

# Assessing the potential for deterioration of engineered rock slopes

Dawn T. Nicholson

*Earth Science Department, University of Leeds, UK*

Steve Hencher

*Earth Science Department, University of Leeds, UK (Currently: Bechtel International, Seoul, Korea)*

**ABSTRACT:** The range of geological, engineering and environmental influences on the progressive deterioration of rock slopes is considered. A classification of modes of deterioration based on UK case studies is presented, together with a discussion of geotechnical implications. A new procedure (Rockslope Deterioration Assessment - RDA) for assessing the susceptibility of new cut rock slopes to deterioration is also outlined. A case study of the M6 and A685 road cuttings at the Lune Gorge in Cumbria illustrates the nature of deterioration, its consequences, remediation measures and the potential for RDA.

## 1 INTRODUCTION

Significant progressive deterioration of rock slopes can occur in engineering time, often giving rise to the need for unplanned maintenance and constituting a safety hazard. Deterioration, however, is rarely given much attention at the design stage; emphasis is on the avoidance of deep-seated failure. When a slope is cut into rock, the release of confining stress and exposure to the environment upset the quasi-equilibrium state, leading to accelerated deterioration (Gagen 1988). Deterioration includes the progressive physical and chemical alteration of rock material and its subsequent detachment and removal from the parent rock mass. It encompasses mineral alteration and the effects of stress release and abrasion, in addition to more commonly recognised geomorphic processes such as freeze-thaw and wetting and drying.

The initiation and propagation of fractures is of particular significance in surface breakdown and may eventually lead to major rockfalls and slope collapse. The precise nature and rate of slope deterioration are difficult to predict quantitatively and this paper is aimed at outlining the development of a pragmatic solution to the problem.

## 2 THE RDA METHOD

Existing rock mass classifications can be useful for the broad assessment of slope instability (eg Romana

1988; Selby 1980), but they are not focused on surface processes. The RDA method outlined here (Figure 1) is aimed specifically at the assessment of deterioration potential in new slopes and is also applicable to existing slopes. The RDA is a two part method. Initially, a scoring system using similar principles to those employed by Romana (1988), is used to classify the rock mass, modified to account for engineering, stress and environmental factors likely to influence deterioration. Secondly, an interpretation is made in terms of the nature of potential deterioration and the need for preventive measures. The classification has been developed through observations of rock slopes in the UK, and ratings therefore relate to a maritime temperate climatic regime. The ratings may need to be adjusted to suit other environmental conditions.

### 2.1 RDA Part One: Rockslope Susceptibility Class

Part one (Table 1) relates to the rock mass itself. Four input parameters - intact rock strength, material weathering grade, discontinuity spacing, and discontinuity aperture - are rated according to their perceived influence on deterioration susceptibility of the rock mass, to give a total score out of 100. This assessment is to be applied to uniform zones identified within the rock mass. The rock mass susceptibility rating is then converted to a Rockslope Susceptibility Class by numerical adjustments relating to adverse engineering, stress and

environmental conditions. Engineering factors include the rate and method of excavation, slope geometry, slope treatment measures and drainage. Stress factors include dynamic stresses such as those imposed by blasting as well as unbalanced static stresses arising from excavation and surcharge loading. Environmental factors include climatic

influences such as moisture and temperature as they relate to weathering. Examples of adverse engineering, stress and environmental factors include exposed, high altitude locations (add 5-12); excavation by bulk blasting (add 7-9); close proximity to quarry blasting (add 2-5); and unfavourable rock mass structure - eg steep,

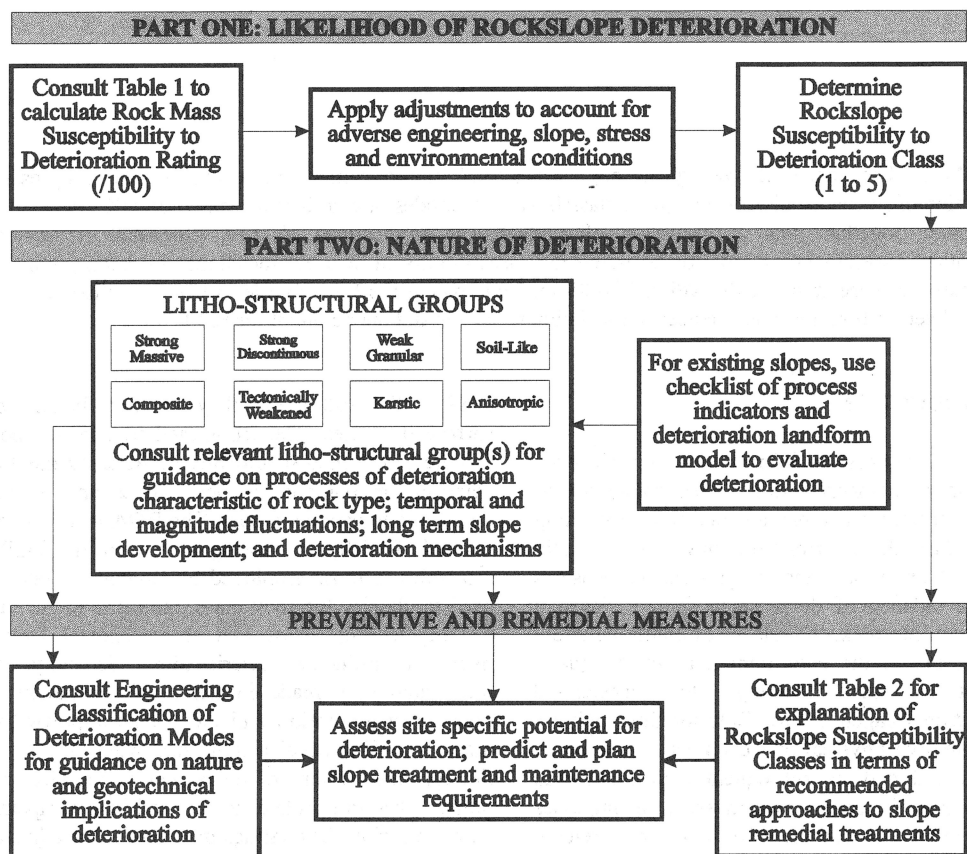
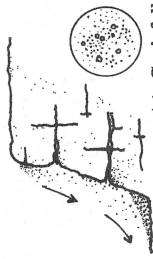
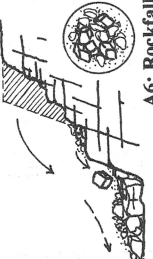

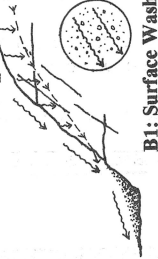
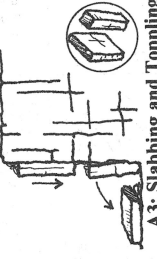
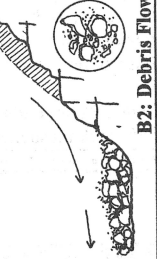
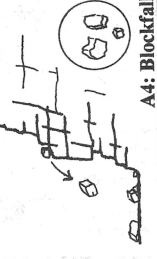
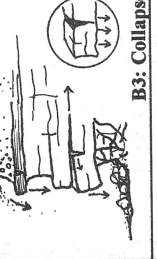

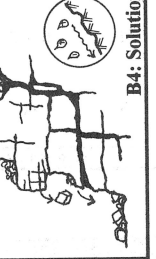


Figure 1: Decision chart for Rockslope Deterioration Assessment (RDA)

TABLE 1: RDA PART ONE: ROCKSLOPE SUSCEPTIBILITY CLASS							
A: DISCONTINUITY SPACING (35)		B: DISCONTINUITY APERTURE (15)		C: INTACT ROCK STRENGTH (35)		D: MATERIAL WEATHERING* (15)	
	Rating		Rating		Rating		Rating
>2m	2	Closed-0.1mm	1	>200MPa	2	I: Fresh, unweathered	1
600mm-2m	8	0.1-0.5mm	3	100-200MPa	5	II: Slightly weathered	5
200-600mm	16	0.5-1.0mm	7	50-100MPa	10	III: Moderately weathered	10
60-200mm	28	1.0-5.0mm	13	12.5-50MPa	18	IV: Highly weathered	14
<60mm	35	>5.0mm	15	5-12.5MPa	27	V: Completely weathered, Residual soil	15
				<5MPa	35		
CLASS = $\Sigma$ (A,B,C,D) + Adjustment (not detailed here)							
* Based upon Geological Society Engineering Group Working Party Report, 1995							

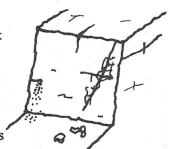

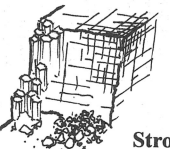
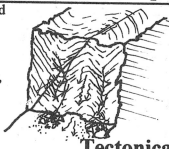




FIGURE TWO: ENGINEERING CLASSIFICATION OF ROCKSLOPE DETERIORATION MODES				
DETERIORATION MECHANISM	DESCRIPTION	GEOTECHNICAL IMPLICATIONS	DETERIORATION MECHANISM	DESCRIPTION
 <b>A1: Grainfall</b>	Fall of individual rock grains from the rock mass with physical disintegration into grains as a necessary prerequisite. Is dependent upon strength of intergranular bonding and grain-related microcracks. May occur on a semi-continuous basis.	Causes general weakening of rock material. Insignificant hazard in itself, but may lead to loss of support and subsequent small-scale collapse. Deposits of fines may clog toe drains. <i>Treatment:</i> Debris clearance at foot; surface cover from geotextiles or biogeotextiles; techniques may assist; shotcrete facing; local reinforcement where collapse likely.	 <b>A6: Rockfall</b>	Fall of many rock blocks as a single, identifiable event. Requires general weakening of the rock mass due to fragmentation, and lack of lateral support. Volume may be dictated by failure along a single, shallow discontinuity plane.
 <b>A2: Flaking</b>	Fall of flakes of material from the rock mass. Flakes are plate-like in form, having one dimension significantly smaller than the remaining two. May reflect lithology eg as found in fine grained, fissile rocks, or may reflect surface penetration of material weathering, leading to spalling, as found commonly in sandstones.	Plate-like fragments less prone to bounce during fall and therefore may not constitute a significant hazard. Creates debris pile at foot, and may clog toe drains. In composite structures, commonly leads to undermining of more competent strata <i>Treatment:</i> Debris clearance of slope and foot; biogeotextiling techniques and geotextiles; shotcrete facing with dentition if severe. Increase standoff or verge to provide fallout area.	 <b>B1: Surface Wash</b>	Detachment and transport of fine material in and by surface water flow. Can occur on low angle slopes, and flow may concentrate into channels leading potentially to gully formation. Random impact may contribute to the detachment phase in weak or soil-like materials.
 <b>A3: Slabbing and Toppling</b>	Fall of isolated rock slabs (plate-like) and prisms with minimum median dimensions of 300mm, involving sliding and rotating actions respectively. A tensile fracture at the rear parallel to the slope plane is usually a prerequisite, followed by loss of support in the case of slabbing.	Occurs infrequently but may involve the fall of large blocks of material and can be a significant hazard. May cause structural damage to drainage channels, fencing and paving. May create overhangs. <i>Treatment:</i> Scaling; intermediate berms; reinforcement with rockbolts, dowels and anchors. Severe cases may require substantial slope reinforcement with retaining structures and underpinning.	 <b>B2: Debris Flow</b>	Rapid transport of coarse and fine rock particles in a water and granular matrix as a dry or saturated flow.
 <b>A4: Blockfall</b>	Occasional fall by gravity of individual rock blocks of any dimension.	Hazard difficult to predict due to wide size range, but large blocks can cause significant structural damage. Fragments with a block-like form are prone to bouncing during fall and can travel far. <i>Treatment:</i> Scaling; wire netting, masonry or shotcrete for locally severe areas. Large blocks may need to be treated as for potential collapse.	 <b>B3: Collapse</b>	Isolated collapse of rock mass or of large blocks (eg >500mm) due to loss of vertical support. Collapsed structures include overhangs; erosion pipes in weak or soil-like materials; honeycomb structure in granular rocks; and solution cavities.
 <b>A5: Ravelling</b>	Frequent fall of rock blocks of any dimension on a semi-continuous basis.	May cause a significant hazard, and can create large debris piles at the foot. <i>Treatment:</i> Slope scaling; netting; and rock masonry and shotcrete may be applied. Large blocks may require securing with bolts, anchors or cables. Severely disintegrated areas may require full support. Reduce slope angle if possible. Very large blocks may need to be treated as for potential collapse.	 <b>B4: Solution</b>	May develop hidden solution cavities which may be prone to collapse. Karst landforms may develop where solution is very active. Excavation may also expose paleokarst features. <i>Treatment:</i> Treat as for collapse, and in more severe cases grout infilling and the use of structural bridging may be necessary (Fookes and Hawkins 1988).
GEOTECHNICAL IMPLICATIONS			DETERIORATION MODES	
May present a significant hazard due to unpredictability. Can involve large volumes of material. Bounce and throw of material during freefall may enable considerable travelling distance to be achieved. Often triggered by freeze thaw activity in Spring and Autumn <i>Treatment:</i> Regular inspection essential. Treatment as for ravelling for known problem areas. Rockfall shelters may be required in severe cases.				
Can cause nuisance by the deposit of fines at the foot, and may modify the slope form. The onset of gullying can be very rapid. <i>Treatment:</i> Control of surface runoff by crest drainage system, with trench drains in severe cases. Surface protection by the use of biogeotextiling techniques and geotextiles will also assist, but shotcrete, dentition (with drainage) and slope retention may be required. In severe cases, reduced slope angle and length, and introduce cross-gully barriers.				
Their unpredictability and deposit of large volumes of material at the foot may create a moderate hazard. <i>Treatment:</i> As for surface wash, and as for rockfall in more severe cases. High moisture content may lead to wide lateral spread of debris at the foot.				
The range of scales over which collapse occurs, and its unpredictability, presents a varying hazard, although potential collapses are relatively easy to identify, enabling early treatment and monitoring. <i>Treatment:</i> Drainage may limit cause of undermining. If small scale, treat as for flaking or blockfall. If larger in scale, reinforce with masonry dentition, underpinning or other more substantial retention.				

daylighting fractures, solution cavities and zones of hydrothermal alteration (add 6-10). The final score, can be used to select general approaches to slope treatment (Table 2).

## 2.2 RDA Part Two: The Nature of Deterioration

A classification of common modes of deterioration is given in Figure 2. It is not sufficient to consider the likelihood or potential for deterioration. The

TABLE 2: IMPLICATIONS OF ROCKSLOPE SUSCEPTIBILITY CLASS			
CLASS	RATING	DESCRIPTION	APPROACH TO SLOPE TREATMENT*
1	0-20	Very Low Susceptibility	<i>Reactive Approach:</i> Maintain or remediate as necessary: Lined cut-off drain behind crest; toe drainage; debris clearance; scaling as required; regular inspection.
2	20-40	Low Susceptibility	<i>Passive Approach:</i> Control the consequences of deterioration by containment and protection: Wire netting; geotextiles; bioengineering techniques; rock catch ditch and fencing; intermediate berms.
3	40-60	Moderate Susceptibility	<i>Active Approach:</i> Reinforce slope to control processes of deterioration: Surface protection - shotcrete, masonry or vegetation; dowel bars, cables, rockbolts and anchors; masonry dentition and associated drainage and facing; localised support from retaining walls.
4	60-80	High Susceptibility	<i>Contain and Support:</i> Substantial intervention: Full support from crib walling, gabions and retaining structures; substantial underpinning; trench and herringbone drains.
5	>80	Very High Susceptibility	<i>Re-Design Slope:</i> Reduce slope angle; introduce benching; increase foot verge or standoff; rockfall shelter at foot.
*Approaches are cumulative, ie a Class 3 slope may require an active approach in addition to the measures already listed in Classes 1 and 2			

FIGURE 3: LITHO-STRUCTURAL GROUPS	
<p><b>Rock Types:</b> Granite; gabbro; dolerite; basalt; rhyolite; metaquartzite; gneiss; limestone; marble</p> <p><b>Characteristics:</b> Resistant to many processes of rock mass deterioration, though may be more susceptible to penetrative material weathering. Localised disintegration around major discontinuities may occur, leading to rare blockfall. Grainfall occurs in slightly weaker rocks.</p> <p><b>Examples:</b> Hoff Quarry, Appleby, Cumbria; Gobbins road cutting, Island Magee, Northern Ireland</p>  <p><b>Strong, Massive</b></p>	<p><b>Rock Types:</b> Interbedded strong and weak strata; flow-banded rock; unconformable strata; igneous intrusions</p> <p><b>Characteristics:</b> Susceptible to differential weathering leading to collapse of overhangs with associated blockfall and occasional rockfall.</p> <p><b>Examples:</b> A629 Elland Road bypass, Halifax, West Yorkshire; Belah Scar, Brough, Cumbria (also <i>weak granular</i>)</p>  <p><b>Composite</b></p>
<p><b>Rock Types:</b> Silica-bonded sandstone and conglomerate; ortho-quartzite; pyroclastics; limestone; dolomite; marble; jointed igneous rocks</p> <p><b>Characteristics:</b> Susceptible to deterioration modes dependent upon fracture network, therefore ravelling and rockfall are dominant, with blockfall, and slabbing/toppling as subsidiary modes. Soluble rocks may develop karst forms. Root wedging and frost shattering are common processes.</p> <p><b>Examples:</b> A66(T) Banks Gate, Sedburgh, Cumbria; Hamby Quarry, North Yorkshire</p>  <p><b>Strong, Discontinuous</b></p>	<p><b>Rock Types:</b> Folded and faulted rock; fault gouge and brecciated zones</p> <p><b>Characteristics:</b> Crushed, sheared and highly fractured zones in association with folding and faulting susceptible to small-scale collapse, ravelling, rockfall and blockfall.</p> <p><b>Examples:</b> M6 and A685 cuttings, Lune Gorge, and A6 Cumbria (also <i>strong discontinuous</i> and <i>anisotropic</i> in places)</p>  <p><b>Tectonically-Weakened</b></p>
<p><b>Rock Types:</b> Friable sandstone; mudstone; calcium, clay or gypsum-bonded sandstone and conglomerate; marl; chalk; weak limestone</p> <p><b>Characteristics:</b> Susceptible to material weathering and weakening leading to flaking, grainfall and surface wash, with occasional collapses and blockfalls. Fragmentation in association with root wedging is common, as is penetrative discoloration.</p> <p><b>Examples:</b> A170 Sutton Bank, North Yorkshire; Bongate Scar, Appleby, Cumbria</p>  <p><b>Weak Granular</b></p>	<p><b>Rock Types:</b> Strong limestone</p> <p><b>Characteristics:</b> Solution cavities susceptible to collapse. Tends to occur in strong discontinuous rock masses, and therefore additionally susceptible to ravelling and rockfall which may be exacerbated by solution activity. Incipient karst forms may develop in strong chalk rock masses.</p> <p><b>Examples:</b> Various disused limestone quarries in the Buxton area, Derbyshire (also <i>strong discontinuous</i>)</p>  <p><b>Karstic</b></p>
<p><b>Rock Types:</b> Chalk; marl; very weak sandstone; partly lithified strata; highly weathered rock and residual soil</p> <p><b>Characteristics:</b> Susceptible to processes of soil erosion leading to rilling, gullying and piping. Deterioration is primarily by surface wash and grainfall, with debris flow and collapse as subsidiary modes.</p> <p><b>Examples:</b> Construction site in Calder Sandstone, West Cumbria; Rucorn Expressway, Merseyside (also <i>weak granular</i>, see Plate 1)</p>  <p><b>Soil-Like</b></p>	<p><b>Rock Types:</b> Thinly-bedded, highly cleaved and fissile shales, flagstones, slates, phyllites and schists</p> <p><b>Characteristics:</b> Primarily susceptible to flaking and slabbing, but commonly leads to undermining and subsequent collapse. Very fine, highly fissile rocks may also be susceptible to surface wash and soil erosion processes. Commonly also strong discontinuous.</p> <p><b>Examples:</b> A649 Godley Cutting, Halifax, West Yorkshire (also <i>composite</i>); A590(T) Penny Bridge, Cumbria</p>  <p><b>Anisotropic</b></p>

*nature* of deterioration characterises the resulting hazard and treatment necessary. It is instructive to consider the nature of deterioration within eight litho-structural groups (Figure 3) which are each typified by particular styles of deterioration. Site-specific deterioration, of course, may also be strongly influenced by the prevailing engineering, stress and environmental conditions. Part two of the RDA (Nicholson, in prep) comprises eight tables, one for each of the litho-structural groups indicated in Figure 3. Each provides a graphic illustration of the more common deterioration processes and underlying causes, together with notes on the influence of certain lithological properties and rock mass structure characteristics. Guidance notes are provided on the likely resulting deterioration modes; temporal fluctuations of magnitude and frequency; and influential environmental, engineering and stress conditions. Some notes are also provided on likely maintenance and safety problems together with suggestions for protective measures and slope remedial treatments.

For existing rockslopes, where an interpretation of current deterioration is required, a checklist of indicators is provided to assist in identification of evidence for deterioration, together with graphic models of depositional and erosional landforms.

### 3 SLOPE ASSESSMENT USING RDA: CASE STUDY M6 AND A685(T) CUTTINGS, LUNE GORGE, CUMBRIA

In 1971 five rock cuttings were excavated 3km south of Tebay on the M6 and the parallel A685(T) (Edwards 1971). The slopes are near vertical, and are of the order of 20m in height. The geology comprises a complex series of folded and faulted strong to very strong Silurian greywackes, siltstones and mudstones. Fracture spacing, including axial planar cleavage is typically moderately to closely spaced (60-600mm). Faults are associated with shatter zones and are sometimes infilled with clay and fragmented rock gouge (Welsh 1994). With respect to the RDA classification, the greater part of the cuttings fall within the group Strong Discontinuous although local zones can be described as Tectonically Weakened or Anisotropic. The slopes are in an area of high rainfall and each year are subject to frost degradation.

Although major sliding failures occurred in these geotechnically complex slopes during construction, deterioration currently is mainly by ravelling and

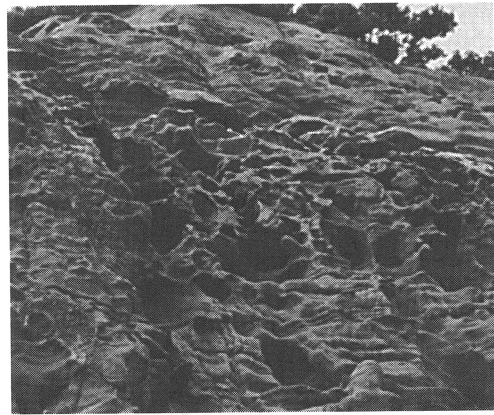


Plate 1: Honeycomb weathering of a weak, Class 2-3 Triassic sandstone along the Runcorn Expressway in Merseyside.

rockfall together with small-scale collapses. Debris piles tend to be associated with highly fractured rock in the axes of tight folds or beneath sheared and crushed rock in faulted zones (see Plate 2). Large debris piles also tend to be associated with zones of

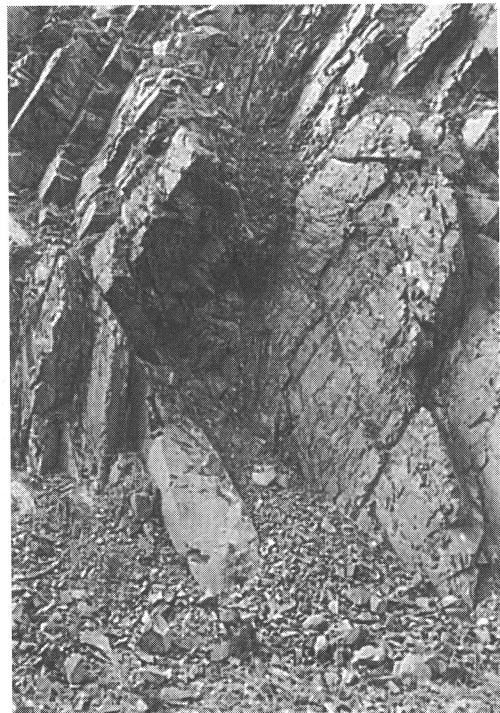


Plate 2: Deterioration on the M6 cutting at Dillicar



Plate 3: Seepage at the stonework - rock interface on the M6 cutting at Jeffreys' Mount

high seepage. Plant roots cause local fragmentation. Deterioration of these cuttings creates significant hazards to highway users and for pedestrians - particularly on educational visits (the slopes have been designated Sites of Special Scientific Interest on the basis of the exposed geology). A large rockfall in 1994 necessitated temporary closure of part of the motorway carriageway for remedial works.

At the time of excavation, thousands of rockbolts were installed for stabilisation, and a variety of additional remedial measures were introduced to control the effects of progressive deterioration. Crest and toe drains were installed, and vertical plastic pipes draining crest catchpits concreted into the slope and faced with stonework (to comply with environmental planning requirements). Subsequent failure of these drains is indicated by considerable seepage from the interfaces between the stonework and in situ rock (see Plate 3). Presumably they have become clogged and fractured internally. Such damage to the engineered system leads to enhanced deterioration. More recently, wire mesh and sometimes finer chicken mesh has been used in places to contain debris fall, and masonry revetments have been constructed where large overhangs threaten collapse. Inspections and maintenance work are undertaken regularly once or twice a year involving at least general scaling and the removal of debris.

Referring to Table 1 of the RDA method, the

cuttings fall into Rockslope Susceptibility Class 3: Where  $A=22$ ;  $B=5$ ;  $C=5$ ;  $D=5$ ; Adjustment  $=+9$  (for high altitude, exposed location; high rainfall; and failure of drainage);  $\Sigma=46$ , indicating an active approach to the remediation and control of deterioration. The slope treatments recommended in Table 2 for Class 3 rock slopes accord well with the measures actually introduced. Furthermore, the Strong Discontinuous litho-structural group is particularly characterised by ravelling and rockfall deterioration modes (see Figure 3) which are very much in evidence here.

#### 4 CONCLUSIONS AND FURTHER WORK

The broad outline of a procedure for assessing the deterioration potential of rock slopes (Rockslope Deterioration Assessment, RDA) has been presented here. The method is based on observations of numerous slopes under UK climatic conditions. A classification has been presented of modes of deterioration and these are linked to specific lithological groups. It is concluded that the use of this method at the time of design and construction may allow timely warning of potential maintenance requirements and encourage the adoption of appropriate preventive measures.

#### REFERENCES

- Edwards R.J.G, 1971 'The practical application of rockbolting - Jeffreys' Mount rock cut on the M6' *Journal of the Institute of Highway Engineers*, Dec 1971, p21-27
- Fookes P.G and Hawkins A.B, 1988 'Limestone weathering: its engineering significance and a proposed classification scheme' *Quarterly Journal of Engineering Geology*, 21, p7-31
- Gagen P.J, 1988 *The Evolution of Quarried Limestone Rock Slopes in the English Peak District*, unpublished PhD thesis, Manchester Polytechnic
- Geological Society Engineering Group Working Party Report, 1995, 'The description and classification of weathered rocks for engineering purposes', *Quarterly Journal of Engineering Geology*, 28, p207-242
- Romana M, 1988 'Practice of SM (slope mass rating) classification for slope appraisal' p1227-1231, Vol 2 In: C.Bornard (Ed) *Landslides, Proceedings 5th Symposium*, Lausanne, Balkema
- Selby M.J, 1980 'A rock mass strength classification

for geomorphic purposes: With tests from Antarctica and New Zealand' *Zeitschrift fur Geomorphologie*, 26, p1-15

Welsh S.P, 1994 *The Effects of Infill on the Shear Strength of Rock Discontinuities*, unpublished PhD thesis, University of Leeds

#### ACKNOWLEDGEMENTS

The authors acknowledge the assistance of staff of Cumbria County Council.