Rock engineering guides to good practice: rock slope remedial and maintenance work

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Foreword

This report is one of three that form a series dealing with key issues related to rock engineering, as follows:
- Rock slope risk assessment.
- Rock engineering guides to good practice: road rock slope excavation.
- Rock engineering guides to good practice: rock slope remedial and maintenance works.

The reports were completed between 1995 and 2000 and although they were circulated to interested parties during the intervening years they were never formally published. The work that informed the reports was undertaken for the predecessor organisation of Transport Scotland over a period of around 20 years. At the request of the Highways Agency, and with the permission of Transport Scotland, these reports are now being published for the first time.

The available time and resources mean that updating and supplementing is not a viable option and the work undertaken to achieve this has been restricted to updating the format to suit the TRL Published Project Report Series and generally tidying up the unpublished versions. The sole major exception to this is the report on Rock slope risk assessment to which an appendix has been added on ravelling. This is intended to open up the system reported and to render it more usable for rock slopes in southern England as well as those in Scotland for which it was originally designed. This appendix was prepared by Ian Nettleton (Coffey Geotechnics), who was closely involved in the application of the system while in the employ of TRL. The authorship of this report has been amended to account for this addition.

This report, Rock engineering guides to good practice: rock slope remedial and maintenance works, covers a wide range of issues including but not limited to rock slope stability, including affecting factors affecting stability, failure mechanisms, their evaluation and stability assessment. The section on risk assessment draw upon the work presented in the report on Rock slope risk assessment and work undertaken in support of the development of the system reported therein.

Risk management and reduction strategy considers how priorities may be set; how remedial works may be selected, designed and monitored. The need for an emergency strategy to ensure that appropriate actions are set in train when low probability events occur is also articulated and guidance on the selection of risk reduction approaches is given.

By far and away the largest section of this report deals with the design and specification of remedial works. This considers the philosophy of design and broad categories of remediation such as removal, control and containment, reinforcement, and support and protection.

The final section covers environmental considerations. It should be noted that this section is strongly weighted towards both the content of the Design Manual for Roads and Bridges extant at the time and to policies specific to Scotland.

I sincerely hope that these reports will be subject to wide industry uptake as have so many TRL Reports before them.

Dr Mike Winter
Head of Ground Engineering
March 2011
Abstract

This report was provides advice and guidance on good practice in rock slope remedial and maintenance works. The subjects covered include rock slope stability, risk assessment, risk management and reduction strategies, the selection of risk reduction strategies, the design and specification of remedial works and environmental considerations.

1 Introduction

Constructing acceptable transport infrastructure through the areas of high topographic relief in Scotland has necessitated the formation of extensive roadside rock excavations. Unfortunately the designs and excavation techniques applied to these rock excavations were not always appropriate for the rock conditions. This has resulted in a legacy of many unstable road rock slopes. Some of these unstable slopes pose a risk to the road and road user, and appropriate management action is therefore required. This guide aims to provide the reader with the basic systems and tools for effective rock slope management.

The guide begins with some definitions and a review of the causes of rock slope instability, and is thereafter structured to reflect the stages in good rock slope management i.e.:

- Risk assessment
- Management strategy
- Appraisal of remedial work options
- Design and specification of remedial works
- Environmental considerations

The guide aims to draw together best practice from a wide range of sources and present it in a form that is accessible to the practicing engineering geologist and geotechnical engineer. The guide is not a substitute for engineering geological training and experience but is intended to complement these. At the heart of the guide are the results of the programme of rock engineering research carried out at TRL in Scotland over the last 10 years, and the combined experience of TRL’s current rock engineering group.

The guide will not provide an answer to all rock slope stability and risk management problems. It should, however, point the reader in the right direction and provide the basis of a logical approach to tackling the problem. If the purpose of this guide were to be summed up in a single statement it would read something like:

‘To introduce and promote the practice of cost-effective, proactive rock slope management, through the application of appropriate expertise and techniques.’

This is an achievable goal and the expertise and techniques are available, as will be illustrated in the guide.

1.1 Definitions

For the purposes of this guide, ‘remedial works’ are defined as:

‘The works required to bring a non serviceable rock slope up to a serviceable condition, i.e. a condition with which the client is satisfied. Remedial works would usually take place during the Contract Defects Correction Period. Remedial works may be required on a slope that is past its Defects Correction Period (ICE 6th Conditions of Contract), if the slope has not been correctly maintained.’
For the purposes of this guide, ‘maintenance works’ are defined as:

'The works required to maintain the serviceable condition of a rock slope throughout its design life (or working life, whichever is the greater).'

The term 'remedial works' has been used in this guide to refer to remedial and maintenance works, unless specifically stated.

Road rock slope remedial and maintenance works are often interrelated. Remedial works are carried out to preserve and treat potentially hazardous slopes, to achieve and sustain a state in which the risk, posed by the slope to the road and road user, is below an acceptable level (see Section 3.2).

Potential Failure of Rock Slopes

Failure of road rock slopes is the sliding or toppling of rock blocks or masses due to instability. Instability is caused by unfavourable discontinuity geometries forming potential failures, which are either natural or induced. Induced discontinuities are caused by excavation of the rock mass during construction.

Hazard and Risk

Hazard and risk are two terms that are loosely used in the everyday life. In this guide hazard and risk are defined as:

\[
\text{Hazard} = \text{Potential for Harm}
\]

\[
\text{Risk} = \text{Hazard} \times \text{Exposure}
\]

1.2 Past and Current Practice

There are many rock slopes that pose a risk to the road and road user through instability. Rock slopes which pose a significant risk to the road require remedial works to ensure the safety of the road and road users. The use of improved techniques in excavation (for example controlled blasting) has considerably improved the stability of modern rock slopes. However, to some extent all rock slopes can be regarded as unstable. Remedial works are required where satisfactory stability has not been achieved through design and construction, and this instability poses a risk to the road. Examples of investigations for and construction of remedial works and are given by Ritchie (1963), Fookes and Sweeney (1976), Peckover and Kerr (1977), Mak and Blomfield (1986), Spang (1987), Martin (1988), Fookes and Weltman (1989) and Kay et al (1993).

There has been a significant amount of rock slope excavation on the Scottish road network. A continued necessity for appropriate and cost-effective solutions and safety awareness has driven research into rock slopes. TRL has carried out research into rock slope stability, remedial works and risk assessment (Matheson 1983, 1985, 1991 and 1995; McMillan 1993, 1994 and 1996).

Road rock slope remedial works have historically been undertaken on a reactive basis, prompted by rockfalls. This reactive approach does not address hazards until after the road and road users have been exposed to them. It also creates budgetary problems because incidents are unforeseen. A proactive approach to rock slope risk assessment has been developed by TRL (McMillan, 1995; McMillan and Blair, 1996; and McMillan and Matheson, 1997). The approach allows identification and treatment of the hazards to the road and road users before incidents occur. It also allows effective priority based budgeting of maintenance funds. The approach can therefore provide the basis of a rock slope management strategy.
2 Rock Slope Stability

2.1 Introduction - what is stability and instability?

In absolute terms any structure that sits above the mean horizontal plane is in a meta-stable state. That is to say, in the long term there is a tendency for pronounced topographical highs to be reduced. However, this view is of little use in engineering terms. A more accepted approach is to define stability in terms of local mechanical equilibrium. For rock slopes this approach also presents problems, as many of the forces acting are transient and difficult to define. For the purposes of this guide therefore, a stable rock slope is one on which there are no active failures, such slopes are rare. Instability therefore implies that there are active failures (Figure 2.1).

![Figure 2.1 Stable and Unstable Rock Slopes (A835, Garve and a quarry slope)](image)

2.2 Factors Affecting the Stability of Rock Slopes

Instability on rock slopes can be classified as either natural or induced and is influenced by a wide range of factors, some of which are controllable and others are uncontrollable (Figure 2.2). Natural instability has come about without the intervention of man. Induced instability is the result of the action of man. Controllable factors can be influenced by man’s actions while uncontrollable factors cannot be influenced by man.

The rock in which slopes are formed may vary considerably. The properties of the rock mass are critical to determining the nature of instability (if any) that is present on a rock slope. Where slopes are formed in rocks with a high material strength (moderately strong or stronger) the stability of the slope is largely controlled by discontinuities present in the rock mass and material strength is a secondary factor. Where slopes are formed in rocks with a low material strength (moderately weak or weaker) the stability of the slope is controlled by a combination of material strength and discontinuities.

This guide is concerned primarily with those slopes formed in rocks that are moderately strong or stronger, that is to say slopes in which instability is largely discontinuity controlled. In such slopes the spatial distribution of discontinuities and their relationships to the excavation geometry determine the mechanism and size of potential failures. The main failure mechanisms are plane, wedge and toppling. The term ravelling is used to describe all small-scale rockfalls for which there is no defined mechanism.
The process of investigating the nature, frequency and scale of potential failures is stability assessment. A stability assessment involves the analysis of data collected from a rock slope.

2.3 Failure Mechanisms

Plane, wedge and toppling are the main failure mechanisms on rock slopes.

Plane failure - sliding movement of a rock block or mass along a discontinuity plane.
Wedge failure - sliding movement of a wedge-shaped rock block or mass.

General Conditions for Failure:
- Two intersecting planes dipping towards each other
- Sliding along both planes in line with intersection
- Dip of the intersection > friction angles on planes
- Intersection line daylights on the slope

Toppling failure - failure involving rotation of rock columns or blocks.

General Conditions for Failure:
- It requires at least two steep release planes and one basal release plane
- The basal release can be either a single plane or the intersection of two planes
- If the basal release is a single plane, it must dip out of the slope less than the rock’s angle of friction.
- If the basal release is two planes, the intersection must dip out of the slope at less than the rock’s angle of friction, and the azimuth must be +/-20° relative to the slope.
- The intersection of the two steep planes must dip into the slope at >60°.
- Toppling Wedges are a special case of wedge geometry and are formed where the intersection of the wedge is dipping out of the face at less than the rock’s angle of friction AND there is a single steep plane dipping into the slope at >60° and with an azimuth of 160° to 200° relative to the slope azimuth.

A fourth common failure mechanism is ravelling failure and this applies to small-scale, superficial rock fall, for which there is no defined mechanism:

Ravelling failure - small blocks of rock that become detached from the rock mass.

General Conditions for Failure:
- Relatively small rock blocks delimited by joints on the slope
- No defined failure mechanisms

Composite failure
Where a failure geometry is repeated frequently throughout a rock mass or more than one failure geometry is present within a localised volume of a rock mass it is
possible for composite failure to occur. In the former case the composite failure is made up of a “family” of failures of the same mechanism but differing in size. In the latter case different failure geometries interact to produce a composite geometry that is the limiting geometry in terms of stability.

All of the failure mechanisms described above are convenient models that approximate potential failure to relatively simple geometries that lend themselves to calculation. In reality the failure geometry may be complex, a best-fit model may be difficult to define and it may not fit any of the classical models described above. It is sometimes advantageous to apply more than one model to a potential failure mass to assess how it is most likely to fail.

2.4 Evaluating Potential Failure Mechanisms

The graphical method (Matheson, 1983) can be used to define or identify potential failure mechanisms that may occur on a rock slope, or confirm mechanisms that have been observed. The graphical method is simple and is based on stereographic projection of discontinuity data. The three dimensional discontinuity orientation data are represented pictorially on a two-dimensional stereographic projection plot. There are various forms of stereographic projections and various ways in which the discontinuity data can be represented on them. The most commonly used projection for assessing potential failure mechanisms is the lower hemisphere, equatorial, equal area projection. The discontinuity data are usually represented as either poles or great circles on these projections. A more detailed discussion of stereographic projection and its uses in rock engineering can be found in Priest (1985). Evaluation of potential failure mechanisms that may occur on a given slope geometry is usually undertaken on a pole and/or intersection plot or contoured pole and/or intersection plot using stability overlays (Matheson, 1983) (Figure 2.3 and Example 2.1).
Figure 2.3 Graphical assessment of Potential Failure Mechanisms (a) Flowchart, (b) Function and Limitations. *Note: the published overlays for toppling failure (Matheson, 1983) do not adequately cater for the range of toppling geometry that can occur on a rock slope. This is particularly the case where the rock slope profile is uneven. A more complete definition of toppling failure criteria is given in Appendix 1.

Example 2.1 Preliminary stability assessment using graphical method for wedge failure (after Matheson, 1983)
Contouring is a statistical procedure used to highlight clusters of poles. Such clusters are generally interpreted as discontinuity sets. Contouring may overshadow the importance of major individual discontinuities that may exert a significant control on the stability of a rock slope. This can be overcome by weighting of the discontinuities.

The graphical method of assessing potential failure mechanisms is not a stability assessment. The fact that poles plot within a stability overlay does not necessarily indicate the slope will be unstable due to that particular failure mechanism. It is however a useful preliminary assessment of which failure geometries are possible on a slope or for confirming potential failure mechanisms observed in the field. In order to carry out a stability assessment more detailed information is required.

### 2.5 Stability Assessment

Stability assessment is an evaluation of the location, nature, frequency and scale of potential failures on a rock slope and requires data collected from the slope.

A comprehensive rock slope stability assessment should involve all of the following elements:

- **Preliminary Visual Assessment**
  - Assessment of geology, structural trends and structural domains
  - Rock mass description
  - Identification of structural domains
  - Identification of failure mechanisms
  - Assessment of the number and size of potential failures
  - Assessment of groundwater conditions
  - Assessment of external factors

- **Detailed Rock Slope Inspection**
  - Establish discontinuity geometry
  - Establish discontinuity properties
  - Define failure mechanisms
  - Define failure geometries and position
  - Define slope geometry
  - Assess groundwater conditions
  - Calculate stability of potential failures

The data that are required to satisfy the requirements of the above are:

- Discontinuities - dip, azimuth, trace length, principal spacing, planarity, roughness, strength, weathering, infill
- Rock material - strength, weathering
- Potential failures - mechanisms, dimensions, height on the slope
- Slope geometry - profile, berms, height, slope angle and azimuth (local to potential failures and average dip and azimuth for the slope), upper slope angle
A critical element of a stability assessment is an analysis of the stability of individual potential failures. The methods employed in such stability analyses are described in sections 2.5.1 to 2.5.3.

### 2.5.1 Limit Equilibrium Analysis

Limit Equilibrium (LE) is a common and practical method of stability analysis. The LE method produces a Factor of Safety (FoS). The FoS is the ratio of the total restoring forces to the total disturbing forces.

\[
FoS = \frac{\sum \text{Restoring Forces}}{\sum \text{Disturbing Forces}} = \begin{cases} 
1, & \text{Critical state} \\
> 1, & \text{Stable slope} \\
< 1, & \text{Slope failure}
\end{cases}
\]

The FoS is calculated using equations derived from a static resolution of forces for idealised failure geometry at limiting equilibrium (Example 2.2). It should be noted that all such FoS equations become prone to error once the balance of forces departs significantly from equilibrium. The "safety" of the slope is usually assessed by comparing the calculated FoS against an acceptable FoS, usually not less than 1.5 for road rock slopes (Hoek, 1991).

#### Example 2.2 Limit Equilibrium Analysis for a Plane Failure

The most common problem associated with the application of limit equilibrium methods is that related to the sensitivity of the failure model to input parameters. The FoS is a "snapshot" of the stability of the potential failure relevant to the input parameters used to derive it. What if those parameters were to change? How much might they reasonably be expected to change by? These questions must be addressed during a rigorous stability assessment by carrying out a sensitivity analysis.

Consider the case of two potential failures, A and B. Both have been analysed using an LE approach to derive FoS values using the "most likely" values for input parameters. The value derived for Failure A is 1.5 and the value for Failure B is 1.2. If the FoS values were taken at face value without a sensitivity assessment...
and used to prioritise remedial works Failure B might well be treated and Failure A is unlikely to be.

A sensitivity analysis is carried out on both potential failures in which the input parameters are varied within the range that might reasonably be expected over the life of the slope. Such sensitivity analyses could well reveal that Failure A is far more sensitive to variation than Failure B and is more likely, during the life of the slope, to reach a critical state i.e. FoS = 1. In such a situation it is Failure A that should be the high priority for remedial works treatment.

Situations such as that described above have come to light on a number of occasions and highlight the need for caution when using FoS in any decision making process.

2.5.2 Probability Methods

Probability-based methods can be used to overcome the uncertainty associated with estimated input parameters in LE methods. Some probability-based analysis methods replace the FoS with a 'probability of failure' or 'reliability' as a measure of slope stability.

The most effective applications of probability-based methods are those in which the relative probabilities of failure are evaluated (or the methodology is used) to illuminate the effects of uncertainties in the parameters (Christian et al, 1992).


The most effective applications of probability theory to the analysis of slope stability have stated the uncertainties in the form of a reliability index:

$$\beta = \frac{E[F] - 1.0}{\sigma[F]}$$

where $\beta$ is the reliability index, $F$ is the calculated FoS and $E[F]$ and $\sigma[F]$ are the mean and standard deviation of $F$.

2.5.3 Other Approaches to Stability Assessment

2.5.3.1 Fuzzy Mathematics Methods

Fuzzy Mathematics (FM) methods are similar to probability-based analysis methods and are potential alternatives for dealing with the uncertainty in real systems.


2.5.3.2 Rock Engineering System Method

The Rock Engineering Systems (Hudson, 1992) approach aims to provide a framework from which a complete design procedure can be evaluated, leading to the optimal result for a whole project. The Rock Engineering Systems approach has been adapted to tackle rock slope stability problems (e.g. Mazzocola and Hudson, 1996).
2.5.3.3 Parametric Methods
The Slope Mass Rating (SMR), proposed by Romana (1993), is a parametric method that derives a rating index that indicates the preliminary situation and gives some rules about the instability of a rock slope. The SMR is based on the Rock Mass Rating (RMR) (Bieniawski, 1989) and considers the slope-discontinuity relationship and the slope excavation method. SMR has the following form:

\[ \text{SMR} = \text{RMR} + (F_1 * F_2 * F_3) - F_4 \]

where \( F_1 \) to \( F_4 \) are adjustment factors selected from look-up tables (Romana, 1993).

The SMR is for preliminary stability assessment since the classes represent the mean field conditions. Experience in using the system ‘in the field’ is important.

2.5.3.4 Further Approaches
Further approaches to rock slope stability assessment include Grey Systems (Chowdhury et al, 1992), catastrophic theory (Miao and Ai, 1988), artificial intelligence (Coulthard, 1993) and integrated intelligent modelling (Feng et al, 1996). Numerical methods such as Finite Element and Discrete Element methods are not widely applied to rock slope stability and are more suited for use as design tools.

Whatever methods are applied, the outcome of a stability assessment is an understanding of potential failures on a rock slope. The stability assessment will not provide an understanding of the consequences of failure of the slope. A stability assessment is therefore not an appropriate tool for the management of rock slopes and the prioritisation of remedial works. Analysis of the consequences of failure converts a stability assessment into a risk assessment.
3 Risk Assessment

3.1 Factors Influencing Risk from Road Rock Slopes

Risk from rock slopes has been defined as the probability of a failure multiplied by the consequences of that failure. This risk is influenced by many factors. Many of these factors have already been discussed in the context of slope stability in Chapter 2. The description of the factors below deals with their role in defining the risk from rock slopes.

3.1.1 Geotechnical Factors

Since this guide is primarily concerned with rock masses in which stability is discontinuity controlled the most important geotechnical factors are those associated with discontinuities. The important discontinuity properties with respect to rock slope risk are as follows (Figure 3.1):

(a) Orientation (Dip and Azimuth (Dip Direction))
(b) Spacing (Principal Spacing)
(c) Trace Length
(d) Dilation
(e) Infill
(f) Surface strength
(g) Surface weathering
(h) Roughness
(i) Planarity

![Figure 3.1 Illustration of Discontinuity Properties](image-url)
Rock material properties also have an influence on the likelihood and consequences of failure. The important material properties are:
(a) Strength
(b) Weathering
(c) Mineralogy

Finally, water conditions on the slope also influence stability. Groundwater is of considerable importance and often acts as the trigger to rock failures. Surface flows can also cause stability problems through washout, erosion and accelerated weathering.

### 3.1.2 Geometric Factors

Geometric factors are those associated with the geometry of rock cuttings, verges and roads. Important rock slope geometric factors are as follows (Figure 3.2):
(a) Slope Height
(b) Slope Angle
(c) Slope Profile
(d) Position and Size of Berms
(e) Angle of Natural Slope Above Cutting

![Figure 3.2 Rock Slope Geometry Factors](image)

Figure 3.2 Rock Slope Geometry Factors

Slope angle has an influence on the potential for failures on a slope. Slope height can influence slope stability and the hazard posed by instability. As slope height increases the scope for unfavourable discontinuities to daylight on the slope increases. Also the higher the slope the greater the height from which a failure can fall. Slope profile and the position and size of berms influence block trajectory thereby influencing the hazard presented by failure.
The geometric factors associated with the road verge are concerned with determining the potential for the verge to act as a rock trap and reduce the risk associated with a rock failure. The larger the trap the lower the risk. The important factors are therefore as follows (Figure 3.3):

(a) Verge Width  
(b) Ditch Width  
(c) Ditch Depth  
(d) Fence Height  
(e) Distance to fence from toe of slope  
(f) Verge Materials  

Figure 3.3 Rock Trap Geometry  

The geometry of a road can have a significant bearing on the risk posed by rockfall. The important road geometry factors are as follows:

(a) Carriageway width  
(b) Sight Lines at rock cutting  
(c) Type of Carriageway (single track, single, dual)  

A rock falling onto a narrow carriageway is more of a hazard than one falling onto a wide carriageway as there is more scope for avoidance on the latter. Sight lines influence the possibility of a vehicle stopping before impacting a rock fall on the road. The type of carriageway is important when considering traffic data (see Section 3.4).

Other topographic factors that influence the hazard posed by a rock slope are as follows:-

(a) Type of cutting (side-long or box)  
(b) A Steep drop opposite the cutting
(c) The proximity of open water
(d) The proximity of buildings
(e) The proximity of services

All of these factors can affect the likely outcome of a rock fall incident. If a vehicle swerved to avoid a rock fall, it could result in a serious incident if any of the above applied to the site.

### 3.1.3 Remedial Work Factors

Many rock slopes have been subject to some form of remedial action in an attempt to reduce the risk presented by rockfall. It is therefore important that the influence of these remedial works on the rockfall risk is taken into account. The most important elements of existing remedial works in relation to risk reduction are as follows:

(a) Percentage of hazards treated by remedial works.
(b) Percentage effectiveness of the works in reducing hazard.

The latter inevitably involves a significant element of professional judgement and should, therefore, only be undertaken by those with an understanding and experience of the following, in relation to remedial works:

(a) Effective design
(b) Mode of action
(c) Limits of effectiveness
(d) Design life
(e) Reliability of construction

### 3.1.4 Traffic Factors

The volume and behaviour of traffic on a road have an influence on the hazard posed by a rockfall. The most important traffic factors are vehicle speed and traffic volume, both of which need to be considered in the context of the speed flow relationships for the relevant class of road. Obviously a rock fall incident on a road which carries traffic volumes near its design capacity is likely to be more serious or at the very least more inconvenient and costly than one on a quiet road.

The factors described above influence risk in one of two ways. They either establish the potential for failure to occur (primary factors) or they influence the likelihood, severity and consequences of failure (secondary factors). Methods of assessing and quantifying the risk are described later in this chapter.

### 3.2 The Principle of an Acceptable Risk Level

All rock slopes will impose some degree of risk to the road and road user. Ideally, a maximum ‘acceptable’ risk level would be defined so that remedial works could be designed to reduce the risks to below this level. Unfortunately, defining such a risk level that is appropriate for all situations is fraught with difficulty.

The risk posed by a road rock slope, like any other risk, is only an estimate of probability of loss from a large population of hazardous opportunities (Hambley & Hambley, 1994). The timing or severity of incidents that could occur at a particular rock slope cannot be accurately predicted. An understanding of the
risks is necessary to set up realistic acceptable risk levels. A fuller discussion of
technical risks is given by Chowdhury (1992).

A simple, quantitative method for defining acceptable risk levels, based on
financial costs, is shown in Figure 3.4. However, acceptable risk levels depend on
value judgements, political and sociological issues, which cannot be readily
quantified. Quantitative risk analysis provides the basis for defining acceptable
risk levels, but their derivation also takes into account social issues. Unfortunately, application of quantitative risk analysis to rock slopes in most
instances requires many assumptions to be made because of a lack of
quantitative data.

![Figure 3.4. A Simple Definition of an Acceptable Risk Level](image)

The lack of adequate quantitative risk analysis causes problems when trying to
define acceptable risk threshold levels for road rock slopes. The situation is
further complicated by the fact that the threshold will vary depending on the
social and economic priorities of the region in which the slope is located and the
perception of the risk by the road users.

At present there is no universally acceptable risk threshold level that can be
specified for rock slopes. The best available approaches involve undertaking some
form of risk assessment and using this to inform the judgement of which slopes
present unacceptable risk to the road and road users. The judgement process can
then take account of the socio-economic and risk perception issues that cannot be
adequately expressed in a purely quantitative approach.

The systems that provide the best support for the risk judgement are the TRL
Rock Slope Hazard Index and Rating, the Oregon State Highway Division Rockfall
Hazard Rating System, and the event tree analysis. These systems provide a
mechanism for comparison of slopes on a consistent basis and therefore allow
identification of the relative risk levels. An evaluation of how these relative levels
relate to the absolute acceptable threshold is where the judgement is required.

### 3.3 Risk Assessment Methods

A number of approaches for evaluating levels of risk are used for risk ‘prone’
industries or structures (for example nuclear power stations or dams). These
approaches are quantitative, probability-based and are governed by clearly
defined conditions, and are therefore termed risk analyses. Evaluating risk levels
for ‘ordinary’ civil engineering structures involves using statistical distributions
during the resistance of the structure to deformation and failure from the
estimated applied loads of its service life. A significant role is then played by the
acceptable risk level taking into account economical, political, sociological,
environmental and/or other factors. However, it is difficult to apply this type of
probability-based, quantitative risk analysis to road rock slopes. Rock masses are
inhomogeneous, discontinuous and non-isotropic and therefore the prediction of
the timing and/or frequency and consequences of failures are very difficult. Risk analysis is rarely applied to rock slopes and the less robust risk assessment takes its place.

Risk assessment for road rock slopes should consider the risk to the road user and the infrastructure.

There are two main approaches to quantitative rock slope risk assessment; hazard or risk comparison and probability estimation. To adopt the latter, and evaluate the probability of rock fall occurrence within a specified time span, historical data of rock falls on individual rock slopes is required. However, historical data is not always available (for example in Scotland) and even where it is available it is rarely reliable and complete. In these circumstances, hazard or risk comparison can be used. Currently there are three approaches to hazard and risk comparison that in the opinion of the authors are reasonably robust and provide a sound basis for comparison. These are:

3. The probability-estimation based ‘Event Tree Analysis’ method.

These are described in the following sections.

3.3.1 TRL Rock Slope Hazard System 1

TRL have developed the Rock Slope Hazard System, a two-stage approach to road rock slope risk assessment. The first stage derives the Hazard Index that is used as a coarse sift to isolate slopes with a relatively low risk potential from slopes with higher risk potential. The second stage is used to derive the Hazard Rating, that can be used to prioritise and optimise remedial work.

To avoid confusion with quantitative risk assessment, TRL's approach used in this system has been termed ‘Hazard’ assessment. TRL has developed the Rock Slope Hazard System as a method of identifying and classifying rock slope hazards. The Hazard Index acts as a 'coarse sift', identifying potentially hazardous slopes. The Hazard Rating identifies the relative level of hazard at each rock slope and allows prioritisation of maintenance. The relationship between the Hazard Index and Rating is illustrated in Figure 3.5.

3.3.1.1 The Rock Slope Hazard Index

The Rock Slope Hazard Index is a rapid method of estimating the hazard presented by highway rock slopes. The system is based around rapid, standardised field data collection in which estimates of influential geotechnical, geometric and remedial work factors are recorded. There are a number of options for each factor and the relevant option is selected from visual assessment of field conditions.

Parameter values have been derived for each input factor option. These parameter values reflect the influence that the input factor options are likely to have on rock slope hazard. The Hazard Index is then derived using a standard calculation procedure with the parameter values as input. The calculation process follows a logical route dictated by the influence of parameters on rock slope instability and rock fall hazard. The field data is combined with traffic flow data and then automatically processed to derive the Rock Slope Hazard Index values.
Systematic, rapid assessment of all rock slopes using the Hazard Index

Rock Slope Hazard Index Values

No Action  Review in 5 Years  Detailed Inspection  Urgent Detailed Inspection

Rock slope review inspections using the Hazard Index

Detailed Inspections using the Hazard Rating on a priority basis

Rock Slope Hazard Rating Values

Prioritised and Optimised Rock slope remedial work

Figure 3.5. The Rock Slope Hazard Index and Rating Systems

The Rock Slope Hazard Index values derived from these calculations are used to prioritise future action through classification of slopes into four action categories as follows:

<table>
<thead>
<tr>
<th>Action Category</th>
<th>Rock Slope Hazard Index Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Action</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Review in Five Years</td>
<td>1 - 10</td>
</tr>
<tr>
<td>Detailed Inspection</td>
<td>10 - 100</td>
</tr>
<tr>
<td>Urgent Detailed Inspection</td>
<td>&gt; 100</td>
</tr>
</tbody>
</table>

A judgement based review of the results using the rock slope photographs and field observations, to check the Hazard Index classification of the rock slopes, is an integral part of the analysis.

The Rock Slope Hazard Index is intended to act as a coarse sift. Slopes with an Index value of less than 1 do not present a hazard to the road user and therefore fall into the 'No Action' category and require no further maintenance. An Index of between 1 and 10 indicates that conditions at a rock slope are such that hazards may develop in the future. These slopes therefore fall into the 'Review in Five Years' category. Slopes in this category require only minimal maintenance commitment as the review will take the form of the initial rapid Hazard Index survey.

An index of greater than 10 indicates that conditions at a rock slope may present a hazard to the road and road users. These slopes therefore require action to investigate the nature and severity of the hazard. Prioritisation of action is achieved by grouping these slopes into two categories of ‘Detailed Inspection’ (10-100) and ‘Urgent Detailed Inspection’ (>100). Slopes in these categories may
require significant maintenance commitment. Firstly they require a detailed inspection and secondly this detailed inspection may reveal the need for remedial action to reduce hazards to an acceptable level.

The Hazard Index gives a range of values for rock slopes that are indicative of the potential for risk on those slopes. For a slope with a high Index value, the geotechnical and geometric conditions are such that they give rise to the potential for risk but the slope is not necessarily a high risk. The actual level of risk for the slope is dependent on whether the potential for risk has been realised. The relative level of risk is determined for potentially high risk slopes (those with high Hazard Index values) by the Hazard Rating.

The Rock Slope Hazard Index has been widely used in the UK and extensively calibrated by experience and with expert opinion.

3.3.1.2 The Rock Slope Hazard Rating

The Rock Slope Hazard Rating provides a method of determining the relative level of hazard presented by a rock slope by considering the sum of the hazards presented by all potential failures on a slope. It is a semi-probabilistic method of analysis and requires detailed field data input from each potential failure under consideration. The Hazard Rating survey is more rigorous than the Index.

The Hazard Rating value indicates the relative level of hazard to the road user. The Hazard Rating values can be used to prioritise remedial work but it is not possible to set a threshold value below which no remedial work is necessary. Deriving the Hazard Rating values involves a lengthy, but automated, calculation procedure.

The analysis of plane, wedge, toppling and ravelling data are undertaken separately. In the case of plane, wedge and toppling an estimate of the probability of a vehicle incident associated with each individual potential failure is derived. The analysis of ravelling failure is simpler, and the probability of vehicle incidents associated with each height category for each sample panel are calculated.

For each rock slope an estimate of the probability of at least one vehicle incident occurring due to rock fall is calculated from the estimated probabilities of vehicle incidents associated with each of the individual potential failures. This value is then divided by the length of the slope to give an estimate of the probability of a vehicle incident per unit slope length. This provides an indication of the intensity of rock fall risk on a rock slope. To make the numbers more user friendly this (usually very small number) is multiplied by 10,000 to give the Hazard Rating value.

The way in which the results of the Hazard Rating assessment can be used to manage rock fall risks and remedial work programs is described in Section 4.

3.3.2 Oregon State Highway Division Rockfall Hazard Rating System

3.3.2.1 Description of the Oregon RHRS

The Rockfall Hazard Rating System (RHRS) was developed by the United States' Oregon State Highway Division (Pierson et al 1990). The Oregon RHRS is one of the most widely accepted rockfall assessment systems in the western US and Canada (Hoek, 1998). The RHRS is designed to be a proactive management tool for rockfall sites on transportation routes, allowing rational expenditure of resources. The system was developed in response to the difficulty of carrying out
detailed investigations and analyses on large stretches of mountainous highways. The purpose of the classification is to identify which slopes are particularly hazardous and which require urgent remedial work, or further detailed study.

The system has two phases, the preliminary rating and the detailed rating. The preliminary rating is primarily concerned with a site’s rockfall potential and groups rock slopes into three broad categories (A to C), with A having the highest estimated potential for rock on roadway and C the lowest.

The detailed rating is then carried out on the slopes classified as 'A'. The detailed rating consists of evaluating twelve categories, that are scored and totalled to produce a rating for the slope. No classifications for rating values are given but Hoek (1998) states that slopes with a rating of <300 are assigned a very low priority and slopes with a rating of >500 are identified for urgent remedial action. The system does not include recommendations on actions to be taken for different ratings.

The following categories are considered in the detailed rating:

1. **Slope Height** - vertical slope height, estimated from road level.
2. **Ditch Effectiveness** - this is the ability of a ditch to prevent falling rock from reaching the roadway. It is recommended that the following are considered: slope height and angle; ditch width, depth and shape; anticipated block size and quantity of rockfall; impact of slope irregularities on falling rocks. It is also recommended that reference is made to the rockfall ditch design chart based on Ritchie (1963), see Section 6.3, and information obtained from maintenance personnel.
3. **Average Vehicle Risk (AVR)** - this is a measure of the percentage of time that a vehicle will be present in the rockfall hazard zone. It is based on:

   \[ \text{AVR} = \frac{\text{ADT (cars/hour)} \times \text{Slope Length (km)}}{100\% \times \text{Posted Speed Limit (km/h)}} \]

   where ADT is the Average Daily Traffic. It is stated that care should be taken to ‘measure only the length of a slope where rockfall is a problem’.

4. **Percent of Decision Sight Distance (DSD)** - this is the actual sight distance, estimated on site, as a percentage of the DSD. The DSD is determined from the speed limit at the rock slope, from a standard table.

5. **Roadway Width (Including Paved Shoulders)** - this dimension is the minimum width of the road at the rock slope, from edge to edge. It represents the available room to avoid a rockfall.

6. **Geologic Character** - slopes are split into either Case 1 or Case 2. In Case 1 discontinuities control rockfall on the slope. In Case 2, differential erosion or oversteepening controls rockfall on the slope.

   Case 1 is split into Structural Condition and Rock Friction. Structural Condition is an estimate of whether the joints are ‘discontinuous’ or ‘continuous’ and ‘favourable’ or ‘adverse’. Continuous is defined as >3.0m in length. Adverse is defined as those contributing to ‘block’, wedge or toppling failures. Rock Friction is an estimate of the surface roughness of a block and affects the potential for one block to move relative to another.

   Case 2 is split into Structural Condition and Difference in Erosion Rates. Structural Condition is an estimate of the erosion features on a slope, where loss of support, locally or over the whole slope, is forming potential failures. Difference in Erosion...
Rates relates directly to the potential for a future rockfall event and is an estimate of the rate at which erosion features develop.

(7) Block Size/Quantity of Rockfall - this is either an estimate of the representative typical rockfall or it can be determined from the maintenance history (if one exists).

(8) Climate and Presence of Water on Slope - this is a combined estimate of the amount of freeze/thaw cycles and the amount of precipitation.

(9) Rockfall History - ideally this should be obtained from documentation (completed by maintenance personnel) or it can be estimated from maintenance costs. This category is stated to be important as it is an indication of the potential for future rockfalls. It is recommended that if the score for a rock slope does not compare with the rockfall history then a review should be performed and that as a better database of rockfall occurrences is developed, more accurate conclusions for the rockfall potential can be made.

As well as scoring the categories, the raters should assess the most appropriate remedial measure, for ‘total fixes’ and hazard reduction and prepare an initial cost estimate. The system produces a hazard value, which can then be rated against other slopes, i.e. it does not include recommendations for actions based on different rating values. Actions for a rating value for a particular rock slope will be dependent on factors such as the budget allocation for remedial works.

3.3.2.2 Comments on the Oregon RHRS

The Oregon RHRS aims to prioritise slopes for remedial action by hazard assessment in a semi-quantitative manner. The system considers (to some extent) the main factors that are pertinent to rockfall hazard assessment, i.e. geotechnical, geometric and traffic factors.

The category for the preliminary rating is either estimated directly by the assessor or dictated by the rockfall history of the site. However, rockfall histories are often not available, and the reliability and/or clarity of existing histories is not always good. Therefore most slopes will be assigned a category on a subjective basis. The preliminary category dictates whether a detailed rating is carried out.

For the ‘detailed’ rating, many of the categories that the assessor is asked to rate are based on subjective judgements and others are very generalised.

(1) Geometric Factors - The choice of slope heights is limited, with only four set heights to choose from rather than a range of values and no values for less than the minimum or greater than the maximum heights. The attention paid to slope irregularities, with regard to the trajectory of falling rocks, in the ‘Ditch Effectiveness’ category is good but the assessor is again asked to subjectively judge their effectiveness (despite reference to ditch design charts).

(2) Traffic Factors - The ‘Average Vehicle Risk’ (AVR) cannot consider long slope lengths or high traffic flows. The AVR also only considers average, and not peak, traffic flows. No account is taken of the type of road in the Traffic Factors, for example dual carriageway as opposed to single carriageway, etc.

(3) Geotechnical Factors - Rockfall is dealt with in a subjective manner in the Geologic Character category for both Case 1 and Case 2. In Case 1 the assessment of discontinuities is particularly subjective. Case 2 has the advantage that it could be used for rockfall for non-rock slopes (for example soil slopes with boulders) as it does not rely on the mechanics of rockfall, but is therefore subjective. A ‘typical’ value is requested for Block Size. However, block size can vary dramatically within a slope, from small ravelling failures (<0.5m3) to very large composite failures (>1000m3) and the Oregon RHRS has a maximum
volume of ~9m³. The system also requires a Rockfall History. As mentioned previously, rockfall histories are often not available, and the reliability and/or clarity of existing histories is not always good. By definition there can be no history for new slopes. Where no history is available a subjective judgement on the likely number of rockfalls must be made. Using history as precedent for the future is also dangerous as failures can occur on slopes where there have been few or no rockfalls in the past. It would be difficult to use maintenance costs as a rockfall history as suggested, as records are likely to be poor, costs are unlikely to be separated into individual slopes and some slopes (the majority in many cases) have had no work carried out on them.

3.3.3 Event Tree Analysis

3.3.3.1 Description of an Event Tree Analysis

Event tree analysis is an estimation of the probability of an event occurring. It is best described by means of an example. The following example involves the risk from rockfall to a car park, situated at the base of a rock slope. It has been analysed to show the risk reduction from a proposed remedial works scheme. It should be noted, however, that the values of probability given refer to this example only. Care should be taken to estimate appropriate probabilities for other circumstances.

For ease of comparison the probabilities have been converted into FAR (Fatal Accident Rate) numbers (Hambly and Hambly, 1994). To calculate the FAR, the probability is simply multiplied by $1 \times 10^8$. Therefore, the FAR is the risk of death per 100 million hours of exposure.

(a) Pre Remedial Works

Assumptions:

(1) Rockfall - 95% of high and medium hazard rockfalls will fail within 100 years.

(2) Car Park - 100% of rockfall material will impact the car park and the rockfall material will effect a 4m wide strip across the car park, i.e. 15% of its area.

(3) Vehicle Occupancy - vehicles occupy 60% of the car park area 33% of the time.

(4) People Occupancy - people occupy 0.7% of the car park area 4% of the time.

Probability Calculations:

Block impact on car park = $0.95 \times \frac{1}{24 \times 365 \times 100} \times 15$

= $1.6 \times 10^{-5}$

Block impact on car = $0.95 \times \frac{1}{24 \times 365 \times 100} \times 15 \times 0.6 \times 0.3 \times 0.1$

= $2.9 \times 10^{-7}$

Fatal Accident = $0.95 \times \frac{1}{24 \times 365 \times 100} \times 15 \times 0.007 \times 0.04 \times 0.1$

= $4.6 \times 10^{-10}$

= 0.046 FAR
(b) Post Remedial Works
Assumptions:
(1) Rockfall - 0.1% of rockfalls will penetrate the rockfall remedial works and 80% of these will impact car park.

Probability Calculations:
Block impact on car park $= 0.95 \times 1/[24 \times 365 \times 100] \times 7.5 \times 0.001 \times 0.8$
$= 6.5 \times 10^{-9}$
Block impact on car $= 0.95 \times 1/[24 \times 365 \times 100] \times 7.5 \times 0.001 \times 0.6 \times 0.3 \times 0.1 \times 0.8$
$= 1.12 \times 10^{-10}$
Fatal Accident $= 0.95 \times 1/[24 \times 365 \times 100] \times 15 \times 0.007 \times 0.04 \times 0.1 \times 0.001 \times 0.8$
$= 1.8 \times 10^{-13}$
$= 1.8 \times 10^{-5} \text{ FAR}$

Therefore, the risk of a fatal accident due to rockfall is estimated to be three orders of magnitude less after the installation of the remedial works above the car park. This compares to estimated FARs of 300 for travel by motorcycle, 15 for travel by car and 1 for travel by bus.

Another example of an event tree analysis, for a highway rock slope is given by Hoek (www.rocscience.com).

3.3.3.2 Comments on the Event Tree Risk Analysis
The Event Tree analysis aims to produce a probability of occurrence of the consequences of a rockfall event. The technique concentrates on the consequences of an event, rather than the causes. The probabilities of occurrence are based on assumed values. Historical data can be used, for example rainfall and rockfall records, if it is available. The analysis is not specific to a particular rock slope unless accurate historical data are available for that individual slope, on which estimated probabilities of occurrence can be based. The impact significance is also based on an assumed probability, however, it is very hard to quantify accurately the consequences of a vehicle incident and therefore the assumed value is justified.

Overall the Event Tree analysis forms a good base for quantifying the risk to roads from rock slopes, if good estimated probabilities of occurrence are available from historic data or they can be estimated. For a road rock slope situation an estimated probability of occurrence for a vehicle impacting a failure should be used, based on vehicle speed and sightlines, at the particular rock slope. Due to the complications in predicting the consequences of a vehicle incident, any incident should be assumed to be significant.
4 Risk Management and Reduction Strategy

4.1 Strategy for Risk Management and Reduction

The purpose of conducting a risk assessment of rock slopes is to provide reference data for use in a risk management and reduction strategy. The risk assessment is therefore a means to an end, and the application of a coherent and logical approach to risk management and reduction is of equal or greater importance than the application of an appropriate risk assessment procedure. To have the former without the latter would leave the infrastructure owner open to significant liability.

The purpose of a risk management and reduction strategy is as follows:

*To allow the infrastructure owner to allocate resources to achieve cost effective risk mitigation and management such that, as far as is practicably possible, the public are not exposed to unacceptable levels of rockfall risk.*

A well executed, effective strategy improves the use of remedial and maintenance works on road rock slopes. However, the main hurdle to achieving this is the determination of acceptable risk threshold levels. This is discussed in Section 3.2 and has, as yet, not been adequately resolved for road rock slopes. There are workable compromises available at present in the form of TRL’s Hazard Index and Rating System (Section 3.3.1) and the Oregon RHRS (Section 3.3.2). The latter does not allow adequate assessment of the risk reduction benefits per unit cost and is therefore a less powerful management tool. Accordingly, the strategy outlined uses the TRL Hazard Index and Rating System to provide risk data.

---

**Figure 4.1 Proposed Risk Reduction and Management Strategy**

1. **Risk Reduction Programme**
   - **Risk Assessment**
     - Hazard Index
     - Prioritise risky slope
     - Hazard Rating
     - Define degree of risk
   - **Select Risk Reduction Approach**
     - Based on Risk Ranking
     - Based on Total Risk Reduction
   - **Evaluate Remedial Options**
     - Design and implement remedial works

2. **Emergency Strategy**
   - **Unforeseen Failure**
     - Hazard Rating
     - Emergency works

3. **Manage & reduce outstanding risks**
   - Observation
   - Interim Works
The key elements of a good risk mitigation and management strategy are illustrated in Figure 4.1. At the heart of the system is the structured and targeted risk reduction programme. A proactive risk assessment procedure forms the first stage in this programme. The approach to using the risk data provided by the risk assessment procedure is an important consideration and two approaches are shown in Figure 4.1, Risk Ranking and Total Risk. The final stages in the programme are the selection and implementation of remedial works. The other key elements to the strategy are the Emergency Strategy and the Management of Outstanding Risks. All elements are discussed in more detail in the following sections.

### 4.1.1 Programme of Risk Reduction

The programme of risk reduction must be cost effective. The best way to achieve this is to target remedial works at the greatest risks identified by the risk assessment. In order to identify appropriate remedial solutions it is essential that the nature and source of the risk is known. The remedial works can then be optimised to deal with that source. It is also important to consider the risks at the various levels relevant to the road owner and user. This means that risks to the road user from rock fall should be considered at all of the following levels:

1. For individual failures
2. For individual slopes
3. For route sections
4. For entire routes
5. For entire networks

Obviously (4) and (5) are only possible if survey data is available for a wide area but (1) to (3) should be possible in most cases. Consideration and treatment of risks at levels (1) and (2) generally follows a risk ranking approach. Consideration and treatment of risks at levels (3), (4) and (5) generally follows a total risk approach. The risk reduction programmes that result from the two approaches can be very different as the causes of the risks at which the works are targeted may be different. This is discussed in more detail in the following sections.

At present the TRL Rock Slope Hazard Rating and detailed event tree analysis are the only assessment tools available that allow the consideration of risks at all of these levels and allow identification of the causes of the risks.

The two ways in which the risk assessment results can be used in a planned programme of risk reduction are outlined below.

### 4.1.2 Risk Ranking Approach

The risk ranking approach involves simply using the risk assessment values to rank slopes and using this ranking to determine the order of a planned remedial work programme. This will ensure that the slopes presenting the greatest risk to the road user are dealt with first.

The ranking approach evaluates remedial work techniques by considering the benefits in reducing risk at each individual slope and not in terms of the total risk reduction on the road or management area. The resulting works are, therefore, targeted at local causes of risk, and are likely to achieve cost-effective risk reduction for these local causes, but may not be cost-effective in reducing the total risk to the road user. The treatment of the worst slope may not achieve
significant total risk reduction for the road user on the road or management area. Depending on the sequence and programming of the works, a significant reduction in the total risk may not be achieved for a significant period of time.

4.1.3 Total Risk Approach

The total risk approach involves using the risk assessment values to determine the total level of risk posed to the road and road user, and to plan remedial works to achieve the most cost-effective means of reducing this total risk to acceptable levels. Using this approach, remedial works will be targeted at, and optimised for, the most common cause of risk rather than optimised for individual slopes.

Using the total risk approach, remedial work techniques are evaluated by considering the benefits of techniques in reducing risk on the road or management area. Therefore, the total risk approach may not achieve as great a risk reduction at any given slope as the ranking approach, but will reduce the overall risks to an acceptable level. In addition it is likely to achieve a more cost-effective and timely reduction in the total risk to the road user.

The approach to risk reduction that should be adopted depends on the nature, scale and severity of risks from the rock slopes. In most cases, the total risk approach is recommended. However, in some cases a few slopes may pose a much greater level of risk than the others, and it may be more appropriate to use the risk ranking approach.

4.2 Selection and Design of Remedial Works

The selection and design of remedial works is critical in achieving the desired outcome to the risk management and reduction programme, i.e. cost-effective risk reduction or risk management. These elements are therefore dealt with in some detail in Chapters 5 and 6 of this guide.

4.3 Emergency Strategy

The TRL Rock Slope Hazard Rating and event tree analyses are both probability based risk assessment procedures. Therefore, the assessments assume that even very low probability events can occur. A management strategy based on these assessments must, therefore, have a contingency for dealing with events that occur on slopes that are not part of the current, planned risk reduction programme.

The first stage of any emergency works should be a risk assessment. Carrying out any work before this assessment has been made could worsen the problem or result in a failure to address the problem and lead to a false sense of security. The risk assessment should take the form of a survey, localised to the immediate area of the event. Widening the survey to involve a larger area is likely to take funds and resources from the planned programme of assessment. In addition, minimising the risk assessment will reduce unforeseen assessment costs.

Following the assessment, the necessary emergency action should be identified and clearly specified and quantified. Only essential work should be undertaken at the emergency stage. This will reduce the costs of this unplanned work and also reduce the possibility for wasteful or ineffective expenditure because of a lack of planning.
4.4 Management of Outstanding Risks

There will be a period of time between the risk assessments and the implementation of the risk reduction programme, during which risks are identified but not treated. The management strategy must deal with these in order to manage the risk to which the road user is exposed.

The action required to manage these risks will vary depending on the nature and severity of the risk and on the likely time delay to the commencement of risk reduction measures. In most cases, regular visual assessment and routine clearing of fallen material will be sufficient. In other cases it may be necessary to implement interim works. Interim risk management plans should be developed once the likely programme of permanent risk reduction works is established.

Only essential works should be carried out at this interim stage. They should be specifically targeted at reducing the immediate risks, and should also be designed and constructed to minimise the possibility of compromising the programme of permanent works.

4.5 Monitoring of Remedial Works

Like all built structures, rock slope remedial works are susceptible to degradation with time. For example, rock anchors are susceptible to corrosion. Remedial works may not last for the service life of the rock slope without maintenance. Therefore, monitoring of remedial works may be required. The monitoring aims to examine the mechanical behaviour of the rock mass, the remedial works and their interaction. Certain types of remedial works are more 'critical' than others with respect to degradation, i.e. corrosion through a rock bolt may lead to a catastrophic failure without warning but corrosion of mesh may only lead to a decrease in its effectiveness, and is readily visible.

From the monitoring results, the in-service performance of remedial works can be evaluated. Maintenance of the works can then be specified. The monitoring results can also be used to develop a database to aid future design of remedial works. Monitoring techniques appropriate to various remedial works are described in Section 6.

In-service monitoring of remedial works using instrumentation can be expensive and potentially unreliable and is therefore rare. Visual assessment in the field is a practical and common alternative. Where instruments are used for monitoring, the following factors should be considered (after Dunnicliff, 1988):

- Definition of the purpose of monitoring
- Selection of parameters to be monitored
- Estimation of the range of parameters to be monitored
- Definition of intervention criteria
- Intervention options
- Assignment of design, installation and operation phases
- Selection of instruments
- Establishment of procedures for correctly taking readings
- Plan of installation and calibration of instruments
- Plan of data collection, interpretation and reporting
- Programme for servicing/upkeep of instruments
The management strategy for rock slopes and remedial works includes a post-construction risk assessment to ensure that the specified risk reduction has been fulfilled. It should be assumed that a rock slope and its remedial works will continuously degrade with time. Therefore, rock slopes should be re-assessed at intervals defined following completion of their remedial works.
5 Selection of Risk Reduction Approaches

5.1 Factors Influencing the Selection of Approaches

Selection of the most appropriate risk reduction approach is essential. Risk reduction approaches for road rock slopes involve using remedial and maintenance work techniques. The risk reduction approach should be appropriate to the objectives of the management strategy.

There are four principal categories of remedial works: removal, containment, strengthening and avoidance. Each of these categories includes a number of different options and the selection of an option (or options) is dependent on various factors. A simple criterion can be used to aid this selection (Figure 5.1).

<table>
<thead>
<tr>
<th>Principle</th>
<th>Yardstick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical: Simple + State-of-the-art</td>
<td>Risk reduction per unit of cost: Maximum</td>
</tr>
<tr>
<td>Financial: Cost-effective</td>
<td></td>
</tr>
</tbody>
</table>

\[
R_c = \frac{R_r}{C_T}
\]

- \(R_c\): Risk reduction per unit of cost
- \(R_r\): Risk reduction per unit of cost
- \(C_T\): Cost of remedial work
- \(R_r\): Rate of risk reduction

\[
R_r = \frac{R_b - R_u}{R_b}
\]

- \(R_b\): Risk level before remedial work
- \(R_u\): Risk level post remedial work

Figure 5.1 A Simple Criterion for the Selection of Remedial Work Options

The factors and sub-factors that influence the selection of a risk reduction approaches are summarised in Table 5.2.

The purpose of road rock slope remedial works is to reduce the risk imposed by hazardous slopes to an acceptable level. The level of risk on hazardous rock slopes can be estimated by risk assessment. Once the level of risk posed by a potentially hazardous rock slope is identified, it can be compared to a specified acceptable level. Remedial works can then be applied to reduce the risk to this acceptable level.

The different stages for implementing remedial works, and their interactions, are shown in Figure 5.2.
<table>
<thead>
<tr>
<th>Factor</th>
<th>Sub-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Existing hazard</strong></td>
<td>● Stability</td>
</tr>
<tr>
<td></td>
<td>● Nature of failure</td>
</tr>
<tr>
<td></td>
<td>● Failure position and volume</td>
</tr>
<tr>
<td></td>
<td>● Geometry of slope and road</td>
</tr>
<tr>
<td><strong>Existing acceptability of risk</strong></td>
<td>● Society’s reaction to a hazard</td>
</tr>
<tr>
<td></td>
<td>● Financial consequence</td>
</tr>
<tr>
<td></td>
<td>● Social consequence</td>
</tr>
<tr>
<td><strong>Strategic transport considerations</strong></td>
<td>● Type of road</td>
</tr>
<tr>
<td></td>
<td>● Traffic flow</td>
</tr>
<tr>
<td></td>
<td>● Traffic volume</td>
</tr>
<tr>
<td></td>
<td>● Traffic speed</td>
</tr>
<tr>
<td><strong>Effectiveness of remedial option</strong></td>
<td>● Mechanism</td>
</tr>
<tr>
<td></td>
<td>● Relative degree of risk reduction</td>
</tr>
<tr>
<td></td>
<td>● Residual risk level</td>
</tr>
<tr>
<td></td>
<td>● Coverage</td>
</tr>
<tr>
<td><strong>Remedial work cost</strong></td>
<td>● Cost of design and construction</td>
</tr>
<tr>
<td></td>
<td>● Cost of materials</td>
</tr>
<tr>
<td></td>
<td>● Indirect cost (e.g. traffic delays)</td>
</tr>
<tr>
<td></td>
<td>● Maintenance costs</td>
</tr>
<tr>
<td><strong>Durability/sustainability</strong></td>
<td>● Service life</td>
</tr>
<tr>
<td></td>
<td>● Weathering/corrosion</td>
</tr>
<tr>
<td></td>
<td>● Revised inspection/monitoring</td>
</tr>
<tr>
<td></td>
<td>● Failure mechanism</td>
</tr>
<tr>
<td></td>
<td>● Failure consequence</td>
</tr>
<tr>
<td><strong>Influence of option</strong></td>
<td>● Influence on adjacent engineered structures</td>
</tr>
<tr>
<td></td>
<td>● Influence on adjacent rock mass</td>
</tr>
<tr>
<td><strong>Environmental impact of R&amp;M option</strong></td>
<td>● Visual impact</td>
</tr>
<tr>
<td></td>
<td>● Other impact</td>
</tr>
</tbody>
</table>
5.2 Remedial Work Approaches

The techniques used to implement the selected approach should be simple, state-of-the-art and cost-effective. The service life of the rock slope is an important consideration in order to achieve the maximum risk reduction per unit cost.

There are four general approaches for risk reduction with remedial and maintenance works - removal, containment, strengthening and avoidance. These approaches and associated techniques are shown in Figure 5.3.

**Containment** – involves allowing failures to occur but containing the failed material within a designed area, to reduce or minimise the risk. Containment includes rock traps and rock netting.

**Removal** – involves removing unstable rock masses to achieve risk reduction. Removal includes scaling and reprofiling.

**Strengthening** – involves the introduction of elements into or onto the rock mass to increase its strength. Strengthening includes reinforcement and support.

**Avoidance** – involves by-passing high risk rock slopes by re-routing the road and therefore minimising the risk by avoiding it.
Table 5.3 Rock Slope Failure Types and Some Appropriate Stabilisation Measures (Fookes and Sweeney, 1976)

<table>
<thead>
<tr>
<th>Failure type</th>
<th>Failure scale</th>
<th>Excavation</th>
<th>Structural support</th>
<th>Drainage</th>
<th>Rockfall control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Plane slope</td>
<td>Bench</td>
<td>Local excavation</td>
<td>Permable facing</td>
</tr>
<tr>
<td>Plane failure Large</td>
<td>1 2 3</td>
<td>3 3 3 1 1 1 2 3 1 1</td>
<td>1 1 1 1 2 1 2 2 2 2</td>
<td>2 2 2 3 3 2</td>
<td>2 2 2 3 3</td>
</tr>
<tr>
<td>Small</td>
<td>2 2 2</td>
<td>3 2 2 1 1 2 3 1 1 2</td>
<td>1 1 1 3 3</td>
<td>2 3 3 3 3</td>
<td>2 3 3 3 3</td>
</tr>
<tr>
<td>Wedge failure Large</td>
<td>1 3 3</td>
<td>3 3 3 1 1 1 3 2 2 1</td>
<td>1 1 1 3 3</td>
<td>2 3 3 3 3</td>
<td>2 3 3 3 3</td>
</tr>
<tr>
<td>Small</td>
<td>1 2 2</td>
<td>3 2 2 1 1 1 3 2 2 1</td>
<td>1 1 1 3 3</td>
<td>2 3 3 3 3</td>
<td>2 3 3 3 3</td>
</tr>
<tr>
<td>Toppling Large</td>
<td>1 3 3</td>
<td>3 3 3 2 2 2 3 2 2 1</td>
<td>1 1 1 3 3</td>
<td>2 3 3 3 3</td>
<td>2 3 3 3 3</td>
</tr>
<tr>
<td>Small</td>
<td>1 2 2</td>
<td>3 2 2 1 1 2 3 2 3</td>
<td>1 1 1 3 3</td>
<td>2 2 2 2 2</td>
<td>2 2 2 2 2</td>
</tr>
<tr>
<td>Rockfall/ravelling</td>
<td>Large</td>
<td>1 2 2</td>
<td>1 1 1 1 1 1 2 3 2 3</td>
<td>1 1 1 3</td>
<td>2 2 2 2 1</td>
</tr>
<tr>
<td>Small</td>
<td>2 1 1</td>
<td>1 1 1 1 1 1 2 3 2 3</td>
<td>1 1 1 3</td>
<td>2 1 1 1 1</td>
<td>2 1 1 1 1</td>
</tr>
</tbody>
</table>

1 - Use will be beneficial; 2 – Possible use depending on situation; 3 – Use unlikely to be economic or effective
5.3 Selection Logic for Risk Reduction Approaches

A cost-effective remedial work programme for a road section is likely to involve a number of the approaches discussed. The approaches should be considered in a logical and systematic manner.

The selection should be carried out in two stages. Firstly, the appropriate approaches should be selected, considering the total risk to the road user. The second stage should involve an evaluation of the choice of techniques in terms of risk reduction, cost-effectiveness, 'buildability' and environmental factors.

The logic for selection of risk reduction approaches is shown in Figure 5.4. Suitable remedial and maintenance approaches can be identified using Figure 5.3 and Table 5.3.

When selecting remedial and maintenance work approaches, the whole-life service costs of different remedial works approaches should be considered, i.e. maintenance and replacement. To achieve cost-effective remedial works, selecting the most appropriate approach or technique is more important than selecting the one with the lowest cost. For the same cost, containment will generally treat a larger area than strengthening, however this does not necessarily make it more cost-effective.
Figure 5.4 Logic for Selection of Remedial Work Options
6 Design and Specification of Remedial Works Methods and Techniques

6.1 Design Philosophy

Following the selection of the correct remedial work approach, the design and specification of individual methods and techniques can be undertaken.

At this stage in any remedial works project, the potential failures on a specific rock slope, and their relative risks to the road and road user, should be known. Hence, any remedial works can be accurately targeted at reducing the risk to below the acceptable level (see Section 3.2), using the most cost-effective techniques.

To achieve an optimal design, the general principles and procedure of design for rock mechanics applications, should be followed (after Bieniawski, 1992). Therefore, such a design should aim to fulfil the following criteria:

(a) **Defined design objective** – reduce the risk posed to an acceptable level

(b) **Geotechnically sound** - a good understanding of the geological conditions

(c) **Simplicity** – the simplest design to achieve the desired objective

(d) **State-of-the-art** - using the latest proven design ideas and materials

(e) **Cost-effective** - the least expensive design to achieve the desired objective

(f) **Buildability** – for efficient construction

(g) **Environmentally acceptable** – environmental input in keeping with location and setting

Acceptable risk levels should underpin the design. Historically, the design of remedial works focused on the eradication of the ‘worst’ individual potential failures, on certain slopes. This caused excessive expenditure on individual failures and slopes, without significantly lowering the total risk from rock fall to the section of road.

There is usually a limited budget for the implementation of risk reduction measures. The designer of remedial works should aim to reduce the total risk level (see Section 4.1) for the whole maintenance unit (network, route or route section). This will achieve the most cost-effective risk reduction, in terms of total risk, to the road.

A good ‘site investigation’ and design are more important in achieving a cost-effective solution than selecting a low cost remedial option (McMillan, 1993). One or more of the following approaches can be used for the design of remedial works:

*The historical approach* - applies observations from previous rock slope failures to risk assessment and the design of remedial options. If the observations are thoroughly made and analysed and the results are applied to the slope, it can produce reliable results.

This approach could not be used as a standard design tool, as the observations are not readily available. It is also potentially dangerous, as rockfalls can occur where none were previously observed or recorded and this is particularly applicable to large failures.

*The experimental approach* - involves using artificially triggered failure events to establish design criteria and input data for design. Ritchie (1963), Mak &
Blomfield (1986) and Chan et al (1986) established general guidelines for the
design of remedial measures using rockfall experiments.

Although the published experimental guidelines can be used as input for design,
this approach would have to be repeated on individual slopes to obtain accurate
results. It is impractical to carry out trials in most cases, as they are expensive
and time-consuming. However, the observational method can be used in certain
circumstances, for example by observing rockfall from scaling or controlled
removal remedial works and modifying the design of containment works on-site.

In some instances it may be cost-effective or desirable (for example for public
confidence) to carry out a trial to test the remedial works. Such tests not only
demonstrate that the design is sufficient but also provide valuable 'in-service'
performance data that can be used to refine future design. Figure 6.1 shows a
trial of a rock catch fence constructed at Abbey Craig, Stirling.

![Figure 6.1 Trial of a Rockfall Control Fence - (a) before and (b) after
(Abbey Craig, Stirling)]

*The analytical approach* - this applies the laws of motion and the theory of
particle collision to the calculation of characteristic values, such as block velocity
and bounce height, for different rock fall events. The calculation results provide
input data required for design of remedial works. This approach can also be used
to back-analyse the results of experimental rock fall trial data. The analytical
approach can be carried out manually, or with the aid of various computer-based
rock fall simulation packages, for example RocFall (Rocscience, 1998). The
computer based systems have the advantage of being able to run a large number
of rock fall ‘trials’ in a short space of time. This is statistically more desirable, as
many elements of the rock fall simulation are judged to be random. However,
care should be taken to calibrate the entered parameters to the specific site
situation, so as not to produce unrealistic results and therefore an invalid design.
Figure 6.2 shows the results from an analysis using the RocFall package.
Limit equilibrium approach - this is a common and practical method for stability analysis (see section 2.5.1). The LE method produces a Factor of Safety, which is the ratio of the total restoring forces against the total disturbing forces. The safety of the slope is assessed by comparing the calculated FoS against an accepted FoS, usually not less than 1.5 for road rock slopes (Hoek, 1991).

Remedial work design, can then be targeted to either directly increase the FoS (for example by strengthening) or making provision for failure to occur in a controlled zone (for example by containment).

Numerical analysis approaches - these include Finite Element analysis (FE) and Discrete Element analysis (DE). FE analysis models the mechanical behaviour of intact rock and discontinuities, and takes the geometry, geology and loading history into account. DE analysis also allows the making and breaking of joint contacts between blocks, large displacements and block rotations. This is particularly significant for the analysis of toppling failures.

Probabilistic approach - these methods replace the FoS with a 'probability of failure' or 'reliability' as a measure of slope stability (see Section 2.5.2).

For the application to road rock slopes, the experimental, analytical, limit equilibrium, numerical and probabilistic design approaches are most appropriate. Most designs use a combination of experimental, analytical and limit equilibrium approaches.

The details of the application of the design approach will vary depending on the type of remedial solution under consideration. Once again, while there may be a dominant remedial works strategy, most schemes involve solutions from one or more of the four main remedial works groups, namely:

(a) Removal
(b) Containment
(c) Strengthening
(d) Avoidance

Each of these is discussed in more detail in the following sections.
6.2 Removal

Removal achieves risk reduction by removing potential failures that are present on a slope. Removal can take the form of scaling, controlled removal and reprofiling. Scaling and controlled removal are particularly suited to treating discrete and clearly defined individual potential failures, including ravelling failures. Reprofiling is more suited to slopes that have intrinsic large-scale stability problems or numerous discrete potential failures.

6.2.1 Scaling

Scaling involves the removal of superficial, loose or unstable material from rock slopes by either light scaling (manually, with hand tools) or heavy scaling (power-tools, plant), see Table 6.1. It is possible to remove many potential failures at relatively low cost by scaling. However, poorly specified, executed and supervised scaling may create further instabilities.

Table 6.1 Scaling - types, methods and specifications

<table>
<thead>
<tr>
<th>Type</th>
<th>Methods employed</th>
<th>Specified Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Scaling</td>
<td>Manually, using hand tools (e.g. crowbars, hammers and wedges)</td>
<td>Area to be scaled (m²), or dayworks</td>
</tr>
<tr>
<td>Heavy Scaling</td>
<td>Non-manual power, tools and techniques including: air powered jack-hammers, plug and feather, hydraulic breakers, air drills, expanding grouts, small explosive charges, pyrotechnics, hydraulic excavators.</td>
<td>Volume of rock to be removed (m²) or area to be scaled (m²), dayworks</td>
</tr>
</tbody>
</table>

Rock face scaling can be undertaken from scaffolding, hydraulic or telescopic boom access platforms, cranes, and by rope access techniques. However, in many locations the use of most of these techniques is not practical due to difficult topography or lack of working space. In such cases rope access techniques may be the only feasible means of access for scaling. Rope access techniques provide a cost effective and safe means of undertaking scaling work, when carried out properly (Figure 6.3). All rope access workers should be qualified to the relevant recognised safety standards, for example IRATA (Industrial Rope Access Trade Association) standards or similar.

In many scaling operations it may be necessary to provide some protection or containment measures to prevent falling rock from causing damage to persons or property, for example road surfaces. In many cases this can be achieved using straw bales, balks or sheets of timber, temporary catch fences or by the removal of damageable objects, for example roadside safety barriers.

Some scaling operations will take place in locations where the quantity of material to be scaled is large, or the locations are within close proximity of persons or property that could be damaged. In these cases scaling will be described as controlled removal (see 6.2.2).

Scaling can be effectively employed to remove unstable material from superficial deposits which typically overlie rockhead. Typically this application will target the larger (>250mm diameter) undermined blocks.

Scaling removes existing potential failures, but it may not be a permanent solution as it does not remove the geological controls that have created the potential for failure. Natural weathering and degradation processes will continue to exploit the geological conditions after the scaling operation. This may lead to
the formation of further potential failures. The rate of formation of such potential failures depends on the geological controls and the environment.

**Figure 6.3 Scaling - using bars and rope access techniques (A82, Ballachulish)**

Scaling is often viewed as a low cost, risk management tool that requires low skill levels and little supervision. However careful specification, control and execution are essential to ensure that it is effective. The objective of scaling is to cost-effectively reduce the immediate risk, without increasing future risks.

This can be achieved through:

(a) Scaling contracts that are carefully and tightly specified in terms of the scope and methodology of the work

(b) Supervision and control by a suitably qualified and experienced engineering geologist or rock engineer.

(c) Employing a specialist contractor, with appropriate experience, skill levels and equipment for the work, particularly if access is difficult.

Scaling contracts can be specified in terms of unit cost per area scaled, volume of rock removed or as dayworks, see Table 6.1. The most important part of any scaling contract is the scope and methodology of the work. The material to be scaled on a slope should be clearly identified in the contract (preferably on photographs), and ideally should be marked on the slope by the supervising engineering geologist or rock engineer.

Tightly specified and supervised scaling contracts will be more expensive than loosely specified, unsupervised contracts in terms of initial cost. However, such contracts are likely to be more cost-effective in terms of the unit cost of risk reduction in the short and medium term. A model scaling specification to help achieve cost-effectiveness has been produced by TRL (McMillan, 1996), see Appendix 2.
6.2.2 Controlled Removal

Controlled removal utilises many of the same techniques as scaling and achieves risk reduction in the same manner. The main difference is the degree of control used in removing the rock from the slope. During controlled removal the rock is removed and is either lowered or guided down the slope, or allowed to free-fall, and comes to rest within a designated area at the toe. For example, the rock can be scaled into wire mesh bags, or the trajectory of the falling rock can be controlled by draped wire mesh or cable guide lines. Controlled removal is generally required for larger masses of rock and to avoid damage to structures adjacent to the slope (Figure 6.4).

The comments in relation to the specification and supervision of scaling, as described in section 6.2.1, are also relevant to controlled removal. Generally, because the material to be removed is more definable than that for scaling, and greater control is required there should be fewer problems than with scaling. However, the larger potential failures involved makes the comments on the precautions for scaling all the more relevant to controlled removal e.g. the use of specialist contractors and the need for careful specification.

Controlled removal is invariably more expensive than scaling. Scaling and controlled removal may well be used in conjunction on one slope.

Figure 6.4 Controlled Removal - using a temporary fence and temporary draped netting to control material on a steep slope above a road (Back O'Hill, Stirling).

6.2.3 Reprofiling

Reprofiling reduces the risk by the design and construction of a new and more stable rock slope profile, or by moving the slope away from the road (i.e. creating a large rock trap). Reprofiling can also improve verge space, rock trap size, sight lines and the carriageway width (see Figure 6.5). Reprofiling can be used to create a completely ‘new’ slope or to treat individual areas to remove unstable
areas of the slope. If an individual area of a slope is to be reprofiled care must be taken to avoid destabilising other areas on the slope.

Reprofiling can be a cost-effective means of risk reduction, as it can permanently reduce the risk to a very low level. It is generally not widely used because of its high initial cost; however, it may be the most cost-effective solution in the long-term.

The design of reprofiled slopes effectively follows the same procedures as normal rock slope design and the appropriate guidance in the Guide to Good Practice for Road Rock Slope Excavation (TRL, 1999) should be followed.

Reprofiling using explosives requires appropriate expertise for design and construction. Careful selection of the blasting technique will achieve optimum slope stability. When excavating new slopes pre-split blasting is often the preferred technique (Figure 6.5). There may be insufficient burden to create a properly formed pre-split face during reprofiling, and smooth or stitch blasting techniques may be required to form a stable face. However, even with little burden, presplit blasting can work in strong rock, if the blast is carefully designed.

6.3 Control and Containment

Control and containment involves allowing rockfall to occur in a managed or designed way to reduce the risk to the road. This includes the use of rockfall control netting and fences and rockfall traps. Rockfall control netting and fences act to control material ‘in-flight’, i.e. they limit its velocity and trajectory. Rock traps contain rockfalls by catching them on, or at the base of, the slope.

6.3.1 Rock Traps

The objective of rock traps is to ensure that rockfall material is contained within a safe zone and, therefore, does not present a significant risk to the road. Rock
Traps vary from verges and ditches to complex systems of flexible and rigid barriers. Rock traps can be used in conjunction with all other types of rock slope remedial works. They are often the cheapest, simplest and most effective way to ‘treat’ rock slope instability.

Rock traps are either on the slope or at its toe. Rock traps at the toe of the slope can only be constructed where there is sufficient space to create a trap of the required size. This is not a problem where rock traps have been designed-in to the slope profile and road geometry. However, there may be limited space at the base of existing rock slopes, between the slope and the road. In the past, slopes may have been constructed with the minimum amount of rock excavation and without regard to rockfall problems.

**Figure 6.6 Illustration of Various Containment Options for Rock Slope Remedial Works (after Fookes and Sweeney, 1976)**

Rock traps can be constructed on the slope to intercept falling material before it reaches the base of the slope. On-the-slope rock traps can be catch fences, barriers or berms (benches). Berms can be included in the slope as part of the original design or as a reprieved slope design. Rockfall barriers, designed to control the trajectory of the rockfall material, rather than to stop it, are discussed in Section 6.4.
6.3.1.1 Types of Rock Traps

There are essentially four types of rock trap: verges, ditches, berms and barriers. Berms are included because they could be used as a form of remedial works on a reprofiled slope.

Figure 6.7 Verge as an Effective Rock Trap (A835, Garve)

Verges - act as rock traps by dissipating the energy of falling blocks so that they do not reach the road and by providing adequate room to hold the volume of
failed material (Figure 6.7). The verge must be wide enough so that all falling blocks stop moving on the verge and, therefore, are often unsuitable for use as rock traps because of the excessive land-take required to provide for stopping distance. Generally, verges can be used as rock traps only when the verge is wide, the slope is of limited height, is steep (>70°) and has a regular profile. Verges should regularly be cleared of any rockfall debris (as for ditches). The width of verge required to form an effective rock trap is dependent upon the slope height, angle and profile and on the shape of the ravelling failures occurring on the slope. The required verge width can be reduced if it is vegetated, or has a thick layer of fine gravel (see Section 6.3.1.2).

**Ditches** - act effectively as rock traps because they provide a barrier to the horizontal movement of rock material (Figure 6.7). The effectiveness of the ditch will decrease if rockfall material is allowed to collect in it. If a failure fills the ditch, the rock debris will act as a hard surface for any further failures to impact on, resulting in an increased likelihood of the failure reaching the road. As a consequence, a regular programme of clearance of accumulated material should be undertaken as part of the post-construction management strategy.

Ditches have a significant effect on risk reduction, according to the field testing carried out by Azzoni and de Freitas (1995), as shown in Figure 6.9. The testing was performed on a slope approximately 45 m high and 60 m long, and with an overall slope angle of about 50° (30°-60°). Two tests were carried out, one without a ditch and one with a ditch 1.5 m wide and 0.9 m deep. Approximately 85% of falling blocks were stopped by the ditch. Without the ditch, almost 80% of the blocks stopped in the range of 10 –25 m from the toe of the slope.

![Figure 6.9 Effect of Ditch at the Bottom of a Slope on run-out distance (from Azzoni and de Freitas, 1995)](image)

**Figure 6.9 Effect of Ditch at the Bottom of a Slope on run-out distance (from Azzoni and de Freitas, 1995)**

Rock trap ditches are usually positioned at the base of slopes, but they can be formed on a berm or just above the crest of a slope (to catch superficial failures). The required ditch dimensions (width and depth) are dependent on a variety of factors, including slope height, angle, profile, block size and block shape, as discussed in Section 6.3.1.2 (Design of Rock Traps).

Rock and/or earth bunds can also be used to effectively increase the depth of a ditch and therefore the rock trap size (Figure 6.11d). The behaviour of bunds is similar to that of ditches.

**Berms** - rock traps are constructed on the slope to intercept falling material before it reaches the base of the slope. On-the-slope rock traps can be berms (benches), with or without catch-fence barriers. The design of berms as rock traps is similar to that for traps at the base of the slope. Berms act as rock traps if the rock face is steep (>65°) and they are carefully constructed. Berms must
be wide (>4.0m) and horizontal or inclined towards the slope. The effectiveness of a berm is increased by the addition of a rock catch fence (Figure 6.6), or by providing a covering of an impact absorbing material (e.g. vegetated peat). For road rock slopes, in many cases, berms are simply a 'by-product' of the drill and blast technique, i.e. each berm is effectively a drilling platform. The use of berms to aid slope stability originates in the open-pit extractive industry, where they were used to limit the extent of large failures. The use of berms can actually decrease the stability of individual potential failures, because lifts between the berms are steeper than the overall slope angle. Poorly constructed berms (especially with outward dipping surfaces), and those on slopes of less than approximately 65º, act as 'launch ramps' for falling material, projecting it out from the face and towards the road.

**Figure 6.10 Effective Rock Trap Barrier (A77, Ballantrae)**

*Barriers* - catch fence barriers act as rock traps by stopping the forward motion of material that has fallen from a rock slope. Barriers must be carefully designed so that all material falls behind and/or is stopped behind the barrier. If the area between the barrier and the rock slope becomes even partially filled, the barrier may be rendered ineffective. Fallen material should therefore be removed at regular intervals, and barrier maintenance is important if the barrier is to remain effective. Barrier height and distance from the rock slope dictate the effective rock trap size and are determined by much the same factors that influence ditch design. Barriers can be used as rock traps anywhere on a rock slope.

Rock trap barriers include walls, for example gabion walls, or adapted traffic-safety barriers (e.g. double Armco barriers). (Figure 6.11a and Figure 6.11b). A rigid barrier is a 'last line of defence', i.e. to definitely stop a falling block. Any deformation of a barrier, when impacted by falling rock, must be less than the verge width, i.e. it must not impinge on the road.

### 6.3.1.2 The Design of Rock Traps

The run-out distance of falling material and the bounce height of rock blocks are two primary factors to be considered in the design of rock traps.
Empirical techniques for rock trap design were proposed by Ritchie (1963). Other investigations include Fookes and Sweeney (1976), Piteau and Peckover (1977), Chan et al. (1986), Mak and Blomfield (1986), Fookes and Weltman (1989), Azzoni and de Freitas (1995). The investigations have collectively contributed to established guidelines of rock trap design.

TRL (McMillan, 1994) have made a comparison between three rock trap design charts, from Ritchie (1963), Mak and Blomfield (1986) and Fookes and Weltman (1989). The comparison revealed the considerable variation in rock trap design, derived for the same slope profile, using the different design charts (Table 6.2 and Figure 6.12).

Table 6.2 Comparison of Rock Trap Design Chart Recommendations*

<table>
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<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>Angle (deg.)</td>
<td>W (m)</td>
<td>H_d (m)</td>
<td>W (m)</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
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<td>1.5</td>
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<td>80</td>
<td>6.2</td>
<td>1.5</td>
<td>NA</td>
</tr>
</tbody>
</table>

* For notation of W, H_d and H_f, see Figure 6.12

---

Figure 6.12 The Shaped Ditch for Catching Falling Rock (after Franklin and Dusseault, 1989)
Table 6.3 Design Criteria for Ditches to Catch Falling Rock (Franklin and Dusseault, 1989, based on Ritchie, 1963 and Piteau and Peckover, 1978)

<table>
<thead>
<tr>
<th>Rock slope angle</th>
<th>Height $H$ (m)</th>
<th>Fallout area width $W$ (m)</th>
<th>Ditch depth $H_d$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near vertical (90°)</td>
<td>5-10</td>
<td>3.7</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>46</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>&gt;20</td>
<td>6.1</td>
<td>1.2</td>
</tr>
<tr>
<td>0.25-0.3:1 (73.3-76°)</td>
<td>5-10</td>
<td>3.7</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>46</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>6.1</td>
<td>1.8*</td>
</tr>
<tr>
<td></td>
<td>&gt;30</td>
<td>7.6</td>
<td>1.8*</td>
</tr>
<tr>
<td>0.5:1 (63.3°)</td>
<td>5-10</td>
<td>3.7</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>46</td>
<td>1.8*</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>6.1</td>
<td>1.8*</td>
</tr>
<tr>
<td></td>
<td>&gt;30</td>
<td>7.6</td>
<td>2.7*</td>
</tr>
<tr>
<td>0.75:1 (53.3°)</td>
<td>0-10</td>
<td>3.7</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>46</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>&gt;20</td>
<td>6.1</td>
<td>1.8*</td>
</tr>
<tr>
<td>1:1 (45°)</td>
<td>0-10</td>
<td>3.7</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>46</td>
<td>1.5*</td>
</tr>
<tr>
<td></td>
<td>&gt;20</td>
<td>6.1</td>
<td>1.8*</td>
</tr>
</tbody>
</table>

*May be 1.2 m if catch fence is used

Figure 6.13. Guidelines for the Design of Rock Traps (from Whiteside, 1986)

It is recommended that Ritchie’s chart should be used for irregular slopes (for example bulk-blasted) and Mak and Blomfield’s chart for regular slopes (for example pre-split). It should be noted however that the trial slope used by Mak and Blomfield had a vertical height of only 12m. The charts are only for relatively
small scale 'rockfall', and the possibility of larger failures has not been considered. Assessing the rock trap dimensions for larger, discrete masses requires more detailed calculations regarding the energy of the failures.

Design criteria for shaped ditches (see Figure 6.12) has also been given by Franklin and Dusseault (1989), based on Ritchie, 1963 and Piteau and Peckover, 1978, as shown in Table 6.3.

The trap design chart produced by Fookes and Sweeney (1976), and based on Ritchie (1963), generally gives a reasonable value for depth but high values of width. Whiteside (1986) revised the Fookes and Sweeney chart, see Figure 6.13 to give relatively reliable guidelines, for low to intermediate height slopes. Azzoni and de Freitas (1995) carried out field tests and suggested that Whiteside's chart is generally accurate but is conservative for the case when the main block motion at the bottom of the slope is rolling with small bounces.

Computer modelling can aid the design of rock traps (see section 6.1) Computer models now deal (to some extent) with irregular block shapes, bounces and movement in more than one plane (Azzoni et al, 1995). The understanding of energy absorption and conservation in relation to rock materials has also improved (Kane et al, 1993). The use of computer modelling can improve the cost-effectiveness of rock trap design, by tailoring it to the specific requirements of each situation. As with all computer modelling, the quality of the input data directly affects the results. The input data must be obtained from investigations at the site, i.e. slope height, angle and roughness, and range of block sizes, etc. The coefficients of restitution for the surfaces that the blocks impacts on are particularly important, with respect to how much energy the block loses with each impact on the slope.

The velocity and bounce height of falling blocks are major input parameters for rock trap fence design, as they are used to calculate the kinetic energy of falling blocks. The kinetic energy of the falling blocks gives the design requirements of the fence. From the requirements, the design can be produced. Part of the design is the physical characteristics of the construction materials.

Rock trap fence design is still partially empirical due to the 'random' nature of block trajectories. Best practice for fence design would involve referring to the most relevant published charts, computer modelling (using field based parameters) and field trials (for critical locations).

6.3.2 Rockfall Control Barriers

Flexible barriers can be used to control rockfall by absorbing some of the energy of falling blocks by deforming. The main advantage of flexible fences is that their flexibility permits kinetic energy dissipation. The action of a rockfall control barrier is illustrated in Figure 6.14 and the degree and type of flexibility can be varied by design. The design of the fences should be based on the work done by the fences in reducing the energy of the falling blocks. Flexible barriers can be used as either a 'last line of defence' or as sacrificial lines of energy dissipaters, to reduce the kinetic energy of a falling block, for example on a large slope or where the failures are particularly large.

A combination of rock catch fences has been installed at the Abbey Craig site in Stirling. The rock catch fences have been installed on a steep lower slope below dolerite cliffs, above a road and buildings. The columnar jointing in the rock gives large competent failure blocks. These blocks were modelled as maximum 2m diameter spheres. A variety of barrier combinations have been used, including intermediate energy dissipation and bottom catch fences, to prevent damage from rockfalls.
6.3.3 **Rock Netting**

Rockfall netting is widely used to treat rockfall. The advantage of netting is that it generally treats all sizes of failure. Experience has shown that well installed, high specification rockfall netting is capable of controlling the descent of large volumes of failed material. For example it has successfully contained failures of up to 80 tonnes (McMillan, 1994). There are few situations where well-designed and installed netting will not achieve a significant reduction in risk from rockfall. However, as with all forms of rock slope remedial work, netting should only be used where it is the most cost-effective solution, in terms of risk reduction. There are three main types of installation approach for rockfall netting, with different modes of action and design considerations.

6.3.3.1 **Design of Rock Netting**

*Netting Type*

The type of rock netting should be carefully specified. The netting should be specialist rockfall netting; typically 2.7mm diameter, galvanised steel, PVC-U coated wire and formed into 100mm by 80mm apertures, with treble twists in the wire, and with a thick edge-selvedge wire (typically 3.4mm). There is no need to overlap adjacent netting panels and they can be stitched edge to edge (Figure 6.15). This saves a considerable amount of material for large rock slopes. Typically the adjacent panels should be stitched together every third aperture.
Figure 6.15 Edge-to Edge Joining of Specialist 'Twist-Wire' Rockfall Netting

Short wire-twist ties or securing rings can be used to join adjacent edge-selvedge wires on mesh panels. Securing rings are fixed by a manual or pneumatic tool. The use of securing rings is recommended as they are more efficient, particularly where large amounts of mesh are being installed. The spacing of rings or ties should generally be 300mm or less. If a horizontal join of netting panels is required, it can be made by vertically overlapping the panels by 500mm and tying the overlap together at 150mm horizontal spacings.

The choice of colour for rock netting is limited. The plastic coating of the netting should be suitably protected against UV degradation and the colour should blend in with the slope.

Single-twist netting is unacceptable for treating rockfall as it is weak and unravels easily, due to its single-twist design. Therefore, it is prone to degradation after only minor damage.

Anchors

The top anchoring of any netting installation influence the whole installation. The recommended installation is shown in Figure 6.17. The netting is placed over the dowels, the top fixing cable is placed over the netting behind the dowels, the netting is overlapped back over the cable and stitched down. A face plate and nut are added to secure the netting and cable. The end anchor for the top cable should be a loop of cable, formed using bulldog clips, secured under the dowel face plate. Eyes that screw directly onto the heads of the dowels can be used in place of face plates.

The dowels should be fully anchored in solid rock to ensure their long-term effectiveness. This may require extra long anchors where a significant thickness of soil or weak rock is present. Alternative types of anchor should be considered to suit the ground conditions, for example self-drill 'duck-bill' anchors can be used in scree-type deposits.

Any intermediate cables for reinforcement (vertical or horizontal) can be attached to the mesh by the same methods used for attaching the edges of the netting panels.
Fixings

Metallic fixings used in netting installation are prone to corrosion. The netting wire itself should be galvanised and PVC coated to prevent corrosion. All other metallic components (dowels, nuts, face plates, cables, wire ties or rings, shackles, etc) should be protected against corrosion, by using either stainless or galvanised steel. Stainless is more durable than galvanised steel and is initially more expensive but will give better long-term cost-effectiveness. Stainless steel would not normally be used for cables because of its high cost.

To prevent electro-chemical reactions causing corrosion at contact points, protection should be provided between all stainless and galvanised components. For example, flexible plastic tubing placed on the galvanised cable will prevent direct contact between it and stainless steel dowels, nuts and face-plates.

6.3.3.2 Draped Netting

Generally, draped netting is the most effective use of netting on rock slopes to control falling failure material (Figure 6.16). The free movement of the netting dissipates the kinetic energy of falling material and it comes to rest at the base of the slope. For the netting to act in this manner, it is essential that plenty of 'slack' is left in the top and bottom anchor cables, i.e. they should not be tensioned.

Draped netting contains falling rock by allowing relative free-fall of material behind the netting. Little load should therefore be transferred from falling rock material to the netting.

The netting is fixed at the top of the rock slope by a top cable, which is anchored by rock dowels (Figure 6.17). The anchor length and diameter, and cable diameter will depend on the height and width of the area of netting that is being installed.

If the netting covers large potential failures, it can be reinforced with vertical cables, attached to the netting and the top anchor cable. Horizontal cables can also be used for netting reinforcement at the base of the slope, particularly where the rock trap or verge is of limited size.

The toe detail of the netting should be suitable for the site conditions, considering the potential rockfall size and rock trap geometry. Two options for fixing the bottom of the netting are illustrated in Figure 6.18. The bottom anchor cable should be left slack to allow failed material to drop out from the netting, into the rock trap, Figure 6.18(a). The bottom cable should be attached to the anchors by shackles or mallions so that it can be disconnected and any trapped failure material released and removed, as part of the post construction maintenance strategy (see Section 4.4).
The bottom of the mesh can also be weighted Figure 6.18 (b) with wooden logs, bars or steel cables. If there is limited room for failed material at the base of the netting, the cable can be tightened to restrain movement. However, if large failure volumes are anticipated then the netting must be reinforced with cables.
Figure 6.18 Examples of Bottom Fixing Options for Rock Netting (a) Loose Cable and (b) Weighted Toe (with logs, bars, cables, etc)

6.3.3.3 Contoured Netting

Contoured netting generally follows the rock face profile and allows controlled rockfall. The failure material is held close to the rock face behind the netting, preventing significant free-fall of the failure material and thereby minimising its kinetic energy (Figure 6.19). Intermediate horizontal cables help to control the fall of the failure material and dissipate energy.

Contoured netting is useful for situations where there are relatively large failures on rock faces with irregular profiles. The design prevents failure material from gaining a horizontal component of velocity from slope irregularities. There are a number of important design considerations for contoured netting:

(a) the use of intermediate cables

(b) the load capacity of the top anchor system

(c) the base details

The netting itself should minimise the free fall of failure material. The intermediate cables should be positioned on 'ledges' to limit the possibility of horizontal motion being transferred to the failure material.

For contoured netting, the load capacity of the top anchor system must be greater than the self-weight of the netting and the load transferred to it by falling material.

The base details are similar to those for draped netting.
Contoured netting is designed to control material after a failure, similarly to draped netting. Therefore, to avoid shock loading of the materials, plenty of slack should be built into the cables, and system in general.

The intermediate cables should be fixed under the netting, by sacrificial ties, to prevent punching failure. The sacrificial ties allow 'give' in the system, dissipating energy, and therefore must be weaker than the netting.

6.3.3.4 Fixed Netting

Netting can be used for rock mass reinforcement by fixing it directly to the rock face using anchors and/or cables (Figure 6.20 and 6.21). This is a useful technique to prevent loss of material in highly fractured or weak rock, to stop further instability developing. Fixed netting differs from draped or contoured netting as it acts to contain and strengthen the rock mass, rather than control falling material. Fixed netting can be used in discrete areas on a rock face, to target particular areas of instability.
For fixed netting, the top and bottom anchor cables should be installed as for draped netting but can be nominally tensioned. Intermediate cables are placed on top of the netting, are nominally tensioned and anchored to the face at regular intervals by dowels or rock bolts. The netting may also be tied to the cables. Dowels and bolts also provide rock mass strengthening (see Section 6.4).

It is particularly important to use high quality materials and construction techniques for fixed netting, because the structural integrity of its components are critical to its action. The conditions of the rock mass must also be fully understood, or the netting system may simply reinforce several potential failures, which could then fail en mass.

The three main types of installation and design considerations for rockfall netting are described below. The common design details are described here.
6.4 Rock Reinforcement

6.4.1 Introduction to Rock Reinforcement

Rock reinforcement involves installing reinforcing elements into the rock mass to increase its strength. The aim of reinforcement is to enhance the rock mass stability by preventing potential failures. Passive reinforcement is not stressed on installation. Active reinforcement is stressed on installation (Figure 6.22).

Figure 6.22 Active and Passive Reinforcement Systems

For remedial works on road rock slopes, reinforcement is unlikely to be used where containment or removal is possible, due to its relatively high cost and the fact that individual reinforcing elements may only treat individual failures. Reinforcement is unsuitable for treating small-scale, widespread potential ravelling failures, but can be used as part of a netting system (Section 6.3.3) to treat these failures. Some applications of rock reinforcement are shown in Figure 6.23, they include:

(a) securing key-blocks
(b) stabilising large, unstable masses of rock
(c) stabilising rock where there is insufficient space for containment
(d) stabilising rock where there is a risk of a road or structure being undermined
(e) anchoring structures that support the rock mass, e.g. retaining walls
6.4.2 **Design of Rock Reinforcement**

The objective of using rock reinforcement on rock slopes is to stabilise either individual potential failures or the general rock mass. More detailed information on the design of rock reinforcement can be found in BS 8081:1989, DMRB (1999), US Army Corps of Engineers (1980), Hoek & Bray (1981) and Hobst & Zajic (1983). The reinforcement selected should suit the conditions of the rock slope, as illustrated in Table 6.4.

The design of rock reinforcement is often based on factor of safety methods (BS 8081:1989). Suitable factors of safety are listed in Table 6.5. The design requires the consideration of:

(a) overall stability
(b) depth of embedment
(c) group effects
(d) fixed anchor dimensions
Table 6.4 Rock Reinforcement - use and rock conditions (after BS 8081:1989)

<table>
<thead>
<tr>
<th>Reinforcement Technique</th>
<th>Use and Rock Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Dowels</td>
<td>Use:</td>
</tr>
<tr>
<td></td>
<td>(a) to ensure stability of areas very near to the excavated surface;</td>
</tr>
<tr>
<td></td>
<td>(b) to reinforce rock to be removed at a later stage;</td>
</tr>
<tr>
<td></td>
<td>(c) for general support when installed very close to an advancing face, when tension is developed after installation;</td>
</tr>
<tr>
<td></td>
<td>(d) for reinforcement prior to an excavation</td>
</tr>
<tr>
<td></td>
<td>Rock:</td>
</tr>
<tr>
<td></td>
<td>(a) suitable for all types. In weak rocks sufficient length should be allowed to develop the tensile strength of the dowel.</td>
</tr>
<tr>
<td>Rock Bolts</td>
<td>Use:</td>
</tr>
<tr>
<td></td>
<td>(a) for general support in all types of underground opening.</td>
</tr>
<tr>
<td></td>
<td>Rock:</td>
</tr>
<tr>
<td></td>
<td>(a) bolts with mechanical fixed anchors are suitable for use in hard rock only;</td>
</tr>
<tr>
<td></td>
<td>(b) bolts with grouted fixed anchors may be used in all rock types. In soft rocks, or where clay infilling has a tendency to line the drillholes, there may be insufficient anchorage capacity available for resin-grouted fixed anchors.</td>
</tr>
<tr>
<td></td>
<td>Maximum support pressure: 300 kN/m².</td>
</tr>
<tr>
<td>Rock Anchorages</td>
<td>Use:</td>
</tr>
<tr>
<td></td>
<td>(a) For reinforcement of large openings which require high support pressure and long length of reinforcement. Generally used in combination with bolts, dowels or sprayed concrete.</td>
</tr>
<tr>
<td></td>
<td>Rock:</td>
</tr>
<tr>
<td></td>
<td>(a) Suitable for all rock types but care should be exercised in rocks with a combination of low RQD, heavily jointed or crushed rock, smooth slickensided or filled joints, high water inflow, high in-situ stresses, swelling or squeezing rock. In weak rocks, anchorage appropriate to soils may be required.</td>
</tr>
<tr>
<td></td>
<td>Minimum support pressure: 200 kN/m².</td>
</tr>
<tr>
<td></td>
<td>Maximum support pressure: 600 kN/m².</td>
</tr>
</tbody>
</table>

1 Support pressure = support pressure available at time of installation
2 RQD = Rock Quality Designation

Table 6.5 Minimum factors of safety recommended for design of individual anchorages (from BS 8081:1989)

<table>
<thead>
<tr>
<th>Anchorage category</th>
<th>Minimum safety factor</th>
<th>Proof load factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tendon</td>
<td>Ground/grout</td>
</tr>
<tr>
<td>Temporary anchorages with a service life up to 2 years, where although the consequences of failure are quite serious, there is no danger to public safety without adequate warning e.g. retaining wall tie-back.</td>
<td>1.60</td>
<td>2.5⁴</td>
</tr>
<tr>
<td>Permanent anchorages and Temporary anchorages where corrosion risk is high and/or the consequences of failure are serious, e.g. main cables of suspension bridge or as a reaction for lifting heavy structural members.</td>
<td>2.00</td>
<td>3.0⁵</td>
</tr>
</tbody>
</table>

⁴ Minimum value of 2.0 may be used if full scale field tests are available
⁵ May need to be raised to 4.0 to limit group creep.

Note 1. In current practice the safety factor of an anchorage is the ratio of the ultimate load to design load. The above table defines minimum safety factors at all the major component interfaces of anchorage system.

Note 2. Minimum safety factor for the ground/grout interface generally between 2.5-4.0. However, it is permissible to vary these, should full scale field tests (trial anchorage tests) provide sufficient additional information to permit a reduction.

Note 3. The safety factor applied to the ground/grout interface are invariably higher compared with the tendon values, the additional magnitude representing a margin of uncertainty.
6.4.3 Passive Reinforcement Techniques

Passive Reinforcement

Passive reinforcement elements are unstressed and only become stressed once deformation/movement takes place in the rock mass. This type of reinforcement includes dowels and cable dowels.

Dowels are rigid bars, usually steel, that are installed in holes drilled into the rock and then grouted in place (see Figures 6.24a and 6.25). Dowels can be designed and installed to act in either tension, or shear, or both (McMillan, 1993).

Cable dowels are flexible steel cables that are installed in holes drilled into the rock and then grouted in place (see Figure 6.24b). Cable dowels are designed to act in tension only (McMillan, 1993).

6.4.3.1 Passive Reinforcement Installation Angle

Rock dowels are often installed roughly perpendicular to the potential failure plane and improve the stability by increasing the shear resistance across the failure plane. The design capacity of the dowel in this case is pure shear (bending). The design assumes that movement of the failure block, and therefore the force acting on the dowel, is parallel to the failure plane (which is assumed to be ‘smooth’), see Figure 6.26.
Figure 6.25 Dowel Installation - drilling from (a) Rope Access (A82, Ballachulish) and (b) a Platform on a 4WD Hydraulic Boom Fork-Lift (A83, Erines)

In reality, discontinuities dilate at shearing, the dilation being dependent on the roughness of the discontinuity. Discontinuities are seldom smooth and therefore the movement of a failure block cannot be exactly parallel to the discontinuity surface, but is at an angle of $i$ (around 40°), to the shearing direction (Hoek & Bray, 1981).
Therefore a dowel installed perpendicularly through a rough discontinuity will be subject to tensile and shearing forces (Figure 6.26). It is likely that the dowel will be loaded in tension before being loaded in shear. This should be considered when designing dowels, as the dowel bar will be stronger and stiffer in tension than in shear.

The shearing resistance of a dowelled discontinuity varies as a function of the angle between the dowel and the discontinuity (Gaziev & Lapin, 1983 and Ludvig, 1983). Therefore, there is an optimum installation angle for dowels, between 35 and 50° (Barton & Bakhtar, 1983).

6.4.4 Active Reinforcement Techniques

Active reinforcement include grouted and mechanical bolts, cable bolts and anchors. They are stressed with a design working load on installation. Application of a working load prevents, or minimises, movement or deformation of the rock mass.

*Rock bolts* are rigid bars, or semi-rigid tubes, usually made of steel and less than 6m long and 32 mm diameter. They typically have a working load of 150-200 kN and are installed in holes drilled into the rock. Rock bolts are designed to act in tension. There are several different types of bolt (see Figures 6.27, 6.28 and 6.29) with differing mechanisms for providing anchorage between the bolt and the rock.

![Grouted Rock Bolt](image)

**Figure 6.27 Grouted Rock Bolt**

(a) *Grouted Rock Bolts* are fixed to the rock by either cementitious or resin grout (see Figure 6.27). Grouted bolts have a "bond length" that is bonded to the rock with a primary grout, and a "free length" that is bonded with a secondary grout, after stressing of the bolt. The "free length" in a grouted bolt is not a true free length because of the secondary grout.
Figure 6.28 Mechanical Rock Bolts

(b) Mechanical Rock Bolts are fixed to the rock by means of a mechanical anchorage system at the distal end of the bolt (see Figure 6.28). There are several forms of mechanical expansion systems, designed for different rock conditions. Mechanical bolts may or may not be grouted after stressing.

c) Friction Rock Bolts are generally hollow steel tubes, fixed to the rock by means of friction between the rock and the bolt (see Figure 6.29). There are two proprietary friction bolt systems in common use, Swellex (Atlas Copco) and Split Set (Ingersoll-Rand). Friction bolts are generally only used as a temporary support in tunnelling and mining operations.
(d) **Cable Bolts** are formed from several flexible, high tensile steel cables or strands that are designed to act in tension (Figure 6.30). They are installed in holes drilled into the rock and then grouted. Cable bolts often have a slightly greater working load than bolts. The flexibility of cable bolts allows them to be used in long un-jointed lengths in areas of restricted access. However, access is not usually restricted on road rock slopes, as it is in underground excavations.

**Figure 6.30 Cable Rock Bolt**

*Rock Anchors* have a higher capacity than rock bolts, with a typical working load in the range 0.3-2.0MN. Anchors can have lengths up to tens of metres, depending on their application. Anchors are either multi-strand or mono-bar. They are designed to act only in tension and are installed in holes drilled into rock and then grouted in place and stressed. All anchors incorporate some form of corrosion protection system, the exact nature of which is determined by the application, rock conditions and design life. Mono-bar anchors are rigid, high-strength steel bars, encased in a protective coating (Figure 6.31). Multi-strand anchors comprise multiple high strength steel strands bundled together and encased in a protective coating (BS 8081, 1989), see Figures 6.32 and 6.33. Multi-strand anchors are generally used in applications where very high working loads are required (>1000kN). An example is illustrated in Figure 6.34.
Figure 6.31 Mono Bar Rock Anchor

Figure 6.32 Multi-Strand Rock Anchor
6.4.4.1  **Active Reinforcement: Installation Angle**

Most bolts and anchors are installed at inclinations below the horizontal, with no regard to the inclination of failure planes, including many on road rock slopes in Scotland (McMillan, 1993).
Figure 6.35 The Variation of Restoring Force $T$ with Angle $a$, for Two Example Cases of Rock Bolting

Shearing failure can be resisted better if the inclination of the anchoring forces to the failure surface is up-slope of the normal, i.e. with an angle $\beta$ of less than $90^\circ$ (Figure 6.35), for a factor of safety specified as:

$$FoS = \frac{(W\cos\alpha + F_a\sin\beta)\tan\phi + l*c}{W\sin\alpha - F_a\cos\beta}$$

(Equation 6.1)

where $l$ is the length of shearing failure face.

An installation angle above the horizontal acts more against the sliding direction force component, resulting in a smaller anchoring force being required, as illustrated below. Equation 6.1 can be written as:

$$F_a = \frac{FoS*W\sin\alpha - W\cos\alpha\tan\phi - l*c}{\sin\beta\tan\phi + FoS*\cos\beta}$$

(Equation 6.2)

An optimal installation angle $\beta$ that allows a minimum anchoring force $F_a$ is determined by differentiating Equation 6.2 with respect to $\beta$, and making $dF_a/d\beta = 0$, which satisfies Equation 6.3:

$$\tan\beta = \frac{1}{FoS}\tan\phi$$

(Equation 6.3)
Taking the Factor of Safety (FoS) as 1, the required perpendicular anchoring force \( F_n \) can be derived as (where \( F_{opt} \) is the optimal installation anchoring force and \( \phi \) is the required angle):

\[
F_{opt} = F_n \sin \phi
\]  
(Equation 6.4)

The value of \( \phi \) can be as low as 30° and therefore Equation 6.4 implies that the \( F_{opt} \) is as low as half of \( F_n \), i.e. the required force can be decreased by up to 50% if the anchor is installed at optimum angle, rather than perpendicular to the failure plane.

The anchoring force is developed by the dimensions of the reinforcing element, i.e. its length and diameter. Therefore, considering the failure geometry with respect to the optimum installation angle can result in significant savings. To achieve cost-effectiveness for rock reinforcement, the optimum installation angle should be used. The geometry of the rock slope and other conditions may impose restraints on the installation angle. A contractor with specialist and appropriate expertise and equipment should be used for reinforcement installation (Figures 6.25).

6.5 **Rock Support and Protection**

Support and protection is used to improve rock slope stability (Figure 6.36). Many of the techniques are interrelated and provide both support and protection.

### 6.5.1 Selection of Support and Protection Techniques

Rock strengthening and protection techniques can be applied to a variety of rock slope instability problems. The design of an effective rock strengthening and protection system usually requires a combination of several of the techniques described. The choice of the most appropriate techniques is complex and is dependent on several factors, including:

(a) design loads  
(b) rock fracture condition  
(c) rock material strength  
(d) potential failure geometry  
(e) design life  
(f) site geometry  
(g) costs
(h) environmental considerations
Advice on the selection of the appropriate rock slope remedial works approach is given in Chapter 5.

6.5.2 Rock Support

Support improves the stability of rock slopes by retention or support of unstable areas with some form of structure.

Retaining Walls and Buttresses provide vertical and horizontal restraint to the rock mass. Retaining walls and buttresses are either anchored (Figure 6.37) or gravity (Figure 6.38). Retaining walls are formed of concrete or alternatives such as gabion baskets. Advantages of gabion basket retaining walls are they are free-draining and can utilise local materials, potentially making them more environmentally acceptable.

Concrete structures can be clad with a stone facing to make them more environmentally acceptable (see Chapter 7). Adequate provision must be made for drainage in the design of retaining structures such as walls and buttresses.

![Figure 6.37. Anchored Retaining Wall](image1)
![Figure 6.38 Retaining Wall (A9)](image2)

Buttresses act in a similar way to retaining walls. Again, there are two types of buttresses; anchored (Figures 6.39 and 6.40) and gravity (Figure 6.41). Many buttresses are anchored to provide lateral restraint.

Sprayed Concrete is both support and protection for rock slopes. It can be used to protect rock masses from further degradation and/or to treat small potential failures. Sprayed concrete can be used to treat larger potential failures when used in a composite system, with netting and reinforcement.

There are two types of sprayed concrete, 'wet' and 'dry'. Dry sprayed concrete or 'gunite' is more commonly used. Drainage should be provided through the sprayed concrete layer to prevent a build-up of water. Sprayed concrete should be applied on a clean surface to achieve a good bond between the rock and the concrete. Over time, sprayed concrete can weather to become virtually indistinguishable from other areas of rock. An example of sprayed concrete is shown in Figure 6.42.
Anchored Beams are again a form of both support and protection for rock slopes and are similar to buttresses. They provide a means of spreading the retention provided by anchors over a greater volume of rock. This technique can be useful where the area that requires stabilisation is part of a weak rock mass, which would break-up around single reinforcement elements. An anchored beam is shown in Figure 6.43.
6.5.3  **Rock Protection**

Rock protection limits weathering and degradation of a rock mass by applying a covering or facing (Figure 6.44). Many of the support techniques described in the previous section also provide protection for the rock mass. The applied facing is generally concrete, masonry or masonry-faced concrete. Masonry facings or 'dentition' are common due to the immediate availability of local materials (i.e. stone from the rock face).

![Figure 6.44 Dentition (A9, Blair Atholl)](image)

Rock protection is often an appropriate option where erosion of a localised weak zone may cause further instability, for example by undermining the area above the weak zone. Adequate drainage should be provided through the facing. The use of local stone improves the appearance of the treated area, by blending it with the natural rock.
6.6 Avoidance

As a remedial work technique, avoidance involves reducing or removing the rock fall risk by circumventing the rock slope with the road.

The main consideration is cost-effectiveness for moving the road compared with carrying out remedial works. In most situations, even major rock slope remedial works will be more cost-effective than moving the road. Avoidance can range from a local change in road alignment to create room for a rock trap, to the construction of a section of road to by-pass the rock slope or slopes. In areas where road rock slopes are required, by-pass is only likely to be possible with major construction work.

6.7 Warning Systems

Warning systems are designed to give some warning of either imminent failures or failures that have just occurred.

Warning systems can be set up for individual potential failures or more widespread potential failures. The systems can consist of instrumented fences, trip wires or motion triggers. The instrumentation could consist of acoustic emission detection devices, accelerometers, extensometers, or electrical wires (to monitor continuity or resistance).

Warning systems are usually set up to relay a warning to the manager of a network. However, warning systems could also be set up to activate traffic signals, variable message signs or gates on the road.

These types of systems have been widely used in North America on railroads but have not been extensively used on roads because of the difficulties of automatically closing a road (Marvin et al, 1985). However, the use of more sophisticated road signing and control could increase the potential of these techniques.

Most rockfall happens instantaneously and thus these warning systems give only minimal warning or reaction time. However they can provide a warning to prevent vehicles from driving into rock fall debris. This could be particularly important if the failure were on a section of road with poor sightlines.

The warning systems currently available are not generally practical or cost-effective. However, they may provide an interim measure while permanent solutions are designed or financed and such systems may prove beneficial for:

- Very infrequent large potential rockfalls.
- Rockfalls from large 'sources' above a road (for example natural mountain slopes).
- Where remedial works or relocation of the road is not practical or feasible.

Rockfall signs can be used to warn the public of the potential rockfall hazard posed by slopes. However, experience has shown that these signs are generally ignored.

"Rockfall patrols" can also be used as a 'warning' system, however, this method is generally not cost-effective in the long term. The patrols must form part of a rock slope management and emergency strategy for the section of road. Material can be removed from the road by the patrol but the location and nature of the rockfall should be recorded and passed on to the network manager. Frequently, large rockfalls can be preceded by small and seemingly innocuous failures, possibly giving an advance warning of active potential failures.
7 Environmental Considerations

7.1 Environmental Impact

In general environmental impact concerns changes that we impose on our surroundings. Such impacts can be broadly split into two groups:

(1) Perceived Impacts or
(2) Actual Impacts

Perceived impacts are those that generally concern our appreciation of our environment. Actual impacts are those that concern damage or change to the environment. These impacts can be viewed as good or bad, acceptable or unacceptable and are judged by the nature and magnitude of the effects or perceived effects.

The majority of remedial works are carried out on rock slopes that have been excavated in the natural ground. Therefore, most remedial works are an addition to an existing man-made structure. However, rock slopes are formed in, and of, natural materials whereas remedial works often involve the introduction or addition of man-made materials. It is the environmental impact of these materials and the associated construction methods and geometries that is discussed here.

Evaluation of perceived environmental impact of remedial works is strongly influenced by personal judgement and opinion. Tourists, local residents, conservationists, motorists, road engineers and geologists can, and do, have widely differing views of acceptability. It is impossible to quantify these differences and, therefore, reaching a consensus on what is environmentally acceptable is always going to be difficult. A further complication with achieving consensus of view is that the attitudes of all of the interested parties vary with time, and at different rates.

Evaluation of actual impacts is slightly simpler than with perceived impact as we are dealing with effects that are at least in part measurable and quantifiable. The difficulties arise in agreeing thresholds of acceptable effects. Once again there are significant differences in opinion of what is acceptable between the interested parties. However, consensus is more likely when dealing with actual impacts than when dealing with perceived impacts.

When considering both perceived and actual environmental impact it is important to differentiate between the short and long term. Short-term impacts are those that nature is capable of repairing or minimising with the passage of time. Long-term impacts are permanent or effectively permanent in terms of the lifetime of the structure. Both can be minimised by good design and construction practice.

7.2 Acceptance and Tolerance

Acceptance and tolerance of environmental impact are very different. Questions of acceptance and tolerance of both perceived and actual environmental impact are closely linked to social attitudes and economic conditions. These are of course dynamic variables and change with time.

At any given time there are likely to be differences between what is tolerated and what is accepted. In general, impacts arising from historical activities will be tolerated at different levels to that set for acceptance of new activities. There are two main reasons for this:

(1) Altering historical works to meet current standards will in itself cause an impact even though it should eventually produce a better outcome.
(2) Altering historical works is often expensive and the approach of continually improving existing works to meet the ever changing new standards is impractical and unsustainable.

There is a third reason that applies to certain types of structures and impacts. Constructions, while not meeting current standards, may become of significant historical importance. Once this occurs they are not only tolerated but also accepted because of this importance.

7.3 Good Practice

There are therefore difficulties in defining perceived and actual environmental impact standards that are going to be tolerated by or accepted by all interested parties. It is clear that the engineering geologist or geotechnical engineer designing or constructing remedial works is faced with significant hurdles to overcome. The designer and construction supervisor need to consider all of the views of interested parties and make difficult decisions based on current best practice and published guidance. Sections 7.4 to 7.7 set out the existing guidance on environmental impact that are currently applicable to Scotland. It is essential that the designer and construction supervisor keep abreast of developments in best practice if they are to achieve any degree of acceptance for their work. Section 7.7 gives practical guidance on reducing environmental impact specifically for rock slope remedial works.

For rock slope remedial works in areas of high environmental sensitivity or importance such as Sites of Special Scientific Interest (SSSI), consultation becomes an integral part of the design and construction process. The authors have been involved in a number of such situations and in all cases have achieved at minimum tolerance of the works and in some cases full acceptance and even appreciation.

A good example of what can be achieved where necessary is the work carried out at Cartland Bridge rock abutment remedial works on the A73. The works received a special Saltire Award for the environmental mitigation measures taken at the site.

7.4 The Policy in Scotland

The Scottish policy on landscape design and management is set out in 'Cost Effective Landscape: Learning from Nature' (The Scottish Office, 1998). The document forms the procedure for landscape design and management for the Scottish Trunk Road Network, but the concepts and procedures are equally applicable elsewhere.

Cost Effective Landscape: Learning from Nature (CEL:LFN) does not give guidance on environmental assessment or route planning but The Scottish Executive Development Department endorses the procedures, guidance and good practice described in the Design Manual for Roads and Bridges (DMRB). They require all professionals concerned with trunk road assessment, planning, design and management to comply with the DMRB. Volume 10 of the DMRB deals with 'Environmental Design' and Volume 11 deals with 'Environmental Assessment'. The advice given in CEL:LFN should be followed in Scotland where advice or procedure differs from Volume 10 of the DMRB. The main aims of the policy are to improve the quality and efficiency of road landscape design and management through the application of natural characteristics and to apply the policy to all relevant landscape tasks. The application of the policy will be subjected to procedural inspections arranged by the client.
The *Bottom Dead Centre* design approach is recommended in CEF:LFN. Bottom dead centre is the state of rest that represents the natural self-reliant landscape and displacement from this position represents the degree of artificiality. The landscape will begin to revert to its natural state or 'bottom dead centre' if energy input declines.

Therefore, the aim is to achieve design objectives as close to the natural state as possible through working with nature. Of particular relevance to rock slope remedial works are the following considerations:

(1) Identification of the natural processes which can be best harnessed to achieve the desired landscape objectives.

(2) Awareness of the short term (capital/construction) costs and long term (revenue/maintenance) costs and the need to balance both types of expenditure.

(3) Search for the sustainability benefits which can be delivered.

To produce quality and cost-effective landscape, designers must demonstrate that:

\[
\text{Landscape Design & Management} + \text{Learning from Nature} = \text{Cost Effective Landscapes} + \text{Environmental Benefits}
\]

The CEF:LFN policy encourages landscape designers to explore alternatives in finding the most appropriate solution. This will produce a more sensitive approach and greater attention to detail and promote the wise and sustainable use of resources. It will also give a more cost-effective use of expenditure.

The policy refers to rock outcrops only in terms of environmental design (as opposed to stability design). The following advice is given:

(1) Understanding the site and its natural characteristics.

(2) The natural characteristics of established and natural outcrops in the vicinity should be used for inspiration to design a rock cutting.

(3) Produce niches in the rock for pioneer plant species to create a diversity of appropriate vegetation.

### 7.5 The DMRB - Environmental Design

The DMRB gives advice on the 'environmental design' of rock slopes, in Volume 10 Section 1 Part 1 Chapter 17 (HA55/92).

Remedial works are not specifically commented on. Issues covered include the use of terraces (berms), using the natural character of the rock and vegetation on cuttings. Photographic examples of good and bad practice are given.

Both the DMRB Volume 10 and the CEL:LFN refer to environmental aspects of design and not to stable rock slope design. In reality, when creating or reprofiling a rock slope, the design will be a compromise between these two factors. Some comments referring to the design of rock slopes in the DMRB are unhelpful, for example: "Good practice - creating the profile that might be found on a quarry...". This is unhelpful both in terms of stability and aesthetics, quarry slopes are generally less stable and have a less 'natural' appearance than road rock slopes and would therefore not be acceptable.
7.6 Application of The CEL:LFN and DMRB Policies

Rock slope remedial works are an addition to the landscape and will therefore have some environmental impact. This may be beneficial or detrimental.

The primary concern of the designer of remedial works is the reduction of risk from rockfall to the road. To find the most appropriate approach or solutions for a particular situation, alternatives that achieve the same reduction in risk should be considered.

The self-reliance or 'bottom dead centre' design approach outlined in CEL:LFN is particularly pertinent to rock slope remedial works. Ideally, once constructed, rock slope remedial works would never require further intervention. The long-term cost-effectiveness of rock slope remedial works, in terms of whole-life costs, is particularly important. However, remedial works are an addition to the existing environment and are therefore not strictly sustainable because they require maintenance. If the 'energy input' is reduced, because maintenance is reduced or stopped, the remedial works become less effective. The less intervention or maintenance required by rock slope remedial works, the more likely it is that their whole-life cost will be low.

The design life of any rock slope remedial works system is ultimately dependent on the design life of its individual components. Remedial works constructed from natural materials, for example rock traps formed by earth bunds or ditches, are generally more cost-effective and self-reliant than 'artificial' materials. However, even these systems require maintenance, i.e. the clearance of fallen debris that reduces the effectiveness of the rock trap.

Using natural, locally-won resources for the construction of remedial works is most sustainable. For example, a rock trap formed by a bund of local material and/or a ditch would be more environmentally acceptable than the construction of a rock catch fence. The use of alternative techniques is dependent on other factors, for example the size of verge available.

For remedial works there may only be one practical solution available. Where this is the case, efforts should be made to reduce the impact, rather than to consider impractical and less cost-effective alternatives.

Environmental impact of remedial works is usually a secondary issue as public safety is the prime concern for those involved in commissioning remedial works. Consideration of environmental issues, in sensitive areas, inevitably increases the cost of a project through mediation with relevant experts on the site's special sensitivity, for example botanists, biologists or archaeologists.

Even in circumstances where public safety is the priority and is only limited financial resources are available, environmental concerns can still be addressed. If it is accepted that remedial works will bring some change to the pre-existing status quo (whether natural or man made) then efforts can be concentrated on limiting the environmental impact.

7.7 Assessment of Environmental Impact

Environmental Impact Assessments (EIAs) are not mandatory for most rock slope remedial works. However, the principles of EIA should be considered as representing and encouraging best environmental practice. The EC Directive 85/337 (Assessment of the Effects of Certain Public and Private Projects on the Environment) set out the requirement for EIA's (McKirdy et al, 1998).

The EIA process is important because it allows all relevant matters, including geological issues, to be considered during the planning process. It is up to the planning authority to ensure that all relevant issues are adequately explored in
the EIA. Only certain developments require an EIA by law, for example motorway construction. Other developments are listed as requiring an EIA if the planning authority decides it is necessary (McKirdy et al, 1998).

For an EIA, an environmental baseline is established to describe the present state of the environment and the way it would change, assuming that the development did not go ahead. The baseline provides a measure against which any changes resulting from the development can be estimated. Various factors should be considered in establishing the baseline, including soil, geology, geomorphology, and ground and surface water. In many projects, geological and surface processes are not considered in depth. The EIA allows for monitoring of the development post-construction, to measure the actual against the predicted impact (McKirdy et al, 1998).

Those who are most affected are the residents that live adjacent to the proposed development site and there is a requirement in an EIA for a non-technical summary of the issues (McKirdy et al, 1998).

EIA’s are unique to the individual circumstances of the scheme. Major schemes in highly sensitive areas will require a more comprehensive assessment than those in less sensitive environments.

Wiltshire et al (1987) give a basic guide to the geological input required for an EIA for a mineral extraction operation. This can be adopted for rock slope remedial works:

**Stage 1:** A statement of the objectives, including a description of the area and a project plan (with time scales). This will be provided by the commissioner and will include geological advice independent of the EIA.

**Stage 2:** A review of the present environmental conditions, including ecology, hydrology, soils and agriculture, and issues such as landscape value, visual aesthetics, historic buildings, protected sites (for example SSSI’s), etc.

**Stage 3:** Requirements of the planning policy should be considered. A dialogue between the contractor, consultants and planning authority should be established.

**Stage 4:** Systematic consideration of the environmental impacts of alternative options. This requires a thorough description of the proposed development actions, particularly those with potentially deleterious consequences.

**Stage 5:** The likely environmental consequences of alternative schemes must be investigated. The impact is assessed by predicting the likely changes in the natural and human environments. The subsequent selection will therefore take account of the possibility of refusal of planning permission on environmental grounds and of any requirement for mitigating measures. Therefore, geological factors must be assessed before advice on minimum impacts is given.

**Stage 6:** The risk reduction, economic and environmental advantages of the preferred scheme must be clearly stated so that the planning authority can understand the basis for the selection of a particular option.

**Stage 7:** A detailed analysis of the potential impacts of the preferred scheme should be made, if this has not been provided in Stage 5. Geological and/or geotechnical specialists may be required to provide expert advice.

**Stage 8:** If the impacts are serious, then the viability of measures, which can limit the potential for environmental damage, must be considered. This may include additional temporary works.

The public community’s perception of the development is an important part of the EIA. The benefits of the remedial works scheme should be discussed at a public meeting, especially if the proposed construction is going to cause any inconvenience to the local community, for example traffic congestion.
necessary, arrangements should be made to minimise disruption to the local community. However, with adequate notice and explanation of the benefits of the development, this may not be necessary.

7.8 Practical Methods to Minimise Environmental Impact

Advice, advantages and practical tips to minimise the environmental impact of various rock slope remedial works options and techniques are given in Table 7.1. Innovative approaches are sometimes required. At Stirling Castle, in areas where concrete support was required, resin mouldings of the original rock face were taken. The mouldings were used to cast concrete facings for the support and so keep the natural form of the rock (Price et al, 1988).

Examples of good practice for minimising the environmental impact of rock slope remedial works are shown in Figures 7.1 to 7.16.
## Table 7.1 Practical Advice and Tips on Minimising Environmental Impact for Remedial Works

<table>
<thead>
<tr>
<th>Options and Techniques</th>
<th>Advice and Tips</th>
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<tbody>
<tr>
<td><strong>Containment</strong></td>
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</table>
| Rock Containment (Fences and Ditches/Bunds) | - Use netting for the fence.  
- Leave natural discontinuities to design the new slope, by obscuring natural slope angles.  
- Use gabion walls constructed with local rock-filled baskets and consider landscaping and vegetating.  
- Use dark-coloured or green netting to help blend in with the natural environment. |
| Rock Traps (Fences and Ditches/Bunds) | - Paint fence posts, anchors, etc., green or appropriate alternative colour.  
- Use green netting for the fence.  
- Remove the minimum amount of vegetation for example by altering the fence line to avoid mature trees (vegetation also compliments the effect of rock traps).  
- Use ditches/bunds (rather than fences) wherever possible and encourage vegetation growth. |
| Removal                |                 |
| Scaling                | - Scaling ‘scars’ weather to become indistinguishable from the natural of the rock mass.  
- Use gabion walls constructed with local rock-filled baskets and consider landscaping and vegetating.  
- Compartmentalise the edge of rock mass.  
- Remove the minimum amount of vegetation, for example by altering the fence line to avoid mature trees (vegetation also weathered & dissipated).  
- Leave natural discontinuities for the new slope. |
| Reproofing             |                 |
| **Strengthening**      |                 |
| Reinforcement          | - Rock colour weathers quickly to natural colour.  
- Consider using natural stones to avoid horizontal lines (betons must not dip out of the slope).  
- Use of dark-coloured or green netting to help blend in with the natural environment.  
- Use of dark-coloured or green netting to help blend in with the natural environment. |

*Note: This table is a practical guide for minimizing environmental impact during remedial works.*
Table 7.1 (Continued)

<table>
<thead>
<tr>
<th>Options and Techniques</th>
<th>Advice and Tips</th>
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<tbody>
<tr>
<td>Support and Protection</td>
<td>• Use natural stone facings of local material, i.e. same rock as face.</td>
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<tr>
<td></td>
<td>• Avoid the use of undisguised concrete beams, etc.</td>
</tr>
<tr>
<td></td>
<td>• Use a pigment to colour concrete to the colour of the natural rock.</td>
</tr>
<tr>
<td></td>
<td>• Use sprayed concrete as it weathers quickly and looks natural in right surroundings.</td>
</tr>
<tr>
<td></td>
<td>• Consider the use of alternative techniques if too unsightly.</td>
</tr>
<tr>
<td></td>
<td>• Produce moldings of the natural rock face before support and use to cast concrete with the formation of the natural rock.</td>
</tr>
<tr>
<td></td>
<td>• Use sculpture to produce concrete facings with the form of natural rock.</td>
</tr>
<tr>
<td></td>
<td>• Create recesses, niches and ledges and plant to establish areas of vegetation</td>
</tr>
</tbody>
</table>

| Avoidance               |                                                                                   |
|                        | • Good as not adding materials to the rock mass and producing an irregular, more natural rock face. |
|                        | • Probably need to incorporate rock trap ditch/berm into scheme.                  |

| Re-alignment           |                                                                                   |
|                        | • Avoid as there will be a large environmental impact to create a totally new route. |

| General                |                                                                                   |
|                        | • Erosion protection, to stop soil or superficial deposit erosion and to encourage vegetation growth (itself limiting erosion) should be used wherever necessary. Where vegetation is used it should be of native species, suitable to the location. |
|                        | • Local natural materials should be used in the construction of remedial works.   |
|                        | • Other remedial work approaches or techniques may become feasible, if the cost of using the preferred option is too great because it has been modified for environmental reasons. |
Figure 7.1 Anchored Concrete Beam - the beam is disguised by its colour and form (A9, Drumochter Pass)

Figure 7.2 Masonry Faced Anchored Concrete Buttress - inappropriate (A82, Urquhart Castle, Loch Ness)

Figure 7.3 Masonry Faced Buttress and Dentition - both blend well with the natural rock face (A9, Drumochter Pass)
Figure 7.4 Rockfall Netting – the netting is rapidly disguised by natural vegetation regeneration (A82, Loch Ness)

Figure 7.5 Retaining Wall above a Slope – the retaining wall is out of character with the landscape; large expanse with sharp straight lines (A9, Killiecrankie)
Figure 7.6 Rock Catch Fence Construction – Posts Painted Green (Abbey Craig, Stirling)

Figure 7.7 Rock Catch Fences – fence line altered to avoid trees (Abbey Craig, Stirling)
Figure 7.8 Rock Slope with Rock Catch Ditch – slope and ditch both well vegetated (A887, Glen Moriston)

Figure 7.9 Scaled Rock Slope – recently scaled areas have a natural appearance and blend well with the slope (A835, Ullapool)
Figure 7.10 Rock Slope with Irregular Face – rough slope profile using the rock’s natural characteristics and with an adequate rock trap but the straight barrier draws the eye and spoils the visual effect (A887, Glen Moriston)

Figure 7.11 Rock Slope with Berms – the trees becoming established are starting to soften the regularity and decrease the visual impact of the berms (A9, Crubenmore)
Figure 7.12 Rock Slope with Inclined Berms – the inclined, large (>4m) and vegetated berms decrease the visual impact of this slope (M90, Perth)

Figure 7.13 Rock Reinforcement with Recessed Head - indicated by arrow. N.B. Difficulties may later be encountered in finding and assessing the condition of recessed reinforcement (Edinburgh Castle)
Figure 7.14 Buttressing and Dentition – the use of natural stone is less obtrusive (A9, Blair Atholl)

Figure 7.15 Gabion Retaining Wall – the visual impact could have been decreased by softening the steps at the top of the wall (A9, near Perth)
Figure 7.16 Sprayed Concrete – the concrete has a similar appearance to the natural rock and it will blend in further with time (Northern Spain)
Acknowledgements

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References


Appendix A  Potential Toppling Failure: General Criteria and Stereographic Overlays
Potential Toppling Failure Criteria and Stereographic Overlay
The general conditions for toppling failure geometry to be realised are set-out in Section 2.3 and are repeated here. Because of the potential variety and complicated nature of toppling failure geometries it should be emphasised that these conditions are general. Toppling failures may occur outwith these conditions due to local peculiarities in geometry and/or the face profile.

General Conditions for Toppling Failure:
(1) It requires at least two steep release planes and one basal release plane.
(2) The basal release can be either a single plane or the intersection of two planes.
(3) If the basal release is a single plane, it must dip out of the slope less than the rock’s angle of friction.
(4) If the basal release is two planes, the intersection must dip out of the slope less than the rock’s angle of friction.
(5) The intersection of the two steep planes must dip into the slope.
(6) 'Toppling Wedges' are an example of a special case of toppling geometry. They are formed where the intersection of two discontinuities forming a 'wedge' dip out of the face at less than angle of friction for wedge failure to occur. For a 'toppling wedge', there must be a single steep plane dipping into the slope, with an azimuth of approximately 160° to 200° relative to the slope azimuth. An example of a toppling wedge is illustrated in Figure A1.1.

![Toppling Wedge Diagram](image)

Figure A1.1 - An example of a toppling wedge failure

Recognition of Potential Toppling Failure

Stereographic overlays for toppling failure (Matheson, 1983) are general and do not cover all potential geometries. It is therefore possible to have toppling failure geometries outside of the traditional toppling failure overlay envelope.

Special cases of toppling failure outside the traditional toppling failure overlay envelope (for example toppling wedges) should be carefully considered during the recognition of potential failure mechanisms. This highlights the importance of a
rock slope inspection in the recognition of all potential failure mechanisms. Failures that are theoretically impossible according to the stereographic overlay envelopes can actually exist on the slope because of local peculiarities in discontinuity geometries and/or the face profile. This is partly a product of the assumption of the stereographic overlays that the 'design' slope is planar, whereas in reality it is often irregular.

The overlay envelope, based on an equal-area projection for 'classical' toppling failure, is shown in Figure A1.2.
Appendix B   Model Specification for Scaling of Rock (for use in Road Rock Slope Remedial Works)
SPECIFICATION

SECTION X: SCALING

Clause X.01

1. Rock scaling work by hand or using hand scaling bars shall be carried out in accordance with the requirements of this section. Should any ambiguity or confusion exist the Contractor shall consult the Engineer before proceeding. The Engineer’s judgement on such matters shall be final. A Method Statement for the scaling work shall be submitted to the Engineer for his approval prior to commencement of work on the site.

2. Light scaling work shall be carried out by hand or by using hand held non-power tools to remove rock and soil materials.

3. Heavy scaling work shall be carried out with the aid of power tools to remove rock materials.

Clause X.02

1. Scaling is to be carried out on the rock face within the area shown on the Contract Photographs. The final locations and extent of the scaling work to be carried out on the rock face shall be indicated on site by the Engineer.

2. If, during the works the Contractor encounters material outside the specified area to be scaled that in his opinion should be scaled he shall contact the Engineer immediately for further instructions.

3. If, during scaling work the Contractor considers that the removal of material from an area may affect the overall stability of the rock face he shall terminate the scaling work immediately and contact the Engineer for further instructions.

Clause X.03

1. The Contractor shall ensure that all loose and unstable rock, soil or vegetation is removed from the area to be scaled, except where instructed to the contrary by the Engineer and subject to Clause X.02.3 of this section.

2. The scaling works shall be executed in such a manner that there is no danger to the Contractor’s personnel, the Engineer’s staff or any third parties, and that any danger to the site environment is kept to a minimum.

3. The Contractor shall make provisions such that there is no damage to buildings, structures, vehicles, plant, road surface, railway infrastructure, or services as a result of the scaling operations. Should any such damage occur the Contractor will be required to put right the damage at his own cost.

4. The Contractor shall make provision to ensure that any damage
to vegetation, shrubs and trees on the rock face and talus slope is kept to the absolute minimum necessary for carrying out of scaling on the rock face.

5. The method statement required under Clause X.01.1 of this section will require details of the precautions the Contractor proposes to take in order to comply with sub-clauses 2, 3 and 4 of this clause.

Clause X.04 1 The Contractor shall provide all supervision on the site for the scaling operations. Supervision

Clause X.05 1. The rock won from scaling work shall be broken up as required and removed to a suitable tip approved by the Engineer. Removal of Materials

Clause X.06 1. All scaling within individual areas of the rock face is to be completed and scaled material removed from the site to an approved tip following vegetation removal and prior to controlled removal and other works. Sequence
This report provides advice and guidance on good practice in rock slope remedial and maintenance works. The subjects covered include rock slope stability, risk assessment, risk management and reduction strategies, the selection of risk reduction strategies, the design and specification of remedial works and environmental considerations.

Other titles from this subject area

INS001  Improving the stability of slopes using a spaced piling technique. D Carder. 2009
PPR406  Use of intelligent compaction technology. D R Carder, B C J Chaddock (TRL) and L Campton (Halcrow Group Ltd). 2009
PPR340  Thermal imaging of slopes and substructures. D R Carder and A Dunford. 2008
PPR302  Performance of an interseasonal heat transfer facility for collection, storage and re-use of solar heat from the road surface. D R Carder, K J Barker, M G Hewitt, D Ritter and A Kiff. 2008
PPR140  Ventilation during road tunnel emergencies. R C Hall. 2006