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Breakdown mechanisms and morphology for man-made rockslopes in North West England

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Abstract

Deterioration of excavated rockslopes occurs in engineering time. It can create a serious safety hazard and has significant resource implications. This paper presents results from a field investigation of more than 100 deteriorating rockslopes in the North West of England. Deterioration is found to be widespread but its nature and consequences vary considerably, notably in relation to rock mass structure and material properties. Deterioration can be characterised on the basis of morphology, mechanisms and relationship to the mass structure and these are used to form the basis of a new rock mass classification.

Key Words

Rockslope, deterioration, breakdown, weathering, classification, North West England

Introduction

When a new highway or quarry slope is cut in rock two fundamental changes are imposed on the rock mass. The release of confining pressure leads to expansive recovery (Gerber and Scheidegger 1969, Feld 1966, Nichols 1980), achieved by an increase in void space due to fracture propagation and dilation. The newly created rock surface is also exposed to ambient environmental conditions (Price 1995), especially temperature and moisture fluctuations, and these encourage weathering. The surface and outer skin of the rockslope are in disequilibrium with their internal and external environment (Gagen and Gunn 1988). Nature works to re-establish this equilibrium through progressive breakdown and erosion. This deterioration of a rockslope is accelerated and occurs in engineering time (i.e. within the lifetime of most engineering structures, say 100 years). Deterioration weakens the rock mass and produces changes in surface morphology, geometry and surface cover. These changes are difficult to predict in time and space and give rise to several significant potential consequences:

Slope maintenance and remedial works: Rockslope deterioration has the potential to generate significant debris, both on the slope and at the foot (Wright 1981; Spang 1987; Hungr and Evans 1988; Gagen 1988; Williams 1990). This debris may require regular clearance to maximise functionality of the slope and its environs. Debris accumulations at the foot of a slope can also influence adversely the trajectory of falling material (e.g. Ritchie 1963; Spang 1987) thereby increasing the safety hazard (Robotham *et al.*, 1995). Deterioration may necessitate the use of stabilisation or protective works to treat weakened areas (Fookes and Sweeney 1976; Fookes and Weltman 1989). Remedial structures are themselves vulnerable to damage by deterioration, and require regular inspection, repair and replacement as necessary.

Safety hazards: Where deterioration is manifest as a freefall of loose material it constitutes a potential safety hazard to people (e.g. pedestrians, quarry workers, educational groups) (Walton 1993; Robotham et al. 1995), vehicles (e.g. road and rail transport, quarry machinery) (Martin 1988) and structures (e.g. toe drains, fencing, pavements). Falls of rock in British quarries were responsible for 25 fatalities or serious injuries in British quarries over a 20-year period (Walton 1993; DETR 2000). Subsidence at the crest and collapse of overhangs can also create potential dangers.

Morphological change: Deterioration can lead to significant modification of slope morphology and there are several implications arising from this:

1. Boundary modification: A receding crest-line or build-up of debris at the foot of a slope can cause encroachment onto land owned by a third party.
2. Aesthetic impact: Modification of slope morphology and the re-distribution of detached material can have a significant influence on the overall appearance of the slope landform and this can be critical in sensitive landscapes (e.g. Nicholson 1995).

3. Conservation impact: Talus accumulation can obscure features of geological interest at conservation sites (Nature Conservancy Council 1990; Moseley 1990).

Deterioration of excavated rockslopes

Deterioration occurs at the rock mass and material scales and involves both chemical and physical processes. Chemical weathering is usually manifest as mineral alteration, decomposition and dissolution and does not commonly occur at sufficient intensity in the North West of England to produce wholesale weakening of a rock mass. However, local modification of rock material can be significant and exposure of palaeo-weathered profiles can also occur. The outcome of physical weathering is the rupture of rock material by the generation and development of fractures (Fookes *et al.,* 1988). This is the case at the rock mass scale where stress relief generates rebound fractures, at the microscopic scale where frost or salt weathering can induce intragranular and grain boundary cracks and at all levels in between. Chemical processes such as stress corrosion also contribute to fracture initiation and propagation (Whalley *et al.,* 1982) and it is likely that fracture processes are active at a nanoscale (Viles and Moses 1998). The characteristics of fractures and their inter-relationships are a major control on the size, shape and spatial distribution of detached material on a rockslope which is available for re-distribution or removal. In situ decomposition by chemical weathering also weakens the rock material, preparing it for detachment and transport. The mode of rockslope deterioration is determined by a combination of material rupture and weakening and is a critical influence on the consequences of deterioration.

Much is known about rock weathering processes (e.g. Chigira 2000, Siegesmund *et al.,* 2002), the mechanics of fracture at all scales (Hencher 1987, Chernyshev and Dearman 1991, Ameen 1995) and applications of these to the analysis of deep-seated slope instability. However, shallow, weathering-related processes are often ignored at the design stage of excavated rockslopes. This is because it is difficult to quantify, its mechanisms are poorly understood, and it is not perceived as a significant risk factor.

In order to address some of the gaps in our knowledge about deterioration of excavated rockslopes, a major field investigation was conducted. In this paper, some results are presented for localities in the North West of England. The ultimate aim of this research is to provide the basis for a new rock mass classification (presented elsewhere) for the evaluation of deterioration hazard on new and existing man-made rockslopes. This will enable potential consequences of deterioration to be identified at an early stage and due budgetary provision made for maintenance, protective and treatment measures.

Study locations

The objectives of the field investigation presented here were to (i) establish the extent of deterioration for excavated rockslopes in the North West of England, UK; (ii) characterise the nature of deterioration; (iii) determine how deterioration mechanisms can be recognised on existing slopes using morphological evidence, and (iv) draw attention to some of the factors, intrinsic and external, that influence and control deterioration. The scope of the field investigation was limited to man-made rockslopes exceeding 45^{o} in gradient. Soil, soil-like and unlithified materials were excluded except where they formed part of a slope substantially cut in rock. A total of 106 distinct slope units were investigated based at 49 sites. Of these, 60% were situated in disused quarries and 37% were sections of road cutting. The remaining slopes were active quarries (1%), semi-active quarries (1%) and natural rockslopes studied for comparative purposes (1%). More detailed information on sites is given in Table 1.

Field investigation methods

Data was obtained from several sources during the field investigation:

Background factual, published and anecdotal information

These sources of data included published maps (e.g. Ordnance Survey) and documents, information from landowners, highway authorities and quarry operators, survey and inspection reports, borehole logs and historical photographs.

Qualitative observational data

Direct and indirect evidence was recorded of:

1. The general **nature and distribution of deterioration**: deterioration mode, magnitude, event frequency and spatial variation within rockslopes were recorded.
2. The **consequences of deterioration**: evidence of stabilisation measures, maintenance works and failed remedial treatments was recorded as well as obvious implications of deterioration for safety, maintenance and slope treatment.
3. **Deterioration processes**: direct or circumstantial evidence of weathering processes and erosive agents was recorded (e.g. the presence and distribution of weathered scars, groundwater seepage).

4. The effects of deterioration on **slope morphology**: erosional and depositional landforms and indications of *in situ* weathering were described and measured.

Quantitative data

A range of measurements and observations were made of quantitative parameters including various rock mass and material properties. Observations made and the methods used are described below. Some of the data indicated below were used to develop a rockslope hazard system published elsewhere (Nicholson 2003).

Rock mass and material properties: Grain size, texture and fabric, colour, weathering grade (adapted from Moye 1955), rock strength (after Geological Society Engineering Group Working Party 1977), Schmidt hammer rebound (after Poole and Farmer 1980), lithological properties (e.g. field estimates of cementation, porosity and mineral composition), rock type (after Norbury et al. 1986), fracture spacing, persistence, origin, set orientation and infilling material (broadly following ISRM 1978). An understanding of rock mass and material properties was used to develop the classification of rock mass structure presented below.

Environmental factors: Climatic conditions, aspect, altitude, vegetation cover and type, degree of shelter and exposure, groundwater seepage and surface water runoff (broadly following ISRM 1978).

Static and dynamic stress conditions: Slope geometry, slope situation, height and general form, surcharge loading at the crest, dynamic stress factors (e.g. close proximity blasting, machine operations), the nature of traffic flow (e.g. volume, speed and proportion of heavy vehicles)

Engineering factors: Presence of stabilisation or protective measures, associated deterioration, evidence of damage to structures by deterioration, slope angle, length of slope, presence of active erosion (e.g. undermining at the base).

Time since excavation: Where possible, the time since excavation was recorded or obtained.

Results and analysis

Consequences of deterioration

It is apparent from the field investigation that deterioration is widespread on excavated rockslopes in the UK. The nature of deterioration (i.e. volume, constituent material, frequency and mechanism) varies considerably. As a result, the consequences of deterioration, the approaches adopted for its mitigation and the stabilisation and protective measures used, also vary. All forms of deterioration were represented, including occasional fall of individual grains resulting from *in situ* disintegration, semi-continuous ravelling of highly fractured rock masses, and isolated rockfall involving large volumes of material. Deterioration occurred to some extent on every rockslope investigated, though in some cases it was inconsequential. A wide range of consequences was observed including damage to structures, debris on the road pavement and over-topping of catch ditches.

Several examples were observed in the field investigation where exposures at Regionally Important Geological and Geomorphological Sites (RIGS) and other localities described in field guides (e.g. Moseley 1990; Cumberland Geological Society 1992) were partially concealed as a result of deterioration and thus their value was reduced. There was an inverse correlation between deterioration and adverse aesthetic impact. The least visually intrusive slopes were those that had developed a weathering crust, had become stained by water flow, had an irregular surface topography or had a good cover of vegetation. Conversely, freshly excavated slopes in which stabilisation measures had been used extensively or where drillholes were in evidence, were the most visually intrusive, though this general rule varied with the nature and quality of the surrounding landscape (Nicholson 1995).

It would appear that deterioration is generally dealt with on an ad hoc basis in response to specific problems being identified. It is a common regime for walkover site inspections to be conducted twice annually in spring and autumn. This is in response to the perception that peaks of deterioration coincide with greater freeze-thaw activity at these times of year. Observed maintenance operations varied from cleaning out catch ditches and drains, face scaling by hand and installation of stabilisation and protective measures (e.g. fences or barriers, wire mesh netting, rocktrap ditch, rockbolts and dowels, shotcrete, buttressing, masonry dentition and a variety of drainage measures).

In active quarries, the treatment of deterioration usually involves mechanical or hand scaling, re-routing of haul roads, or more commonly, simply closing off access. In disused quarries, the most common approach to deterioration mitigation was to increase standoff distance or use protective measures such as wire mesh netting or fencing.

Controls and influences on deterioration

Some trends were identified in the intrinsic and external properties and conditions which control and influence deterioration and these are considered below.

Intrinsic properties: As expected, deterioration in the form of block release is more pronounced where there is both a high fracture intensity and wide apertures. In rock masses which were highly fractured but where fracture aperture was very tight, slopes were much more stable. This was also the case in highly fractured rock masses where blocks were tightly interlocked. Deterioration was in greater evidence in highly fractured rock masses in weak material than in strong rock masses with a comparable fracture network. The most severe deterioration occurred in slopes with both poor rock mass and material properties.

Although major discontinuity sets such as bedding planes and joints often determined the overall structure of a rock mass, it was the smaller, less persistent, often highly irregular and dense networks of fractures where most block release occurred. This is comparable to the findings of Dixon and Cox (1993) who found that on road cuttings in rhyolite and Coal Measures rocks, the *most* urgent stabilisation measures were needed in highly fractured zones, loose blocks at the top of slopes and shear zones. This was despite the fact that they identified several potential planar, wedge and toppling failures formed in association with major joint sets. These small, non-persistent and irregular fractures form from stress release, blasting (Figure 1) and vegetation and weathering effects. They were commonly associated with, and formed along, small scale flaws in the rock such as laminations, lithological variations, cleavage, mineral veins, weathered bands, macro fossils and cavities. This finding is at odds with existing slope hazard methods which emphasise the role of major discontinuity sets.

The type of deterioration varied in slopes with different rock mass and material properties. For instance, in weakened materials with a coarse granular texture (e.g. sandstone and gritstone), deterioration was dominated by *in situ* breakdown, cavity development (Figure 2), grain ravelling and surface scaling. Block release, whether as isolated falls, ravelling or major rockfall events, was much more common in stronger, fractured rock masses.

External factors: Deterioration was enhanced in the vicinity of groundwater seepage, sometimes due to *in situ* decomposition or disintegration associated with the presence of moisture, and other times due to cleft water pressure through the fracture network leading to block release. There was a statistically significant correlation between aspect and deterioration (Nicholson, *in prep*). A greater severity of deterioration was associated with west, north-west and north-facing slopes, and the least severity of deterioration was associated with east, south-east and south-facing slopes. Though there are many complex relationships between weathering and aspect (e.g. Robinson and Williams 1998, Williams and Robinson 2000)

Figure 1: Wide aperture fractures resulting from blast-induced stress release: Block release could induce larger scale rockfall (Knock Pike Quarry, Lake District).

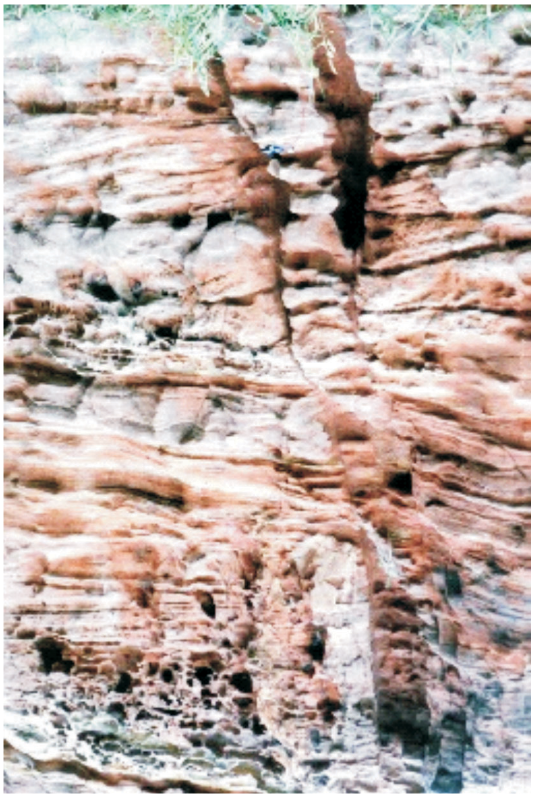


Figure 2: Honeycomb weathering leading to risk of cavity collapse (Runcorn Expressway, A557).

the key factors appear to be rock moisture retention, exposure to prevailing wind and rain, and frost (cycles and intensity). In these respects, northerly and westerly facing slopes appear to fair worst. These slopes are cast semi-permanently in shade, commonly retain surface water and often have a widespread cover of moss and algae. Material weathering in such localities was found to be greater than slopes which received sun and occasionally dried out.

Other climatic influences were also evident. Deterioration was more severe at higher altitude and in exposed locations. There was a clear correlation between slopes with extensive groundwater seepage and the presence of vegetation. Woody vegetation in particular (e.g. perennial shrubs and trees), usually coincided with intensely fractured zones.

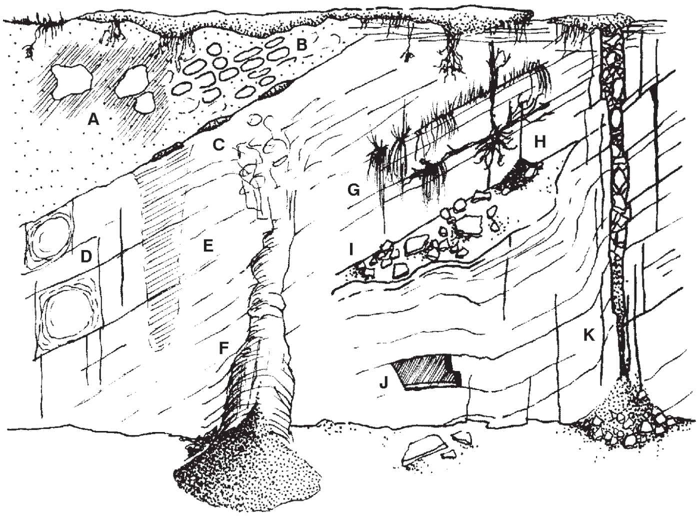
Slopes which had been excavated by bulk blasting were more highly fractured than those that had been excavated by pre-splitting, mechanical methods or by hand. Bulk blasted slopes were more likely to exhibit signs of severe deterioration than the others. Older slopes (e.g. more than 100 years) tended to be more stable than their younger counterparts. However, it is difficult to say whether this is purely a function of age and equilibrium, or whether it reflects fundamental changes in the excavation method used over this period.

Deterioration morphology

The field investigation revealed that a range of slope micro-landforms could be identified which were related to the deterioration processes acting. These were an important factor in enabling assessment of the deterioration mechanisms operating in each case. Deterioration morphology can be sub-divided into erosional landforms (Figures 3 and 4), depositional landforms (Figure 5) and process indicators (Figure 6). Deterioration morphology is summarised in Table 2 and a fuller description is found in Nicholson (2000). Images of many of these morphological forms are available online at URL: http://www.egs.mmu.ac.uk/users/dnicholson/rda/morphology.pdf

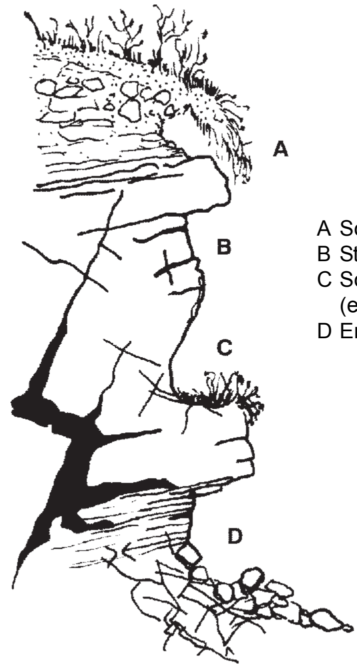
Classification of deterioration modes

The field investigation revealed a range of distinct modes of deterioration. Since the mode correlates strongly with the likely consequences of deterioration, it was deemed useful to identify, describe and classify the mechanisms observed. Existing classifications of landslides were reviewed to assist in this process. However, most existing classifications either address deep-seated failures (e.g. Varnes 1958; Hoek 1973; Hutchinson 1988) or make little distinction between different small-scale deterioration-



A Surface crust and scaling
B Honeycomb structure
C Bedding plane cavities
D Onion-ring (exfoliation) weathering
E Laminations picked out by surface runoff
F Erosion chute
G Draped grass
H Root growth in cracks
I Structural chute with debris
J Surface scar
K Fracture chute

Figure 3: Erosional morphology due to deterioration.



A Soil overhang
B Structural overhang
C Solution overhang/cavity (e.g. tafoni)
D Erosion (composite) overhang

Figure 4: Deterioration-related slope overhangs.

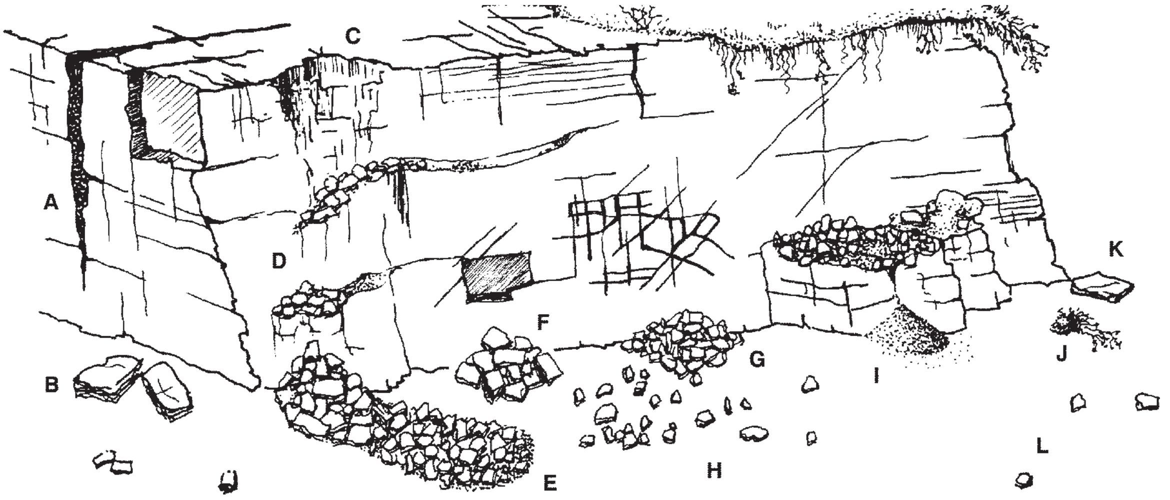


Figure 5: Depositional morphology due to deterioration.

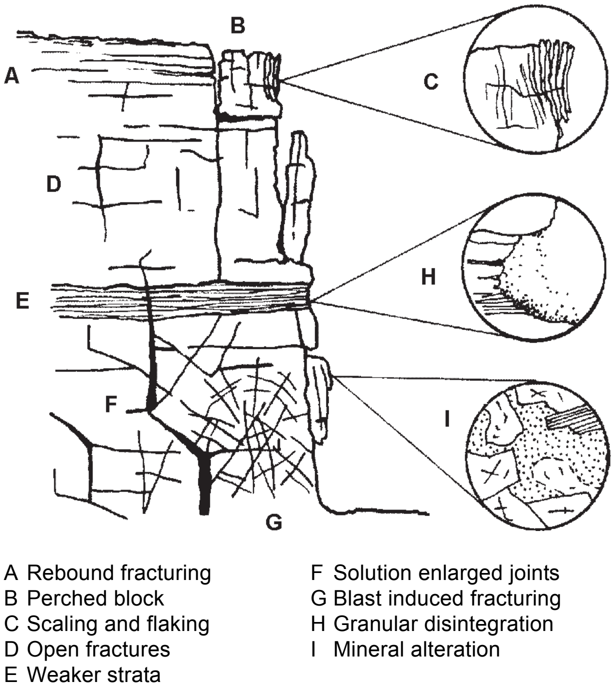


Figure 6: Deterioration process indicators.

related processes (e.g. Carson and Kirkby 1972; Walton 1988). Commonly, many deterioration mechanisms are described under the catch-all term of 'rockfall' (e.g. Rapp 1960; Whalley 1984). There are some exceptions to the rule (e.g. Franklin and Senior 1997), but the application of such classifications is often limited by a narrow lithologic or geographic bias.

A classification of deterioration mode based on the field observations described is proposed (Figure 9). Modes are distinguished according to frequency of occurrence, relative velocity of movement and size of constituent material. Event magnitude can also be inferred from the deterioration mode. The classification is intended primarily to assist in the assessment of deterioration mitigation and guidance notes have been published elsewhere (Nicholson *et al.*, 2000; Nicholson 2003). A summary of the main deterioration modes is given below.

Semi-continuous modes of deterioration: Five semi-continuous modes of deterioration are recognised. (i) **Ravelling** is the frequent and semi-continuous fall of material. Three size divisions are recognised: grain ravelling (clay, silt, sand and fine gravel <20mm), stone ravelling (coarse gravel and cobbles 20 to 200mm) and block ravelling (boulders >200mm). Grain ravelling can be transitional with wash erosion (see below). (ii) **Flaking** is a form of ravelling involving the frequent and semi-continuous fall of material with a distinctive platy form, and occurs predominantly in fissile rocks such as shales and slates. (iii) **Wash erosion** involves detachment and transport of fine material entrained in surface water runoff. (iv) **Solution** is dissolution of soluble mineral grains and cementing material in aggressive, acid solutions, including rainwater. When this process affects the character of the rock mass it can be described as **karstification**. (v) **Flexural toppling** is a slow, progressive deformation and sliding of layered strata due to gravitational forces upon removal of lateral constraint.

Sporadic modes of deterioration: Three sporadic modes of deterioration are recognised. (i) **Fall** is the occasional fall of individual fragments. The same size divisions for ravelling are also used to give grainfall, stonefall and blockfall. (ii) **Contour scaling** is a special form of fall involving the infrequent exfoliation of thin layers of rock material formed parallel to the slope surface. (iii) **Slabfall and toppling** are the infrequent fall of large, tabular slabs and rotation of large prismatic blocks (typical 'a' axis dimension of 1m).

Isolated modes of deterioration: Three isolated modes of deterioration are recognised. (i) **Rockfall** is used as a specific term to describe the fall of many blocks of varying sizes in a single, identifiable event, and involve elements of freefall, slide, bounce and roll or a combination of these. (ii) **Debris flow** is the rapid transport of a mixture of coarse and fine particles in a partially saturated, grain-supported flow, and involves initial sliding and subsequent flow. (iii) **Rockslide** is the rare, large scale and rapid translational movement of rock, often along a distinct discontinuity plane. Strictly, this mode does not result from deterioration, but since small rockslides occur, and since the trigger mechanism for rockslide is commonly largely weathering-related, it is included for completeness.

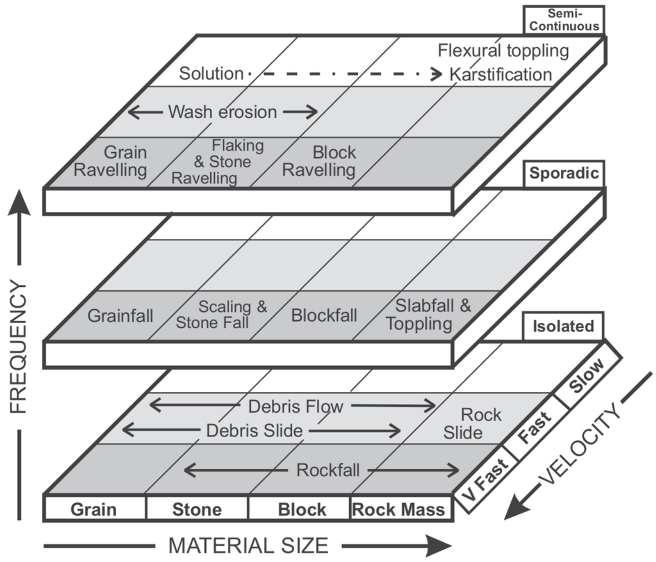
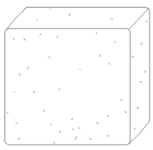
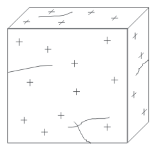


Figure 9: Engineering classification of deterioration modes for excavated rockslopes.

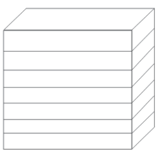
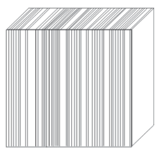
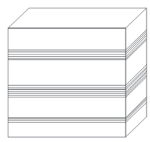
Classification of rock mass structure

During the field investigation it was apparent that deterioration modes related strongly to three rock mass properties in particular, namely rock type, fracture network and rock strength. In order to simplify correlation between these, a classification of rock mass types is proposed. The primary distinguishing factors for each rock mass are the arrangement of fractures and the rock mass structure. Three primary categories are recognised: **massive** (sub-divided in to weak and strong), **layered** (sub-divided into normal, composite and fissile) and **blocky**, (sub-divided into regular and irregular). Additional descriptive terms such as rubbly and prismatic can be used as appropriate. Three subsidiary rock mass structures are recognised: intensely fractured zones, soluble rock mass and composite rock mass. Brief definitions of rock mass types are given in Figure 10.

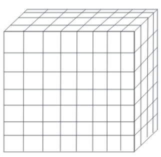
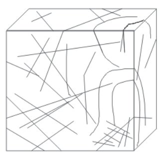
MASSIVE

Weak massive Weak (e.g. <30MPa) rock masses with no dominant structure (i.e. essentially homogeneous), or very thickly bedded. May have occasional fractures, or many closed discontinuities. 	**Strong massive** Strong rock masses with no dominant structure (i.e. essentially homogeneous), or very thickly layered. May have occasional fractures, or many closed discontinuities. 

LAYERED

Layered Repeated layering of strata at any angle. Strata may be lithological (e.g. bedding) or structural (e.g. jointing). 	**Fissile (layered)** Very thinly layered rock due to thin bedding, schistocity, cleavage or lamination. 	**Composite (layered)** Inter-layered strata with contrasting material properties. Can be sedimentary bedding or igneous intrusions. 

BLOCKY

Regular Orthogonal blocky structure due to intense intersection of fractures. 	**Irregular** Irregularly shaped and variably sized blocks due to non-structured intersection of fractures. 

SUBSIDIARY ROCK MASS TYPES

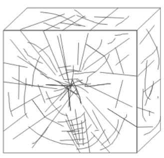
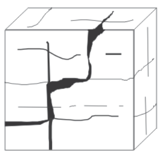
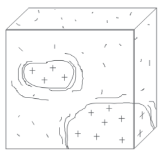
Intensely fractured zone Intense, *localised* fracturing and shattering of the rock mass leading to a very loose structure. 	**Soluble rock mass** Solution, leading to enlargement of existing fractures, micro-solution features, macro karst development. 	**Composite structure** Rock mass composed of contrasting structural elements (e.g. corestone development, irregular intrusions). 

Figure 10: Classification of rock masses for evaluation of rockslope deterioration.

Occurrence of deterioration modes

The percentage frequency occurrence of deterioration modes for all the slopes investigated is given in Figure 11. The total number of occurrences of deterioration modes was 289 and the total number of slope units was 106. The former value reflects the fact that for many slopes, more than one deterioration mode was in evidence. The chart shows that the fall of isolated fragments (both stone or block sized) is the most common mode of deterioration. Several modes which relate to material properties are also important, including wash erosion, grain ravelling and scaling, while the large scale modes of debris flow, rockslide and flexural toppling occur least commonly. While karstification occurred in slopes investigated as part of a wider survey of slopes in the British Isles, it was not identified in any of the slopes visited in the North West region but is included in the charts for completeness. Rockfall and stone ravelling occurred in around 10% of slopes and this is significant because these modes probably lead to the most rapid accumulation of debris and slope regression. They may not be the most hazardous modes, because even a single block can cause a fatality, but they are the most serious in terms of the volume of material involved.

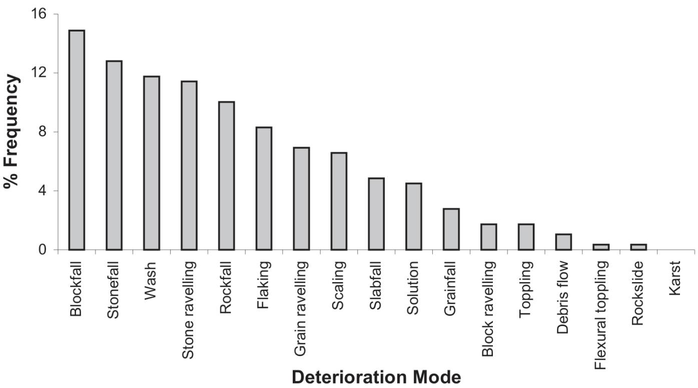


Figure 11: Percentage frequency occurrence of deterioration modes.

Figure 12 shows the relative percentage frequency occurrence of deterioration modes for sedimentary, igneous and metamorphic slopes respectively. Two important findings are implicit in this chart. First, some deterioration modes occur with similar frequency for all rock groups. For instance, stone ravelling and blockfall are ubiquitous, being ranked most or second most common for all rock groups. Since these modes depend upon the presence of intersecting fractures, their ubiquity across all rock groups may reflect the preponderance of fractures, joints, bedding and blast-induced fractures regardless of lithology.

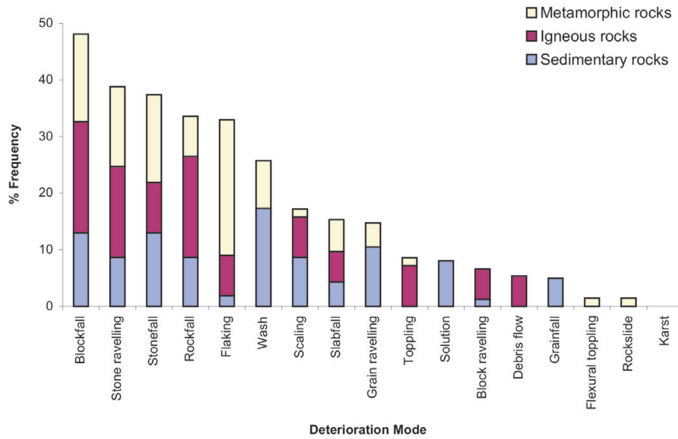


Figure 12: Occurrence of deterioration modes in relation to rock group.

Second, some deterioration modes occur with much greater frequency in some rock groups than others. For example, in the sedimentary group, the relatively high rankings for wash erosion, solution and scaling are particularly notable, reflecting the greater importance of material breakdown. In the metamorphic group, flaking is dominant. This clearly reflects the large number of slopes with metamorphic cleavage, and a number of meta-sediments in which original thin bedding was strongly retained. This group also boasts the only occurrence of flexural toppling as a major mode, probably also a reflection of the importance of cleavage. The igneous group is dominated by deterioration modes which depend upon the fall or ravelling of stones or blocks defined by discontinuities (e.g. blockfall, rockfall and stone ravelling). The importance of modes based on material weathering (e.g. grain ravelling, grainfall, solution and wash erosion) is very low for this group, reflecting the high material strength and resistance to weathering.

Occurrence of rock mass types

The frequency distribution of rock mass types observed in the field investigation is given in Figure 13. The chart shows that layered rock masses are significantly more common than other types. However, since the frequency distribution is partly a reflection of the rockslopes investigated, it is helpful to consider the distribution of rock mass types with reference to the three rock groups, sedimentary, igneous and metamorphic. The chart in Figure 14 shows that there are clear relationships between rock group and rock mass type:

Layered rock masses dominate the sedimentary group. Metamorphic rock masses are also commonly layered, reflecting the sedimentary, bedded origin of many metamorphic rock masses. Layered slopes in igneous rock masses were usually dominated by parallel, *vertical* jointing. Igneous rock masses are dominantly blocky and irregular blocky. Many are also strong massive, indicating an absence of open fractures. This reflects the higher strength of igneous rock masses compared with the other rock groups. Some rock mass types only occur in one or two rock groups. For example, weak massive rock masses only occur in the sedimentary group and fissile and composite rock masses are absent from the igneous group. Irregular blocky rock masses are more likely to be igneous in origin, a reflection of the general absence of regular discontinuity patterns. The relatively high proportion of fissile rock masses in the metamorphic group is reflected in the increased role of flaking as a deterioration mode noted earlier.

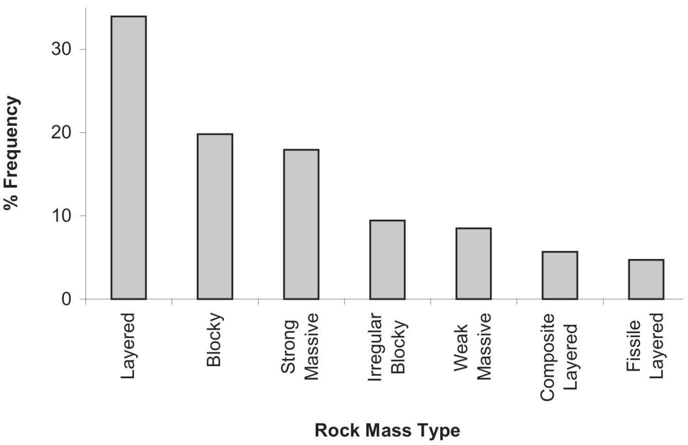


Figure 13: Percentage frequency occurrence of rock mass types.

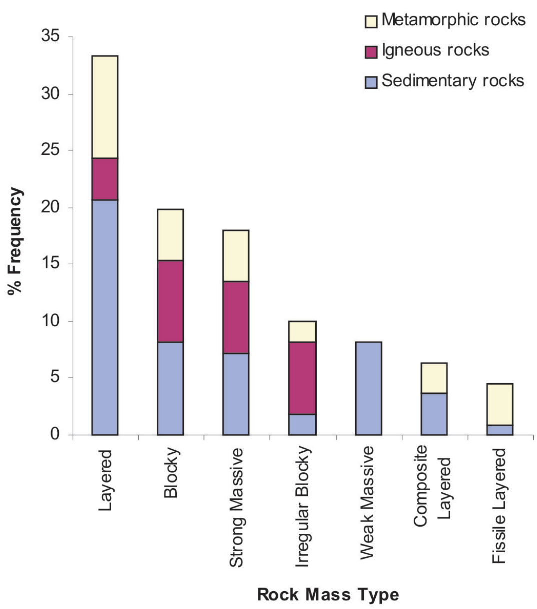


Figure 14: Occurrence of rock mass types in relation to rock group.

Discussion and conclusions

The percentage frequency occurrence of deterioration modes for different rock mass types is given in Figure 15 (a to g). It is evident that some deterioration modes are closely associated with particular rock mass types, while others are independent. For example, weak massive rockslopes are dominated by deterioration modes where the focus is on material breakdown (e.g. grainfall, grain ravelling, wash erosion and scaling). Stonefall, the most frequent deterioration mode, is the exception to this, although stonefall does include very small fragments (>20mm). There is a similar emphasis on material breakdown for strong massive rock masses, though a slightly broader range of deterioration modes. In contrasts, and as might be expected, blocky rock masses are most affected by mechanisms which depend upon the detachment of blocks. Common deterioration modes include stone ravelling, stonefall, blockfall and rockfall. In addition to these, toppling and debris flow occur in irregular blocky rock masses. This probably reflects the wider variety of particle sizes typically present in irregular blocky slopes. Layered and composite layered rock masses show a similar range of deterioration modes, with a mixture of discontinuity-dependent and material dependent mechanisms evident. Blockfall has a greater dominance in composite layered slopes and this probably reflects the greater opportunity for collapse of overlying blocks due to undermining of weaker material below. Fissile rock masses are dominated by the flaking mechanism as might be expected.

The data described above indicate that rock masses have a built-in propensity to deteriorate in a certain way. As such, it is likely that there is a degree of predictability involved and this has practical implications for slope hazard assessment. In fact, a new rock mass classification scheme, called Rockslope Deterioration Assessment (RDA) has been developed (Nicholson 2000, 2003), based on the findings presented herein. RDA is a process that utilises the relationship between rock mass properties, deterioration mechanisms and deterioration morphology to enable systematic evaluation of deterioration potential and nature. The method has applications for safety management in working quarries, for hazard assessment in disused quarries and for maintenance planning and safety assessment of highway cuttings.

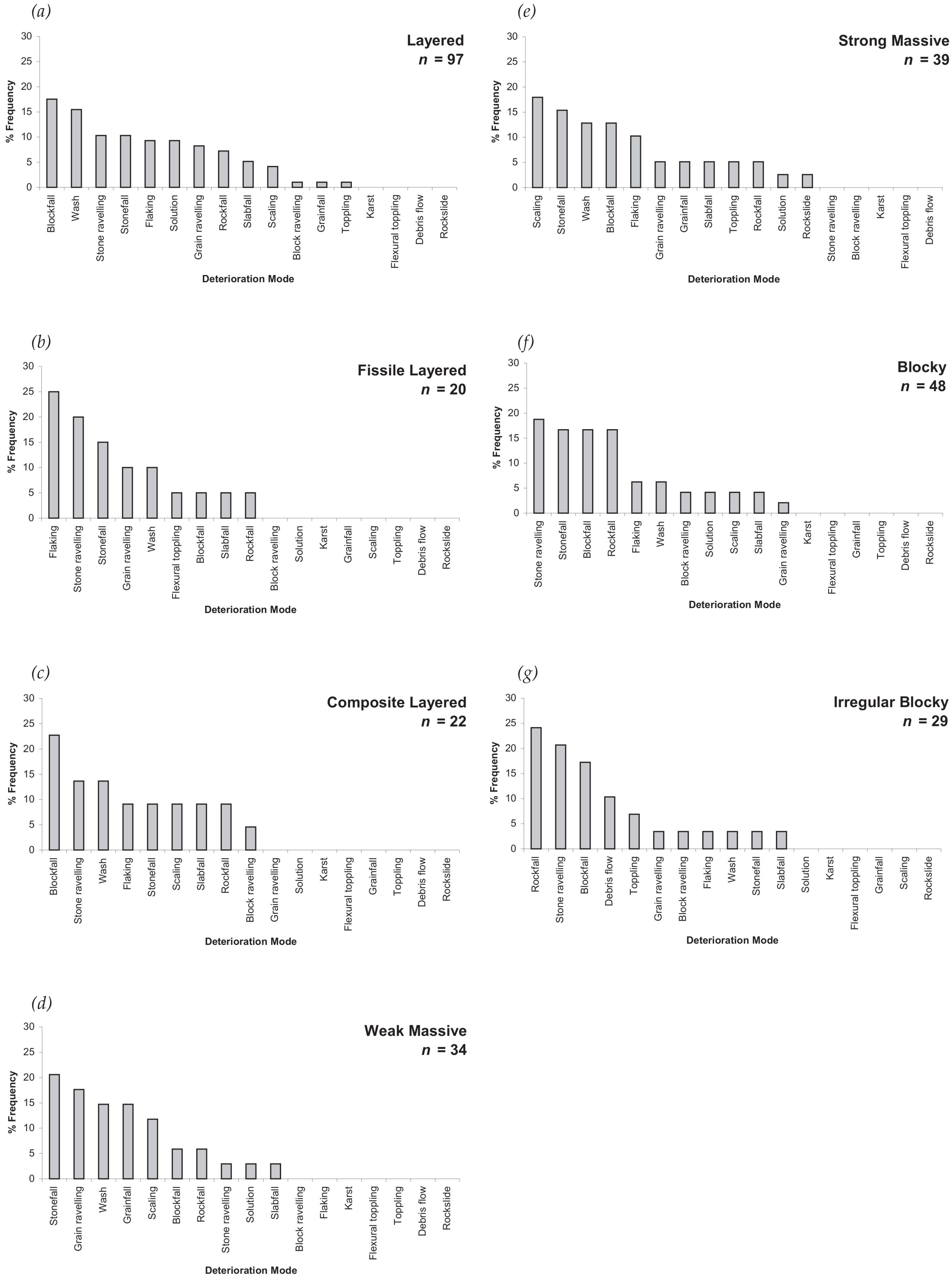


Figure 15: Occurrence of deterioration modes in relation to rock mass type.

Table 1: Summary of sites investigated.

SEDIMENTARY ROCKSLOPES	
Total number of slopes Total number of slope units	24 53
Slope type	Road cutting = 24; disused quarry = 29; semi-active quarry = 1; active quarry = 1; natural slope = 1
Rock type*	Sandstone = 32 (including 3 gritstone and 1 turbidite) Limestone = 19 Mudstone = 8 (including 2 siltstone and 4 shale) Other = 4 (2 breccia and 2 coal)
IGNEOUS ROCKSLOPES	
Total number of slopes Total number of slope units	10 26
Slope type	Disused quarry = 26
Rock type*	Granitic = 13 (including 11 microgranite and 2 granite) Pyroclastics = 13 (including 10 tuffs and 3 ignimbrite)
METAMORPHIC ROCKSLOPES	
Total number of slopes Total number of slope units	15 27
Slope type	Road cutting = 16; disused quarry = 11
Rock type*	Metasediments (metamorphosed turbidite sandstones, siltstones and mudstones) = 20 Slate = 7

* The total number of rock types exceeds the total number of slope units since some slopes comprised more than one rock type.

Table 2: Deterioration morphology.

Erosional landforms

Erosion only takes place when material which has become detached from the rock mass is removed by transport agents, to be subsequently deposited elsewhere. Much material may remain *in situ* (see below).

Chutes are quasi-channels down which loose material is transported. They are characterised by having debris piles at the foot, in some cases with a wide spread of debris in or on chute surfaces. Three sub-types of chute were identified. Erosional chutes occur where rock material has been cut into by erosive agents, usually surface water runoff. They can also form from dissolution. Fracture chutes occur where fracture aperture has been enlarged (e.g. due to wall breakdown). Structural chutes are strictly not an erosional landform. They are the product of the intersection of discontinuity planes with the slope plane. Nevertheless, they provide conduits for downslope movement of material and commonly contain accumulated debris, soil and vegetation. They therefore function as chutes and are susceptible to surface erosion.

Overhangs occur in a range of situations and three sub-types can be recognised. Structural overhangs have a similar origin to structural chutes. Erosional or composite overhangs occur where competent materials are undermined by erosion of underlying weaker strata or by basal undercutting in homogeneous materials (Figure 7). Solution overhangs may be produced in soluble rocks. Runnels may be regarded as incipient solution chutes.

Cavities are an erosional form which may be transitional with overhangs (e.g. tafoni). There are several types of deterioration-related cavity. Honeycomb weathering often produces small cavities in the form of alveolar structure. Localised and small scale cavities often form along horizontal discontinuities such as bedding planes, probably representing the early stages of undermining. Larger scale Man-made cavities such as mine adits may rarely be exposed in excavations. Cavities of a wide range of shapes and sizes can be formed from solution. Palaeo-solution cavities may also be exposed in excavations.

Surface scars form when material has been removed from the slope and these were a very common sight in the field investigation. In some cases, scars are visible because the newly exposed rock is more weathered than the adjacent material, indicating that weathering had penetrated, either through the material or along discontinuities, at least to the depth of the scar. In other cases, the reverse may be true, in that scars may reveal fresh, unweathered material behind. This is often an indication that the material which had been removed, was itself weathered. Scars are an excellent means of locating the likely origin of debris found at the foot of slopes.

Depositional forms

Depositional landforms are formed from the debris which results from rockslope deterioration and can be located at the foot of the slope or on the slope itself. Depositional landforms are a useful means of estimating the likely magnitude and frequency of deterioration mechanisms involved (Figure 8).

Debris piles are concentrations of debris, either of a uniform constituent size or multiple sizes. Debris piles probably develop from one of two processes, either the fall of a large volume of material in a single event, or the semi-continuous fall of material from the same location on the slope. Evidence from scars indicates that debris piles formed from single fall events tend to have more lateral spread and a shallower gradient, forming quasi-fans. Gradual accumulation of debris from ravelling produces more concentrated, steeper debris piles, particularly for platy fragments derived from shales.

Scattered debris is defined as an extensive scatter of material at the foot of a slope, perhaps with some localised concentrations. This is produced mainly by ravelling of blocky materials. Constituent material size is often quite uniform.

Isolated debris is the result of rare falls of materials from different locations. Constituent material size is often very variable.

Fracture infilling in particularly wide aperture fractures is relatively common. Several types of infill material can be identified including (i) fines resulting from the disintegration of fracture walls (effectively *in situ* infilling), (ii) fines washed into fractures from soil or detrital material, (iii) blocks dropped into fractures, and (iv) mineral precipitates (e.g. veins, healed fractures). The occurrence and properties of these different types of discontinuity infill are considered by Welsh (1994).

continued over

Process indicators

Process indicators are features which give an indication of the cause of deterioration.

Water flow: Moisture supply is integral to most weathering processes and therefore direct or circumstantial evidence of surface or groundwater flow is usually good indirect evidence of actual or potential weathering activity. Indicators of regular water flow include damp fracture infill, surface discolouration, moss and algae, preferential development of honeycomb weathering, ripples in sediment accumulations, the presence of vegetation, flattened or 'draped' grass, fractures enlarged or rounded by dissolution, protruding rock structures (e.g. fine laminations) due to surface water erosion.

Vegetation: Vegetation is often an indicator of the availability of moisture. Vegetative roots are often found in association with *in situ* fragmentation.

In situ decomposition: Evidence of *in situ* decomposition can be found where material weathered by chemical processes has not been removed by erosive agents. Evidence includes exfoliation or 'onion skin' weathering and incipient corestones. These were especially found in sandstones and basalts and was in some cases related to penetration of chemical weathering from joint boundaries. Solution features are also commonly observed, producing micro-solution pits, runnels and surface rounding. Honeycomb weathering is common in Triassic sandstones and is thought to develop from a combination of case hardening and differential weathering (Winkler 1994). The role of salt weathering in honeycomb development is unclear (Mustoe 1982). Breakdown of intergranular cement may also be evident. This probably results from both chemical and mechanical effects.

In situ disintegration: Evidence of *in situ* disintegration can be found where material weathered by mechanical processes has not been removed by erosive agents. Evidence at the material scale includes general weakening and increases in surface porosity. At the mass scale, evidence is largely derived from the nature of fractures present and includes increasing frequency of near-surface fractures due to rebound. Stress relief fractures induced by blasting are also common, as are zones of particularly intensely fractured rock, often relating to drillhole locations. Occasionally, shattered loose blocks may be found, due to freeze-thaw weathering.

Figure 7: Risk of blockfall from beneath soil overhang (Wasdale Beck, A6).

Figure 8: General ravelling and flaking of metasediments leading to debris accumulation (Dillicar, M6).

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