

# The Control of Small Scale Instability in Rock Excavations — A Review

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**SUMMARY** The mechanisms of small scale failure in rock excavations including sliding, toppling and collapse are reviewed. Factors that influence stability such as the orientation and strength properties of geological discontinuities, and the presence of groundwater are discussed.

A systematic approach to geotechnical investigation and design, construction evaluation and post-construction inspection is suggested, recognising that the extent of small scale instability can seldom be accurately predicted before construction.

A variety of treatments to stabilise slopes during or following construction are identified for each failure mechanism. Finally, means of protection are outlined for situations where stabilising treatments are impractical or ineffective.

## 1 INTRODUCTION

Near surface excavations up to 30m deep are commonly constructed for roads, railways, dam spillways and for mining facilities such as crushers and conveyors. In all these situations the close proximity of critical installations and pedestrian or vehicular traffic, requires that careful attention be given to the possibility of rockslides and rockfalls.

Most slope stability studies concentrate on the potential for large scale instability. However, a single, one tonne boulder falling from a cutting and coming to rest on a road can pose the same hazard to a highway user as a large, deep-seated rockslide involving half a mountain. Moreover, the potential for instability of the boulder is more likely to be overlooked during design and construction of the excavation.

## 2 MODES AND CAUSES OF SMALL-SCALE FAILURE

The most common modes of small-scale failure in rock excavations are:-

- a. Sliding of joint blocks either along single discontinuities (plane sliding), intersecting discontinuities (wedge sliding) or a series of sub-parallel discontinuities (stepped sliding). These are the most common mechanisms of superficial failure and can occur in most types of rock masses. Sliding is able to occur in situations where discontinuities dip in more or less the same direction as the excavated slope but at angles less than the slope angle. Whether or not sliding will occur depends on the extent of the discontinuities, the friction along the discontinuities, the presence of water occupying fractures in the rock mass and, in some situations, ground motions.
- b. Toppling of joint blocks. Toppling occurs in situations where closely-spaced, parallel discontinuities dip into an excavated slope leading to an overhanging or undercut profile. Toppling causes rockfall where the

centre of gravity of a joint block is located over the overhang. It has been recorded in excavations through columnar jointed basalt rock masses in Victoria, and steeply dipping meta-sediments in the northwest of Western Australia.

- c. Combined sliding and toppling. In this situation forces induced by a tendency to topple by one block may overcome resistance to sliding of an adjacent block. The opposite situation of sliding inducing toppling may also occur. This type of slope failure may develop slowly and lead to intermittent rockfall and rock sliding over long periods.
- d. Collapse. Rockfalls due to collapse occur where support is removed from boulders or joint blocks due either to erosion of underlying soil materials or by weathering and subsequent erosion of underlying rock materials. The former mechanism commonly occurs near the top of excavated slopes where there are boulders in a soil matrix overlying the intact rock mass. It has also been observed in lateritic profiles where erosion of extremely weathered portions of the profile leads to undercutting of a lateritic caprock. The other mechanism is common in interbedded sandstone-claystone sequences where the claystone is susceptible to slaking on exposure. It is also commonly seen in road cuttings close to the coast, where the action of salt causes rapid weathering of argillaceous beds. Rock falls due to this mechanism occur along the Lawrence Hargreaves Drive north of Wollongong, N.S.W. and along the Great Ocean Road in Victoria.

In order to evaluate the potential for instability of a rock excavation, the following parameters need to be investigated:-

- (i) Sub-surface configuration of soil and rock units - depth of soil, weathering profiles and structural relationships of different rock types.

- (ii) Properties of soil materials:- density, strength and dispersion properties.
- (iii) Patterns of discontinuities in rock masses:- the range of orientations, spacings and extents of each set, and the presence of fillings and coatings.
- (iv) Frictional properties of discontinuities and filling materials.
- (v) Physical properties of rock substances:- density and, in the case of very weak rocks, strength.
- (vi) Durability of rock substances.
- (vii) Presence of groundwater within the rock mass and, where possible, the seasonal fluctuation of the water table.
- (viii) The potential for ground motions at the site:- either natural (due to seismic events) or man-made.

### 3 APPROACH

Minimisation of the risk of small scale instability requires a three stage approach involving:-

- o Geotechnical investigation and design,
- o Construction evaluation,
- o Post-construction inspection and monitoring.

#### 3.1 Geotechnical Investigation and Design

The objective of this stage is to establish the overall design profile(s) which optimise(s) safety and economy.

The procedures for geotechnical investigation and design of surface excavations of shallow to medium height are well established. Investigation commonly includes the following components:-

- (i) Review of regional geology and assessment of the geological history of the area of interest.
- (ii) Detailed surface mapping to delineate soil and rock types and to obtain data on the orientations of geological discontinuities in the rock mass.
- (iii) Geophysical surveys to assess the depth of soil cover, depths of weathering, depth to groundwater and, in some cases, to aid in structural interpretation.
- (iv) Exploratory excavations to remove the soil cover exposing the underlying rock mass and enabling more discontinuity orientation data to be collected.
- (v) Drilling to identify the types of materials at depth, their structural relationships, discontinuity patterns and the presence of groundwater. Coring is carried out to provide samples for laboratory testing and core orientation is used to enable the orientations of discontinuities to be measured.

- (vi) Laboratory testing to provide data on the strength of soil and rock samples, the friction along discontinuity surfaces and the durability of suspect materials.

The information for the investigation is compiled to produce one or more geological models for analysis. Each model corresponds to a situation in which geological structure, material properties, discontinuity patterns and groundwater conditions are defined within the available limits.

Where the subsurface model can be defined within close limits, one or more of the well established deterministic methods is used for analysis of block sliding, wedge sliding and/or toppling failure (Hoek & Bray, 1981). Slope design is based on achieving an adequate factor of safety for the most critical failure situations.

Where, as is usual over long, linear excavations for roads and railways, the subsurface structure is not precisely known and the structural configuration, strength and discontinuity data show a range of distribution, statistical methods (McMahon 1971 and 1975) are more appropriate. Slope design in this case is based on achieving an acceptably low probability of deep-seated failure. For excavations such as those to which this paper refers in which the overall stability is critical, a very low probability of failure will be selected and applied to the overall slope. Higher probabilities of failure may be accepted for small failures on individual batters, which can be accommodated in the slope design by the provision of benches or other stabilising or protective means.

Whichever methods of analysis are used, there are two important considerations that apply to slope design:-

1. No matter how well the site investigation has been conceived and executed, there is always the risk of undetected factors which can lead to instability, and
2. Slopes excavated on the basis of minimising the potential for deep-seated mass failure are commonly subject to superficial instability. The most common reason for this situation is that particular types of discontinuities (e.g. tension joints) may not be continuous over sufficient distance to cause deep-seated failure; however, they may be a very common cause of superficial instability. For many such situations the adoption of slopes to avoid superficial instability would represent over conservative or uneconomic design; the costs of additional excavation involved in producing flatter slopes would far exceed the costs of stabilisation and protection.

#### 3.2 Construction Evaluation

The objectives of construction evaluation are to confirm the interpretations that led to the design decisions, to check for unforeseen conditions that could influence stability and to recommend design modifications, stabilising treatments or safety protection provisions. It is only after excavation is well advanced that the key aspects of the geological model can be checked. The results of detailed mapping of the excavated

batters are compared with the model and, if significant differences are apparent, re-analysis may be required to evaluate stability.

The results of detailed mapping are also used to assess requirements for stabilisation or protection measures which should be carried out prior to completion of the excavation. It is usually necessary for analysis and formulation of recommendations to be made on site immediately following the mapping. The use of simplified methods of analysis such as graphical techniques for wedge and block stability analysis (John, 1968), and the use of design charts (Hoek & Bray, 1981) are invaluable in these circumstances. However, a high level of judgement is also required, particularly in assessing the likely extent of discontinuities behind the rock face.

A reasonable level of cleanup is required before excavated faces can be mapped in detail and this should be recognised in the contract specification. It is important for the engineering geological evaluation to be carried out before the personnel and equipment associated with cleanup are demobilised so that additional scaling can be prescribed after the geological evaluation.

In cases where sliding or toppling modes of failure are possible, the detailed engineering geological mapping is aimed at identifying "key blocks" the retention of which is necessary for maintenance of stability. In the past, the identification of key blocks has involved application of experienced judgement. However, the recent development of rigorous techniques for key block identification (Goodman and Shi 1982) promises to become a valuable tool.

In most cases, the detailed mapping of the excavated faces provides sufficient information, both to check the geological model and to assess areas of superficial instability. However, it should be recognised that it is not possible to obtain a complete three dimensional picture of the rock mass from mapping of a planar rock batter, and, in some instances, further investigation may be required to complete the picture.

It is normal practice in slope design for the upper bench to correspond to the surface zone of soil and/or highly weathered rock, with a berm width sufficient to accommodate failures from this zone. Commonly, overbreak during excavation of the subsequent bench reduces the berm so that widening may be necessary at that time. Similarly, particular sections of a batter comprising very weak rock or containing unfavourably oriented discontinuities may be flattened, using excavation equipment, at this stage. Usually, however, it is more practical and less costly at this stage to stabilise such areas without further mass excavation.

Stabilising treatments include rock bolting, dowelling, application of protection against surface weathering, surface drains to reduce ingress of water to the rock mass, drain holes to lower the phreatic water level behind the slope and the installation of concrete buttresses.

Other safety protection measures are aimed not at preventing rock slides or rock falls but at interception or deflection of the falling or sliding rock. Such measures include, rock ditches, barriers or fences on berms or at the toe of a slope, and wire or cable mesh draped across the excavated face.

### 3.3 Post-Construction Inspection

The objective of post-construction inspection is to check for deterioration in the integrity of the rock mass and to confirm the effectiveness of the stabilising or protection systems. Changes that may occur in the rock mass include loosening of joint blocks, the opening of incipient joints due to stress relief, chemical weathering, and erosion due to wind or water. Other factors that may cause changes include ground motion due to equipment-induced vibration or seismic shaking, and even vandalism.

The programme for post-construction inspection of artificial slopes differs depending on the geological situation, the consequences of rock sliding or rockfall and the degree of protection provided by the design and subsequent construction stabilisation. However, some form of inspection is always prudent and in some cases its importance is critical.

An inspection programme should include both regular scheduled visits and unscheduled visits in response to particular circumstances such as intense rainfall events. Inspection staff who are not geotechnical specialists should be instructed in recognition of signs of impending failure and contingency procedures should be formulated to ensure that appropriate remedial action is taken.

## 4 STABILISING TREATMENTS

### 4.1 Rock Bolts

Rock bolts may be installed either in a designed pattern, or individually located in order to stabilise specific portions of a slope.

Pattern rock bolting is designed to preserve the three-dimensional interlocking structure of a rock mass. Used in a pattern, the bolts increase the shearing resistance along potential slide planes, and also restrict relaxation of the rock mass so that friction is retained along the sides of potential slide masses.

In some geological situations such as dip slopes (Figure 1) the installation of bolts upslope of a proposed excavation, prior to construction, may provide the only practical means of producing a stable slope. Where pattern rock bolting is applied to excavated faces, it is important that the bolts be installed before stress relief leads to loss of interlock.

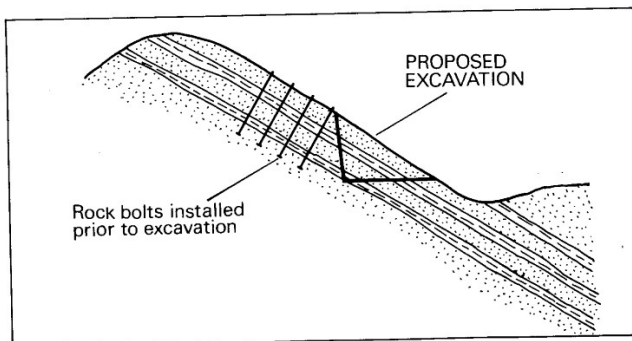


Figure 1 Stabilisation of slope by pattern rock bolting prior to excavation

The other approach to rock bolting is based on identification and stabilisation of key blocks.

If the key block is assessed to be subject to sliding, one or more bolts is installed, preferably perpendicular to the potential sliding plane. If toppling is the potential failure mode, the optimum orientation for a bolt is the tangent to the rotation arc, i.e. horizontal to upwardly inclined.

Selection of bolt lengths is based on a critical examination of failure possibilities following detailed engineering geological mapping. Techniques for calculating tensioning requirements are given in Fookes & Sweeney, 1976.

#### 4.2 Dowel Bars

Grouted, untensioned dowel bars do not significantly increase the shearing resistance along potential sliding planes and therefore have little value for stabilising against sliding. They do have considerable tensile strength which may make them suitable for use in stabilising key blocks against toppling. However, the difficulty of satisfactorily grouting the bars in upwardly inclined holes leads to a preference of rock bolts in most situations.

#### 4.3 Buttress Structures

The purpose of a buttress is to act as an artificial key block which provides restraint to the natural key block against which it is installed. Typically, the buttress is keyed or bolted into the underlying rock mass. Concrete buttresses are used in situations where bolting of an existing key block is difficult or dangerous, either due to its location or because it is judged to be close to limiting equilibrium. In the latter case, vibration caused by drilling for rock bolt installation could be sufficient to induce sliding.

Masonry buttresses may be used in situations where potential sliding forces are known to be low.

Similar to buttresses are "dental fillings" which are used to replace erodible materials or fill concavities in rock faces, progressive enlargement of which would otherwise lead to collapse of overhanging blocks.

#### 4.4 Drainage

Water contributes to most rock slides and rock falls in artificial as well as natural slopes. Water can initiate failure by erosion of weak materials, softening of soil seams within discontinuities, accumulation in rock mass openings leading to development of cleft water pressures or, in some areas, by pressures due to ice formation.

Drainage aimed at avoiding instability involves two objectives:-

- o Minimisation of the opportunity for water to enter the rock mass, and
- o Providing means by which water can readily drain from the rock mass.

The former involves installation of drains upslope of the excavation to intercept surface run-off and to shed it away from the excavation. Infiltration may be further reduced by screening of the ground surface behind the slope, including the drains, with fine grained soils or artificial pavements.

Drainage of the rock mass is normally achieved by the installation of horizontal or upward sloping holes drilled into the excavated face. In designing such drainage systems it is important to recognise that water flow within discontinuities in a rock mass follows localised paths of least resistance so that many holes may need to be installed before effective drainage is achieved.

#### 4.5 Controlled Blasting

There is a widespread belief that excavations in which the batters are formed by controlled blasting techniques such as pre-splitting or smooth blasting are intrinsically more stable than those formed without the application of such techniques. Certainly, controlled blasting can be very effective in avoiding the ragged rock faces with overhangs, detached blocks and blast-induced cracks that are a consequence of overblasting. However, there are three respects in which the stability of excavation produced using controlled blasting may be disadvantaged. These are:-

- o In situations where a block is close to limiting equilibrium for a sliding failure mode, conventional blasting will usually result in sliding of the block during excavation. In a controlled blast situation the block may remain until failure is initiated by cleft water pressure or ground motion.
- o Drainage of groundwater from the rock mass is facilitated where discontinuities have been opened by blasting.
- o The post-construction effects of stress relief in an excavation formed by controlled blasting may possibly be more severe than in the conventional situation where relief of stresses can be largely accommodated within the zone where the rock mass has been loosened by blasting. This aspect warrants research.

On the other hand, the advantages of controlled blasting in minimising rock mass damage, overbreak and the consequent need for hand cleanup are compelling. The fractures induced by blasting may also contribute to instability. However, in the author's experience, this is rare.

Where there is potential for the toppling mode of failure, pre-splitting provides a very effective means of maintaining key blocks in position, so that the overhangs necessary to induce toppling are avoided. This is illustrated on Figures 2 and 3, which show the likely excavated profile with and without controlled blasting.

#### 4.6 Erosion Protection

Soil and rock substances susceptible to rapid weathering and/or erosion can be readily protected by the application of mortar. Shotcrete is commonly used if the susceptible substances are widespread. On steep faces it is necessary for the mortar to be anchored or pinned to the rock mass. Weep holes are required to avoid buildup of water behind the treated face.

In many parts of Australia, strong lateritic cappings overlie highly or extremely weathered rock or soil materials which may be highly erodible. The best approach for stabilising excavations in these situations is the establishment of vegetation over the weaker

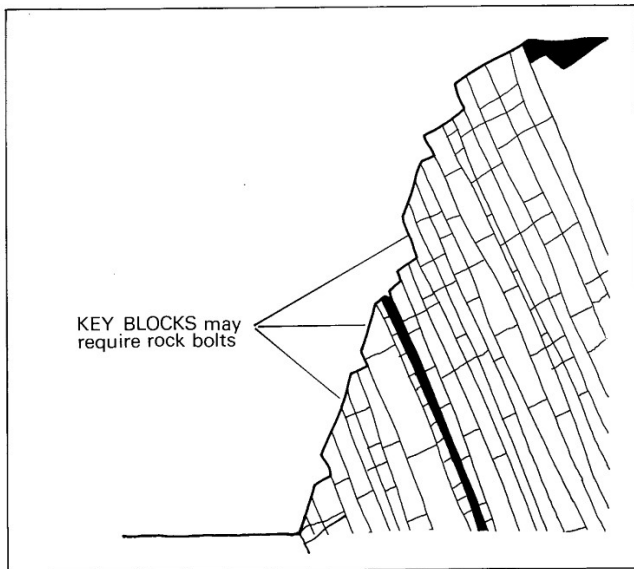


Figure 2 Pre-split excavation in rock mass prone to toppling failure

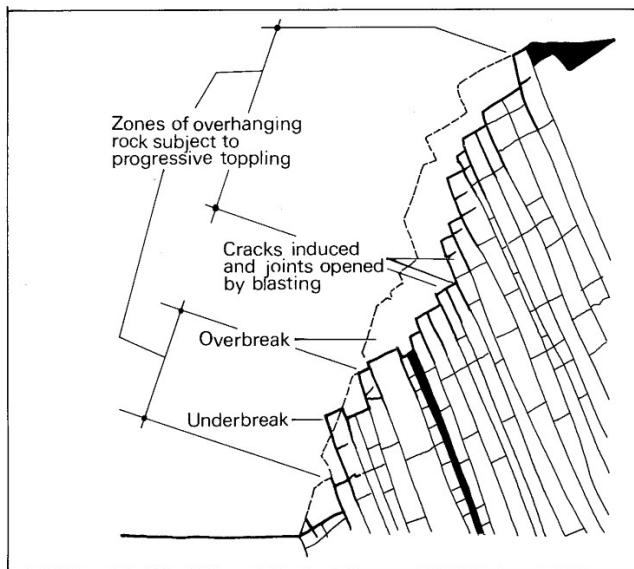


Figure 3 Uncontrolled excavation in rock mass prone to toppling failure

materials (Figure 4). Mini-terracing may be required to retain a layer of topsoil suitable for plant growth, and bitumen stabilised mulch is used to provide short term erosion protection until the vegetation is established. An alternative is to protect the slope with a layer of hand-placed rocks.

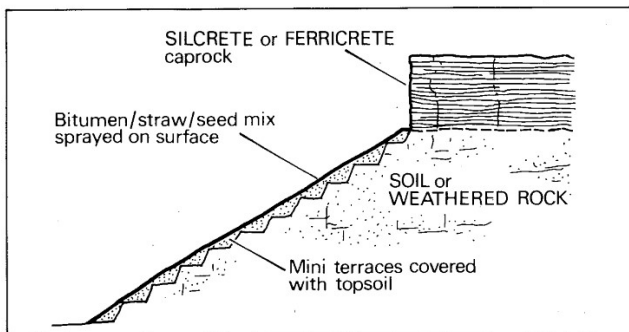


Figure 4 Stabilisation of erodible slope below caprock layer

## 5 PROTECTIVE TREATMENTS

These treatments are intended not to reduce instability but to ensure that rock falls and slides do not threaten public safety or the operation of important installations.

It is normal practice in the design of excavations to cater for small rock slides and rock falls by incorporation of one or more berms in the slope profile and to allow a buffer zone out from the toe of the slope. Other protective treatments, which can be incorporated in the design or added after construction evaluation, are outlined below:-

### 5.1 Rock Ditches and Barrier Fences

These are aimed at retaining or diverting rocks that have rolled or bounced down a slope. The location and design of these structures is based on principles of Newtonian physics by which the trajectory, stopping distance and impact energies of a block can be calculated and protective structures designed accordingly (Fookes & Sweeney, 1976; Ritchie, 1963; Pells, 1982).

### 5.2 Draped Mesh

In situations where there is insufficient space for a rock ditch or barrier fence, a cable or wire mesh can be draped over the face of the excavation. The mesh, which is anchored at the top, acts as a flexible constraint to rocks moving down the slope, damping their tendency to bounce and ensuring that they come to rest close to the toe of the slope.

The mesh is installed from above the excavation and does not require access to the batter itself.

## 6 REFERENCES

- FOOKES, P.G. and SWEENEY, M. (1976) "Stabilisation and Control of Local Rock Falls and Degrading Rock Slopes". Quart. Journ. of Eng. Geol. Vol 9, No 1.
- GOODMAN, R.E. and SHI, GEN-HUA (1982) "Geology and Rock Slope Stability - Application of the Keyblock Concept for Rock Slopes". Proc. 3rd Int. Conf. on Stability in Surface Mining, Society of Mining Engineers, U.S.A.
- HOEK, E. and BRAY, J.W. (1981) Rock Slope Engineering, Revised 3rd Edition, Inst. Min. Metall.
- JOHN, K.W. (1968) "Graphical Stability Analysis of Slopes in Jointed Rock". J. Soil Mech. and Found. Div. A.S.C.E. Vol 94, No SM2.
- McMAHON, B.K. (1971) "A Statistical Method for the Design of Rock Slopes". Proc. 1st Aust-N.Z. Conf. on Geomechanics. Vol 1, Melbourne, 1971.
- McMAHON, B.K. (1975) "Probability of Failure and Expected Volume of Failure in High Rock Slopes". Proc. 2nd Aust-N.Z. Conf. on Geomechanics, Brisbane, 1975.
- PELLS, P.J.N. (1982) "Brief Notes on Designing Protection Systems Against Rocks Falling Down Slopes". Notes for Sydney Branch Meeting of Australian Geomechanics Society, 1982.
- RITCHIE, A.M. (1963) "The Evaluation of Rockfall and its Control". Highways Research Record, Vol 17.