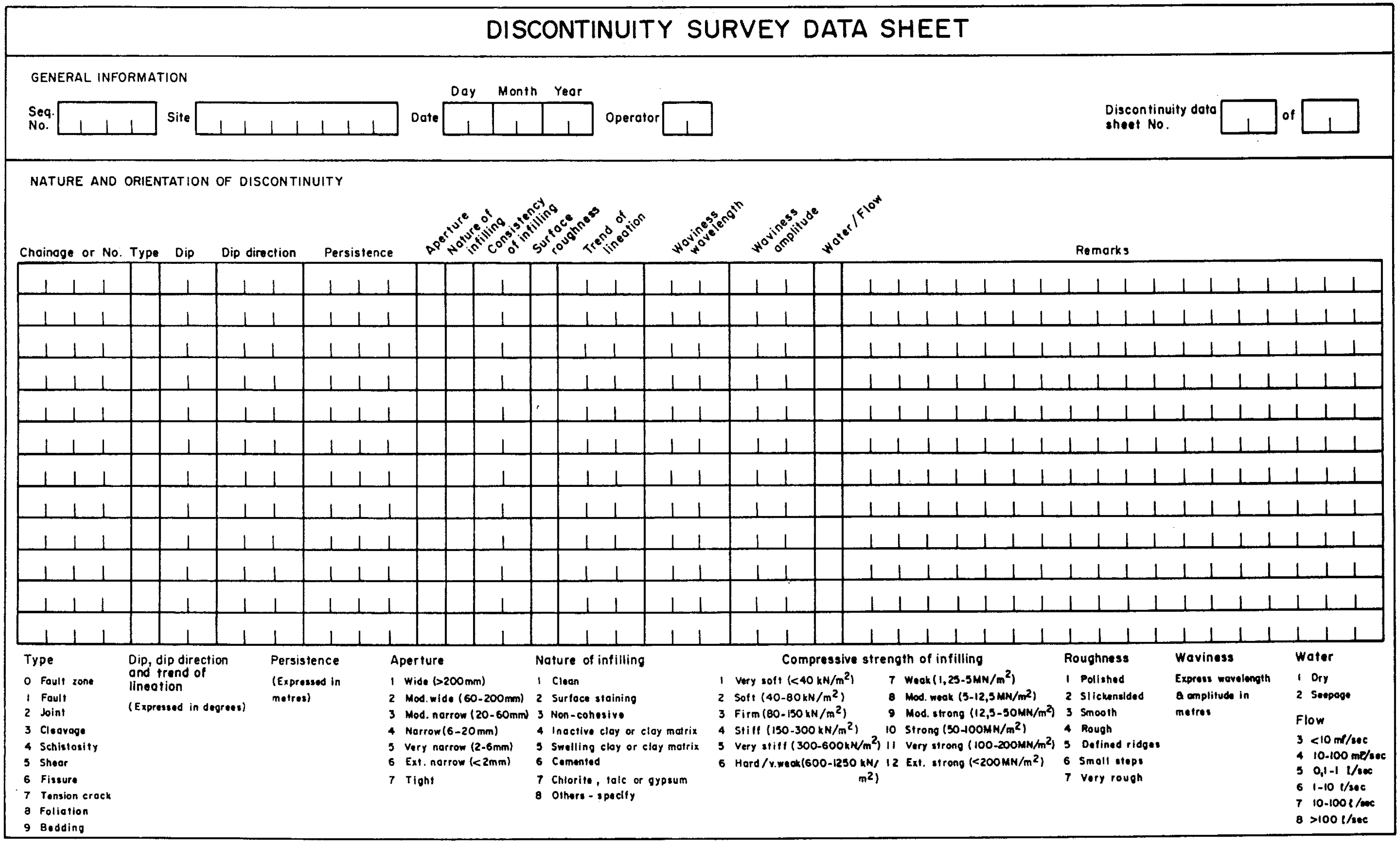
The main problem with field testing is that most materials involved in cut construction in southern Africa consist of overconsolidated soils and weathered rock. Failure is therefore unlikely to follow the classical "slip circle", but will be associated with pre-existing planes of weakness and discontinuities. To identify these planes and to test their shear strength, obviously pose a problem.

In the rare cases where materials consist of normally consolidated clays without gravel, cobble-sized particles or interconnecting planes of weakness, techniques such as vane-shear testing will yield meaningful results.

Techniques such as dynamic and static penetration tests can provide useful information. This information, however, is largely empirical and can lead to misinterpretation in variable materials.

For cuts in unweathered or weathered rock, field testing can be very expensive and time-consuming and, unless the mechanism of failure is completely understood, the testing will probably not be realistically applicable to any potential failure. Large-scale direct shear tests in trenches excavated to the depth of probable failure, may yield useful results but the equipment needed is generally not freely available.

An important aspect of the stability of deep or important rock slopes (and some soil slopes with a relict structure) is an accurate and complete representation of the geological structure. A joint survey is therefore necessary. If there are no neighbouring cuts, an inspection trench will have to be excavated to expose sufficient joints. A random or line survey of the joints must be conducted in both the horizontal and vertical directions. As a certain amount of experience is necessary for a good joint survey, it is recommended that specialist assistance be obtained for this work. The non-specialists can undertake joint surveys for shallow cuts with few discontinuity sets by using a form similar to that shown in Figure 8. These data should then be plotted on a stereographic projection and the attitudes of dominant and critical joint sets identified. The use and interpretation of stereographic projections requires specialist knowledge and is not discussed in this manual but is fully covered by Phillips[15] and Hoek and Bray[16].



DISCONTINUITY SURVEY DATA SHEET

GENERAL INFORMATION

Seq. No. ☐ Site ☐ Date Day ☐ Month ☐ Year ☐ Operator ☐ Discontinuity data sheet No. ☐ of ☐

NATURE AND ORIENTATION OF DISCONTINUITY

Chainage or No.	Type	Dip	Dip direction	Persistence	Aperture	Nature of infilling	Consistency of infilling	Surface roughness	Trend of lineation	Waviness wavelength	Waviness amplitude	Water/Flow	Remarks

Type
0 Fault zone
1 Fault
2 Joint
3 Cleavage
4 Schistosity
5 Shear
6 Fissure
7 Tension crack
8 Foliation
9 Bedding

Dip, dip direction and trend of lineation
(Expressed in degrees)

Persistence
(Expressed in metres)

Aperture
1 Wide (>200mm)
2 Mod. wide (60-200mm)
3 Mod. narrow (20-60mm)
4 Narrow (6-20mm)
5 Very narrow (2-6mm)
6 Ext. narrow (<2mm)
7 Tight

Nature of infilling
1 Clean
2 Surface staining
3 Non-cohesive
4 Inactive clay or clay matrix
5 Swelling clay or clay matrix
6 Cemented
7 Chlorite, talc or gypsum
8 Others - specify

Compressive strength of infilling
1 Very soft (<40 kN/m^2)
2 Soft (40-80 kN/m^2)
3 Firm (80-150 kN/m^2)
4 Stiff (150-300 kN/m^2)
5 Very stiff (300-600 kN/m^2)
6 Hard/v.weak (600-1250 kN/m^2)
7 Weak (1,25-5 MN/m^2)
8 Mod. weak (5-12,5 MN/m^2)
9 Mod. strong (12,5-50 MN/m^2)
10 Strong (50-100 MN/m^2)
11 Very strong (100-200 MN/m^2)
12 Ext. strong (<200 MN/m^2)

Roughness
1 Polished
2 Slickensided
3 Smooth
4 Rough
5 Defined ridges
6 Small steps
7 Very rough

Waviness
Express wavelength & amplitude in metres

Water
1 Dry
2 Seepage

Flow
3 <10 mℓ/sec
4 10-100 mℓ/sec
5 0,1-1 ℓ/sec
6 1-10 ℓ/sec
7 10-100 ℓ/sec
8 >100 ℓ/sec

FIGURE 8 *DISCONTINUITY SURVEY DATA SHEET*

4.3 LABORATORY TESTING

Only two important material properties are required for slope design and acceptable values for these can usually be determined in the laboratory. They are the shear strength of the material or discontinuity involved and the density of the material. In addition, expected porewater pressures are required in many analyses. The density of the material is fairly easily measured, either in the field or in the laboratory. Undisturbed samples are required for the determination of shear strengths. It must be borne in mind that the act of sampling causes some disturbance of the samples by compaction or stress release and even the most carefully collected samples are not truly undisturbed. The collection and testing of "undisturbed" samples should be carried out by experienced people.

Sampling for the testing of shear properties should not be done haphazardly or randomly. The tests involved can be fairly costly and time-consuming, and therefore only that portion of the material likely to lead to failure should be sampled. A good understanding of the fundamental behaviour of the material, its composition, structure and properties, the variation of these, and probable modes of failure, is therefore essential before any shear testing is undertaken.

For soils, triaxial compression testing or direct shear testing is usual. Triaxial testing can be carried out under a number of different conditions such as drained or undrained, consolidated or rapidly sheared, each condition being valid for a different in situ material state. Because of the short drainage pattern in the direct shear test, effective stress parameters are obtained for all but the most plastic clays.

The choice of triaxial testing method should be left to a geotechnical specialist. An advantage of triaxial testing is that the field condition can be simulated very closely and any changes that occur during construction such as drainage and stress release, can be incorporated into the testing programme.

The actual shear strength of a material or discontinuity used in an analysis can vary between the peak strength and the residual strength. Depending on the mineralogy of the material and/or on the roughness of the discontinuity, the residual strength can be substantially lower than the peak strength. Should any sign of previous movement be noted, residual strength should be used for analysis. However, in certain partially saturated soils where deep-seated saturation is unlikely eg Berea Red Sand, the residual strength (ϕ_r) is conservative.

5 DESIGN

Complex slopes or cuts that may result in dangerous or expensive consequences if they fail, should be designed by a geotechnical specialist. Shallow cuts or temporary cuts, where the consequences of failure will be minor, can usually be designed on past experience or by using empirical methods (Sections 3.6 and 3.8).

Certain intermediate slopes, however, may be designed by non-specialist engineers by means of simple stability analysis and adequate testing. It is costly and of dubious value to conduct extremely accurate analyses when material properties are at all suspect or where sound sampling and selection procedures were not carried out. With the ready availability of simple computer programs to analyse stability, it is often very useful to carry out sensitivity analyses to investigate the effect of differences in the material properties and ground-water conditions which may occur and obtain an overall understanding of the potential problems.

5.1 PHILOSOPHY OF DESIGN

With computerization of traditional simple stability analysis techniques[17,20] available to all engineers a quick, inexpensive estimate of the optimum design of a soil, weathered rock or rock slope is possible, provided that the input parameters are reliable. Because of the inherent variability of geological materials, the design of each slope is, however, unique.

Before any design is attempted, the following data are required:

- a thorough understanding of the surface and subsurface stratigraphy and geological structure;

- a knowledge of the underground water levels, sources and flow paths;

- a confident estimate of the probable mode of failure of the cut;

- a reliable estimate of the range of material properties involved in any possible failure and

- an acceptable minimum value for the required factor of safety or acceptable risk which takes into account the economic consequences of precautionary measures and the consequences of failure.

No analysis should be attempted until each of the above requirements has been met. If economic or practical constraints do not permit a reliable estimate of any parameters, a sensitivity analysis may be carried out.

5.2 FACTORS OF SAFETY

A factor of safety can be defined in a number of ways, all relating to the ratio between the forces within a slope resisting strain (ie shear strength of the soil or discontinuity) and the factors causing strain (eg gravity, surcharge). If all the parameters involved in an analysis could be determined with absolute reliability for the worst possible state, a factor of safety (FOS) of 1 would be acceptable. However, because of the uncertainties involved in the determination of the material properties and the exact plane of failure, and because of the heterogeneous nature of geological materials, a degree of risk is allowed for and a factor of safety of between 1,25 and 1,5 is usually required.

A survey of recommended factors of safety indicated a value of 1,5 as being generally acceptable in cases where there is a risk of danger to people or property, whereas a value of 1,25 is acceptable where this risk is less. The following factors of safety can be accepted for the different standards of road (Table 4). However, the volume of material involved in a potential failure and the consequences of the failure should be taken into account.

TABLE 4 Recommended minimum factors of safety for various standards of road

Standard of road	FOS[a]	FOS[b]
Interurban freeways and major interurban roads	1,5	1,3
Major rural roads	1,3	1,2
Lightly trafficked roads	1,25	1,1

[a] Factor of safety for areas where failure would be of major consequence

[b] Factor of safety for areas where failure would be of minor consequence

These factors are recommended minima and where possible attempts should be made to exceed them. However, external constraints may make it necessary to use these values. The material properties and ground-water conditions vary with time and the factor of safety may therefore be lower than required for short periods. A value of 1,1 should only be used where the risk of damage is inconsequential ie loss of life is highly improbable, alternative routes are available and the cost of property or land use is low.

It is important to ensure that the calculated factor of safety is in fact a minimum for that situation. In analyses utilizing iterative converging systems, this is usually achieved. However, when probable non-circular slip planes are subjectively assessed, it is possible that, with the minimum factor of safety, the failure plane will, in all probability, not be that which occurs in reality.

Recently, the risk analysis technique incorporating probability of failure and potential failure damage has become increasingly popular. This is a powerful technique, but the problem of comprehending a calculated probability of failure in terms of well-known safety standards and acceptable limits may require a change in the thinking of many clients (See Section 5.5.2).

5.3 PRACTICAL DESIGN CONSIDERATIONS

It must be noted that many constraints affect the final slope batter.

(a) In urban areas and in mountainous regions, batters are often of necessity very steep.
(b) Stability considerations may require shallow slopes.
(c) Ravelling and erosion may require steep slopes to reduce the area exposed to erosion or shallow slopes in order to reduce run-off velocities and to retain weathered material.
(d) Revegetation of slopes requires batters less than 1:1,5 in order to establish and maintain the vegetation.
(e) Aesthetic requirements often dictate the nature and angle of the slope, ie type of blasting, revegetation etc.
(f) In many cuts the material requirements for adjacent fills determine the angle of the cut so that the cut/fill balance is correct.
(g) Influence of retaining structures (See section 5.6.3).

Once these constraints have been taken into account the final design of the slope can be completed.

At the end of the reconnaissance stage the non-specialist will be able to design many of the cuts on a project if he uses Figure 5, past experience and engineering judgement, together with the data obtained from the reconnaissance eg surface geology, presence of water and batters of neighbouring slopes. Table 5 indicates probable steepest stable batters for different material types to assist in this decision.

The path to follow in the actual design of slopes contains various degrees of sophistication. The simplest designs are those based on design charts. Many design (stability) charts are available but caution should be exercised in their use. Charts such as those of Hoek[16] and Taylor[17] are graphical representations of analytical solutions. Charts relating simple geotechnical properties to stability, however, should not be used for stability analysis.

Most stability charts make a number of assumptions to simplify their development (eg normally consolidated materials, saturated soils, homogenous materials). Many of these assumptions are invalid under local conditions and should the charts be used as preliminary indicators of instability, these factors should be considered. A useful first approximation for the factor of safety (FOS) for quick and slow draining conditions has been developed by Savage[18] based on the Bishop and Morgenstern method of slices[19].

TABLE 5

Probable steepest stable slopes for various materials
Vertical : Horizontal

	Material Type (See Table 3)	Water-surplus area			Rest of South Africa		
		Soil*	Weathered	Unweathered	Soil*	Weathered	Unweathered
1	Metamorphic rocks	1:1,5	1:1,5	1:1,5	1:1,5	1:0,5	1:0,25
2	Acid igneous rocks	1:1	1:0,5	1:0,25	1:1	1:0,25	1:0,25
3	Basic igneous rocks	1:1,5	1:1	1:0,25	1:1,5	1:0,5	1:0,25
4	Arenaceous and rudaceous rock	1:1,5	1:0,5**	1:0,5**	1:1,5	1:0,5**	1:0,25**
5	Argillaceous rock	1:2	1:2**	1:2***	1:2	1:2***	1:2***
6	Diamictites	1:2	1:1,5**	1:0,5**	1:1	1:0,5	1:0,25
7	Carbonate rocks	1:2	1:1,5	1:0,25	1:1,5		1:0,25
8	Other sedimentary rocks	-	1:0,5	1:0,25	-	1:0,5	1:0,25
9	Residual materials	1:1,5	-	-	1:1	-	-
10	Transported materials	1:2	-	-	1:2	-	-

* Recommended not steeper than 1:2 to establish vegetation

** Subject to bedding not dipping into the cut

*** Subject to material not being highly slaking and not dipping into cut

NB: This table should only be used as a rough guide together with local experience, studies of neighbouring slopes and engineering judgement. Weathered materials can be classified as those where weakening of the joints has occurred and their properties are dictated primarily by the joint or gouge strength.

In certain areas it is often useful to cut some granitic soils and argillaceous rocks vertically or at 1:0,25 to reduce erosion of the slopes. However, their stability at these steep batters should be ensured first.

$$FOS_{(quick)} = 5{,}4C + 0{,}5\sqrt{CTS} + 1{,}85T\,(S + 0{,}6)$$

$$FOS_{(slow)} = 5{,}4C + 1{,}3\sqrt{CTS} + 0{,}56T\,(S - 0{,}75)$$

where $C = c/\gamma H$ (ie cohesion (c in kN/m^2) / density (γ in kN/m^3) x height of slope (H in m))
$T = \tan \phi$ (angle of friction of material (ϕ in °)
$S = \cot \beta$ (β = angle of excavation)

The decision as to whether the slow or quick method is used should be based on an estimate of the potential drainage within the material. It is unlikely that at this stage in the investigation, field measurements to assist with this decision will be available.

The next progression is to use simple stability analyses. A number of these are discussed in the following sections.

5.4 SIMPLE STABILITY ANALYSES

Many stability analysis procedures have been devised since the development of the original method of slices of Fellenius[20]. Each method has its attributes and can be used in certain situations. The complexity of some of these analysis methods reduces them to research or academic value only. Applications of some of the simpler, more useful methods are discussed below. These methods should only be used with a clear understanding of the type of expected failure, the material properties and the constraints of the procedure or else the implications of the inclusion of inaccurate data should be appreciated.

5.4.1 Soil slopes

5.4.1.1 Planar slip failure

When a weak layer or discontinuity dips towards the cut face in a cut slope, sliding along this plane may occur as shown in Figure 9.

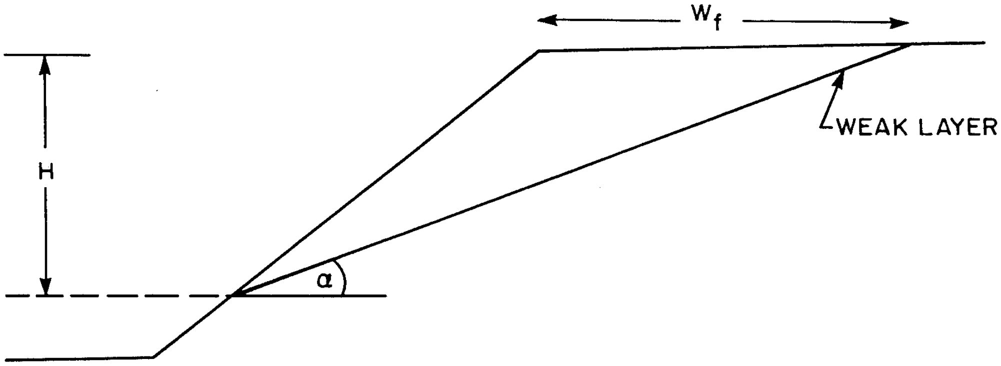


FIGURE 9

PLANAR SLIP FAILURE ANALYSIS

The factor of safety (F) is defined by the equation below[21]:

$$F = \frac{2 \operatorname{cosec} \alpha \, (c'/\gamma W_f) + [(1-r_u) \cos \alpha - C_s \sin \alpha] \tan \phi'}{\sin \alpha + C_s \cos \alpha}$$

where c' = cohesion in terms of effective stress

ϕ' = friction angle in terms of effective stress

γ = density of soil (kg/m^3)

W_f = width of failed area (see Figure 9)

r_u = pore-pressure ratio = $\gamma_w h/\gamma H$ with γ_w being the density of water, h the piezometric head and H the height of the potential failed portion of the slope

C_s = seismic coefficient

Most instances of instability observed in South Africa can probably be classified as planar slip failure. In most moderately to completely weathered rocks and their residual soils, failure follows a combination of existing planes of weakness eg joints, shrinkage cracks or contact between relatively stronger and weaker materials.

Janbu[22] produced a simple method of analysis for non-circular failure which has subsequently been incorporated in a widely used computer program that can generate irregular surfaces, surfaces of sliding block character and general surfaces of irregular shape (STABL and later versions)[21].

5.4.1.2 Non-circular slip failure

A simple program (SWASE) to determine the factor of safety of a slope when up to three planes of weakness exist in the slope is provided by Huang[21] (in both BASIC and FORTRAN).

An important aspect to be noted is that the definition of the pore-pressure ratio (r_u) used by Huang[21], is not the same as that originally defined by Bishop and Morgenstern[19]. Huang[21] defines r_u as follows:

$$r_u = \frac{\text{cross-sectional area of sliding mass under water}}{2 \times \text{total cross-section of sliding mass}}$$

as opposed to Bishop and Morgenstern's definition of

$$r_u = \frac{\gamma_w h}{\gamma d}$$

where γ_w = density of water

γ = density of soil

h = the piezometric head acting on the slip face

d = thickness of the layer or slice (Figure 10)

Huang's definition simply assumes that the density of soil is twice that of water.

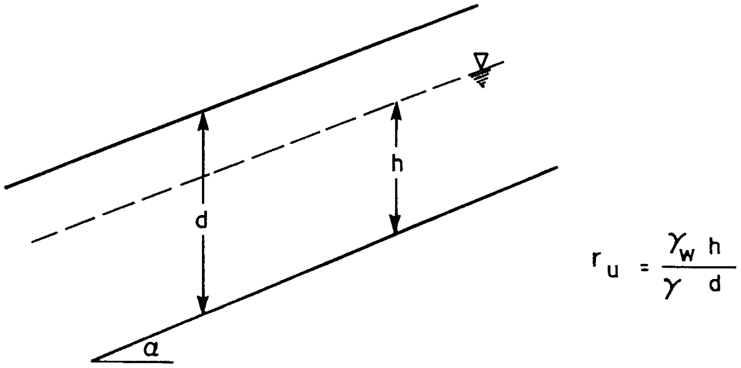


FIGURE 10

PORE-PRESSURE RATIO PARAMETER (r_u)

5.4.1.3 Circular failure

There are many methods for the analysis of circular-type failures and many programs are available for their computation. Each method has its merits and pertains to certain conditions. For example, the friction-circle method of Taylor[17] pertains only to homogenous slopes with a given friction angle. Taylor has presented his analyses in graphical form ie stability charts. However, these are in terms of total stress. Both homogeneous slopes and total stress failure conditions are uncommon in South Africa, which makes Taylor's charts unsuitable for most local conditions.

The method proposed by Bishop[23] is extensively used and although it is fairly simple, it requires a computer because of the iterative procedure used to arrive at the minimum factor of safety. This program (SLOP4) is available from the Division of Roads and Transport Technology[24].

Huang[21] has developed a rapid computer program for the rotational equilibrium analysis of multi-layered embankments. The program (REAME) is particularly useful for those with minimal computer experience, and the manual contains a full source listing in BASIC and in FORTRAN. The program uses either the simplified Bishop method or the "normal method", the results of the latter usually being more conservative than those of the Bishop method.

5.4.2 Rock slopes

5.4.2.1 Plane failure

The stability of all but the simplest rock slopes should be investigated by a specialist. For rock slopes that include obvious inclined planes along which sliding may occur, a simple plane failure is possible and the factor of safety can be defined as[16]:

$$F = \frac{cA + (W\cos\psi_p - U - V\sin\psi_p)\tan\phi}{W\sin\psi_p + V\cos\psi_p}$$

where $A = (H-Z)\mathrm{cosec}\psi_p$

$U = \frac{1}{2}\gamma_w z_w (H-Z)\mathrm{Cosec}\psi_p$

$V = \frac{1}{2}\gamma_w z_w^{\,2}$

$W = \frac{1}{2}\gamma H^2\{(1 - (Z/H)^2)\cot\psi_p - \cot\psi_f\}$ if the tension crack is in the upper slope surface (Figure 11a)

or $W = \frac{1}{2}\gamma H^2\{(1 - (Z/H)^2)\cot\psi_p - \cot\psi_p\tan\psi_f - 1)\}$ if the tension crack is in the slope face (Figure 11b)

where c = cohesion of sliding surface

γ_w = density of water

γ = density of sliding material

ϕ = angle of friction of sliding surface,

H = total depth of cut

Z = depth of tension crack

and the other symbols are as defined in Figure 11

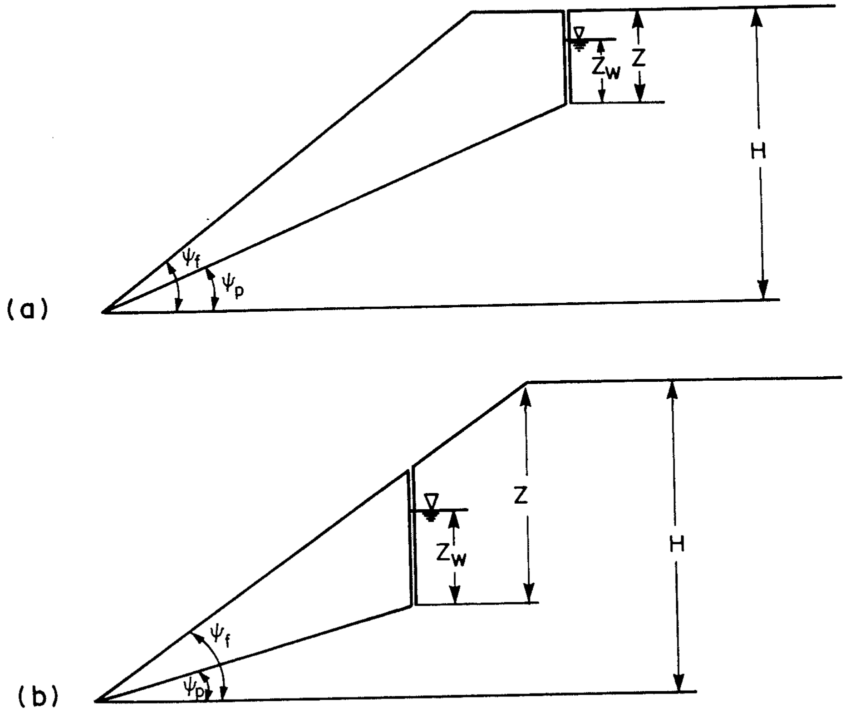


FIGURE II

PLANE FAILURE IN ROCK SLOPES

5.4.2.2 Wedge failure

When failure is likely to follow a number of intersecting discontinuities, an extensive joint survey as described in 4.2 should be carried out. A stereographic projection compiled from the results of the fracture survey can be interpreted, by a specialist to indicate probable three-dimensional wedge failures.

If the stereographic projection indicates a possibility of unstable wedges, a full analysis incorporating cohesion, friction and water pressures should be conducted by a geotechnical specialist.

5.4.2.3 Toppling failure

Toppling failure is a common cause of fairly minor, but maintenance intensive instability. The regular dribbling of rocks and boulders from near horizontal or sub-horizontal strata with steeply dipping joint sets is common. It is, however, not always possible to determine an accurate factor of safety for this mode of failure. The potential for failure can be deduced by analyzing a typical block resting on an inclined plane. If the weight vector which passes through the centre of gravity of the block falls outside the base of the block, the condition for toppling is satisfied and toppling will occur. For potentially large toppling failures, an estimate of the safety factor may be determiend using the method of Hoek and Bray[16]

5.5 OTHER METHODS

5.5.1 Finite element method

Many other methods of stability analysis are available, each having attributes suited to a particular situation. Finite element methods can be used to determine the stability of a slope by two-dimensional plane strain analysis. This type of analysis requires a large input of time and computer use and is most suitable for routine analysis of large slopes such as open-pit mines and quarries. Only in rare circumstances will a cut slope for roads require a finite element analysis and this should be carried out by an experienced specialist.

5.5.2 Probabilistic approach to safety

This approach has been gaining in popularity for some time[25,26,27,28]. Because of the large variation in the strength properties of soil an element of risk is unavoidable in limit equilibrium analyses incorporating the factor of safety. The probabilistic approach takes into account this variability by offering a systematic way of dealing with uncertainties. Although in principle, a large number of test results are required to define the variability of the shear strength accurately, work in the last decade has refined the use of the point estimate method[28]. This allows the prediction of the expected value and variance of a material property from a single representative test[28].

Unlike deterministic methods where a factor of safety is used, probability techniques represent the stability in terms of the mean safety margin ($\bar{\rho}$), which is the numerical difference between the average shear strength ($\bar{s}$) and the average shear stress ($\bar{\tau}$). When this value is less than or equal to zero, the probability of failure (ρ_f) is defined as:

$$\rho_f = \frac{1}{2} - \psi\left(\frac{\bar{\rho}}{\sigma_\rho}\right)$$

where ψ = cumulative probability function (area under the normal curve) of the standard normal variate ($\bar{\rho}/\sigma_\rho$)

$\bar{\rho}$ = mean safety margin ($\bar{s} - \bar{\tau}$)

σ_ρ = standard deviation of the safety margin ($\sqrt{\sigma^2_s + \sigma^2_\tau}$)

The use of probabilistic techniques is best left to the specialist but is described fully in texts such as Harr[27,28] and Huang[21].

A problem encountered with the probabilistic method is the interpretation of the safety margin or probability of failure in terms of experience. The wide experience regarding the factor of safety method allows a factor of safety of 1,5 to be easily understood, but a safety margin of 0,05 (ie a 5 per cent chance of failure) is harder to relate to. This characterisation of risk has been extensively discussed for other disciplines[29,30,31] but no recommended values for roads have been published.

5.6 FINAL DESIGN

It is often necessary to incorporate stabilization or protective devices into the design to improve marginal stability or to control minor instability. Although these measures are usually installed after problems have occurred, they should in many cases be incorporated in the design. The following measures are the most important.

5.6.1 Rock fall control

Where slopes are steep and the material is naturally closely jointed or consists of loose blocks or boulders in a matrix, some form of rock fall protection is necessary. This protection depends on the angle of the slope. Vertical slopes allow rocks to fall freely and as the angle of the slope decreases the rocks bounce, roll or slide down the slope[32,33]. Based on the trajectory to be followed by falling rocks, fall-out areas, catch fences or concrete catch walls have to be designed (Figure 12 and Table 6). Often, anchoring a sturdy wire-mesh blanket over the face will be sufficient to keep falling rocks close to the cut face[33]. Large boulders or masses of falling material, however, often break the wire rendering these blankets ineffective. Overblasting during construction often causes loose boulders. Proper barring down of rock slopes will reduce the incidence of rock falls substantially. Good construction practice is to bar down loose rock as the cut is deepened and not to wait until the cut has been completed. At this stage it may be dangerous to try and remove loose rock by hand. The practice of barring down also makes the face safer for workers in the cut.

5.6.2 Block slide control

In many materials, especially in inclined sedimentary and well-jointed igneous rocks, sliding blocks of various sizes may occur. It is usually necessary to stabilize these with steel pegs, rock bolts or even cable anchors. These stabilization measures should, however, be designed by a specialist.

TABLE 6

Design parameters for fall-out ditches[30]

Rock slope		Fall-out area width	Ditch depth
Angle	Height (m)	(m)	(m)
Near vertical	5-10	3,7	1,0
	10-20	4,6	1,2
	>20	6,1	1,2
0,25:1 or 0,3:1	5-10	3,7	1,0
	10-20	4,6	1,2
	20-30	6,1	1,8*
	>30	7,6	1,8*
0,5:1	5-10	3,7	1,2
	10-20	4,6	1,8*
	20-30	6,1	1,8*
	>30	7,6	2,7*
	0-10	3,7	1,0
	10-20	4,6	1,2
	>20	4,6	1,8*
1:1	0-10	3,7	1,0
	10-20	3,7	1,5*
	>20	4,6	1,8*

* May be 1,2 m if catch fence is used

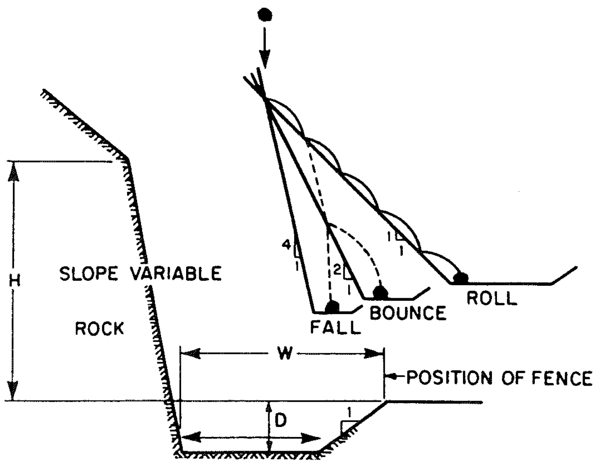


FIGURE 12

PATH OF ROCK TRAJECTORY FOR VARIOUS SLOPE ANGLES AND DESIGN CRITERIA FOR SHAPED DITCHES (After Ritchie, 1963[32])

5.6.3 Buttresses and retaining walls

For larger slopes and soil slopes retaining walls and/or concrete buttresses may be necessary to support localized areas of instability. Retaining walls (revetments) can be used to support small slides in which the failure plane exits from the cut face. Deeper slides with failure planes beneath the toe of the cut cannot usually be stabilized with retaining walls unless they are anchored beneath the failure plane or anchored to piles carefully designed to resist shear at the failure plane (ie pile walls).

Numerous techniques such as cladding a slope face, the use of proprietary products such as Gabions, Reinforced Earth and Löffelstein blocks all have applications in loading toe zones and stabilizing mainly shallow-seated failures.

5.6.4 Drainage

Drainage is seldom incorporated as part of the original design of a slope. However, often during construction or shortly after completion instability is observed and drainage measures are incorporated as part of the rehabilitation. **The incorporation of adequate drainage measures during the design of cut slopes is strongly recommended.** Detail attention should be paid to both the surface and subsurface water.

5.6.4.1 Surface water

Surface water may affect the slope in two ways:

- it may seep into the slope at the top of the cut and
- it may flow down the face of the slope.

Surface interceptor or cut-off drains (Figure 13) are generally sufficient to eliminate the problem. The drains should preferably be lined with concrete or gunite or else the grade should be adequate to remove the water collected at a sufficient rate to avoid seepage into the slope. If the drains are lined, periodic inspections should be made to ensure that slope movement has not caused cracking of the lining. Flexible drains such as bitumen-impregnated geotextiles should be considered if movement is possible.

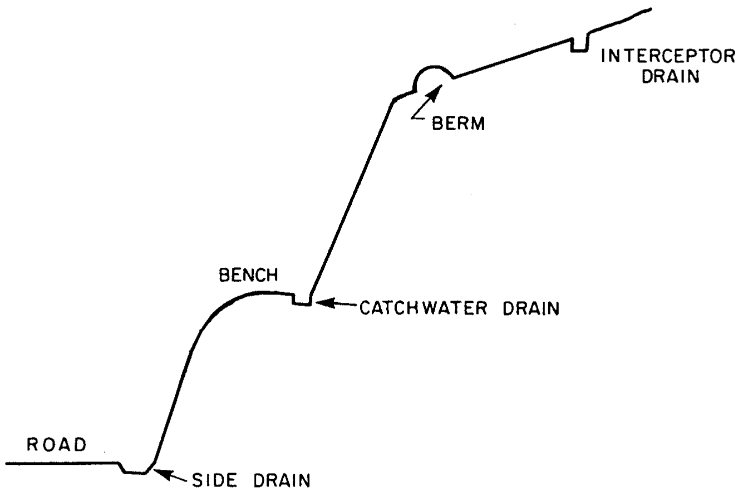


FIGURE 13
CONTROL OF SURFACE WATER

Possible areas of ponding above the slope should be eliminated and the top of the slope should be reshaped to provide controlled run-off. Protective berms above and next to the cut have also proved successful. Regular maintenance of drains is imperative.

5.6.4.2 Ground-water

There are numerous techniques for controlling ground-water, most of which are costly and complicated. Before any ground-water control is considered, a ground-water study should be conducted to investigate the quantity, location and sources of water. Random installation of drains is a complete waste of time and money because only the necessary volume of hill slope should be drained. The natural drawdown of the ground-water caused by excavation of the cut must be considered in the drainage design.

A brief summary of some of the most important and useful techniques follows. These methods are covered fully in many text books[16,21,34,35,] and have been summarized by Paige-Green[36].

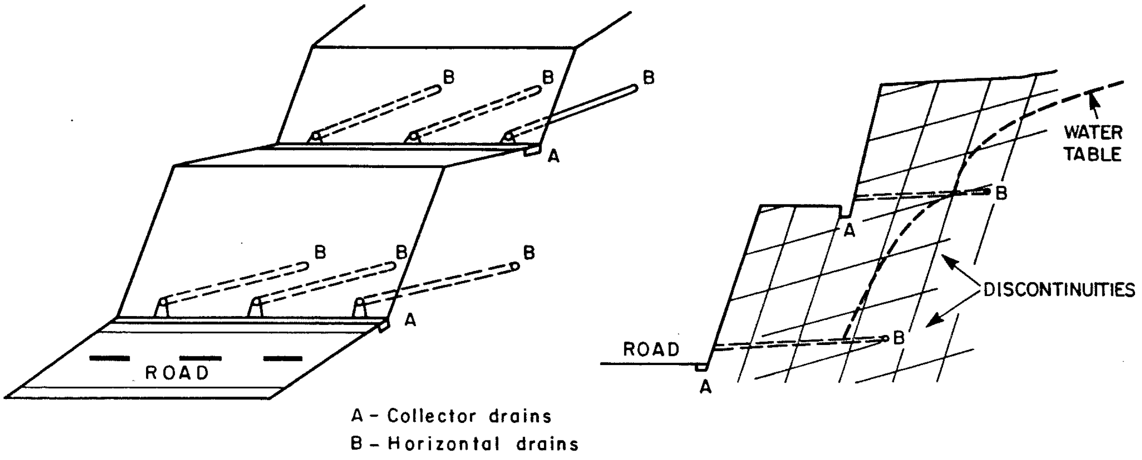
Subhorizontal drains (Figure 14a) consist of small-diameter holes (usually 25 to 50 mm in diameter) drilled on a grade of 5 per cent and fitted with perforated pipes for soils and pipes perforated in the vicinity of water flow-paths for rock slopes. To drain the slope it is imperative that the drains intersect the water-bearing strata or structures. These are probably the least expensive drains as they may be constructed with percussion drills (although core drilling gives a better idea of whether the water paths have been intercepted) and are drained by gravity. Horizontal drains should be installed during construction of the cut.

Vertical wells (Figure 14b) consist of a vertically bored hole fitted with a pump that is activated when the water level reaches a specified height. A drainage system consisting of vertical wells is flexible as pumping from certain wells can be stopped or additional wells can be sunk if necessary. In many cases vertical wells may be combined with horizontal drains to reduce the expense of pumping. Vertical wells should be designed by a specialist.

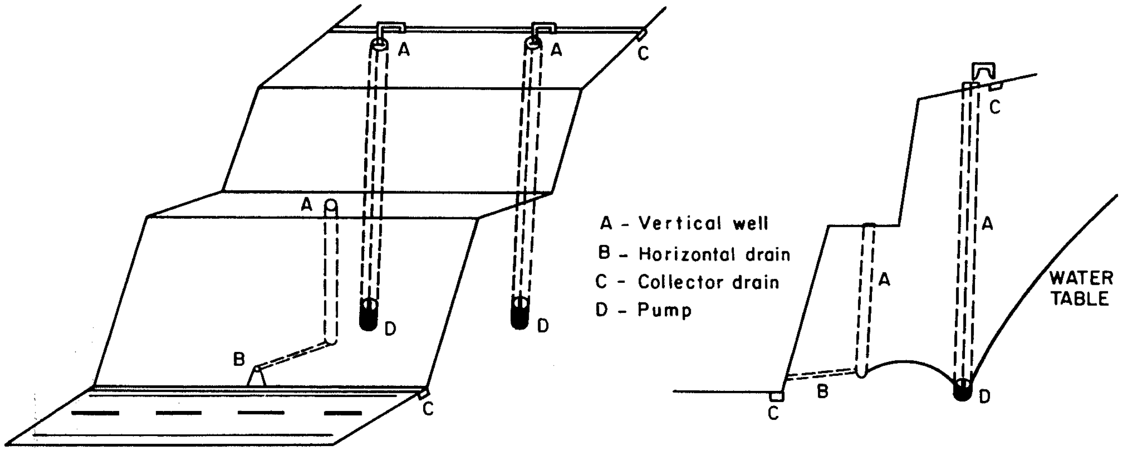
Trench drains (Figure 14c) can be excavated down the face of the slope to a depth of 5 m or 6 m and be backfilled with free-draining granular fill. If they are deeper and extend into stronger material beneath possible slides, a reinforcing action occurs. Interceptor drains cut parallel to and behind the slope, are a specific type of trench drain.

The cheapest, and one of the most effective forms of drainage is revegetation above and behind the slope. The effect of trees (especially non-deciduous trees such as the eucalyptus species) in lowering the ground-water table by evapo-transpiration cannot be over-emphasized. In addition, the root growth reinforces the material in the slope. As trees take some time to establish, other dewatering measures are often required during the early stages of the project. It is important to remove as few trees from behind the slope as possible during construction and to ensure that trees planted for stabilizing the slope by drainage are not removed.

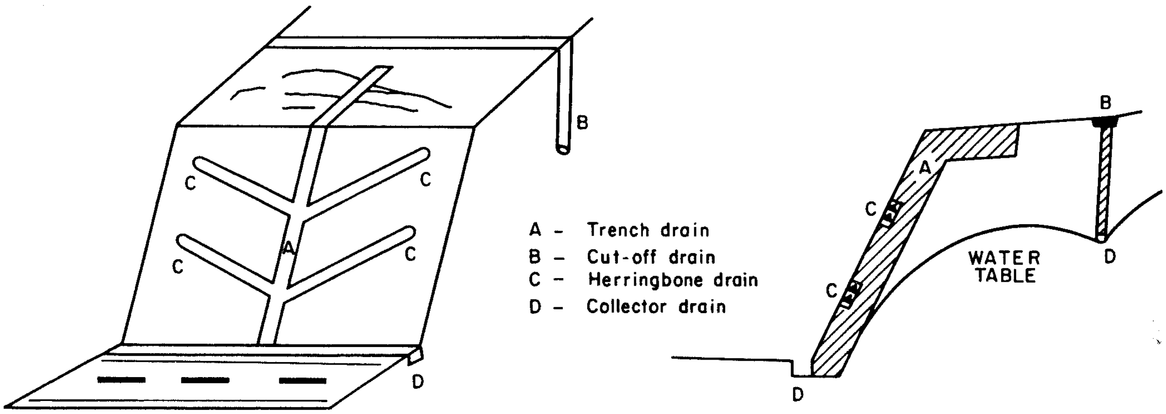
It is also important to drain the pavement within a cut as porewater pressures due to the excess head in the adjacent cut may lead to pavement distress. Provision for drainage must be made in the road foundation.



(a) HORIZONTAL DRAINS



(b) VERTICAL DRAINS



(c) TRENCH DRAIN

FIGURE 14

CONTROL OF GROUND WATER

940-4-5318/12 BS

5.6.5 Benches

Benches can be incorporated into the slope design for erosion control, to provide access for maintenance and to lined surface drains or rockfall traps. They should, however, not be regarded as slope stabilization structures, and are often considered to be aesthetically unacceptable.

5.6.6 Berms

Berms are often constructed above and behind the slope (Figure 13) to reduce the flow of water down the cut face. If used, they should be constructed carefully and should be compacted to prevent seepage through the berm. A well-graded drain should be constructed behind the berm and it should be maintained regularly. If a gravelly horizon occurs below the position of the berm it may be necessary to remove this permeable layer before the berm is constructed to prevent seepage of water under the berm. The berms should be built to canalize water with a flat slope closely following the contour and should not just follow the line of the cut.

6 CONSTRUCTION

Certain aspects regarding the construction of cuts are important and these are discussed below.

6.1 SITE PREPARATION

Unlike embankment construction which calls for careful preparation of the ground surface by removal of vegetation and compaction of the in situ material prior to construction, cuts require very little preparation.

Once the limits of the excavation have been surveyed and pegged out the humus-rich topsoil within the excavation area should be carefully stripped and stockpiled in a convenient position on site. This material will be replaced on the cut faces to restore the vegetation (see 6.4)

The removal of vegetation, especially large trees, from behind the slope should be minimized. Apart from the reinforcing effect of the roots in the soil, a substantial amount of water is removed from the slope by evapo-transpiration of the trees.

6.2 CONSTRUCTION CONSIDERATIONS

It is important that the resident engineer during construction be given an adequate background to the design of the cuts. Geotechnical supervision is desirable on most projects but is essential when insufficient information has been obtained during the site investigation. Any deviations from the expected conditions will thus be recognized timeously and remedial action can be taken before any failure occurs. The site investigation should only be regarded as complete once the cut has been constructed.

The excavation characteristics of the material can usually be determined from the seismic refraction survey and from the geological investigation. The intensity and attitude of fractures in hard rocks may be such that, although the seismic velocity indicates blasting, ripping may be possible[12].

The question of excavation of the cut face in rock by blasting may be resolved in one of two ways:

(a) On rock slopes steeper than 1:1 it will prove difficult to establish vegetation and the use of pre-split blasting is recommended. This results in minimal fracture of the adjacent cut face and thus reduces the problem of loose rocks.

(b) Should the aesthetic aspect of pre-split blasting be unacceptable, normal blasting can result in a rough finish and an incomplete covering of indigenous plants can be established. Blasting should, however, be carefully designed and controlled. Although a rough finish is required, overblasting results in dilation of joints and therefore in increased unstable areas. However, the maintenance of the foot of the slope then becomes a necessary routine and wider side drains are required to retain the debris. Most parts of southern Africa are fairly dry and therefore the vegetation established should be drought-resistant eg aloes and succulents. A list of drought-resistant plants is available from the Botanical Research Institute in Pretoria.

The final finishing-off of the cut face should be rough so as to form a good bond between the sub-soil and the top soil.

A specialist geological input is required for an adequate blast design, especially for pre-splitting. Should a joint set parallel to the proposed pre-split plane be present, this could control the bulk blast to a greater extent than portions of the pre-split plane and could result in a totally unpredictable final slope. A full discussion on pre-split blasting is referenced[37].

The effect of ground vibrations generated during blasting on neighbouring slopes and other structures and the potential effects of fly-rock should be carefully investigated before blasting is initiated, especially in built up and environmentally sensitive areas.

During construction of the drains, it is important to construct the drain linings as soon as possible after excavation of the trenches to reduce the possibility of water being collected in the trenches which will affect the slope.

The necessity for an appropriate geotechnical input during the construction process cannot be overemphasised.

6.3 SLOPE PROTECTION

All slopes cut in soil or highly weathered rock and some cut in unweathered rock such as mudstone, require some form of erosion protection. Both the action of the impact of raindrops and the run-off of the accumulated water result in erosion of the surface material. Even in more arid areas wind erosion can result in unnecessarily dusty conditions and the wind will transport material from the slope onto and into culverts and drains. Roads through areas of active dunes can become covered by sand within a matter of hours.

During the investigation stage of the project the weathering and erodibility potential of the materials that are likely to be exposed in the cut should be examined.

The potential to weather or erode may have an important influence on the final design of the slope. It must be decided whether the slope should be cut to as steep an angle as possible to reduce the area exposed to weathering, erosion and the impact of rain or whether the slope should be cut to a much flatter angle so that the potential for erosion by rapid run-off of water is reduced.

The cut material may weather and erode by different processes, each with a unique result and each requiring different identification and protection procedures (Table 7).

The usual means of slope protection is the establishment of vegetation, especially grasses and small plants. In addition to the control of erosion, aesthetic enhancement of the structure is a bonus (see 6.4). For this reason, it is important to stockpile the topsoil together with its grass roots and seeds during construction (in thin uncompacted layers (less than 1,5 m high to allow aeration) and to apply it to the slope as construction proceeds. The thickness of soil applied should be adequate to provide sufficient nutrients to sustain plant growth. However, it should not be so thick that sliding is initiated when wet (less than 75 mm on slopes steeper than 1:3). It is often necessary to scarify the slope prior to the placing of the topsoil to provide the required bond, or else some mechanical pegging or battering device should be used to retain the topsoil. The scarification and planting should be carried out in stages as construction proceeds.

Prior to attempting revegetation the following should be noted:

(a) The revegetation of slopes steeper than 1:2 is often unsuccessful[41]. It depends to a major degree on the material, climate and the use of special techniques.
(b) Maintenance of vegetation on slopes steeper than 1:1½ is extremely difficult.
(c) It is often adequate to apply nutrients and seeds without topsoil[42].
(d) The vegetation should be indigenous to the area. If not, the suitability of the vegetation type for the area should be carefully investigated to ensure that it will adapt to local conditions and not become invasive.
(e) The prevailing micro-climate should be considered when planning the establishment of vegetation. Different micro-climatic environments are often encountered on slopes depending on their inclination and orientation with respect to the sun and wind.

Numerous techniques have been used to establish vegetation on slopes.

In the past, minibenches and wattling or planking retaining "walls" were used to establish vegetation with varying degrees of success. "Revegetation capsules" have been found to be very successful (generally on higher-grade cuts (eg freeways) because of their expense). Recently, geotextile envelopes containing seeds and nutrients have proved most successful. Most of these patented measures work well but should be investigated for economic viability. Hydroseeding is the most common technique used. Sodding and strip-sodding are also successful and much cheaper than "capsules".

In environmentally sensitive areas and urban areas where vegetation establishment is of the utmost importance, consideration should be given to flattening the slopes to 1:2 or less wherever possible to encourage luxuriant vegetation.

It is normally necessary to use specialists to ensure the correct application of materials and techniques.

TABLE 7

Weathering and erosion prediction and protection techniques

PROCESS AND MATERIAL TYPE	CAUSE AND RESULT	RECOGNITION	PROTECTION
DISPERSION			
Saline residual and transported soils	Tunnelling and piping of the cut by removal of fines in suspension	Crumb test, pinhole test, chemical tests[38],[44]	Cation saturation with Ca2+, seal against water penetration.
EROSION			
Sandy, silty and low cohesion clayey soils	Channelling and material loss due to high run-off and rain impact stresses	Low cohesion[39]	Compact, topsoil, fertilize, establish vegetation with thick root network, reduce run-off velocity
SLAKING			
Mudrocks, certain dolerites and clayey soils.	Slaking due to water absorption/drying out cycles	Slake durability, water immersion[40]	Compact, topsoil, remove water rapidly, establish vegetation with thick root network by means of sodding

Many rock or weak rock slopes are too steep for the application of soil and yet may still be prone to erosion. A thin layer of shotcrete or gunite (preferably with wire mesh) should be applied to these slopes . The addition of a colouring agent to the sprayed material can go a long way towards aesthetic improvement.

6.4 ENVIRONMENTAL ASPECTS

The impact on the environment of engineering structures such as roads and cuts is steadily assuming an increased importance during the design of these structures. Apart from the aesthetic necessity of revegetation discussed earlier, a number of other aspects should be considered. An environmental impact study should be made at all times, but is especially important when an environmentally sensitive area must be traversed.

Large cuts in wilderness or environmentally sensitive areas should as far as possible be constructed with variable natural-looking slopes to blend in with the environment. The slope batters should be selected to simulate the natural conditions in that material, and the indigenous vegetation established must be similar to the surrounding vegetation on similar materials. This will ensure that an ecological imbalance will not occur where the symbiosis of the vegetation is disturbed. Exotic vegetation should not be introduced.

Other aspects to be borne in mind are the borrow and spoil areas. Where possible, the material extracted from the cut should be used for the approach fills and the construction aggregate. This will result in minimal waste (which requires spoiling, usually in the form of unsightly dumps). If necessary, the batters of the approach fills can be flattened to an exaggerated extent. The use of the extracted material will also result in a reduced borrow requirement, reducing, or even eliminating, the scars usually resulting from borrow pits. Borrow pits should be worked in a way that will make restoration fairly easy. The result will be that the area blends in with the environment.

7 MAINTENANCE

The maintenance of cut slopes and their associated structures is of the utmost importance. It is pointless to construct sophisticated rock trap or drainage systems and not to maintain them. This usually results in a source of water instead of removal of water.

7.1 MAINTENANCE REQUIREMENTS

7.1.1 Benches

The incorporation of benches in cut faces is not recommended for the simple reason that they are seldom adequately maintained. If benches are constructed, they should be adequately drained and should be wide enough for mechanized maintenance operations to be carried out (eg for tractor-drawn mowers and front-end loaders). Where benches occur, a maintenance programme should be drawn up and diligently adhered to.

7.1.2 Drains

All drainage structures from cut-off drains, side drains and interceptor drains to vertical wells must be regularly cleaned and their effective operation confirmed or corrected if required. Where lined drains are provided above and behind the slope, the absence of cracks in the lining should be confirmed regularly. **Drainage outlets should be distinctly marked to assist the maintenance staff in locating them.**

7.1.3 Vegetation

The vegetation cover on slopes should be regularly cut for a number of reasons. Thick grass and plants are often a fire hazard and, apart from the safety aspect with respect to vehicles using the road, fires may remove all the vegetation which will open the way to surface erosion. In addition, the burning of the vegetation removes the organic nutrients required to sustain the vegetation. To allow succession grass should only be cut after the seeds have ripened. Thick vegetation also tends to cause problems with certain drainage structures, especially side drains in high-rainfall areas and hampers the inspection of cuts for cracking and subsidence.

Re-fertilisation of slopes is important, especially if the vegetation shows signs of stress and deteriorates. The addition of the correct nutrients could prevent serious rehabilitation works.

7.1.4 Erosion

Should surface erosion occur, the gulleys and cavities formed may be lined with geotextile and backfilled with boulders in an attempt to reduce further erosion. Certain materials such as highly weathered granite are particularly susceptible to erosion and gulleying eventually resulting in significant slumping. Severe erosion problems may require specialist attention. Erosion also leads to blocking of drains (by the sediment removed from the slope) and the fouling of dams and streams.

Grass should be established as soon as possible after restoration techniques have been implemented.

8 INSPECTION AND MONITORING

Cuts should be inspected regularly during routine maintenance. Maintenance staff should be instructed in the identification of unstable features such as tension cracks, offset fences, unexpected water flows, etc. and should automatically inspect for these during maintenance.

Although monitoring is not necessary for every slope, certain cuts in which the design parameters were suspect or in which marginal factors of safety were obtained should be monitored if failure could cause loss of life or damage to property or could result in unnecessarily expensive remedial action. If a drainage system or some other remedial action had been required during construction, monitoring should be carried out to ensure that the measures implemented are having the desired effect and that they continue to function.

The simplest form of monitoring is obviously regular visual inspection. This should be carried out during construction and the appearance of tension cracks or seepage should attract attention.

Other fairly inexpensive, but effective, monitoring techniques include the observation of water levels in boreholes (preferably using piezometers), periodic surface surveying and simple extensometric measurements across tension cracks. In cases other than these, it is recommended that specialist advice be obtained. Numerous techniques are used by specialists in the field. These include sophisticated extensometers and strain meters, inclinometers, piezometric measurement and acoustic emission monitoring.

9 REMEDIAL ACTION

Should visual inspection or more sophisticated monitoring indicate impending instability, remedial measures should be investigated. The first and most important step is to protect property and life from possible failure by removing movable property and, if necessary, evacuating fixed property.

A specialist should be consulted to investigate the cause of the problem. This will usually involve core drilling or in situ inspection of the unstable mass and water pressure monitoring. Before the cause of the instability has been identified, remedial measures cannot be taken.

If water is identified as the problem, remedial action usually involves the installation of drains. If the cause is inherent instability of the material mass, the remedial action will be required to reduce the driving forces, eg to flatten the slope or to increase the resisting forces by such techniques as anchoring, or the construction of retaining walls or buttresses.

Numerous techniques are available and it is up to the specialist to design the most economical and effective remedial measure.

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