This document is divided into two main sections:

Section A is a review of slope treatment measures. First, the document sets out some basic principles for consideration of treatment measures for deteriorating rockslopes. Then general approaches to treatment are considered. A brief review of drainage measures is then provided, followed by a consideration of the potential role of vegetation in both rockslope deterioration and treatment. The final section addresses some of the special considerations for dealing with treatment of quarried slopes.

Section B presents two tables used in RDA. Table 1 presents general approaches to slope treatment with the corresponding RDA_A Class and deterioration susceptibility. This table is for use with RDA Stage One. Table 2 sets out indicative treatment measures suitable for given RDA_A Classes and given deterioration transport mechanisms. This table is for use with RDA Stage Three.

SECTION A: PREVENTIVE AND REMEDIAL TREATMENT FOR DETERIORATING ROCKSLOPES

Introduction

It is the general premise of RDA that the decision as to what mitigation and maintenance treatments to apply to a rockslope depends on a combined understanding of (i) the probability and severity of deterioration (ie risk) *and* (ii) the nature of deterioration (ie the hazard). The guidance given in RDA also presumes that the *consequences* presented by the hazard are unacceptably high. As stated earlier, though, this is a value judgement which must be made by those responsible. In recognition of the importance of both risk and hazard, selection of appropriate slope treatments in RDA is dealt with in two stages. In the first stage, the RDA_A Class is used to suggest a general approach to mitigation. In the second stage, a more detailed matrix of treatment measures is provided which relates RDA_A Class to deterioration mode. In this, specific treatment measures are suggested, pertaining not only to the likely risk of deterioration, but also to the likely characteristics of the deterioration mechanisms involved. Clearly, this guidance can be used to assist in the evaluation of potential capital and ongoing maintenance costs associated with a proposed rockslopes, and can therefore assist in the pre-excavation design and planning process.

Selection of treatment measures and design of a maintenance programme also depends on a variety of other factors including (i) cost; (ii) availability of materials; (iii) aesthetic or other environmental impact; (iv) availability of expertise; (v) conditions set out in planning permissions; (vi) local political issues; (vii) land use; (viii) land ownership and associated constraints; (ix) long term management and aftercare commitment; (x) safe access to the slope. Guidance given in RDA is independent of these considerations, which must be considered locally.

Approaches to rockslope stabilisation, protection and maintenance

Deterioration of rockslopes can be mitigated using a variety of approaches. Slope treatment can be *reactive*, that is, works are carried out in response to infrequent or minor deterioration of a slope. Works can be *passive*, where the consequences of deterioration are reduced by containment and protection. An *active* approach can be adopted, where the materials forming the slope are either improved or reinforced. An *intrusive* approach can be adopted whereby substantial slope support, buttressing and retention are introduced. As a final alternate approach, if it is accepted that the consequences of deterioration are either too severe to be acceptable or to be mitigated successfully, then major *slope re-design* can be undertaken. A number of reviews of rockslope stabilisation and treatment measures have been published, including Fookes and Sweeney (1976); Peckover and Kerr (1977); Dubin et al (1986); Martin (1988); Fookes and Weltman (1989); Giani (1992); Dixon and Cox (1993) and Abramson et al (1996). A detailed review will not be repeated here, but some of the principle types of mitigation measure appropriate to each of the above approaches is briefly described, with information being based largely on the above-named review articles and field observations.

1. Reactive approach

In certain situations, it might be appropriate to literally ‘do nothing’ about deterioration. For such an approach to be viable the potential consequences arising from deterioration need to be acceptable. The essence of the reactive approach is that maintenance works and stabilisation measures are implemented on an 'as-needed' basis. Infrequent slope inspections can be undertaken to identify any maintenance requirements and to pre-empt problems. However, drainage measures are usually constructed immediately following excavation as a standard precaution, regardless of deterioration potential.

2. Passive approach

The essence of the passive approach is that deterioration is allowed to happen but its consequences are minimised by containment and protection. One of the simplest ways of achieving this is to increase the standoff distance between the slope and the potential casualty. An example would be to build a highway with a particularly wide verge. For some disused quarries where there is informal or formal public access, fencing and warning signs can be used to deter entry to danger areas. Protective barriers can also be used to prevent damage to structures by falling debris.

If deterioration is allowed to occur, then it is usual to adopt a more formal programme of maintenance works such as face scaling and clearance of debris. Loose or unstable material (and vegetation in some cases) lying on the surface of a slope can be removed using simple hand scaling tools and a hydraulic lift for access if needed. This includes debris accumulations on ledges and potentially dangerous overhangs. One difficulty encountered in scaling highly fractured rockslopes is that there is often no distinct boundary between stable and unstable materials. There is then the risk that stable material will be disturbed unintentionally (Dubin et al 1986). In order to plan scaling and associated works, a plan of regular inspections can be followed, perhaps including some limited monitoring of critical blocks, either visually or by using instrumentation. The process of scaling might lead to critical blocks or areas being identified which necessitate mechanical excavation, perhaps using a pneumatic hammer or drill (Dubin et al 1986).

The most common solution for deteriorating rockslopes is to absorb the energy of falling material by constructing a rocktrap ditch, often with a protective fence or other protective barrier. Design data and charts have been produced which offer guidelines on the relationship between the depth and width of rocktrap ditches and catch fences in relation to the height and angle of slope (Ritchie 1963; Fookes and Sweeney 1976; Mak and Blomfield 1986; Whiteside 1986; Fookes and Weltman 1989). Sophisticated rockfall trajectory software programmes are now available to assist in slope design (eg Robotham et al 1995). Rockfall shelters can also be constructed to protect people, vehicles or structures at the foot of the slope from falling debris (Giani 1992). Another solution is to hang galvanised wire mesh netting over the slope face. If weighted at the bottom, material is thus prevented from being thrown out from the face and allowed to collect in a purpose made ditch at the foot. Some modern wire mesh nets are designed to catch blocks with energies up to 3500kJ. These not only reduce the velocity of falling debris but limit its trajectory. Netting is particularly useful where fracture spacing is very close, such that individual blocks cannot be retained or reinforced using other methods (Dixon and Cox 1993). Netting is usually fixed to the face with dowels or short anchors.

A further, environmentally-friendly method of absorbing the impact and energy of falling debris is to establish a dense cover of low growing shrubs and herbaceous plants at the foot of the slope. Trees and shrubs which reach a significant height could intercept falling material in such a way that it is thrown out from the slope. This is likely to be particularly hazardous. Vegetation used in this way might not be appropriate for all localities, and is certainly not recommended where a substantial accumulation of debris is anticipated (eg flaking, ravelling, rockfall). But for less severe deterioration modes such as stonefall, wash erosion, scaling and grain ravelling it might be useful.

3. Active approach

The aim of the active approach is to reinforce the slope, either by improving the strength of the material, or by improving continuity of the rock mass. The latter can be achieved by reinforcement of individual blocks using dowels or rock anchors. *Dowels* are made of steel and are in the form of bars or rods, drilled or grouted into the surface at close spacing, and near vertical to maximise shearing resistance for sliding blocks. Their strength enables them to resist bending moments, and tensile or shear forces. Dowels are not tensioned and are therefore passive, in other words, they do not actually do any work until the slope moves and then the tensile strength of the dowel is mobilised. Dowels can be used in both homogeneous and heterogeneous materials. They are often used in conjunction with shotcrete (see below). Dowels are cheap to use, requiring only light construction equipment. They can therefore be adopted on small slopes with difficult access. *Rockbolts* are also steel rods inserted into pre-drilled holes usually 3-10m in length. They are often pre-tensioned and can be fitted with instrumentation for monitoring purposes (Dixon and Cox 1993). They can be applied as a general grid over the face, known as pattern bolting, (more applicable for general instability) or applied to specific critical blocks. Since they are tensioned, bolts are active in preventing block movement. Rockbolts are vulnerable to corrosion if not properly treated. This can lead to enhanced material breakdown along the rod, and behind the head of the bolt at the surface. In severe cases, steel cables 10-40m in length can be used, but these would be mainly applicable to large scale or deep-seated instability. A further method of reinforcement is the *grouting or sealing* of fissures and voids. This will also prevent water access to critical fractures and stiffen surrounding rock. This can be achieved with shotcrete, clay, concrete or bitumen. In particularly large fractures, bulk material can be used to fill the void prior to sealing.

Temporary reinforcement can be gained by cable or chain lashing of individual, large blocks. The cable or chain can be anchored, or fixed to intact rock with dowels. Anchors are generally avoided, particularly for small scale deterioration problems, because of the potential for corrosion and long term maintenance and monitoring requirements (Dubin et al 1986).

The strength of the material can be improved by applying a surface protective cover. The materials used in any such treatment must be sufficiently durable to resist prevailing weathering conditions. The selection of suitable materials is influenced by the area to be covered and whether or not aesthetic considerations are important. Several techniques are possible: *Shotcrete* is conventional concrete, applied by pump action to the slope surface. It is often reinforced with steel mesh or fibres (eg Dixon and Cox 1993) and weepholes are installed to assist drainage. Shotcrete serves two functions, it binds loose material together and offers protection against the influence of weathering. In particular, it reduces infiltration of surface water. Shotcrete is often used in combination with rockbolting, with the shotcrete being sprayed over the boltheads after installation. One of the attractions of using shotcrete is that large areas can be covered quickly and cheaply. Its appearance can be improved with the use of a colouring agent. *Masonry blocks* are ideal where aesthetic considerations are important, but they are more expensive than other forms of surface protection. Stone blocks are bedded on gravel, sand or other free-draining material, and side joints are mortared. Again, weepholes would normally be installed at the top and base of the slope.

In suitable materials, *vegetation cover* can also be established in conjunction with geotextiles (eg coir netting or geosynthetic materials). This also applies to soil-like overburden materials at the top of a rockslope, which might nevertheless be degrading, contributing to the general deterioration hazard. Dubin et al (1986) also report the successful use of a proprietary spray-on seeded binder on near-vertical, moderately weathered rockslopes in Hong Kong. The binder is resin-based, with organic fibrous matter (as a cultivation base), plant seeds and a cement binding agent. The material is sprayed onto the rock surface using a wet process similar to that used for hydroseeding.

Local rock mass continuity and improvement in material strength can be achieved with use of *dentition,* particularly for individual blocks, small overhangs and weak zones or layers. The area is trimmed back and cleaned up and packed with a filler or concrete. Usually, the surface is faced with masonry or reinforced concrete and weepholes installed. Dentition is often used in conjunction with dowels (Fookes and Sweeney 1976). For very small areas, mortar can also be applied directly to the rock.

4. Intrusive approach

The aim of the intrusive approach is to provide support to weak parts of the slope using buttressing, retention, application of dentition to large areas, and underpinning.

Underpinning is appropriate for larger cavities and overhangs using concrete or timber beams, or steel girders in some cases. These can be anchored in place or fixed to stable rock with dowels (Fookes and Weltman 1989). *Buttressing* is often used to support zones of highly fractured or weathered material such as are found in shear zones (Dubin et al 1986; Dixon and Cox 1993) and as such is ideal for the treatment of intensely fractured zones and erosion or fracture chutes. Buttresses are usually designed as gravity retaining structures (Dubin et al 1986) and usually contour the rock face. They can be constructed entirely of concrete, entirely of masonry, or a combination of both. They are fixed to the rock surface using dowels or bolts and can be reinforced. As with many of the treatment measures described here, drainage is essential and might be provided by a series of regular weepholes or inclined drains (Dixon and Cox 1993). Particular care is needed to ensure good drainage at the junction between buttressing and intact rock. If not, seepage erosion and enhanced weathering might occur, with the boundary zone acting as an erosion chute.

Retaining walls are usually constructed as gravity structures (their resisting force comes from their dead weight), though tieback walls, anchored into the slope behind, are also used. In this case, their resisting strength comes from their anchorage into the slope beyond the deteriorating rock mass. This anchorage transfers the load via steel cables, rods or wires, which are grouted into strong bearing rock (Abramson et al 1996). Retaining walls would be most useful for supporting weakened slopes which are vulnerable to high magnitude events such as rockfall, debris flow, rockslide and flexural toppling. Any retaining structure must therefore be capable of withstanding overturning and sliding forces, as well as internal shear and deformation, and the ground on which it is located must have sufficient bearing capacity. Again, drainage behind and beneath the retaining wall is usually essential. Retaining walls can be constructed using concrete (pre-cast and cast on site), gabion baskets, and pre-cast concrete or timber crib blocks.

Crib walls are usually constructed with pre-cast concrete or timber beams and backfilled with granular fill. For shallower angle, planar slopes, the use of *grascrete* can also be effective (Dubin et al 1986). Topsoil forms the uppermost layer of fill to enable vegetation to establish where desirable. Although more commonly used to retain soil masses, *gabion units* can also be used for retention of small areas of weak and weathered material. These are rock-filled baskets which have the advantage of being strong, heavy, permeable and deformable (Hoek and Bray 1981).

5. Slope re-design

If rockslope deterioration is deemed too severe to mitigate in any of the above ways, or where mitigation works are not deemed to be reducing the consequences adequately, slope re-design might be the only solution to the problem. In the case of proposed slopes, where severe deterioration is anticipated, it might be possible to avoid the issue by re-location or complete re-design. However, this solution is rarely an option, except at the stage immediately following preliminary site investigation. Any later than this could incur significant wastage of resources. This approach is also unlikely to be viable in the context of mineral extraction since the primary choice of site will depend upon the quality and extent of the mineral resource available. A further option to minimise deterioration potential for proposed rockslopes is the selection of a less damaging excavation method (eg pre-split blasting). Again, this method would be inappropriate for use in mineral extraction where the principal objective is to maximise fragmentation. In theory, it could be viable for production of final 'restoration' slopes in worked out quarries, but aesthetic and cost considerations might prohibit this.

For existing slopes, the slope geometry may be modified. The gradient can be reduced either by re-excavation or addition of fill material, or benching can be introduced, where a slope is divided into sub-slopes of smaller dimensions. One drawback of modifying slope geometry in these ways, as well as the costs involved, is the need for additional landtake. Apart from the obvious legal, planning and economic implications of this, there are geometric factors to consider too. For example, the effect of introducing benching into a slope situated beneath rising topography will be to increase the total slope height. Also, unless bench surfaces incorporate rockfall protection (eg ditch or protective fence), they might cause falling debris to be thrown out further from the slope foot than would have otherwise have been the case.

The deterioration situation can be significantly improved by the removal of surcharge load at the crest of the slope. This is dependent upon access to the upper part of the slope with heavy machinery. Trees often add surcharge to a slope. The amount of load involved depends upon the mass of the tree, which includes the stem, the crown spread above ground and the root spread below ground. Normal loads of 0 to 2 kN/m^2 are not uncommon for forested slopes, but can be *much* higher for individual mature trees with a narrow root spread.

Slope drainage measures

Drainage measures have been ignored till now because they deserve special attention and because their use in reducing deterioration potential can be applied for any of the mitigation approaches described above. Slope drainage has several beneficial effects, it increases shear strength of the rock by reducing pore water pressure; reduces the unit weight of overlying material; reduces or prevents infiltration of surface runoff and thereby contributing to groundwater flow; and removes water from the surface and sub-surface, important contributors to many weathering processes. Drainage measures can be broadly classified in terms of surface and sub-surface methods. A schematic illustration of various drainage measures suitable for rockslopes is shown in Figure 1 (after Fookes and Sweeney 1976).

(a) Surface drainage

Surface drainage can be achieved by the use of shallow ditches or purpose made concrete or plastic channels. There are three main types. *Shallow collector drains* are situated at the slope crest or on the surface of individual berms. They are shallow, gravel or stone-filled ditches, usually 0.5-1.0m deep and lined with a geotextile fabric. Their primary purpose is to reduce infiltration of surface water into the slope. *Collector drains* are located on the slope surface. In soils, highly weathered rock and soil-like materials they can be constructed as before but set out in a herringbone pattern. In stronger materials they might simply take the form of vertical or sub-vertical pipes, often built into the slope and covered with masonry or concrete. Their primary function is to transport surface water or water collected up from crest drains, to diversion drains at the slope foot. *Diversion drains* are often constructed as pre-cast concrete channels, and are situated at the slope foot. Their main function is to collect water from the slope and transport it into a soakaway or into the mains system.

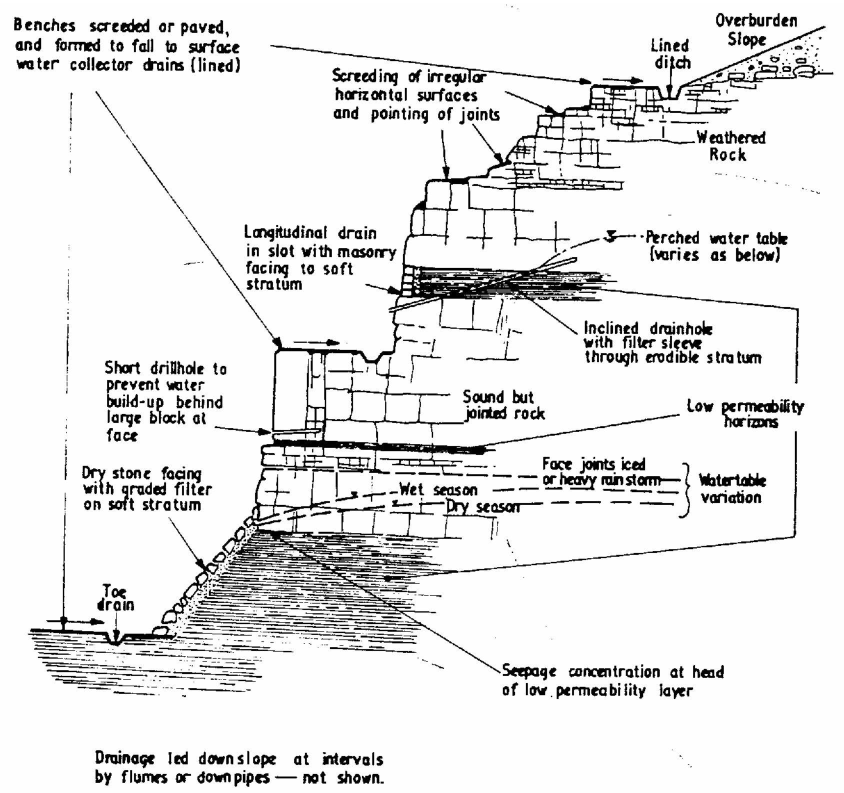


Figure 1 Schematic illustration of drainage measures suitable for rockslopes (*after Fookes and Sweeney 1976*)

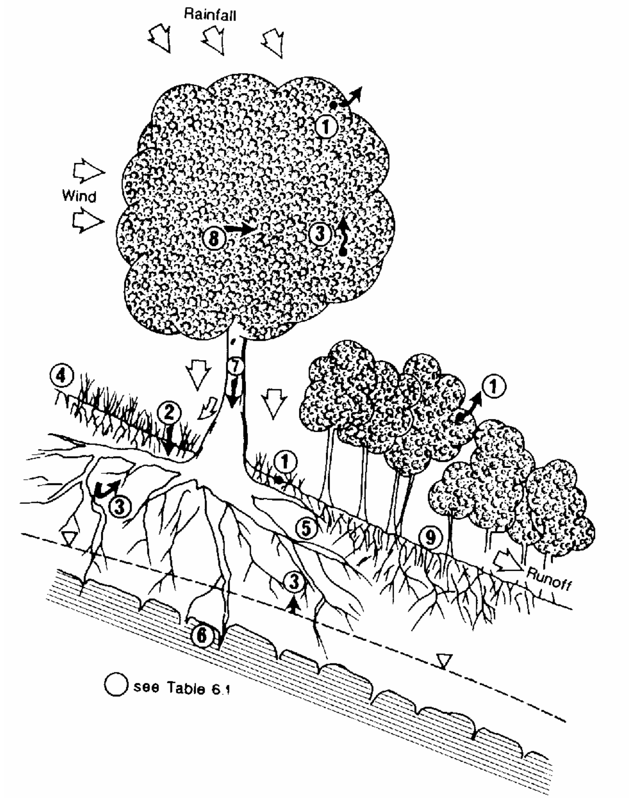
(b) Sub-surface drainage

Sub-surface drains usually require excavation of the rock mass, either at the top of the slope, on its surface or at the foot. This is expensive and can lead to significant disturbance, so is only used in more severe cases and where there is an excellent chance of successful mitigation. Several types of sub-surface drain are possible but most are either applicable to soil slopes (eg trench drains) or to large landslide masses. The main options for rockslopes are the use of lined *cut-off drains* at or near the top of a slope to intercept groundwater flow where it occurs near the surface. They are usually situated parallel to the slope. *Inclined drains*, usually simple drillholes with a filter sleeve, are also commonly used in association with buttress walls or to drain weak strata within otherwise competent rock. Short drillholes or *weepholes* are usually used in conjunction with dentition and masonry walls.

The role of vegetation in rockslope deterioration and stabilisation

1. The potential effects of vegetation on rockslope deterioration

Vegetation can be regarded as having three potential effects on rockslope deterioration: It may be involved in a variety of bio-mechanical and bio-chemical material weathering effects; it may modify the weathering environment at and near the slope surface; and it may interact with the processes of slope erosion. Some of the ways in which vegetation interacts with slopes to affect instability are shown in Figure 2.



Hydrological factors

1. Foliage interception of rainfall;
2. Increased infiltration capacity;
3. Reduction of pore water pressure due to moisture extraction;
4. Desiccation cracking of the soil.

Mechanical factors

5. Root reinforcement of soil;
6. Tree root anchorage of soil;
7. Surcharge due to weight of trees;
8. Windloading;
9. Binding of soil and rock particles at the surface.

Figure 2 Idealised interactions between a slope and vegetation in ways which affect stability (*after Greenway 1987*).

(a) Biotic weathering

The wedging apart of rock by the growth of plant roots is well known anecdotally (eg Ollier 1984; Dubin et al 1986; Mitchell 1988; Coppin and Richards 1990; Selby 1993; Gellatley et al 1994; Winkler 1994; Cherubini and Giasi 1997). However, there do not appear to be any data corroborating the mechanism involved. There are two ways in which the potential role of plant root growth in rock breakdown can be viewed: (i) Plant root growth is opportunistic and simply exploits existing cracks, or (ii) roots penetrate tightly closed cracks and their growth produces sufficient mechanical force to overcome the tensile strength of the rock causing fracture dilation and extension.

The relative balance between these two possibilities remains unclear. However, axial pressures of 3MPa exerted by growing plants indicate that mechanical action alone would be insufficient to cause fracture in all but the weakest of rocks (Bland and Rolls 1998 - source of data not attributed). In either case, it is clear that bio-chemical reactions between plant roots and fracture walls has considerable potential to enhance rock breakdown.

There is growing evidence (eg Moses and Smith 1994; Viles and Pentecost 1994; Simms 2000) of the importance of bio-erosion in rock breakdown. Lower plants such as bacteria, algae, lichens, mosses and fungi are known to contribute to rock mass deterioration. For instance, lichens can live on bare rock surfaces and exploit cracks in rock, extracting nutrients by ion exchange (chelation), a process which is directly involved in the mechanical and chemical alteration of minerals. The release of carbon dioxide into accumulated soil due to respiration of plants and animals also enhances dissolution effects. Lower plants might cause granular breakdown due to root growth, and the action of burrowing organisms causes mixing and transfer of weathered materials. This in turn, may increase the surface area available for subsequent chemical attack (Brunsden 1979). Organic matter accumulation from the decomposition of vegetative material may create an acidic environment at the rock surface, enhancing solution and other chemical effects, and also increasing soil moisture retention.

(b) Modification of the weathering environment

Plants modify the microclimate near the rock surface, particularly rock temperature, which can influence freeze-thaw and insolation processes. Plants increase shading, for instance, and may reduce wind velocity (Brunsden 1979). The presence of vegetation also modifies the rock surface humidity environment and may therefore influence wetting and drying and salt weathering processes. Vegetation may also reduce evaporation of surface moisture, but this may be counteracted by the increase in moisture removal by transpiration.

(c) Vegetation and slope erosion

The presence of vegetation on a slope has several direct benefits for slope erosion and stability: (i) Vegetation may physically protect the rock surface from abrasion by wind, flowing water and freefall debris impact. It also intercepts precipitation directly, thereby limiting raindrop impact, and thus reduces the total volume of moisture reaching the slope surface. (ii) Vegetation adds to the 'roughness' of a slope and can obstruct surface flow, reducing its velocity. (iii) Plant roots have significant tensile and shear strengths (Greenway 1987; Luke 1988) and can therefore provide reinforcement in the upper part of a slope, significantly increasing factor of safety for shallow soil movements (Ingold 1988). This is akin to the action of a geosynthetic membrane (Cherubini and Giasi 1997). Norris and Greenwood (2000) have even developed a modified factor of safety equation for slope stability which incorporates a term for root reinforcement.

Vegetation may also modify the erodibility of surficial materials which can have both adverse and beneficial effects. For instance, the accumulation of organic material may enhance chemical weathering. Also, the rate of soil moisture removal is increased by transpiration and this may lead to more rapid drying out of the slope surface. This removal of moisture, on the one hand, could inhibit chemical and physical weathering and reduce pore water pressures (Ingold 1988) but on the other hand, could generate more frequent wetting and drying cycles.

In addition to the biotic weathering effects described above, adverse effects on slope erosion and stability from vegetation can also be recognised: (i) The roots of plants provide pathways for moisture infiltration into the rock material, so that although the amount of precipitation reaching the surface is reduced, the proportion of that which infiltrates is increased (Luke 1988). (ii) Higher plants, particularly large shrubs and trees, can de-stabilise slopes due to windthrow. (iii) The death of a woody plant, the roots of which have hitherto provided soil reinforcement, can lead to collapse of a substantial volume of material bound up in the root system.

2. The use of vegetation as a stabilisation tool

In civil engineering, the use of vegetation for slope and ground stabilisation is known as *bioengineering*. Vegetation has long been used in erosion control and its application in slope stabilisation is increasingly becoming apparent (Thomson 1988). Many bioengineering applications apply to soils, soil-like materials and highly weathered rock. However, vegetation can also be purposely established on rockslopes, either on fragmented screes or in specially created niches. These methods have been used in the restoration of worked out quarries to serve the dual functions of stabilisation and habitat creation. Attempts have also been made to utilise vegetation in rockslope protection for highways located in sensitive areas (Blunt and Dorken 1994). However, successful establishment of vegetation is governed by a wide range of factors pertaining to the tolerance and needs of the plants used; the nature of the substrate and its nutrient capacity; and the prevailing climatic conditions. Blunt and Dorken (1994) achieved limited success in their widespread seeding of shaley highway slopes and suggest that the primary reason for this was lack of suitable soil material. The site location in exposed, upland Wales might also have been a contributory factor. They recommend that pocket planting of trees and shrubs in specially prepared niches could prove to be more successful.

Some advantages of using vegetation for slope stabilisation are that it is usually cheap and easily available; it can be visually attractive; and it is relatively easy to put in place. Disadvantages are that vegetation can take a very long time to establish (though rapid growing species can be utilised); it can be damaged due to drought, blight, waterlogging, exposure and pollution; it can be difficult to establish in poor ground conditions, poor quality soils and on steep slopes. It is important to bear in mind that because it is a living material, a long-term programme of vegetation management and maintenance will be necessary.

Special considerations for quarried slopes

Assessment of the consequences of deterioration of *disused faces contained within working quarries* addresses similar issues to those for highway slopes, considered above. The primary issues are safety of workers, both at the foot and above the face, and maintenance, especially where the fallout zone of a slope impinges on haul roads or other working areas. However, there is often greater flexibility in a quarry environment to deal with problems arising from deterioration. For example, it is relatively easy to move an endangered haul road or working area to another part of the quarry. It is also fairly straightforward to prevent access to unsafe areas by vehicles, machinery and workers, as well as preventing public access. Operation of standard safety procedures in quarries might also help to limit the potential consequences of slope deterioration, for example, by restricting lone working, ensuring good communications between workers, providing first aid and emergency procedures and undertaking regular face inspections.

In *disused quarries*, the consequences of deterioration depend largely on the use to which to the land is put. However, planning conditions, local politics and environmental considerations might take on a much more influential role in terms of how deterioration is mitigated. The consequences of deterioration in disused quarries relate largely to after use. Disused quarries can be utilised for a variety of purposes, some actively encouraging public access and some permitting access on a more casual basis (Coppin 1981). What is more critical is whether or not the quarry face plays an intrinsic part in the activity. This is likely to be the case with rock climbing, SCUBA diving in flooded quarries, and geological conservation sites. The public are also likely to come into close contact with the face at a variety of other disused quarry sites such as industrial estates; forestry, caravan or car parks; and recreational sites where the face is incidental (eg country parks).

Mineral planning authorities are likely to have made it a condition of planning permission that once worked out, the quarry is restored in a particular way. Stabilisation measures utilised for road cuttings might not be appropriate because of the potential for aesthetic impact, cost, the lack of expertise available in the quarry industry, and the possibility of such measures interfering with intended after uses. For instance, measures which cover large parts of the slope surface (eg shotcrete) would clearly not be compatible with geological conservation. Indeed, slope deterioration can actually be a benefit for certain after uses. As already mentioned, weathering might enhance the appearance of a slope and this could be important for quarries located in sensitive areas. Alternately, a loose, weathered material presents a better medium for plant establishment and for nesting sites in quarries given over for wildlife conservation.

Certain 'treatment' techniques can also be adopted in disused quarries which would be unusual for road cuttings. For example, it might be possible to substantially re-grade slopes or undertake partial or full backfilling. Restoration blasting techniques could be used to create a completely new profile, and the establishment of vegetation is much more likely to be a requirement rather than an option. Given these differences and the wider variety of considerations involved, these treatment measures are not specifically addressed in RDA, since their selection is less related to the risk or hazard of deterioration, and more to other factors. Some of the treatments unique to disused quarries are considered briefly below. This of course, does not negate the use of RDA for quarry slopes since it still enables evaluation of the probability and severity of deterioration, as well as the nature of the hazard. These factors will, despite consideration of a wider range of other factors, play an important role in determining the suitability of after uses, slope treatment and long term site management.

1. Restoration blasting

The *restoration blasting* technique was developed by Gagen (1986, 1988) and Gagen and Gunn (1987a, 1987b, 1987c, 1988) for use in limestone quarries and has subsequently been applied to other rock types. The original concept was to replicate natural 'daleside' landforms modelled on the White Peak of Derbyshire. This was to be achieved by application of specially developed blast specifications enabling the re-creation of daleside landforms with rock screes, buttresses and headwalls This led to research into the most effective means of vegetation establishment appropriate for the same environment. Trials included hydroseeding, pit planting of tree transplants, general planting of tree seedlings and hand sowing of tree seed (Gagen et al 1993). The idea was for restoration blasting to be carried out at the cessation of quarrying, prior to closure. A number of trials, with varying success, have been reported in the publications cited. Vegetation establishment has not always been successful and concerns have been raised over the stability of buttresses which are exposed on three sides (A. Kirk: Discussion in Wakefield et al 1992) and of the upper parts of headwalls and buttresses (Walton 1993), particularly in the context of rockfall activity. A further concern of industry is the inevitable need for landtake. This means either, acquisition of, and planning approval for, extra land, or the surrender of recoverable mineral reserves (Wakefield et al 1992). Nevertheless, there has been significant interest in the technique and it has been applied with reasonable success in a modified form in other rock types and geographic locations.

2. Backfilling and re-grading

With increasing pressure on land, dual uses of land have been sought. One result of this is the increasing number of worked out quarries which have been re-developed for landfill. Not all rock types have been suitable for this in the past, but increasing confidence in the long term durability of geosynthetic and natural liner materials has enabled more and more quarries to be landfilled. It is not uncommon for both extraction and landfilling to operate simultaneously.

3. Vegetation establishment

Given the considerations above , it is actually desirable in many cases for vegetation to be established on disused quarry faces, despite the likelihood of associated deterioration. A range of techniques are available. Figure 3 is taken from a limestone quarry restoration scheme (details confidential) designed by the author in 1994 in which vegetation establishment trials were proposed and accepted by the Mineral Planning Authority. These largely involved pocket planting in specially created niches supplied with suitable cultivation material. Some quarry operators have experimented with extensive soil application and planting along quarry benches with no modification of the slope form (eg Whatley Quarry, Frome, Somerset). Others have used a modified form of restoration blasting. Instead of formally designing restoration blasts, rock piles left at the cessation of quarrying have been covered with subsoil and topsoil medium, and then seeded or planted (eg Minera Quarry, Wrexham, North Wales). At Llynclys Quarry near Oswestry in North Wales, substantial backfilling of quarried slopes has been undertaken. The surface of the backfill has then been thinly covered with fines taken from drained tailings ponds and left to colonise naturally. Because there is an excellent natural seed pool in the local area, natural colonisation has been both successful and rapid.

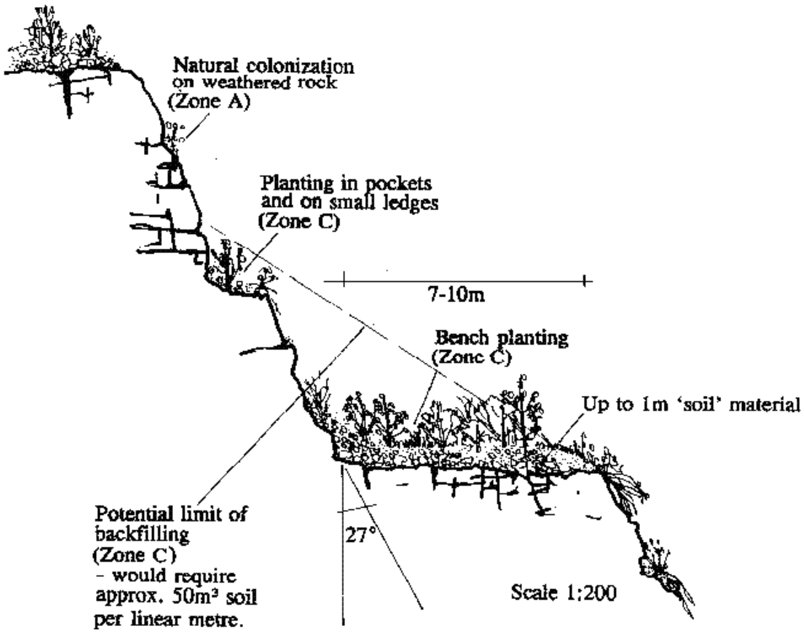


Figure 3 Pocket planting proposals for restoration of a limestone quarry

SECTION B:
RDA MITIGATION MATRIX

Application of RDA Class: general meaning of classes

Table 1 below indicates the general approaches to slope treatment required for each RDA_A Class (RDA stage one). However, treatment measures will differ considerably for different deterioration modes and so this table should only be used as a general guide. It could be useful for feasibility planning and at the desk study stage of a proposed excavation in which several sites in similar rock masses were being compared. It could also be used to compare likely mitigation requirements of different zones within a single excavation. This table is not intended to provide a basis for detailed planning of mitigation and protective measures.

Deterioration of rockslopes can be mitigated using a variety of approaches. Slope treatment can be *reactive*, that is, works are carried out in response to infrequent or minor deterioration of a slope. A *passive* approach can be adopted, where the effects of deterioration are reduced by containment (e.g. rocktrap ditch and fencing) and protection (e.g. barrier). An *active* approach can be adopted where the quality of materials forming the slope is either improved or reinforced (e.g. shotcrete, dentition and rockbolting). An *intrusive* approach can be adopted where substantial slope support, buttressing and retention are introduced (e.g. retaining walls and underpinning). If it is accepted that deterioration has too much damage potential to be treated or mitigated successfully, major *slope re-design* can be undertaken (e.g. modify geometry, increase standoff). In all of these approaches it is probable that drainage measures will form a part of the overall solution.

A more detailed indication of appropriate treatments, based on an understanding of the likely nature of deterioration, is given in Table 2 below.

RDA_A Class	Adjusted rating	Level of risk	Approaches to remedial treatment*
1	<21	Very low risk	**Reactive approach:** Maintain or remedy as necessary. Examples include infrequent inspection and debris clearance.
2	21-40	Low risk	**Passive approach:** Control the consequences of deterioration by containment and protection. Examples include scaling; wire netting; rock catch ditch and protective fencing.
3	41-60	Moderate risk	**Active approach:** Reinforce the slope and slope materials to resist processes of deterioration. Examples include surface protection (eg shotcrete, geotextiles and vegetation); dowels, cables, anchors and rockbolts; dentition.
4	61-80	High risk	**Intrusive approach:** Retain and support the slope. Examples include crib walls, gabions and buttresses; underpinning.
5	>80	Very high risk	**Slope re-design:** Examples include reducing slope gradient; benching; increasing stand-off; rockfall shelters.
* Approaches to remedial treatment are cumulative, ie a class 3 slope will require an 'active' approach *in addition* to measures indicated for classes 1 and 2.			

Table 1 General approaches to treatment of deteriorating rockslopes (based on stage one of RDA)

Detailed treatment measures matrix

The matrix given in Table 2 is intended to act as a guide for treatment measures suitable for different deterioration modes likely to occur in rockslopes with varying levels of risk. However, it is important that the actual selection of works is based on detailed site appraisal and engineering judgement. It should be noted that certain classes of RDA_A are unlikely to occur for certain deterioration modes. This assertion is based on analysis of the results of applying RDA to a wide range of rockslopes in the UK. The treatment measures suggested are cumulative for each class. For example, treatment measures suggested for class 4 stone ravelling should be undertaken, as necessary, *in addition* to measures deemed necessary for classes 1, 2, and 3. In any class, it will usually be unnecessary to apply all of the treatment measures listed, but with engineering judgement and a good understanding of site conditions, to make an appropriate selection.

In addition to treatment measures associated with deterioration of the rockslope, maintenance and management might be required for the stabilisation works themselves. For example, rockbolts might need monitoring, repairing or replacement, planted vegetation might require management (eg thinning, pruning, re-seeding) and masonry walls might require re-pointing. Drainage channels will also need regular clearance and any leaks identified need to be repaired. As indicated above, the general treatment categories (passive, semi-active etc) are not intended to be rigid and this is reflected in the treatment matrix given in Table 2. In some cases, for example, it might be appropriate to adopt retention and support measures (intrusive aproach – class 4) for a class 3 slope, or to use lesser measures for a higher class.

Deterioration mode	RDA$_A$ Class				
	1	2	3	4	5
Grain ravelling	Unlikely to occur	Collector drain at crest; diversion drain at toe; debris clearance (eg from clogged toe drains).	Local reinforced shotcrete application; local mortar screeding; sealing of erosion and fracture chutes; low growing woody vegetation cover at the slope foot.	Widespread shotcrete or dense vegetation cover to reinforce; limited grascrete or crib wall retention.	Unlikely to occur
Stone ravelling	Occasional debris clearance and inspection.	Cut-off drain at crest; rocktrap ditch and fencing; regular scaling and debris and vegetation clearance; local wire netting.	Extensive reinforced wire netting; shotcrete or dentition for small, weak areas; masonry support of small overhangs; weepholes for all surface cover.	Inclined drainage; extensive shotcrete, dentition, underpinning or buttressing as needed (with drains); gabions for weak areas	Benching with intermediate berms; re-excavation if loose areas due to blast damage
Block ravelling	Unlikely to occur	Cut-off drain at crest; regular inspection; rocktrap ditch and anchored or reinforced fencing or barrier; regular scaling and debris and vegetation clearance; limited, high strength wire netting.	Extensive reinforced high strength netting; dentition or masonry walls for weak areas; underpinning of overhangs; weepholes for all surface cover; dowels, bolts or cable lashing for large blocks.	Inclined drainage; underpinning and local buttressing as necessary (eg concrete or masonry wall with drainage layer); gabion retention for large loose areas; rockfall shelter; warning signs and restricted access.	Unlikely to occur
Flaking	Unlikely to occur	Frequent debris clearance; cut-off drain at crest; diversion drain at toe; rocktrap ditch; very close mesh wire or plastic netting.	Surface protection with geotextiles; widespread vegetation cover (grasses and herbs) in suitable materials; large rocktrap ditch and close mesh fence or protective barrier; seal erosion and fracture chutes.	Retention with gabion baskets, crib blocks or grascrete.	Standoff area increased or slope gradient reduced.
Wash erosion	Cut-off drain at crest; diversion drain at toe; regular drain clearance.	Regularly spaced weepholes or inclined drains; local surface protection with geotextile membrane for shallow gradients and vegetation cover in suitable materials	Slope drainage; widespread surface protection with geotextiles and vegetation (grasses and herbs); seal erosion and fracture chutes; shotcrete for local weak areas; dentition with weepholes for local cavities and overhangs; low growing woody vegetation cover at the slope foot.	Surface protection and retention with grascrete (planar slopes only); cross flowpath barriers; underpinning for areas with gullies.	Slope angle and length reduced; benching.
Solution & karstification	Collector drainage at crest.	Regular inspection and removal of vegetation.	Slope drainage; seal and drain vertical fractures and chutes; mortar screeding or dentition of small cavities.	Underpinning of large solution cavities.	Grout infilling of large solution cavities.
Flexural toppling	Unlikely to occur	Infrequent inspection.	Long term movement monitoring; seal and drain major vertical fractures.	Bolting or anchorage of individual key blocks; concrete, masonry or gabion retaining walls.	Unlikely to occur
Grainfall	Unlikely to occur	No action necessary.	Local surface protection with geotextile matting or shotcrete.	Limited dentition; sealing of chutes; inclined drainage.	Unlikely to occur
Stonefall	Infrequent inspection.	Scaling of loose blocks; rocktrap fencing.	Dentition and local underpinning for small cavities and overhangs; rocktrap ditch; low growing woody vegetation cover at the slope foot.	Local buttressing.	Unlikely to occur
Blockfall	Infrequent inspection.	Scaling of loose blocks; rocktrap ditch and reinforced fencing.	Dentition and local underpinning for cavities and overhangs; dowels, bolts or cable lashing for large blocks.	Underpinning of large overhangs; local buttressing; warning signs and restricted access.	Unlikely to occur
Contour scaling	Infrequent inspection.	Removal of loose blocks.	Surface protection with shotcrete or geotextile; containment with wire mesh netting; low growing woody vegetation at the slope foot or rocktrap fencing.	Inclined drainage; extensive shotcrete application.	Unlikely to occur
Slabfall and toppling	Infrequent inspection.	Scaling of loose blocks; rocktrap ditch and reinforced fencing; Movement monitoring.	Dentition and local underpinning for cavities and overhangs; bolts or cable lashing for key blocks; seal vertical fractures.	Underpinning of large overhangs; buttressing; cable reinforcement for potential topples.	Unlikely to occur
Rockfall	Unlikely to occur	Cut-off drains at the crest; diversion drainage at the toe; inclined drains at critical slope locations; movement monitoring; regular inspection; removal of loose blocks; rocktrap ditch and fence.	Reinforcement of key blocks with dowels; local underpinning or buttressing; sealing of vertical fractures at the rear of the slope; warning signs and restricted access.	Substantial retention (eg crib and gabion walls) and local buttressing; reinforced underpinning of overhangs; rockfall shelter.	Re-excavation of slope, removing all loose material back to the new surface.
Debris flow	Unlikely to occur	Cut-off drainage at crest; diversion drainage at toe; inclined drains at critical slope locations; regular drain and ditch clearance; rocktrap ditch and barrier.	For small constituent size: wire mesh netting; local shotcrete; surface cover with geotextiles or vegetation for suitable materials. For large constituent size: dowel reinforcement of key blocks; local underpinning or buttressing; seal vertical fractures at the rear of the slope.	Retaining walls (eg crib blocks and gabion baskets).	Re-excavate slope, scale back to new surface; reduce slope angle and length; cross flowpath barriers.
Rockslide	Movement monitoring.	Inclined drainage.	Anchor or bolt reinforcement for key blocks; seal critical fractures; toe buttressing or gravity retention.	Unlikely to occur	Unlikely to occur

Table 2 Treatment measures matrix for different deterioration modes and levels of risk.

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