Excavation-Induced Deterioration of Rockslopes

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INTRODUCTION

Engineered and quarried rockslopes deteriorate in engineering time and this can lead to unplanned maintenance requirements and the development of safety hazards. Deterioration is defined here as the progressive alteration, detachment and removal of material from the surface of a parent mass by mechanical and chemical processes. It occurs because confining pressures are released due to excavation leading to expansive recovery of the rock mass, and because of exposure of the excavated rock face to the external environment. A third factor may be the effect of changes to water throughflow paths consequential to excavation. It is standard engineering practice to use rock mass classifications such as the Slope Mass Rating (Romana 1993), slope stability hazard assessments (eg Mazzacola and Hudson 1996; McMillan and Matheson 1997) and limiting equilibrium analyses in the evaluation of deep-seated instability of slopes. Scant attention is given, however, to the evaluation of shallow surface processes because deterioration is often not perceived as a significant risk, it is difficult to quantify, and its mechanisms are poorly understood. Another difficulty is the common practice of describing many forms of deterioration under the umbrella term 'rockfall' without further distinction. This paper addresses the nature and consequences of excavation-induced deterioration under UK conditions. A classification of deterioration modes is presented which can be used as a basis for slope design modification, maintenance and remedial treatment.

CLASSIFICATION OF DETERIORATION MODES

A field investigation has been undertaken for nearly 100 excavated rockslopes in the UK to gather data on their deterioration in engineering time. For each rockslope, records were made of mass and material properties, morphological forms attributable to deterioration, direct or circumstantial evidence of weathering activity and deterioration products. Potential influences and controls on deterioration were also noted, including prevailing environmental conditions, slope design and engineering factors including geometry. Where known, the time since excavation was recorded. On the basis of this field investigation, several distinct modes of deterioration were identified and have been classified according to frequency of occurrence, velocity of movement, size of debris product and event magnitude. The classification differs from existing classifications of landslides (eg Varnes 1978; Hutchinson 1988; Dikau et al 1996) in that it is specific to man-made slopes and limited to a relatively small scale surficial processes. It is intended for use in engineering practice primarily for the evaluation of deterioration on existing rockslopes. Implications of each deterioration mode for slope maintenance, hazard potential and remedial treatment are included in the classification, together with general guidance for action. Since it is rare to observe deterioration processes in

Landslides in research, theory and practice, Thomas Telford, London, 2000.

action, each mode can be recognised by the products of deterioration (size, amount and form of debris), morphological forms (eg overhangs and scars) and other indicators of weathering activity. Though there are many contributing factors, the investigation showed that the nature of the fracture network and rock material strength are commonly of overriding importance in determining which deterioration modes prevail or dominate. Seven *rock mass types* (regular blocky, irregular blocky, strong massive, weak massive, fissile, composite and layered) which can be identified on the basis of these two parameters correlate well with the modes of deterioration identified. Many excavated rockslopes, therefore, have a built-in propensity to deteriorate in a certain fashion, a factor which can be exploited in evaluating or predicting deterioration potential. While one mode may dominate, rockslopes are usually prone to several forms of deterioration, and transitional modes are also common.

DESCRIPTION OF DETERIORATION MODES

The classification of deterioration modes is illustrated in Figure 1 and described below.

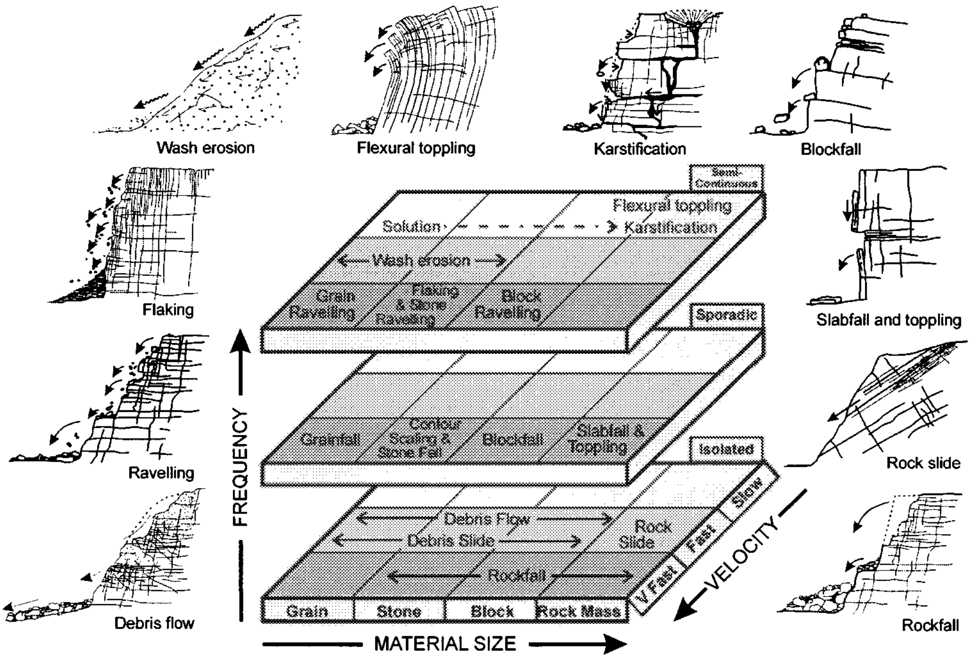

Figure 1. Classification of deterioration modes

Semi-continuous modes of deterioration

Ravelling is the frequent and semi-continuous fall of material of any dimension. It is difficult to predict, in time or space, the fall of individual particles due to ravelling, though weakened or intensely fractured zones which may be prone to this mechanism can usually be identified. Three sub-types are recognised:

a) Grain ravelling occurs in weak, granular and soil-like rock masses which are prone to grain detachment. Grain ravelling may be transitional with wash erosion, and can be enhanced by raindrop impact or wind erosion. Direct consequences of grain ravelling are minimal but periodic clearance of debris from clogged drains and any vegetation that may

taken root in the drainage system may be required. Surface treatment by shotcrete, or using membranes such as coir netting may be appropriate.
b) Stone ravelling may also be transitional with wash erosion and occurs in moderately strong, intensely fractured rock masses. Debris at the slope foot is often widely scattered, particularly if stones bounce on descent. Regular inspection and removal of loose stones and clearance of debris may be necessary. Where there is an unacceptable risk, loose material can be retained cost-effectively using wire mesh and sometimes drape nets. Shotcrete is also effective for small constituent material. Rocktrap ditches are very effective in containing debris although periodic clearance may be necessary. Other active mitigation measures may include fencing.
c) Block ravelling occurs in strong, fractured rock masses such as layered sandstone or blocky limestone and also produces a wide scatter of debris at the slope foot. Blocks may land at some considerable distance from the slope, particularly if they bounce or roll during descent or disaggregate on impact. For unprotected slopes where there is some risk, regular inspection is required, as is the removal of loose blocks and clearance of debris. Falls of material can be contained with a rocktrap ditch and fence, and intermediate rocktrap fences on benches will limit throw due to bouncing. Many sophisticated rockfall trajectory software programmes are now available to assist in slope design (eg Robotham, Wang and Walton 1995). Most standard wire fences are inadequate to stop impact, but some modern nets are designed to catch blocks with energies up to 3500kJ. Larger blocks can be secured individually with grouted dowels or rockbolts, but areas prone to severe ravelling may require full support (eg local buttressing), containment (eg substantial revetment or gabion walling), and protection (eg rockfall shelters and warning signs for severe cases). Drape nets are often effective to reduce the velocity and restrict the trajectory of blocks and blocks that fall to the toe can be restrained by fences which may need to be cleaned out regularly.

Flaking is a special form of ravelling, involving frequent and semi-continuous fall of material with a distinct platy form. It occurs in very fissile rocks like shales and slates and can rapidly lead to steep, extensive debris piles at the slope foot. Debris is unlikely to spread far, but build up commonly occurs so rapidly that very frequent foot clearance is needed. Flaking often results from large or rapid changes in moisture content. Retention of individual flakes is clearly impractical, and deep penetration of weathering often precludes the removal of loose material. A cover of fine wire mesh, shotcrete or geotextile membrane, however, may be effective although any hard covering may need to be pinned to the slope. Standoff area at the slope foot can be increased to provide more fallout space for debris, or rocktrap ditches used to contain it. In particularly weathered material, vegetation cover can be effective.

Wash erosion involves the detachment and transport of fine material entrained in surface water runoff. It occurs in weak, soil-like rock masses such as weathered sandstone and mudstone, commonly on low angle slopes. It may also occur locally in highly fractured rock masses where constituent materials are variably weathered. Raindrop impact may contribute to particle detachment, and in some cases surface flow may be concentrated into channels with greater erosive power, with the potential for rill and gully development. Debris deposition at the foot is usually widespread and includes a large proportion of fines which can cause nuisance by clogging drains. Severe wash erosion leading to gullying will change the geometry of the slope. A key factor in remedial treatment is the removal of the primary source of erosion by installing drainage, the extent of which will relate to the potential severity of deterioration. Crest and slope drainage are essential and trench drains can be used in severe cases. Toe drainage also helps to reduce scour. Benches or other cross flowpath barriers can be constructed in severe cases to reduce downslope flow velocity, and in the severest of cases, slope angle and length can be reduced. Slope surface protection using geotextiles and vegetation is usually very effective in reducing runoff velocity and hence erosive power, and in severe cases rockfill mattresses can be used as surface cover (eg cribbing or gabions). Localised shotcrete application (with drainage holes) may also be helpful.

Solution and karstification involve the dissolution of soluble mineral grains and cementing material in aggressive, acid solutions, including rainwater. This process may develop karst forms in some soluble rocks, particularly limestone, though this is less common in chalk. Karstification occurs rapidly in gypsum, though is rarely encountered in excavated rockslopes. Solution cavities may develop and are prone to collapse. Palaeokarst forms may also create a hazard where they are exposed in excavations. Large cavities can be underpinned or otherwise supported and smaller cavities can be infilled with mortar screeding. Water ingress may be reduced by crest and slope drainage, together with sealing and draining of vertical fractures at the rear of the slope.

Flexural toppling is a slow, progressive deformation and sliding of layered strata due to gravitational forces upon removal of lateral constraint. It commonly occurs in fissile, thinly bedded and composite rock masses and usually requires steeply dipping strata, the exposed tops of which tend to bend downslope. A similar problem is sometimes reported where exposed faces lose strength rapidly *en masse*, generally associated with some softening process. Claystone and mudstone slopes are particularly vulnerable to this phenomenon. While flexural toppling in itself presents little hazard, it frequently leads either to failure of the rock mass by rockfall or toppling, or to ravelling. Long term movement monitoring is essential in the remediation process. It may be possible to seal and drain vertical fractures at the rear of the slope to reduce water pressure. Rock anchorages such as patterned dowels can be used to gain substantial support. Identifying key blocks is important.

Sporadic modes of deterioration

Grainfall, stone fall and blockfall describe the occasional fall of individual rock fragments. The larger the particle size, the easier potential falls are to identify and treat. Many isolated falls occur in previously displaced material which accumulates on ledges. Three sub-types of fall are considered separately below.

a) Grainfall occurs in weak massive rock masses with a granular texture, and presents very little hazard. Treatment is rarely necessary. This can be confirmed by infrequent inspection.

b) Stone fall occurs in stronger rock masses with loose zones. Bouncing and rolling of detached stones increases the spread of debris, and can present a serious risk (to road users, for instance). Regular slope inspection is necessary to identify vulnerable stones for removal. Masonry dentition or shotcrete can be applied to retain loose material, and small overhangs can be supported. Use of rocktrap ditches or fencing (refer to above discussion on block ravelling) will largely remove the risk in many cases.

c) Blockfall occurs in strong, blocky, layered and composite layered rock masses with widely spaced fractures, and is most commonly associated with freefall from small overhangs or areas affected by root wedging from woody vegetation. Bouncing and rolling of detached blocks and their disaggregation on impact increases the debris spread and presents a serious hazard. The fall of large blocks can also cause direct impact damage to structures such as toe drains and pavement edges. Regular slope inspection coupled with movement monitoring is necessary to identify vulnerable blocks, which can be secured with bolts, dowels, and cables where inaccessible. Loose blocks can be retained with masonry dentition and underpinning of overhangs. Rocktrap ditches reduce debris spread, and fencing may counteract high bouncing.

Contour scaling is a special form of fall involving the infrequent exfoliation of thin layers of rock material formed parallel to the slope surface. The thickness of layers, usually several millimetres, often corresponds with the depth to which material weathering has penetrated. It occurs most commonly in moderately strong, massive rocks such as some sandstones and chalks. Large scales may disaggregate on impact causing limited debris spread at foot, but the risk is often small. Loose material can be removed periodically, though selective application of shotcrete or netting may also be effective.

Slabfall and toppling are also forms of fall, involving isolated and infrequent freefall of large, tabular slabs and rotation of large prismatic blocks. A typical minimum 'a' axis dimension of such slabs and blocks is one metre. Material of smaller dimensions which fails in this way can be described as stonefall or blockfall as appropriate. Slabfall and toppling occur in stronger rock masses with discontinuities parallel to a steep slope plane. Because of the large material size involved, there may be a significant risk. Slabs and topples may damage drainage channels, fencing and paving by direct impact, though debris is unlikely to spread far unless disaggregation on impact or bouncing on ledges occurs. It is common for overhangs and unstable areas to be left behind on the slope after slabfall or toppling has occurred. Individual vulnerable blocks are generally easy to identify, and can either be removed, or retained by bolts, anchors or cable support. Overhanging slabs can be supported by underpinning, and severe cases may require the construction of substantial support structures. Depending on the scale of the potential hazard, rocktrap ditches and fencing may be inadequate to mitigate risk.

Isolated modes of deterioration

Rockfall is used here as a specific term to describe the fall of many blocks of varying sizes in a single, identifiable event, and may involve slide, roll, bounce and freefall. Rockfall occurs in many highly fractured and weakened rock masses on steep slopes where lateral and/or vertical support has been removed (eg due to undercutting, erosion and weathering), but is a relatively infrequent occurrence. The volume of material involved may be dictated by the presence of a shallow, but irregular failure plane, though many rockfalls are associated with collapse of overhangs and cavities. Rockfalls can result in the spread of a considerable amount of debris at the foot in a way which is rarely predictable. The potential consequences of this, on a highway for instance, can be severe. If the cause of weakening can be identified it should be treated or removed, and the slope monitored. Scaling back to a failure plane is problematic if there is potential for retrogression, and containment using wire mesh, shotcrete, or dentition is only useful if the potential rockfall is small. Local underpinning of medium potential falls, and full support of large potential falls is usually required (eg substantial revetment, underpinning with anchored, reinforced concrete beams, buttressing, gabion or crib walling). Mitigation measures include rockfall shelters, protective walling and warning signs.

Debris flow is the rapid transport of a mixture of coarse and fine particles in a saturated, matrix-supported flow, and involves initial sliding and subsequent flow processes. It occurs in highly fragmented, weathered and soil-like rock masses, usually at relatively shallow slope angles (<60°). Debris flows are rare, but small scale forms, transitional with wash erosion are common. These small scale forms may be mitigated with shotcrete and local dentition. The potential for debris flow initiation is difficult to identify, though they are normally triggered by heavy rainfall. Debris flows may result in large depositional lobes with extensive spread at the foot due to channelisation and entrainment of debris. Rocktrap ditches and fences may quickly become overwhelmed. The most effective measures involve complete support at source with use of revetments, buttressing, gabion or crib walling. Crest and slope drainage is also essential to reduce infiltration and other active drainage measures should be considered. Where stabilisation at source is not possible and the consequences cannot be mitigated by moving structures out of the potential pathway, cross flowpath barriers can be constructed and the slope angle reduced.

Rock slides are very rare, large scale rapid translational movements of rock often along a distinct, planar discontinuity (eg bedding plane, foliation). Where the material is fragmented or grain-supported, the term debris slide can be adopted, and rock slides commonly degenerate downslope into debris slides as intact material is disaggregated. Slides may be considered as quantifiable slope failure mechanisms and may be analysed by limit equilibrium methods, so are strictly outside the scope of this paper - they are included here only for completeness. Rock slides have massive potential for damage, destruction and loss of life, chiefly due to the volume of material involved and the associated extensive spread of debris. They occur where discontinuities strike roughly parallel to the slope plane and dip at a relatively steep angle for the available shear strength. They can be triggered by progressive pre-failure weathering along the discontinuity and it may be possible to treat this weathering at source to limit weakening. Failure is often preceded by relatively minor movements possibly associated with small block falls. Infilled or open vertical fractures behind the slope can also be an important indicator of future failure. Remedial treatment of potential rock slides is as for severe cases of rockfall, plus cable reinforcement and toe weighting. Prevention or restriction of public access may be considered to mitigate risk. Movement monitoring may give prior warning in some situations.

CONCLUSIONS

Numerous observations of road cuttings and disused and restored quarries in the UK indicate that rockslope deterioration is widespread, in many cases is severe, and locally constitutes a serious safety hazard. It is also apparent that there is little consistency of approach to assessing or resolving the problem. The classification presented here has been designed for use in rock engineering practice to provide a means of identifying the likely mode of deterioration of existing rockslopes on the basis of the descriptions given. The likely maintenance burden, safety hazard and remedial treatments required can then be determined from the information provided. The classification also provides a standard reference criteria by which deterioration of excavated rockslopes can be compared, and ideas communicated between the different parties involved.

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