A RISK ASSESSMENT PROCEDURE FOR OPTIMISING SLOPE-FAILURE PREVENTIVE MAINTENANCE PROGRAMMES

Transfund New Zealand Research Report No. 135

A RISK ASSESSMENT PROCEDURE FOR OPTIMISING SLOPE-FAILURE PREVENTIVE MAINTENANCE PROGRAMMES

RIDDOLLS & GROCOTT LTD
Christchurch, New Zealand

Transfund New Zealand Research Report No. 135

ISBN 0-478-11093-6
ISSN 1174-0574

Riddolls & Grocott Ltd. 1999. A risk assessment procedure for optimising slope-failure maintenance programmes. *Transfund New Zealand Research Report No. 135.* 56pp. (includes appendices).

Keywords: assessment, benefit, benefit/cost, cost, cost optimisation, geotechnology, hazard, instability, maintenance, Monte Carlo simulation, New Zealand, probability, risk, roads, rockfall, slope

AN IMPORTANT NOTE FOR THE READER

The research detailed in this report was commissioned by Transfund New Zealand.

Transfund New Zealand is a Crown entity established under the Transit New Zealand Act 1989. Its principal objective is to allocate resources to achieve a safe and efficient roading system. Each year, Transfund New Zealand invests a portion of its funds on research that contributes to this objective.

SYMBOLS & DEFINITIONS

B/C	Benefit/Cost Ratio
Ef	Effectiveness of maintenance programme in reducing failure probability
Es	Effectiveness of maintenance programme in reducing spatial probability
Et	Effectiveness of maintenance programme in reducing temporal probability
Ev	Effectiveness of maintenance programme in reducing vulnerability of element at risk
FOS	Factor Of Safety
NPV	Net Present Value
P(F)	Probability of Failure
P(S)	Spatial Probability
P(T)	Temporal Probability
V	Vulnerability of element at risk
μ	mean
σ	standard deviation
RA	Risk Assessment
USPWF	Uniform Series Present Worth Factor

Workbook	Microsoft (MS) Excel file which may contain one or more worksheets.
Worksheet	Individual page in an MS Excel workbook.
Spreadsheet	Term applied to an electronic ledger in the context of its generic type of software, of which MS Excel is an example.

CONTENTS

SYMBOLS & DEFINITIONS . . . 4
EXECUTIVE SUMMARY . . . 7
ABSTRACT . . . 8

1. INTRODUCTION . . . 9
1.1 Background . . . 9
1.2 Objectives . . . 9

2. RISK ASSESSMENT PHILOSOPHY . . . 10
2.1 Definition of Risk Assessment . . . 10
2.2 Accommodating Uncertainty . . . 10
2.3 Reliability of Quantitative Risk Assessment . . . 11

3. PROCEDURE FOR SELECTING OPTIMUM MAINTENANCE PROGRAMME . . . 12
3.1 Outline of Procedure . . . 12
3.2 Defining Scope of Analysis . . . 12
3.3 Determining Existing Risk . . . 14
3.3.1 Failure Modes . . . 14
3.3.2 Elements at Risk . . . 15
3.3.3 Consequences . . . 18
3.3.4 Risk Calculation . . . 18
3.3.5 Costs of Consequences . . . 21
3.4 Determining Future Risk . . . 21
3.4.1 Definition of the "Do Minimum" Maintenance Programme . . . 21
3.4.2 Alternative Maintenance Programmes and Costs . . . 21
3.4.3 Effectiveness of Maintenance Programmes . . . 22
3.4.4 Calculation of Mitigated Risk . . . 23
3.5 Selection of Optimum Maintenance Programme . . . 23
3.5.1 Economic Evaluation . . . 23
3.5.2 Acceptability of Risk . . . 24
3.5.3 Sensitivity Analysis . . . 25

4. IMPLEMENTATION GUIDELINES . . . 26
4.1 Workbook Layout . . . 26
4.1.1 Header Worksheet . . . 26
4.1.2 Individual Risk Assessment Worksheets RA1 to RA12 . . . 26
4.1.3 Economic Analysis Worksheet . . . 26
4.1.4 Risk Summary Worksheet . . . 26
4.2 Functioning of the Worksheet . . . 27
4.3 Instructions for Use of Worksheet . . . 27
4.4 Worked Examples . . . 28
4.4.1 Example 1. SH73, Christchurch to Arthur's Pass, Paddy's Bend, Site 4 . 29
4.4.2 Example 2. Argillite Cut, British Columbia, Canada . . . 32

5. APPLICABILITY AND LIMITATIONS OF PROCEDURE . . . 33

6. REFERENCES . . . 34

APPENDICES

1. WORKED EXAMPLE 1 35
2. WORKED EXAMPLE 2 47

TABLES

3.1 Examples of effectiveness of remedial actions in reducing the component probabilities of risk. 22
4.1 Risk calculation by alternative formulae, Worked example 2, Argillite Cut, British Columbia, Canada. 32

FIGURES

3.1 Methodology for selecting optimum highway maintenance programme. 13
3.2 Probability density functions used in the analysis. 16
3.3 Relationship between Factor of Safety and probability of failure for two hypothetical cut slopes. 17
3.4 Event tree illustrating risk assessment philosophy. 19
4.1 Calculation of B/C ratio by Monte Carlo simulation for Site 4, SH73, Paddy's Bend, near Arthur's Pass, New Zealand. 30
4.2 Calculation of NPV by Monte Carlo simulation for Site 4, SH73, Paddy's Bend, Arthur's Pass, New Zealand. 31

EXECUTIVE SUMMARY

Introduction

This report is the second in a two-part study of probabilistic methods for the optimisation of slope-failure preventive maintenance along highways. Part 1 of the study, carried out in 1997-98 (and published as Transfund New Zealand Research Report No. 134, in 1999), included a review of current methods and selected one for detailed study in the context of its suitability for New Zealand roads. To verify the suitability of the method, a section of SH73 in the Waimakiriri Valley near Arthur's Pass, Canterbury, was selected for a field trial. The trial indicated the technique to have practical application to roads in New Zealand.

Part 2 of the study (this report), carried out in 1998-99, involves the modification of the methodology trialed in Part 1, to allow its general use by consultants and roading authorities responsible for the maintenance and management of New Zealand's highways. The methodology has been simplified and modified to suit a generic format applicable to a range of situations.

Procedure

The methodology has been developed in this study to assist in selecting optimum slope-failure preventive maintenance programmes for highways. The existing risk to road users from slope instability is first quantified, then the effectiveness of maintenance programmes in reducing the risk to road users is determined and the mitigated risks are quantified. The risks are then expressed in economic terms and the implementation costs associated with each programme incorporated into the database.

The technique allows for the consideration of uncertainty in various input parameters (both geotechnical and economic). Monte Carlo simulation allows analysis outputs to be expressed in terms of probability distributions. The analysis method has been implemented as a Microsoft Excel '97 spreadsheet, with the ability to model uncertainty in input parameters using @RISK add-in software. The uncertainty associated with the analysis outcome may therefore be quantified, leading to better informed decision-making and prioritisation of expenditure. A Microsoft Excel '97 file has been developed to allow the technique to be applied to a range of slope stability situations. Two worked examples are provided to verify the worksheet calculations and to illustrate the approach. The Excel file is contained on a diskette, supplied with the report. To use this file the @RISK version 3.5e add-in (not included) is required.

The method detailed in this report allows an optimum maintenance programme to be selected for a site affected by slope instability. The method is based on both cost and level of risk. It also provides an approach for demonstrating "duty of care" by the roading authorities to road users with respect to slope stability hazards. For sites where slope stability is a problem, the methodology allows meaningful quantitative risk assessments to be carried out, and appropriate engineering responses to be implemented when risks are above acceptable limits.

Applicability and Limitations of Procedure

- The analysis method presented in this report assumes all probabilities remain constant in each year of the time period considered. As such it is best suited to situations where the annual probability of slope failure is high, and no major changes in site conditions are expected over the analysis period. Examples would be sections of highway repeatedly closed or otherwise affected by ongoing slope failures in an average year.

- The method is less applicable to situations where the probability of failure increases with time. An example could be progressive undercutting of a slope by a river. This situation requires the probability of failure to be increased for each year of the period under consideration.

- The method is also less suited to "random" low probability/high consequence events such as major earthquakes, extreme floods, etc. In these cases consideration of the likely timing of the event become significant, and an alternative approach is required. An example of an analysis method possibly more suited to this situation is given in Transfund (1997).

- Probabilistic analysis is an attempt to model a real situation, which is infinitely complex. As such it will never be 100% successful. It is intended as a guide to understanding of the concepts of risk assessment as well as a tool to aid sound decision-making and informed management of slope instability risk.

- The generic approach to slope stability assessment proposed in this report will not be suitable for all situations. Neither is it intended as a substitute for a full understanding of the analysis concepts.

- No analysis should even be contemplated without a full comprehension of the engineering geology of the locality. The geological controls and failure mechanisms must be understood before meaningful analysis inputs can be selected.

ABSTRACT

A methodology has been developed, based on a study carried out in 1998-99, to assist in selecting optimum slope-failure preventive maintenance programmes for highways. The existing risk to road users from slope instability is first quantified, then the effectiveness of maintenance programmes in reducing the risk to road users is determined and the mitigated risks quantified. The risks are expressed in economic terms and the implementation costs associated with each programme are incorporated into the analysis.

The technique allows for the consideration of uncertainty in various input parameters (both geotechnical and economic). Monte Carlo simulation allows analysis outputs to be expressed in terms of probability distributions. The uncertainty associated with the analysis outcome may therefore be quantified, leading to better informed decision-making and prioritisation of expenditure. A Microsoft Excel '97 file has been developed to allow the technique to be applied to a range of slope stability situations. The Excel file is contained on a diskette, supplied with the report. To use this file the @RISK version 3.5e add-in (not included) is required.

1. INTRODUCTION

1.1 Background

This report is the second in a two-part study carried out over 1997-99, of the use of risk assessment techniques in optimising slope-failure preventive maintenance programmes along highway corridors. Part 1 of the study, completed in 1997-98 (Riddolls & Grocott Ltd 1999a), reviewed current international practices and examined the applicability of a selected methodology to New Zealand roads.

The analysis method adopted is based on a risk assessment technique developed by a North American geotechnical consultant for use in optimising road maintenance programmes to deal with slope instability effects (Roberds 1991). It has been implemented using commercially available spreadsheet software and is potentially applicable to a wide range of geotechnical situations. The method offers the potential for rigorous decision-making by incorporating probabilistic techniques to take account of uncertainty, and is quantitative in terms of the definition of costs and benefits for the various maintenance programmes.

This report further develops the risk assessment philosophy adopted in Part 1, simplifying some concepts and terminology where appropriate. The analysis methodology is discussed in detail, and a description of its implementation as a Microsoft Excel '97 workbook is presented. The report concludes with worked examples of two risk assessments using the workbook. The Excel file (filename riskmstr.xls) is contained on a diskette, placed in a pocket inside the back cover of this report. Open it in Microsoft Excel '97. To use this file, the @RISK version 3.5e add-in (not included on diskette) is required.

This project comes under Transfund New Zealand's key topic area "Natural Hazards/Lifeline Engineering".

1.2 Objectives

The specific objectives of this report are to:

- Review the procedures developed in Part 1, with simplification and standardisation as necessary.
- Modify the worksheets developed in Part 1 in such ways that they may be used by those with limited familiarity with probabilistic analysis.
- Verify the accuracy of the workbook.
- Prepare procedural guidelines.

2. RISK ASSESSMENT PHILOSOPHY

2.1 Definition of Risk Assessment

Risk assessment may be defined as:

> *Assessment of the probability of an undesirable consequence occurring to an element at risk due to an undesirable event.*

In the context of this study, "consequences" may be material damage, injury or death, "elements at risk" are road users, and "undesirable events" are slope failures.

An example could be:

assessment of the probability of *total loss* of a *vehicle* caused by *rockfall.*

More than one risk may be present at a particular locality. Using the above example, the following additional risk is also likely to exist:

the probability of *death* occurring to a *single vehicle occupant* caused by *rockfall.*

While the initiating event is the same for each, the consequences (and therefore costs) may be quite different. If a rock impacts a part of the vehicle, which is unoccupied, the vehicle may be written off with no life lost. If, however, the rock impacts the vehicle's windscreen for example, a life may be lost with comparatively minor damage to the vehicle. Also, the "value" attached to a human life is likely to be considerably greater than the value of the vehicle.

A meaningful risk assessment must therefore address all the significant *individual risks* present at a given site. The costs associated with each individual risk may then be summed to provide the total expected costs due to slope failure.

A clear definition of the individual risks to be considered is fundamental to the method adopted in this study.

2.2 Accommodating Uncertainty

There will always be a degree of uncertainty in the inputs to risk assessments and economic analyses. A common technique for accommodating uncertainty is Monte Carlo simulation. Each input variable is represented not as a single value but as a range of possible values defined by a probability distribution. The analysis is repeated many times, each time using input values selected from their respective probability distributions. As the analysis is repeated, the outcomes themselves build up probability distributions. This technique allows the uncertainty in the analysis outcomes to be considered during the selection of the optimum maintenance programme.

Monte Carlo simulation is incorporated into the analysis worksheets using Palisade @RISK Version 3.5e software in conjunction with Microsoft Excel. Analysis inputs, about which there is significant uncertainty, are specified in terms of probability distributions. There are many different types of distribution that could be used. Triangular distribution and truncated normal distribution have been used in this study as they are easily understood and the input data are often insufficiently precise to warrant the use of more sophisticated distributions.

The @RISK functions within the worksheets return the "expected value" of the probability distribution. In some cases these will be sufficiently accurate for quantitative risk analysis.

If more information on the uncertainty of the outcomes is required, a Monte Carlo simulation may be carried out which repeats the analysis many times (1000 iterations have been found to give repeatable results). The actual distributions of selected output cells may be viewed via @RISK, but this procedure requires a working knowledge of @RISK. An example (Worked Example 1) is presented in Appendix 1.

2.3 Reliability of Quantitative Risk Assessment

Any analysis is only as good as the input data. In some geotechnical situations the data may be insufficient to undertake quantitative analysis (i.e. the uncertainty is too great), and to do so would be misleading. In such cases experienced judgement may be the best choice.

3. PROCEDURE FOR SELECTING OPTIMUM MAINTENANCE PROGRAMME

3.1 Outline of Procedure

The approach adopted in this report incorporates both risk assessment and simple economic analysis. The methodology is described as follows:

- Determine whether or not sufficient data are available to warrant quantitative analysis.

If so:

- Identify the site boundaries.
- Identify the individual risks present (in terms of failure mode, element at risk and consequence).
- Quantify each individual risk as an expected annual probability of occurrence.
- Determine the *existing* expected annual cost of all the consequences.
- Identify the alternative maintenance programmes for the site, including a "do minimum" programme (this is often but not always a continuation of the existing situation).
- Estimate the effectiveness of each programme in reducing the individual risks relative to the "do minimum" programme.
- Calculate the *mitigated* individual risks and the expected cost of consequences for each maintenance programme.
- Determine the optimum maintenance programme based on a consideration of the expected reduction in cost of consequences versus the implementation/ maintenance costs.
- Check that the levels of risk associated with the optimum programme are acceptable.

The process is illustrated as a flow chart (Figure 3.1).

Each aspect of the analysis is discussed below. Step by step explanation of the use of the worksheet is presented in Section 4.3.

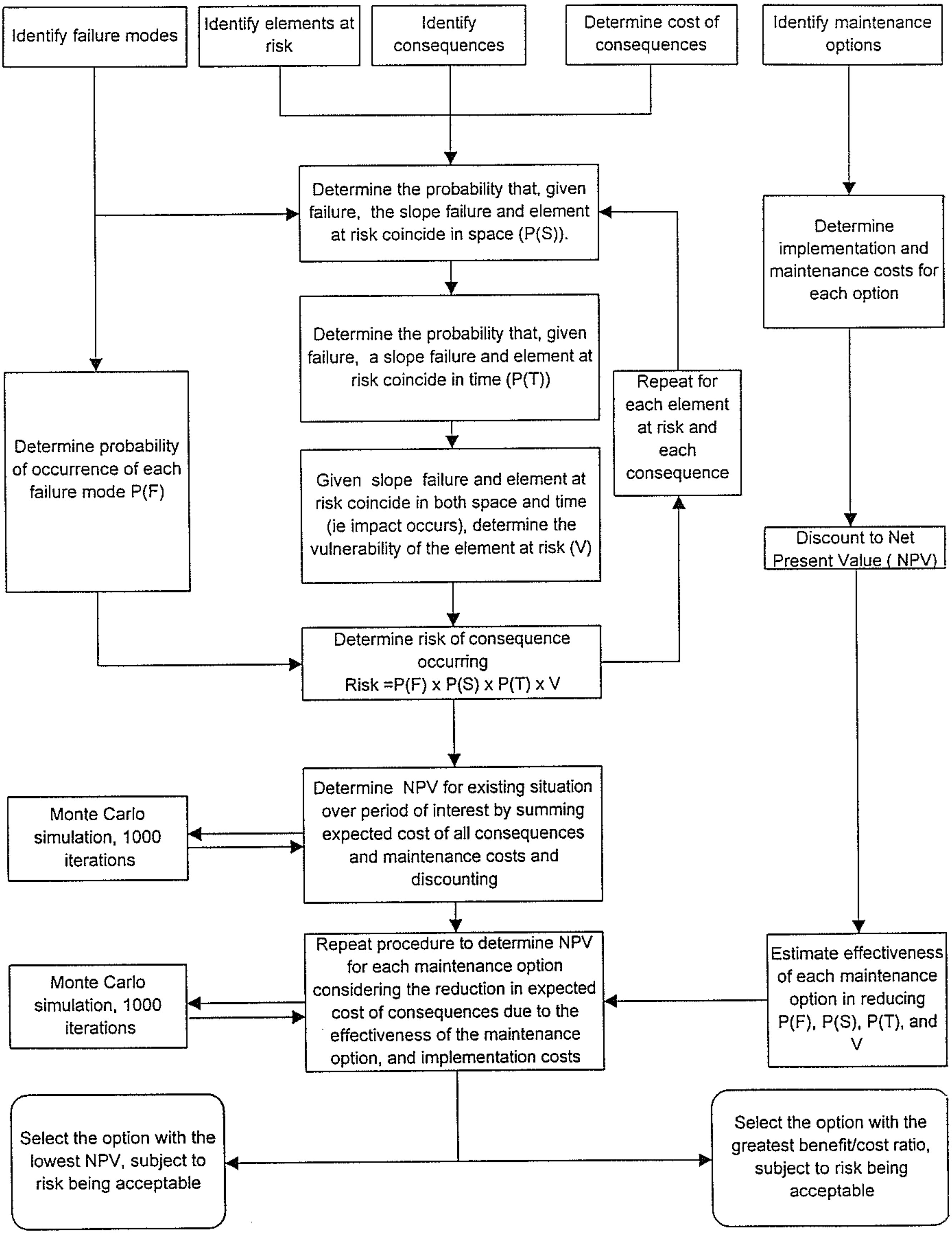
3.2 Defining Scope of Analysis

A clear definition of the objectives and scope of the analysis is critical. Initially, the boundaries of the site under consideration must be clearly defined.

The following inputs are required for analysis:

- failure mode(s) (S3.3.1)
- element(s) at risk (S3.3.2)
- consequence(s) and costs (S3.3.3, 3.3.5)
- alternative maintenance programme(s) and costs (S3.4.2)
- effectiveness of maintenance programmes (S3.4.3)
- risk acceptability criteria.

Figure 3.1 Methodology for selecting optimum highway maintenance programme.



The number of each of these components should be kept as small as possible. The complexity of the analysis increases rapidly as more scenarios are considered.

The analysis then calculates:

- present risk(s) and their cost
- expected risk(s) associated with each of the alternative maintenance programmes and their costs
- Net Present Value (NPV) of each maintenance programme
- Benefit / Cost (B/C) Ratio of each maintenance programme compared with the lowest cost ("do minimum") programme

The final output of the analysis is identification of the optimum maintenance programme for a particular site in terms of cost and acceptable risk.

3.3 Determining Existing Risk

The analysis starts by determining and quantifying the existing risk(s) present at the site under consideration.

3.3.1 Failure Modes

A site may be affected by one or more slope failure modes. Examples include: landslide, debris flow, rockfall, rock avalanche, etc. In some cases it may be convenient to treat different sized failures as different failure modes (for example, rockfalls < 1 m^3 volume versus rockfalls 1 to 10 m^3 volume). A full engineering geological assessment of the site is required to identify the modes of failure likely to affect the site, together with their magnitude, probability of occurrence, likely travel paths and potential consequences. The assessment should include:

- Review of previous technical reports, photographs, and published geological information for the site.

- Engineering geological field investigations to determine magnitude and timing of previous slope failures and potential for future instability.

- Numerical stability analyses (for example limiting equilibrium methods) if appropriate. If previous failures are sufficiently well documented, back-analysis may also be useful in determining failure probability (see Section 3.3.1.2 below).

- Study of construction and maintenance records for the section of highway affected, and for some distance on either side.

- Analysis of traffic accident data.

- Interviews with long serving maintenance staff, local residents and transport operators.

3.3.1.1 Probability of failure

Consideration of all of the above combined with an element of judgement will allow an estimate of the annual probability of each identified failure mode, P(F), to be made.

In this analysis for this study, probability of failure is treated as a triangular probability distribution to accommodate uncertainty. The triangular distribution is defined in terms of a minimum, most likely, and maximum value. The probability density function therefore has a triangular shape (Figure 3.2).

Strictly speaking, P(F) in the context of this study is actually an expected annual failure frequency, in that if more than one failure is expected in a single year, P(F)>1.

3.3.1.2 Determining probability of failure

Many deterministic numerical analysis methods express the theoretical stability of a slope in terms of factor of safety (FOS) as follows:

FOS = force driving instability/force resisting instability

This approach ignores uncertainty in the analysis inputs and gives no indication as to probability of failure. Figure 3.3 illustrates theoretical distributions of FOS for two hypothetical slopes. Assuming FOS is normally distributed, Slope 2 has a higher factor of safety (FOS = 2.00) than Slope 1 (FOS = 1.55), but also has a higher probability of failure (P(F) = 0.048) than Slope 1 (P(F) = 0.011). This is a function of the higher degree of uncertainty associated with Slope 2 (indicated by the broader shape of the distribution).

Several statistical techniques are available to determine failure probability from a conventional deterministic FOS stability analysis. These include Monte Carlo simulation, First Order Second Moment extrapolation, and the Point Estimate Method. In simple terms they involve repeating the analysis with different input variables to define a probability distribution of FOS, thereby allowing failure probability P(F) to be derived, as illustrated in Figure 3.3. Pine (1992) and Riddolls & Grocott Ltd (1999b) provide further guidance and examples of these techniques.

3.3.2 Elements at Risk

The particular elements at risk from slope failure must also be defined. Clearly the principal element at risk is the "road user", who may be defined in a number of ways:

- A specific road user, making one trip per year.
- A specific road user making regular trips (e.g. a commuter might make 200 return trips per year).
- Any specific road user within a 1 year period.
- The average number of occupants in a vehicle, including the vehicle itself.

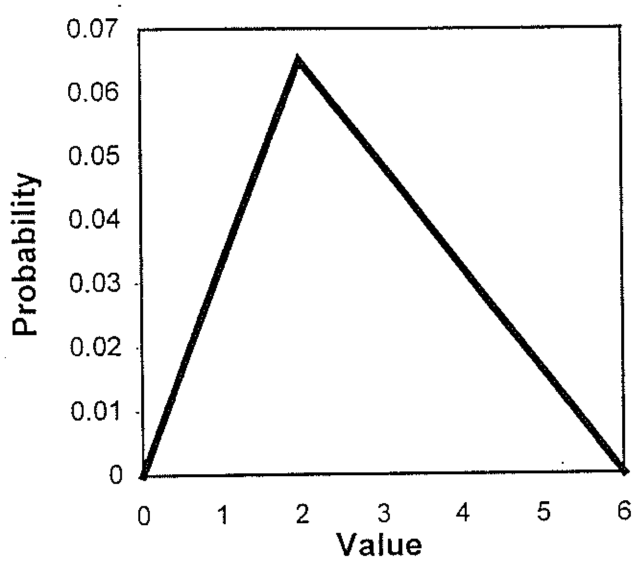
All of these and more may be valid, depending on the objective of the analysis. Also at risk may be the serviceability of the highway. If the road is closed for a period by a slope failure, parties other than actual road users may be affected.

Figure 3.2 Probability density functions used in the analysis.

Triangular Distribution

Used for:
Probability of Failure (P(F)
Spatial Probability (P(S))
Temporal Probability P(T)
Vulnerability (V)
Cost of Consequences
Implementation costs of
Maintenance Programme

Example Parameters	
Minimum	0
Most Likely	2
Maximum	6



Truncated Normal Distribution

Used for:

Effectiveness of Maintenance Options,
Ef, Es, Et, Ev

Example Parameters	
Mean, μ	0.8
Std Dev, σ	0.2
minimum	0
maximum	1

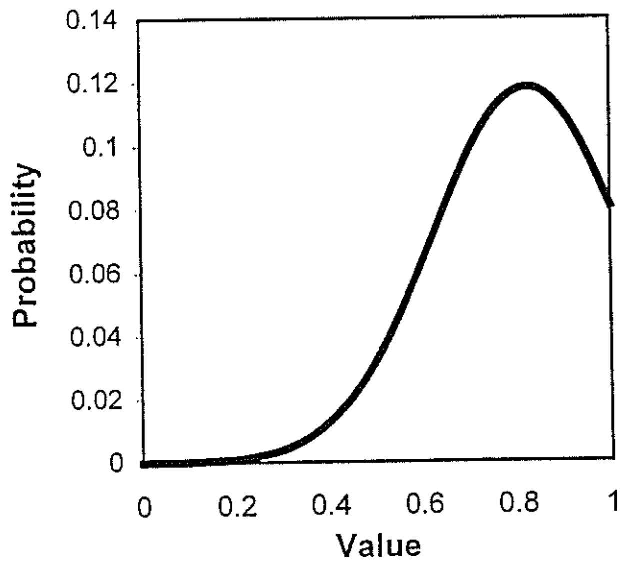
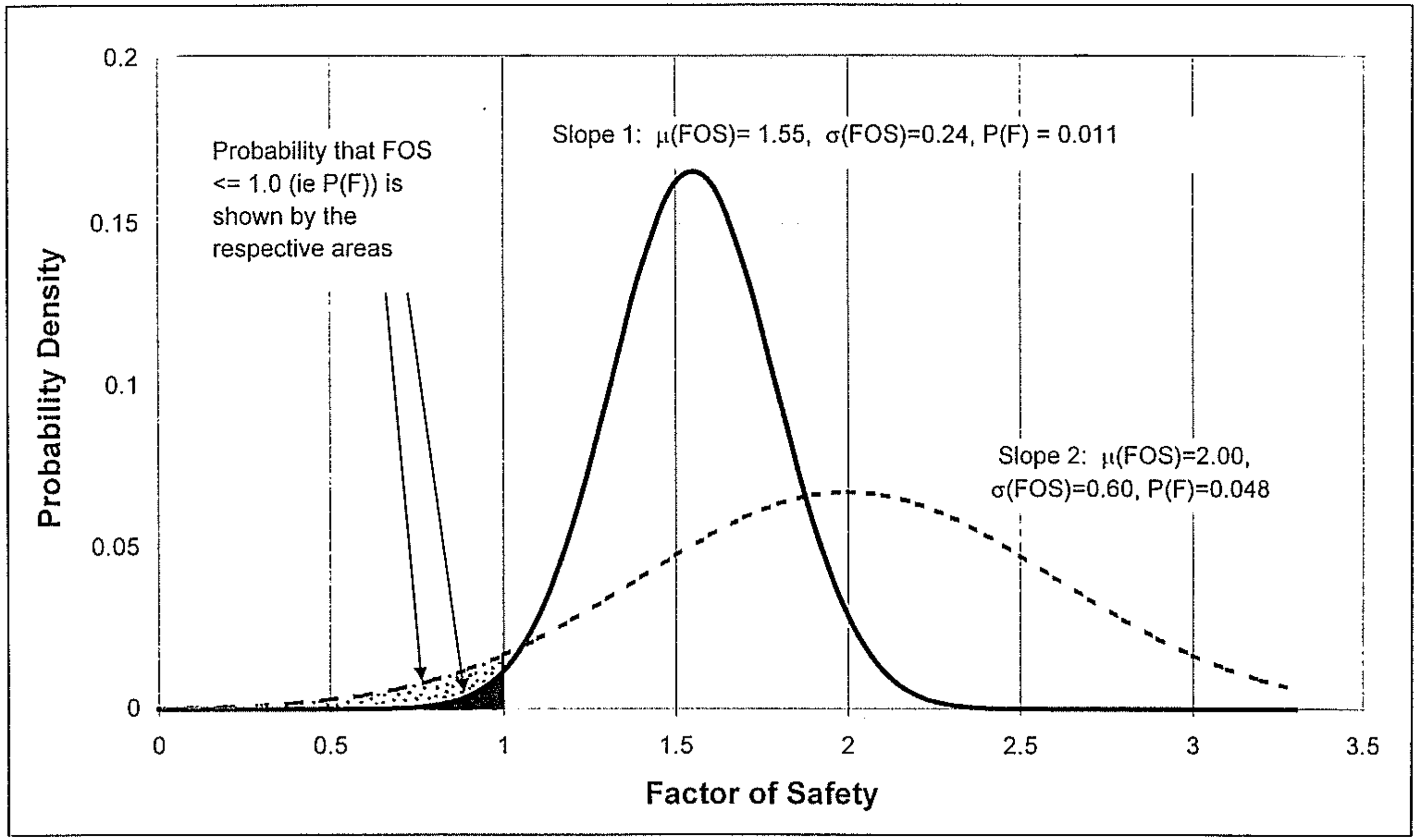


Figure 3.3 Relationship between Factor of Safety and probability of failure for two hypothetical cut slopes.



It is therefore critical to clearly define the elements at risk to be considered in the analysis. The analysis rapidly becomes complicated if too many elements are considered. It is therefore necessary to simplify and combine the elements at risk where possible.

3.3.3 Consequences

The consequences of slope failure for each element at risk must also be clearly defined. For example a rockfall impacting a moving vehicle may result in a range of consequences, as follows:

- minor damage to vehicle
- serious injury accident
- fatal accident
- multiple fatal accident
- litigation.

A clear statement of the consequences under consideration is also necessary to allow the cost of the consequence to be estimated. This is required later for the economic analysis.

3.3.4 Risk Calculation

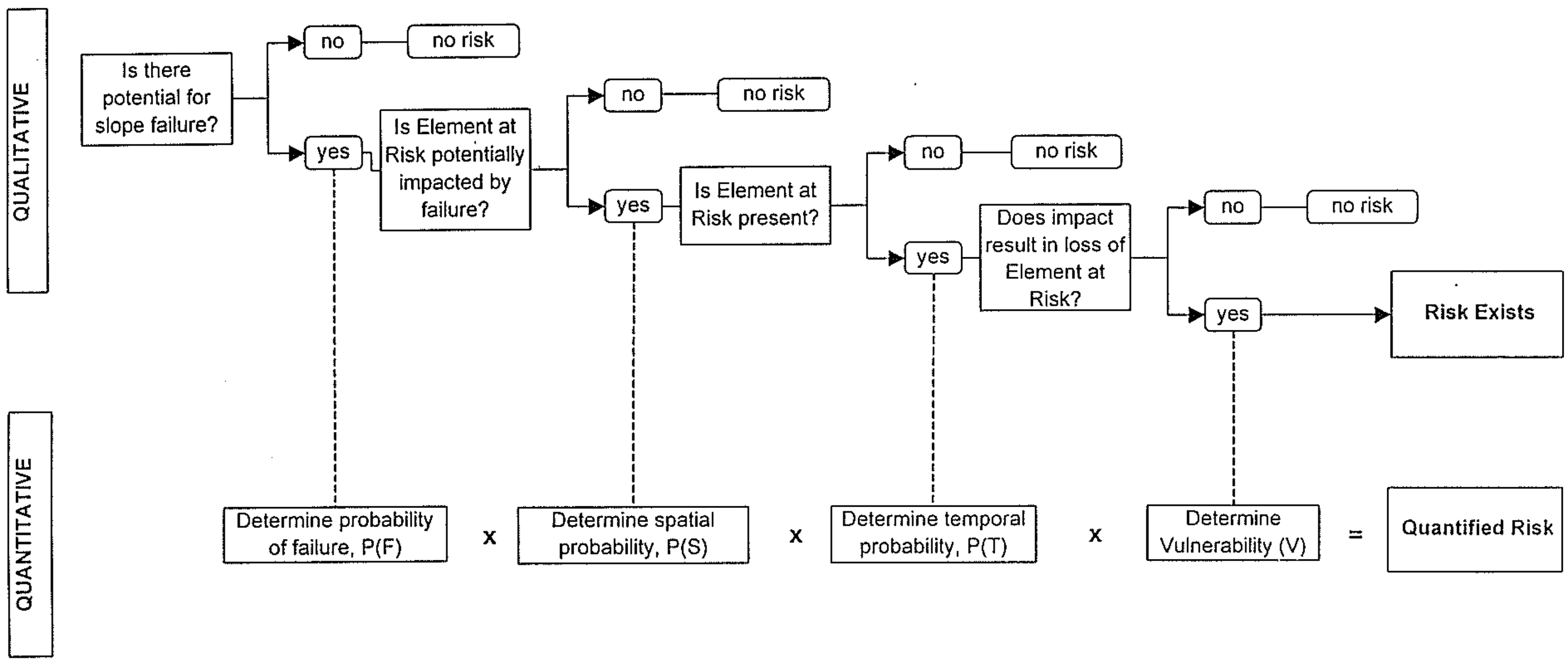
The next step in the analysis is to determine a series of conditional probabilities that together define the probability of the consequence occurring *given that failure has occurred*. This must be done for each individual risk defined above.

These *conditional probabilities* are described below and illustrated by the simple example of a *vehicle* being *totally destroyed by a rockfall*. Each conditional probability is treated as a triangular probability distribution (i.e. minimum, most likely, and maximum value) to accommodate uncertainty. The interaction between the probability of failure, P(F), and the various conditional probabilities that make up risk is demonstrated in an event tree diagram (Figure 3.4).

- **Spatial Probability**, P(S) – the probability that a slope failure will affect the element at risk in space, *given that failure has occurred*. For example, not all rocks falling within the study area will impact a particular vehicle-sized area of the carriageway. Estimating the spatial probability requires an understanding of the likely magnitude, velocity, travel distance and trajectory of each failure mode. A number of studies have derived empirical relationships for some or all of these parameters for specific failure modes.

  Hungr et al. (1998) developed a methodology for estimating travel distances for natural slope failures in Hong Kong. Azzoni et al. (1995) developed computer software for predicting trajectory and travel distances for rockfall. Such methods may be used to determine the areas more likely to be affected by a particular failure and hence the spatial probability. They are also useful in quantifying the effectiveness of remedial options by comparing "before" and "after" simulations.

Figure 3.4 Event tree illustrating risk assessment philosophy.



However in many cases, the best approach will be based on site-specific engineering geological mapping and historical records. Techniques such as air photo analysis and terrain evaluation can also be used to zone a study area on the basis of spatial probability.

If data are sparse or a quick preliminary assessment is required, slope failures may be assumed (simplistically) to be uniformly distributed in space within the potential impact zone (e.g. Bunce et al. 1997). P(S) may then be defined as the average area affected by a single failure divided by the total area of the potential impact zone.

- **Temporal Probability**, P(T) – the probability that a slope failure will impact the element at risk in time, *given that failure and spatial coincidence have occurred.*

  For example, a car will not always be present even if a rockfall does impact upon a particular vehicle-sized section of carriageway. (Note: P(T) for non-mobile elements at risk, permanently located within the affected area, is 1.0.) In most cases the temporal probability is readily determined from a knowledge of the typical behaviour of the element at risk. For example the temporal probability of a vehicle being present on a particular section of highway may be readily determined from traffic volume statistics.

- **Vulnerability**, V – the probability that the consequence to the element at risk is fully realised if impact occurs. For example, the car may escape total destruction even if actually impacted by a rockfall. Vulnerability may be estimated intuitively or be based on studies of similar past events. Findlay et al. (1999) proposed a series of vulnerability guidelines for persons in a number of "at risk" situations. Other guidelines are provided in Riddolls & Grocott Ltd (1999b).

The product of the probability of failure, P(F), and the three conditional probabilities, P(S), P(T), and V, gives the overall probability that the consequence will occur, i.e. the quantified **risk**:

$$\textbf{Risk} = \textbf{P(F)} \times \textbf{P(S)} \times \textbf{P(T)} \times \textbf{V} \qquad \text{(Formula 1)}$$

As with failure probability P(F), values for P(S), P(T) and V will often be based on judgement and a consideration of accident and maintenance records for the site. Published data available for other sites may also be relevant. In some cases it may be difficult to separate out the component probabilities of risk. For example, if records indicate "3 accidents occurred as a result of rockfall over 7 years", the annual "observed" risk of an accident is 3/7 = 0.43. Deriving the component conditional probabilities that make up this risk is difficult. In such cases approximate values for P(F), P(S), P(T), and V may be estimated as long as their product is equal to the observed risk.

3.3.5 Costs of Consequences

Each individual risk is then multiplied by the cost of the consequence. For example if the annual risk of destruction of a vehicle by rockfall is 0.001, and the average cost of a vehicle is, for argument's sake, \$30,000 (ignoring injury to any occupants), the annual expected cost of the consequence is:

$$0.001 \times \$30{,}000 = \$300$$

Costs of consequences are input as a triangular probability distribution (i.e. minimum, most likely, and maximum costs) to accommodate uncertainty.

The cost of consequence for each individual risk is calculated and the costs are summed to give an total annual expected cost of consequences. This annual cost is discounted over 25 years at a discount rate of 0.1 (or 10% per annum) to obtain a Net Present Value (NPV) of the cost of consequences over this period (Transfund 1997).

3.4 Determining Future Risk

3.4.1 Definition of the "Do Minimum" Maintenance Programme

The analysis outlined above represents the **existing** situation at the site. The next step is to define a realistic future "do minimum" programme against which the various maintenance programmes may be assessed. In many cases the "do minimum" programme will be a continuation of the existing situation. Even if this is the case, some modification of the existing situation may be required to account for expected changes in traffic volumes over the period of interest.

In cases where the existing situation is not a viable "do minimum" programme (for example if one or more of the individual risks is socially unacceptable), an alternative "do minimum" programme must be defined. This will generally be the lowest cost maintenance programme commensurate with maintaining an adequate level of service at an acceptable level of risk (Transfund 1997: pp. 2-5).

3.4.2 Alternative Maintenance Programmes and Costs

At this stage a range of maintenance programmes for the site must be formulated. Maintenance programmes may comprise one or more remedial actions. Rough order costings are prepared for each programme incorporating both initial implementation costs and ongoing maintenance costs. The costs are expressed in terms of Net Present Value over a fixed period (Transfund uses 25 years) to allow direct comparison between programmes. Procedures for calculating NPVs are fully described in Transfund (1997: pp. 5-24, 25).

Implementation costs for each programme are treated as triangular probability distributions (i.e. minimum, most likely, and maximum value) to accommodate uncertainty.

3.4.3 Effectiveness of Maintenance Programmes

The effectiveness of each programme in reducing each of the component probabilities in the risk calculation (i.e. P(F), P(S), P(T), and V) must also be estimated for each programme.

Different remedial actions will affect different components of risk. An understanding of how a remedial action will mitigate risk is fundamental to the approach advocated in this report. This concept is illustrated in Table 3.1.

Table 3.1 Examples of effectiveness of remedial actions in reducing the component probabilities of risk.

Remedial Actions	Components of Risk Reduced				Explanation
	P(F)	P(S)	P(T)	V	
Rock bolting, shotcrete, scaling, retaining wall	YES	NO	NO	NO	These actions lessen the risk by reducing the probability of a rockfall occurring in the first place.
Rock sheds, catch fence, collection ditches	NO	YES	NO	NO	These actions lessen the risk by reducing the *size* of the area potentially impacted by rockfall.
Warning signs, stopping restrictions, vehicle class restrictions	NO	NO	YES	NO	These actions lessen the risk by reducing the amount of *time* an element at risk is present within the area potentially impacted by rockfall.
	Note: reduction of vulnerability effectively requires the modification of the element at risk itself. This is not generally practical in the highway context but maybe applicable in other geotechnical situations.				

Effectiveness is expressed as a decimal value between 0 and 1.0, with 0 indicating that the maintenance programme has no effect at all, and 1.0 indicating complete effectiveness. Effectiveness values will largely be based on judgement and experience at similar sites.

Following the recommendation of Roberds (1991), effectiveness is expressed in terms of a truncated normal probability distribution (see Figure 3.2). This distribution requires only a mean value and standard deviation to be entered, and is truncated at 0 and 1 (i.e. the lower and upper limits of effectiveness). Roberds recommends a standard deviation value of 0.2. It should be noted that the expected value of this distribution is not necessarily the mean value. The selection of this type of distribution over the triangular distribution used elsewhere in the analysis reflects the greater uncertainty likely to be associated with estimating effectiveness.

3.4.4 Calculation of Mitigated Risk

The *mitigated* individual risks (i.e. the reduced risks following implementation of each maintenance programme), and therefore the *mitigated* expected cost of consequences, may then be determined for each maintenance programme taking into account the effectiveness of the maintenance programme. The mitigated risk may be expressed as follows:

Mitigated Risk = (Ef x P(F)) x (Es x P(S)) x (Et x P(T)) x (Ev x V)

where:

Ef = Effectiveness of programme in reducing probability of failure
Es = Effectiveness of programme in reducing spatial probability
Et = Effectiveness of programme in reducing temporal probability
Ev = Effectiveness of programme in reducing vulnerability of element at risk

3.5 Selection of Optimum Maintenance Programme

3.5.1 Economic Evaluation

The outputs of the risk assessment are the expected costs of consequences for each maintenance programme and the expected cost of implementing each programme. Both are expressed as NPVs based on a 25-year period using a discount rate of 0.1. If Monte Carlo simulation is used the outputs are represented as probability distributions rather than expected values.

Various economic indices may be readily calculated from this data and used as a basis for selecting the "optimum" programme. This analysis calculates the overall NPV and B/C ratio for each programme (Australian Department of Finance 1997a,b). Further economic analysis following the procedures described in Transfund (1997) may be carried out separately using the results of the analysis.

3.5.1.1 Net present value (NPV)

The NPV of each maintenance programme is defined as the NPV of the expected cost of consequences plus the NPV of implementation costs (this is analogous to the "Total Equivalent Cost" referred to in Riddolls & Grocott Ltd 1999a). The programme with the lowest NPV represents the lowest overall cost programme. If Monte Carlo simulation is used, the NPVs for each maintenance programme will be expressed as probability distributions. From consideration of the probability distributions it is possible to determine uncertainty (and the level of confidence) associated with a particular option being the cheapest. An example of this calculation is discussed in Section 4.4.

The NPV is usually a preferred selection criteria because of its simplicity, reliability and intuitive appeal (Australian Dept of Finance 1997a).

3.5.1.2 Benefit/cost (B/C) ratio

The B/C ratio is defined as the ratio of present value benefits to present value costs compared with the "do minimum" programme. The benefits of each maintenance programme are the reduction in the expected cost of consequences relative to the "do minimum" programme. Costs are the implementation and maintenance costs of the programme over and above the costs of the "do minimum" programme. As with NPV, the B/C ratios for each maintenance programme will be expressed as probability distributions if Monte Carlo simulation is carried out, allowing the level of uncertainty to be quantified (see Section 4.4).

B/C ratios provide a ready means of comparing different maintenance programmes. They may however be unreliable if comparing programmes of different size and scope. A simple example of the difference between NPV and B/C ratio selection rules is presented as follows.

Consider two alternative maintenance programmes (A and B) compared with a "do minimum" programme.

Programme	Cost of Consequences	Cost of Implementation	NPV	B/C
"Do minimum"	$5,000	$0	$5,000	1
Programme A	$2,000	$1,000	$3,000	3
Programme B	$4,000	$250	$4,250	4

Programme A has the lower NPV while Programme B has the highest B/C ratio. Programme A represents the most comprehensive resolution of the problem, whereas B represents the best value for each dollar spent.

3.5.2 Acceptability of Risk

The final stage in selecting the optimum maintenance programme is a check that the mitigated risks associated with the favoured programme are "acceptable" (i.e. socially, commercially, and politically). Risk acceptability guidelines are both subjective and contentious. There are no universally established guidelines for slope instability risk, nor is consensus likely in the near future. Guidance on some existing risk acceptability criteria is given in Riddolls & Grocott Ltd (1999b).

It is the responsibility of roading authorities to demonstrate a reasonable and defensible "duty of care" by ensuring that the risks posed to road users by a particular maintenance programme are commensurate with "accepted levels of risk". If the favoured maintenance programme falls outside the risk envelope that is deemed "acceptable", it must be rejected in favour of a less risky alternative, and the increased cost is to be born.

The analysis summarises all of the individual risks for each of the maintenance programmes in a single table. In this form they are readily compared with any risk acceptability threshold values to ensure compliance. It may be necessary to sum several individual risks to derive the total risk to a particular element at risk. A certain amount of judgement is required at this stage.

3.5.3 Sensitivity Analysis

Some analysis inputs will have a greater influence on the outcome than will others. Sensitivity analysis investigates the degree to which uncertainty associated with each input can change the outcome. This may be carried out by manually repeating the analysis varying one input while holding all others constant. In this way those inputs which have the most effect on the outcome may be identified. If the uncertainty can be reduced by further investigation, the analysis accuracy will be improved.

4. IMPLEMENTATION GUIDELINES

4.1 Workbook Layout

A Microsoft Excel workbook has been developed to carry out the risk assessment and economic evaluation described in this report. The workbook comprises a number of worksheets, described below.

4.1.1 Header Worksheet

This worksheet is used to define the objectives of the analysis and to identify the failure modes, elements at risk and consequences under consideration. These define a series of individual risks, which are analysed separately in Worksheets RA1 to RA12 (i.e. up to 12 individual risks may be considered). The various maintenance programmes are also entered on the header sheet. The header represents a statement of the analysis inputs, scope, and objectives.

4.1.2 Individual Risk Assessment Worksheets RA1 to RA12

Each of these worksheets is identical, and is used for calculating each of the individual risks defined in the header sheet. Values of P(F), P(T), P(S), and V are entered on these sheets, together with the expected cost in the event that the consequence occurs. The effectiveness of each maintenance programme is also entered on each sheet allowing the mitigated risks to be calculated. The output is the individual risk expressed as a probability of occurrence, and the expected annual cost of the consequence for the existing situation and for each maintenance programme.

4.1.3 Economic Analysis Worksheet

The NPV implementation costs for each maintenance programme are entered on the *Economic Analysis* worksheet. The costs of all consequences are automatically summed for each maintenance programme, discounted to NPV, and are also presented on this sheet. From this information the NPV and B/C ratio are calculated for each programme and presented for direct comparison. Selection of the optimum maintenance programme may be made on the basis of either of these indices.

4.1.4 Risk Summary Worksheet

All of the individual risks calculated in worksheets RA1 to RA12 are tabulated for each maintenance programme on the *Risk Summary* worksheet. This allows comparison of each risk with any risk acceptability criteria adopted for the particular analysis. This allows the selected optimum maintenance programme to be checked to ensure the associated risks are acceptable. If not, another maintenance programme must be selected.

Risk acceptability threshold values are input in the right hand column of the worksheet. They may then be compared manually to the individual risks on the same row. If a colour screen or printer is used, the individual risks for each programme are automatically highlighted in red if they exceed the threshold, and green if they do not. Individual risks may be summed, in which case they must be compared with risk threshold manually.

4.2 Functioning of the Worksheet

The analysis workbook is written for Excel '97, and its use requires @RISK version 3.5e add-in. Its use requires a working knowledge of both packages. There are a number of links between individual worksheets to allow data to be automatically carried forward. This minimises the need to input duplicate data. Those inputs, which are carried forward to later worksheets, are highlighted in grey.

It is important not to edit greyed cells by "drag and drop" as this will effect later worksheets, which refer to these values.

Each of the RA worksheets contains a number of hidden columns in which additional calculations are made. Care should be taken to ensure these are not inadvertently deleted or otherwise compromised.

Any RA worksheets not required should be left blank, and need not be printed. They should not be deleted.

The worksheets are protected to allow only those cells requiring entries to be modified.

Hidden comments are included within selected cells to provide a fuller description of the cell's function.

4.3 Instructions for Use of Worksheet

A step by step guide to the use of the worksheets is presented below. These instructions should be read in conjunction with the worked examples in both Appendices 1 and 2, and an open copy of the Workbook file on the user's computer.

1. Enter project details and objective on header sheet.

2. Enter failure modes, elements at risk, and consequences on header sheet.

3. Use the above (from Step 2) to define and enter a series of individual risks (up to 12) for analysis. Enter these under "contents" on the header sheet (cells E38-E49, G38-G49, I38-I49).

4. Enter maintenance programmes (up to 6) on header sheet (cells C28-C33).

A description of each individual risk will appear at the top of each risk assessment worksheet (RA1-RA12).

5. On each individual risk assessment sheet, enter:

- Minimum (MIN), most likely (ML), and maximum (MAX) cost of consequence (cells E13, F13, and G13).

- Minimum, most likely, and maximum annual probability of failure (P(F)) (cells E15, F15, and G15).

- Minimum, most likely, and maximum temporal probability (P(T)) of consequence given failure (cells E16, F16, and G16).

- Minimum, most likely, and maximum spatial probability (P(S)) of consequence given failure (cells E17, F17, and G17).

- Minimum, most likely, and maximum vulnerability (V) of element at risk given impact (cells E18, F18, and G18).

- Enter effectiveness of maintenance programme in reducing P(F), P(T), P(S), and V (0 = no effect, 1 = completely effective) (cells J15-Y15, J16-Y16, J17-Y17, J18-Y18).

6. Enter minimum, most likely, and maximum implementation costs for each maintenance programme (expressed as NPV) on the economic analysis sheet (cells H9 – N11).

7. If Monte Carlo simulation is required it should be carried out at this point. The probability distributions of NPV and B/C ratio may then be determined for each maintenance option using @RISK. This requires a working knowledge of @RISK and is not automatically calculated by the worksheets themselves. @RISK also has tools available to carry out sensitivity analysis. Alternatively, the expected values presented at the bottom of the Economic Analysis Worksheet may be used.

8. Select optimum maintenance programme based on either NPV or B/C ratio.

9. Enter any risk acceptability thresholds on the risk summary sheet (cells K12-K23). The programme will highlight any individual risks which are higher than the thresholds entered. Note it may be necessary to sum several individual risks to derive the total risk to an element at risk. This should be done manually.

10. Assuming the programme identified and selected in step 8 above does not exceed any risk acceptability criteria, this programme should be recommended for implementation.

4.4 Worked Examples

Two worked examples are included in Appendices 1 and 2. These provide an illustration of the use of the worksheets as well as a verification of the calculations.

4.4.1 Example 1

State Highway 73, Christchurch to Arthur's Pass, Paddy's Bend, Site 4

This example replicates the analysis carried out for Part 1 of this study (Riddolls & Grocott Ltd 1999a), using the simplified worksheets presented above. This study calculated the "cost" of four classes of accident to a vehicle and occupants, as well as the risk of detritus removal and loss of service to the highway network.

The site has been affected by ongoing rock fall since the early 1980s resulting in a number of non-injury accidents every year. The effectiveness of five alternative maintenance programmes (M1 - M6) was investigated and compared to a "do minimum" programme of regular detritus clearance (M0).

Full details of the site, and selection of input parameters are presented in Riddolls & Grocott Ltd (1999a).

Monte Carlo simulation was employed in calculating the B/C ratios and NPV for each maintenance programme in this example. The resulting actual distributions of B/C and NPV are presented as Figures 4.1a and 4.2a respectively. Although these distributions are somewhat ragged, a sufficient number of iterations have been carried out for the general form of each to be clear. Further iterations would result in smoothing of the curves. If normal distributions are assumed, idealised distributions based on the mean and standard deviations calculated by @RISK may be plotted (Figures 4.1b and 4.2b).

Figure 4.1 indicates Maintenance Programme M2 to have the highest B/C ratio in almost all cases, even allowing for uncertainty. The very small overlap in the distributions for programme M2, and the next favoured programme, M3, equates to a 99.9% confidence that M2 will have the highest B/C ratio.

However, Figure 4.2 shows the distribution of NPV for M2 to have a large overlap with the corresponding distributions for M3 and M4. This equates to only a 61.8 % confidence that M2 will have a lower NPV than M3 and a 76.8 % confidence that it will be cheaper than M4.

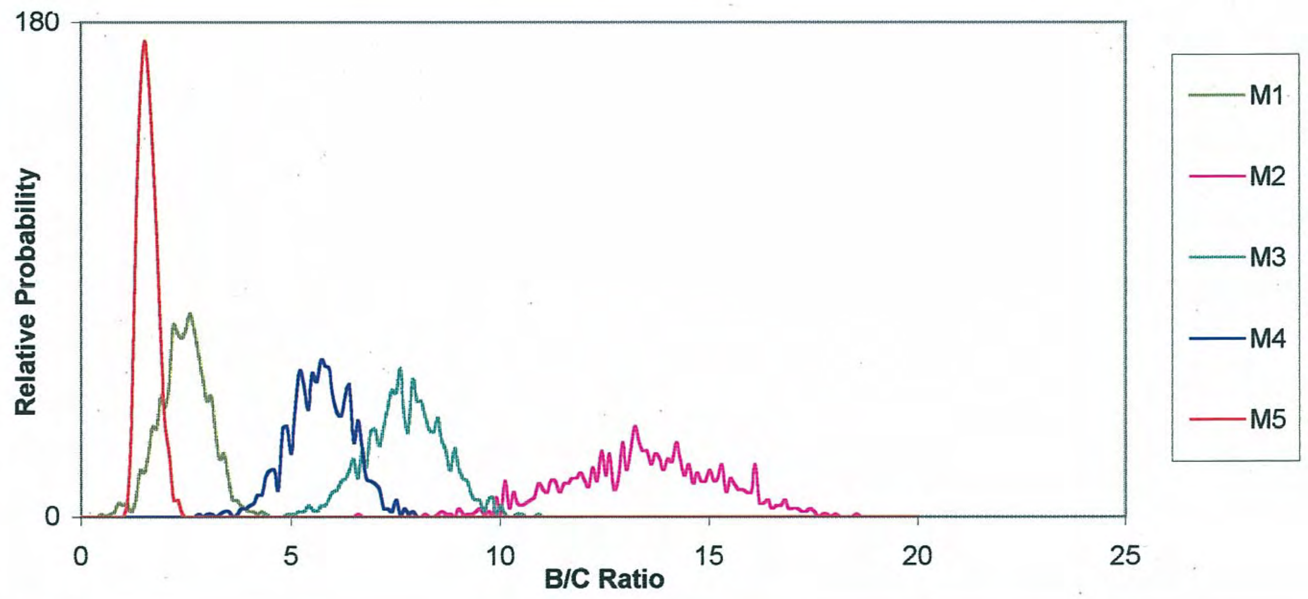
This example illustrates the additional information that can be gained from consideration of the uncertainty involved in risk assessment, as opposed to using only the single expected values. The difference is illustrated in the following statements:

The conclusion of analysis using expected values only is:
"Maintenance programme M2 has the lowest NPV and the highest B/C ratio".

The conclusion of analysis using Monte Carlo simulation to model uncertainty is:
"Maintenance programme M2 has a 62% probability of being cheaper than M3 and a 77% probability of being cheaper than M4. M2 has a 99.9 % probability of having the highest B/C ratio".

Figure 4.1 Calculation of B/C ratio by Monte Carlo simulation for Site 4, SH73, Paddy's Bend, near Arthur's Pass, New Zealand.

a. Actual distribution of B/C ratios for each maintenance programme after Monte Carlo simulation (1000 iterations).



b. B/C ratios for each maintenance programme approximated to normal distributions.

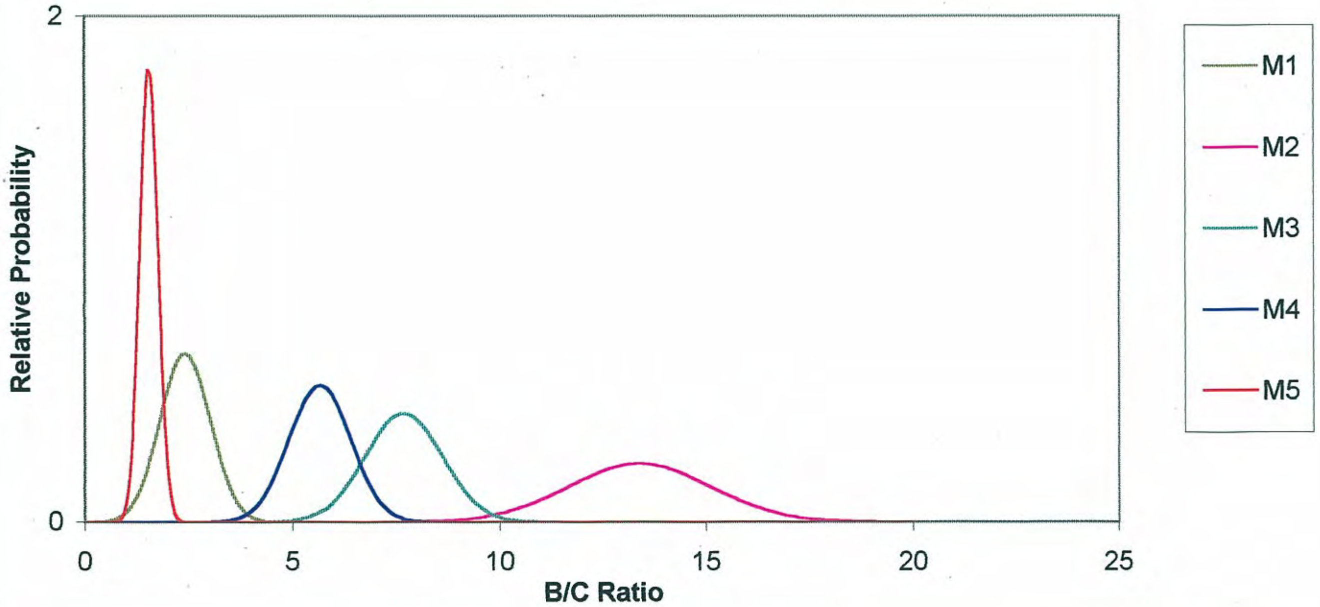
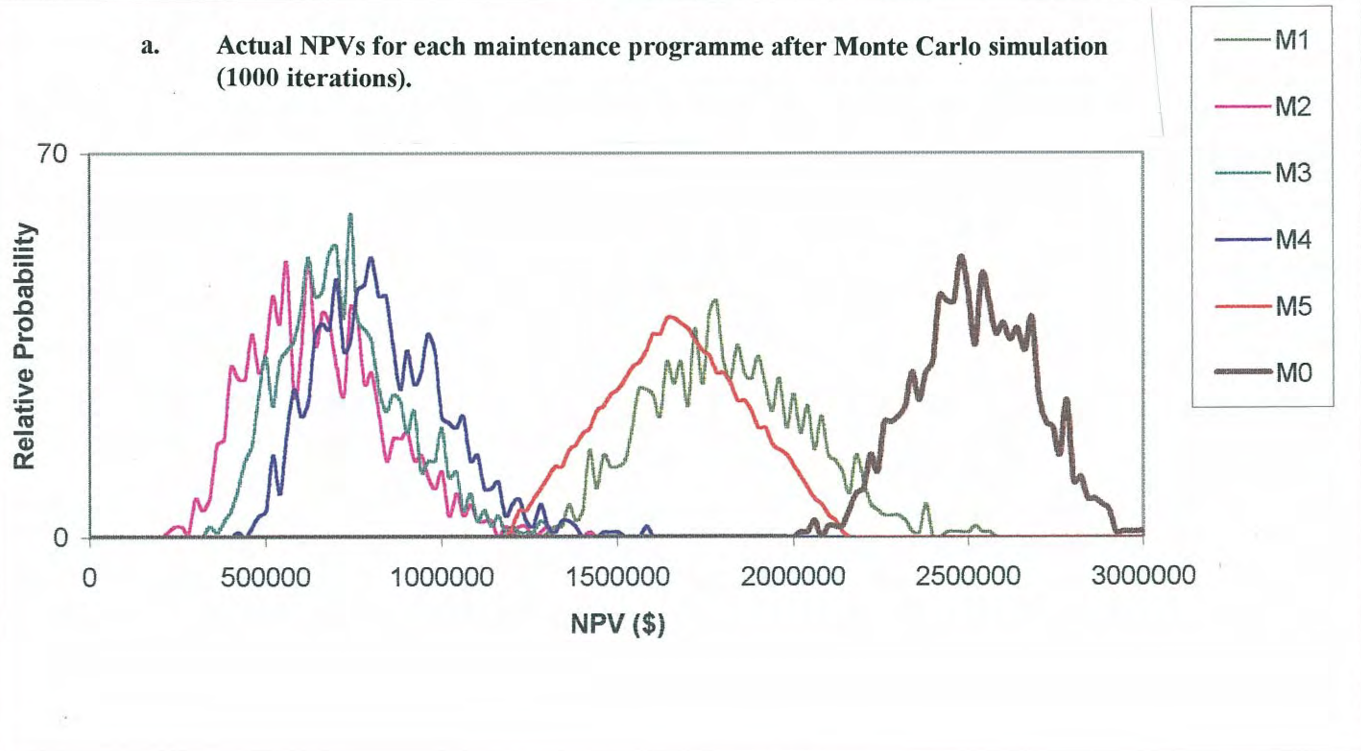
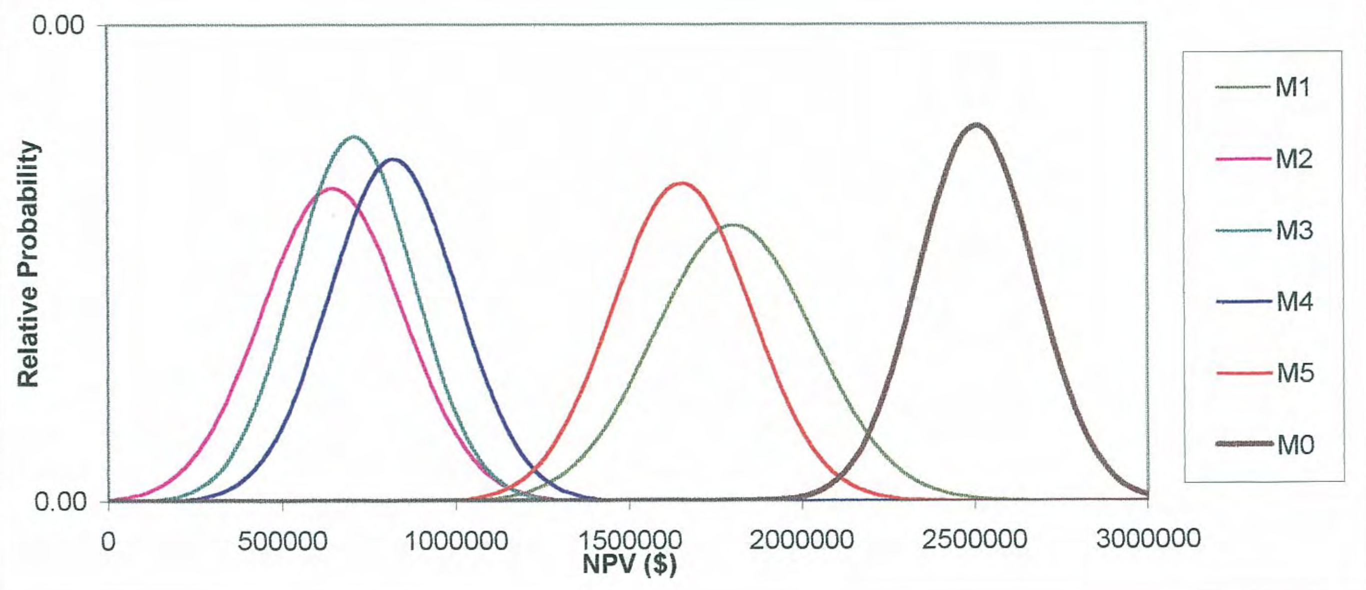


Figure 4.2 Calculation of NPV by Monte Carlo simulation for Site 4, SH73, Paddy's Bend, Arthur's Pass, New Zealand.

a. Actual NPVs for each maintenance programme after Monte Carlo simulation (1000 iterations).



b. NPVs for each maintenance programme approximated to normal distributions.



4.4.2 Example 2. Argillite Cut, British Columbia, Canada

This example replicates an analysis carried out by Bunce et al. (1997) of the hazard posed by rockfall at the site of a rockfall fatality in British Columbia, Canada. It is included in Appendix 2 to provide verification of the worksheets using an independent case study.

The study calculated the risk of three consequences of rockfall to two elements at risk requiring six RA worksheets. No potential maintenance programmes or cost of consequences were investigated. Neither has uncertainty been considered in this example, although the original analysis was reworked for three different estimates of failure probability, P(F). The calculation presented in Appendix 2 assumes a P(F), or failure frequency, of 2.2 rockfalls per year.

The study objective was to determine the risk faced by motorists using the particular section of highway. Bunce et al. (1997) calculate the risk in a slightly different way to Roberds (1991) as follows.

Roberds (1991) (and the study presented in this report) used the formula:

$$\textbf{Risk} = \textbf{P(F)} \times \textbf{P(T)} \times \textbf{P(S)} \times \textbf{V} \qquad \text{(Formula 1)}$$

Bunce et al. (1997) used this formula:

$$\textbf{Risk} = \textbf{P(T)} \times (1 - (1 - \textbf{P(S)})^{P(F)}) \times \textbf{V} \qquad \text{(Formula 2)}$$

Formula 2 represents a more refined approach based on the binomial probability theorem (Benjamin & Cornell 1970). It is however less suited to a generic approach as it requires a "failure frequency" greater than 1 per year.

Table 4.1 Risk calculation by alternative formulae.
Worked example 2, Argillite Cut, British Columbia, Canada.

Failure Mode	Element at Risk	Consequence	Risk Formula(1)	Risk Formula(2)
Rockfall	Any vehicle	Rock hits stationary vehicle	9.78E-05	5.50E-05
Rockfall	Individual vehicle	Rock hits stationary vehicle	1.38E-06	1.37E-06
Rockfall	Any vehicle	Falling rock hits moving vehicle	2.86E-02	2.84E-02
Rockfall	Individual vehicle	Falling rock hits moving vehicle	1.63E-08	1.68E-08
Rockfall	Any vehicle	Vehicle hits fallen rock	6.82E-01	5.62E-01
Rockfall	Individual vehicle	Vehicle hits fallen rock	3.89E-07	3.18E-07

(1) Roberds 1991
(2) Bunce et al. 1997
Notation: E represents "ten to the power of", e.g. 9.78E-05 = 9.78×10^{-5}

Cell H20 of worksheets RA1- RA6 in Appendix 2 have been changed to formula (2) above for the worked example in that Appendix. The results are however similar for each method as illustrated in Table 4.2.

Expected value analysis only has been carried out for this example. Monte Carlo simulation could however be used to model uncertainty in the same manner as Worked Example 1.

5. APPLICABILITY AND LIMITATIONS OF PROCEDURE

- The analysis method presented in this report assumes all probabilities remain constant in each year of the time period considered. As such it is best suited to situations where the annual probability of slope failure is high, and no major changes in site conditions are expected over the analysis period. Examples would be sections of highway repeatedly closed or otherwise affected by ongoing slope failures in an average year.

- The method is less applicable to situations where the probability of failure increases with time. An example could be progressive undercutting of a slope by a river. This situation requires the probability of failure to be increased for each year of the period under consideration.

- The method is also less suited to "random" low probability/high consequence events such as major earthquakes, extreme floods, etc. In these cases consideration of the likely timing of the event become significant, and an alternative approach is required. An example of an analysis method possibly more suited to this situation is given in Transfund (1997).

- Probabilistic analysis is an attempt to model a real situation, which is infinitely complex. As such it will never be 100% successful. It is intended as a guide to understanding of the concepts of risk assessment as well as a tool to aid sound decision-making and informed management of slope instability risk.

- The generic approach to slope stability assessment proposed in this report will not be suitable for all situations. Neither is it intended as a substitute for a full understanding of the analysis concepts.

- No analysis should even be contemplated without a full comprehension of the engineering geology of the locality. The geological controls and failure mechanisms must be understood before meaningful analysis inputs can be selected.

6. REFERENCES

Australian Department of Finance. 1997a. *Handbook of Cost Benefit Analysis.* Australian Government Publishing Service, 139 pp.

Australian Department of Finance. 1997b. *Introduction to Cost Benefit Analysis for Programme Managers.* Australian Government Publishing Service, 29 pp.

Azzoni A., Barbera, G.L., Zaninetti, A. 1995. Analysis and prediction of rockfalls using a mathematical model. *International Journal of Rock Mechanics and Mineral Science 32(8):* 709-724.

Benjamin, J.R., Cornell, C.A. 1970. *Probability, Statistics and Decision for Engineers.* McGraw-Hill, New York.

Bunce, C.M., Cruden, D.M., Morgenstern, N.R. 1997. Assessment of the hazard from rock fall on a highway. *Canadian Geotechnical Journal 34:* 344 - 356.

Findlay, P.J., Mostyn, G.R., Fell, R. 1999. Landslides: prediction of travel distances and guidelines for vulnerability of persons. *Proceedings 8th Australia New Zealand Conference on Geomechanics, Hobart, 1:* 105-114.

Hungr, O., Yau, H.W., Tse, C.M., Chueng, L.F. 1998. Natural slope hazard and risk assessment framework. *International Conference of Urban Ground Engineering,* Institute of Civil Engineers, Hong Kong.

Pine, R.J. 1992. Risk analysis design applications in mining geotechnics. *Transactions of the Institute of Mining and Metallurgy 102:* A149-A158.

Riddolls & Grocott Ltd. 1999a. Risk assessment techniques for optimising slope-failure preventive maintenance programmes. *Transfund New Zealand Research Report No. 134.* 178pp.

Riddolls & Grocott Ltd. 1999b. Quantitative assessment methods for determining slope stability risk in the Building Industry. *Building Research Association of New Zealand Study Report 83.*

Roberds, W.J. 1991. Methodology for optimising rock slope preventive maintenance programs. In *Proceedings, Geotechnical Engineering Congress, American Society of Civil Engineers, New York, 1:* 634 - 645.

Transfund New Zealand (Transfund). 1997. Project Evaluation Manual. First revision, May 1997, +subsequent revisions. Transfund New Zealand, Wellington, New Zealand.

APPENDIX 1

WORKED EXAMPLE 1

Project Title:	SH73, Christchurch to Arthur's Pass, Paddy's Bend	
Analyst:	Riddolls & Grocott Ltd	
Date:	01-Jan-99	

Riddolls & Grocott Ltd

transfund NEW ZEALAND

Standard Deviation for Effectiveness 0.2

Objective

Slope instability at Paddys Bend, has affected State Highway 73 between Christchurch and Authurs Pass for over 20 years.The objective of this analysis is to determine the relative economic benefits of a range of remedial options. This analysis is presented in full in Part 1 report for this study. It is reworked below using the simplified worksheets developed during Part 2 of the study.

Failure Modes Investigated

Rockfall

Elements at Risk	Consequences
Vehicle and Occupants	Fatal Accident
Vehicle and Occupants	Serious Accident
Vehicle and Occupants	Injury Accident
Vehicle and Occupants	Minor Accident
All Road Users	Detritus Clearance
All Road Users	Service Disruption

Remedial Programmes

1. Monitoring/Warning System
2. Toe Gabion Wall, Minor Realignment
3. Scaling, Bolting and Wire Mesh
4. Rock Catch Fence
5. Rock Shed
6. Not Used

Contents

Header Sheet						
RA1	Risk of	Detritus Clearance (yr)	to	All Road Users	due to	Rockfall
RA2	Risk of	Service Disruption(1hr)	to	All Road Users	due to	Rockfall
RA3	Risk of	Fatal Accident	to	Vehicle + Occupants	due to	Rockfall
RA4	Risk of	Serious Accident	to	Vehicle + Occupants	due to	Rockfall
RA5	Risk of	Minor Accident	to	Vehicle + Occupants	due to	Rockfall
RA6	Risk of	Non-injury Accident	to	Vehicle + Occupants	due to	Rockfall
RA7	Risk of		to		due to	
RA8	Risk of		to		due to	
RA9	Risk of		to		due to	
RA10	Risk of		to		due to	
RA11	Risk of		to		due to	
RA12	Risk of		to		due to	
Economic Analysis						
Risk Summary						

Project Title: SH73, Christchurch to Arthur's Pass, Paddy's Bend

		Existing Situation				Effectiveness of Remedial Programmes					
Risk of:	*(Consequence)*	Detritus Clearance (yr)				Monitoring/Warning System	Toe Gabion Wall, Minor Realignment	Scaling, Bolting and Wire Mesh	Rock Catch Fence	Rock Shed	Not Used
To:	*(Element at Risk)*	All Road Users									
Due to:	*(Failure Mode)*	Rockfall									
		Probability Distributions									
		Min	ML	Max	Exp. Value						
Cost of *Consequence* ($)		63895	63895	63895	63895						
Annual *Probability of Failure*, P(F)		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.96	0.00	0.00	
Temporal Probability that *Element at Risk* is present within the potential area of influence of the failure, P(T)		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Spatial Probability that *Element at Risk* and failure will coincide in space given that element is present and failure has occurred, P(S).		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Vulnerability to *Element at Risk* given that failure impinges on element, V.		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.90	0.00	0.95	1.00	
Annual ***Risk*** of *Consequence* occuring to *Element at Risk*, Risk = P(F) x P(T) x P(S) x V					1.00E+00	1.00E+00	2.02E-01	1.75E-01	1.79E-01	0.00E+00	
Expected *frequency of occurrence* of *Consequence* (years)					*1.00*	*1.00*	*4.96*	*5.72*	*5.59*	*0.00*	
Expected annual cost of *Consequence*					63895	63895	12883	11170	11435	0	

RA1

Project Title: SH73, Christchurch to Arthur's Pass, Paddy's Bend

		Existing Situation			
Risk of:	*(Consequence)*	Service Disruption(1hr)			
To:	*(Element at Risk)*	All Road Users			
Due to:	*(Failure Mode)*	Rockfall			

	Probability Distributions				Effectiveness of Remedial Programmes					
	Min	ML	Max	Exp. Value	Monitoring/Warning System	Toe Gabion Wall, Minor Realignment	Scaling, Bolting and Wire Mesh	Rock Catch Fence	Rock Shed	Not Used
Cost of *Consequence* ($)	3109	3109	3109	3109						
Annual *Probability of Failure*, P(F)	1.75E+03	2.63E+03	3.51E+03	2.63E+03	0.00	0.00	0.96	0.00	0.00	
Temporal Probability that *Element at Risk* is present within the potential area of influence of the failure, P(T)	1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Spatial Probability that *Element at Risk* and failure will coincide in space given that element is present and failure has occurred, P(S).	1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Vulnerability to *Element at Risk* given that failure impinges on element, V.	1.67E-03	1.67E-03	1.67E-03	1.67E-03	0.00	0.90	0.00	0.95	1.00	
Annual ***Risk*** of *Consequence* occuring to *Element at Risk*, Risk = P(F) x P(T) x P(S) x V				4.38E+00	4.38E+00	8.83E-01	7.66E-01	7.84E-01	0.00E+00	
Expected *frequency of occurrence* of *Consequence* (years)				*0.23*	*0.23*	*1.13*	*1.31*	*1.28*	*0.00*	
Expected annual cost of *Consequence*				13622	13622	2747	2381	2438	0	

RA2

Project Title: SH73, Christchurch to Arthur's Pass, Paddy's Bend

		Existing Situation				Effectiveness of Remedial Programmes					
Risk of:	*(Consequence)*	Fatal Accident									
To:	*(Element at Risk)*	Vehicle + Occupants									
Due to:	*(Failure Mode)*	Rockfall									
		Probability Distributions									
		Min	ML	Max	Exp. Value	Monitoring/Warning System	Toe Gabion Wall, Minor Realignment	Scaling, Bolting and Wire Mesh	Rock Catch Fence	Rock Shed	Not Used
Cost of *Consequence* ($)		2570000	2570000	2570000	2570000						
Annual *Probability of Failure*, P(F)		1.75E+03	2.63E+03	3.51E+03	2.63E+03	0.00	0.00	0.96	0.00	0.00	
Temporal Probability that *Element at Risk* is present within the potential area of influence of the failure, P(T)		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Spatial Probability that *Element at Risk* and failure will coincide in space given that element is present and failure has occurred, P(S).		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Vulnerability to *Element at Risk* given that failure impinges on element, V.		1.00E-05	1.00E-05	1.00E-05	1.00E-05	0.85	0.95	0.00	0.96	1.00	
Annual ***Risk*** of *Consequence* occuring to *Element at Risk*, Risk = P(F) x P(T) x P(S) x V					2.63E-02	5.98E-03	4.70E-03	4.59E-03	4.59E-03	0.00E+00	
Expected *frequency of occurrence* of *Consequence* (years)					*38.05*	*167.12*	*212.59*	*217.64*	*217.64*	*0.00*	
Expected annual cost of *Consequence*					67548	15378	12089	11808	11808	0	

RA3

Project Title: SH73, Christchurch to Arthur's Pass, Paddy's Bend

		Existing Situation				Effectiveness of Remedial Programmes					
Risk of:	*(Consequence)*	Serious Accident									
To:	*(Element at Risk)*	Vehicle + Occupants									
Due to:	*(Failure Mode)*	Rockfall									
		Probability Distributions									
		Min	ML	Max	Exp. Value	Monitoring/Warning System	Toe Gabion Wall, Minor Realignment	Scaling, Bolting and Wire Mesh	Rock Catch Fence	Rock Shed	Not Used
Cost of *Consequence* ($)		236000	236000	236000	236000						
Annual *Probability of Failure*, P(F)		1.75E+03	2.63E+03	3.51E+03	2.63E+03	0.00	0.00	0.96	0.00	0.00	
Temporal Probability that *Element at Risk* is present within the potential area of influence of the failure, P(T)		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Spatial Probability that *Element at Risk* and failure will coincide in space given that element is present and failure has occurred, P(S).		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Vulnerability to *Element at Risk* given that failure impinges on element, V.		1.80E-05	1.80E-05	1.80E-05	1.80E-05	0.75	0.95	0.00	0.96	1.00	
Annual ***Risk*** of *Consequence* occuring to *Element at Risk*, Risk = P(F) x P(T) x P(S) x V					4.73E-02	1.37E-02	8.47E-03	8.27E-03	8.27E-03	0.00E+00	
Expected *frequency of occurrence* of *Consequence* (years)					*21.14*	*72.74*	*118.11*	*120.91*	*120.91*	*0.00*	
Expected annual cost of *Consequence*					11165	3244	1998	1952	1952	0	

RA4

Project Title: SH73, Christchurch to Arthur's Pass, Paddy's Bend

		Existing Situation				Effectiveness of Remedial Programmes					
Risk of:	*(Consequence)*	Minor Accident									
To:	*(Element at Risk)*	Vehicle + Occupants									
Due to:	*(Failure Mode)*	Rockfall									
		Probability Distributions									
		Min	ML	Max	Exp. Value	Monitoring/Warning System	Toe Gabion Wall, Minor Realignment	Scaling, Bolting and Wire Mesh	Rock Catch Fence	Rock Shed	Not Used
Cost of *Consequence* ($)		21400	21400	21400	21400						
Annual *Probability of Failure*, P(F)		1.75E+03	2.63E+03	3.51E+03	2.63E+03	0.00	0.00	0.96	0.00	0.00	
Temporal Probability that *Element at Risk* is present within the potential area of influence of the failure, P(T)		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Spatial Probability that *Element at Risk* and failure will coincide in space given that element is present and failure has occurred, P(S).		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Vulnerability to *Element at Risk* given that failure impinges on element, V.		1.80E-04	1.80E-04	1.80E-04	1.80E-04	0.60	0.90	0.00	0.93	1.00	
Annual ***Risk*** of *Consequence* occuring to *Element at Risk*, Risk = P(F) x P(T) x P(S) x V					4.73E-01	1.94E-01	9.54E-02	8.27E-02	8.88E-02	0.00E+00	
Expected *frequency of occurrence* of *Consequence* (years)					*2.11*	*5.15*	*10.48*	*12.09*	*11.26*	*0.00*	
Expected annual cost of *Consequence*					10124	4152	2041	1770	1900	0	

RA5

Project Title: SH73, Christchurch to Arthur's Pass, Paddy's Bend

		Existing Situation				Effectiveness of Remedial Programmes					
Risk of:	*(Consequence)*	Non-injury Accident				Monitoring/Warning System	Toe Gabion Wall, Minor Realignment	Scaling, Bolting and Wire Mesh	Rock Catch Fence	Rock Shed	Not Used
To:	*(Element at Risk)*	Vehicle + Occupants									
Due to:	*(Failure Mode)*	Rockfall									
		Probability Distributions									
		Min	ML	Max	Exp. Value						
Cost of *Consequence* ($)		2400	2400	2400	2400						
Annual *Probability of Failure*, P(F)		1.75E+03	2.63E+03	3.51E+03	2.63E+03	0.00	0.00	0.96	0.00	0.00	
Temporal Probability that *Element at Risk* is present within the potential area of influence of the failure, P(T)		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Spatial Probability that *Element at Risk* and failure will coincide in space given that element is present and failure has occurred, P(S).		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Vulnerability to *Element at Risk* given that failure impinges on element, V.		2.00E-02	2.00E-02	2.00E-02	2.00E-02	0.60	0.90	0.00	0.93	1.00	
Annual ***Risk*** of *Consequence* occuring to *Element at Risk*, Risk = P(F) x P(T) x P(S) x V					5.26E+01	2.16E+01	1.06E+01	9.19E+00	9.86E+00	0.00E+00	
Expected *frequency of occurrence* of *Consequence* (years)					*0.02*	*0.05*	*0.09*	*0.11*	*0.10*	*0.00*	
Expected annual cost of *Consequence*					126160	51734	25437	22055	23673	0	

RA6

Project Title: SH73, Christchurch to Arthur's Pass. Faddy's Bend

Project Lifetime (years) 25

Discount Rate 0.10

USPWF, end year 1: 0.9538

USPWF, end final year: 9.5237

	Implementation Costs of Maintenance Programmes						
	Existing	Monitoring/Warning System	Toe Gabion Wall, Minor Realignment	Scaling, Bolting and Wire Mesh	Rock Catch Fence	Rock Shed	Not Used
min	0	426565	136412	246939	316870	1163962	
ml	0	495404	151359	269778	360240	1651154	
max	0	578830	165624	293947	416808	2141026	

Costs of Consequences

Individually Assessed Risks		Summary of Annual Costs of Consequences ($)						
1 Risk of Detritus Clearance (yr) to All Road Users due to Rockfall		63895	63895	12883	11170	11435	0	
2 Risk of Service Disruption(1hr) to All Road Users due to Rockfall		13622	13622	2747	2381	2438	0	
3 Risk of Fatal Accident to Vehicle + Occupants due to Rockfall		67548	15378	12089	11808	11808	0	
4 Risk of Serious Accident to Vehicle + Occupants due to Rockfall		11165	3244	1998	1952	1952	0	
5 Risk of Minor Accident to Vehicle + Occupants due to Rockfall		10124	4152	2041	1770	1900	0	
6 Risk of Non-injury Accident to Vehicle + Occupants due to Rockfall		126160	51734	25437	22055	23673	0	
7 Risk of to due to		0	0	0	0	0	0	
8 Risk of to due to		0	0	0	0	0	0	
9 Risk of to due to		0	0	0	0	0	0	
10 Risk of to due to		0	0	0	0	0	0	
11 Risk of to due to		0	0	0	0	0	0	
12 Risk of to due to		0	0	0	0	0	0	
Economic Analysis								
Total cost of all consequences considered	($)	292515	152025	57195	51136	53206	0	
Implementation Cost of Maintenance Programme	($)	0	500266	151132	270221	364639	1652047	
Net Present Value of consequences over project lifetime	($)	2506809	1302833	490156	438225	455968	0	
NPV expected savings due to Maintenance Programme	($)	-	703709	1865521	1798363	1686201	854761	
NPV Total Equivalent Cost of each Maintenance Programme	($)	2506809	1803099	641287	708446	820608	1652047	
Benefit Cost Ratio of each Maintenance Programme		1.00	2.41	13.34	7.66	5.62	1.52	
				Lowest NPV Highest B/C				

Project Title: SH73, Christchurch to Arthur's Pass, Paddy's Bend

Individually Assessed Risks	Existing Situation	Remedial Programmes / Mitigated Risks: Monitoring/Warning System	Toe Gabion Wall, Minor Realignment	Scaling, Bolting and Wire Mesh	Rock Catch Fence	Rock Shed	Not Used	Risk Acceptance Threshold
1 Risk of Detritus Clearance (yr) to All Road Users due to Rockfall	1.00E+00	1.00E+00	2.02E-01	1.75E-01	1.79E-01	0.00E+00		
2 Risk of Service Disruption(1hr) to All Road Users due to Rockfall	4.38E+00	4.38E+00	8.83E-01	7.66E-01	7.84E-01	0.00E+00		
3 Risk of Fatal Accident to Vehicle + Occupants due to Rockfall	2.63E-02	5.98E-03	4.70E-03	4.59E-03	4.59E-03	0.00E+00		
4 Risk of Serious Accident to Vehicle + Occupants due to Rockfall	4.73E-02	1.37E-02	8.47E-03	8.27E-03	8.27E-03	0.00E+00		
5 Risk of Minor Accident to Vehicle + Occupants due to Rockfall	4.73E-01	1.94E-01	9.54E-02	8.27E-02	8.88E-02	0.00E+00		
6 Risk of Non-injury Accident to Vehicle + Occupants due to Rockfall	5.26E+01	2.16E+01	1.06E+01	9.19E+00	9.86E+00	0.00E+00		
7 Risk of to due to	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
8 Risk of to due to	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
9 Risk of to due to	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
10 Risk of to due to	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
11 Risk of to due to	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
12 Risk of to due to	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	

APPENDIX 2
WORKED EXAMPLE 2

Project Title:	Argillite Cut, BC, Bunce et al, (1997)
Analyst:	Riddolls & Grocott Ltd
Date:	01-Mar-99

Riddolls & Grocott Ltd

transfund NEW ZEALAND

SD for effectiveness function 0.2

Objective

This example replicates an analysis carried out by Bunce et al (1997) of the hazard posed by rockfall at the site of a rockfall fatality in British Columbia The study calculated the risk of three consequences of rock fall to two elements at risk. No remedial programmes were investigated. No economic analysis was carried out.

Failure Modes Investigated

Rockfall

Elements at Risk	Consequences
Any vehicle	Rock hitting stationary vehicle
Individual vehicle	Vehicle hitting fallen rock
	falling rock hitting moving vehicle

Remedial Programmes

1. Not used
2. Not used
3. Not used
4. Not used
5. Not used
6. Not used

Contents

Header Sheet						
RA1	Risk of	Rock hitting stat vhcl	to	Any vehicle	due to	Rockfall (reported)
RA2	Risk of	Rock hitting stat vhcl	to	Individual vehicle	due to	Rockfall (reported)
RA3	Risk of	Falling rock hitting moving	to	Any vehicle	due to	Rockfall (reported)
RA4	Risk of	Falling rock hitting moving	to	Individual vehicle	due to	Rockfall (reported)
RA5	Risk of	Vehicle hitting fallen rock	to	Any vehicle	due to	Rockfall (reported)
RA6	Risk of	Vehicle hitting fallen rock	to	Individual vehicle	due to	Rockfall (reported)
RA7	Risk of		to		due to	
RA8	Risk of		to		due to	
RA9	Risk of		to		due to	
RA10	Risk of		to		due to	
RA11	Risk of		to		due to	
RA12	Risk of		to		due to	
Economic Analysis				Not carried out		
Risk Summary						

Project Title: Argillite Cut, BC, Bunce et al, (1997)

		Existing Situation				Effectiveness of Remedial Programmes					
Risk of:	*(Consequence)*	Rock hitting stat vhcl				Not used	Not used	Not used	Not used	Not used	Not used
To:	*(Element at Risk)*	Any vehicle									
Due to:	*(Failure Mode)*	Rockfall (reported)									
		Probability Distributions									
		Min	ML	Max	Exp. Value						
Cost of *Consequence* ($)		0	0	0	0						
Annual *Probability of Failure*, P(F)		2.20E+00	2.20E+00	2.20E+00	2.20E+00	0.00	0.00	0.00	0.00	0.00	
Temporal Probability that *Element at Risk* is present within the potential area of influence of the failure, P(T)		5.70E-05	5.70E-05	5.70E-05	5.70E-05	0.00	0.00	0.00	0.00	0.00	
Spatial Probability that *Element at Risk* and failure will coincide in space given that element is present and failure has occurred, P(S).		7.80E-01	7.80E-01	7.80E-01	7.80E-01	0.00	0.00	0.00	0.00	0.00	
Vulnerability to *Element at Risk* given that failure impinges on element, V.		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Annual ***Risk*** of *Consequence* occuring to *Element at Risk*, Risk = P(F) x P(T) x P(S) x V					5.50E-05	5.50E-05	5.50E-05	5.50E-05	5.50E-05	5.50E-05	
Expected *frequency of occurrence* of *Consequence* (years)					*1.82E+04*	*1.82E+04*	*1.82E+04*	*1.82E+04*	*1.82E+04*	*1.82E+04*	
Expected annual cost of *Consequence*					0	.0	0	0	0	0	

RA1

Project Title: Argillite Cut, BC, Bunce et al, (1997)

		Existing Situation				Effectiveness of Remedial Programmes					
Risk of:	*(Consequence)*	Rock hitting stat vhcl				Not used	Not used	Not used	Not used	Not used	Not used
To:	*(Element at Risk)*	Individual vehicle									
Due to:	*(Failure Mode)*	Rockfall (reported)									
		Probability Distributions									
		Min	ML	Max	Exp. Value						
Cost of *Consequence* ($)		0	0	0	0						
Annual *Probability of Failure*, P(F)		2.20E+00	2.20E+00	2.20E+00	2.20E+00	0.00	0.00	0.00	0.00	0.00	
Temporal Probability that *Element at Risk* is present within the potential area of influence of the failure, P(T)		5.70E-05	5.70E-05	5.70E-05	5.70E-05	0.00	0.00	0.00	0.00	0.00	
Spatial Probability that *Element at Risk* and failure will coincide in space given that element is present and failure has occurred, P(S).		1.10E-02	1.10E-02	1.10E-02	1.10E-02	0.00	0.00	0.00	0.00	0.00	
Vulnerability to *Element at Risk* given that failure impinges on element, V.		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Annual ***Risk*** of *Consequence* occuring to *Element at Risk*, Risk = P(F) x P(T) x P(S) x V					1.37E-06	1.37E-06	1.37E-06	1.37E-06	1.37E-06	1.37E-06	
Expected *frequency of occurrence* of *Consequence* (years)					*7.30E+05*	*7.30E+05*	*7.30E+05*	*7.30E+05*	*7.30E+05*	*7.30E+05*	
Expected annual cost of *Consequence*					0	0	0	0	0	0	

RA2

Project Title: Argillite Cut, BC, Bunce et al, (1997)

		Existing Situation				Effectiveness of Remedial Programmes					
Risk of:	*(Consequence)*	Falling rock hitting.moving veh.				Not used	Not used	Not used	Not used	Not used	Not used
To:	*(Element at Risk)*	Any vehicle									
Due to:	*(Failure Mode)*	Rockfall (reported)									
		Probability Distributions									
		Min	ML	Max	Exp. Value						
Cost of *Consequence* ($)		0	0	0	0						
Annual *Probability of Failure*, P(F)		2.20E+00	2.20E+00	2.20E+00	2.20E+00	0.00	0.00	0.00	0.00	0.00	
Temporal Probability that *Element at Risk* is present within the potential area of influence of the failure, P(T)		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Spatial Probability that *Element at Risk* and failure will coincide in space given that element is present and failure has occurred, P(S).		1.30E-02	1.30E-02	1.30E-02	1.30E-02	0.00	0.00	0.00	0.00	0.00	
Vulnerability to *Element at Risk* given that failure impinges on element, V.		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Annual ***Risk*** of *Consequence* occuring to *Element at Risk*, Risk = P(F) x P(T) x P(S) x V					2.84E-02	2.84E-02	2.84E-02	2.84E-02	2.84E-02	2.84E-02	
Expected *frequency of occurrence* of *Consequence* (years)					*3.52E+01*	*3.52E+01*	*3.52E+01*	*3.52E+01*	*3.52E+01*	*3.52E+01*	
Expected annual cost of *Consequence*					0	0	0	0	0	0	

RA3

Project Title: Argillite Cut, BC, Bunce et al, (1997)

		Existing Situation				Effectiveness of Remedial Programmes					
Risk of:	*(Consequence)*	Falling rock hitting moving veh.				Not used	Not used	Not used	Not used	Not used	Not used
To:	*(Element at Risk)*	Individual vehicle									
Due to:	*(Failure Mode)*	Rockfall (reported)									
		Probability Distributions									
		Min	ML	Max	Exp. Value						
Cost of *Consequence* ($)		0	0	0	0						
Annual *Probability of Failure*, P(F)		2.20E+00	2.20E+00	2.20E+00	2.20E+00	0.00	0.00	0.00	0.00	0.00	
Temporal Probability that *Element at Risk* is present within the potential area of influence of the failure, P(T)		5.70E-07	5.70E-07	5.70E-07	5.70E-07	0.00	0.00	0.00	0.00	0.00	
Spatial Probability that *Element at Risk* and failure will coincide in space given that element is present and failure has occurred, P(S).		1.35E-02	1.35E-02	1.35E-02	1.35E-02	0.00	0.00	0.00	0.00	0.00	
Vulnerability to *Element at Risk* given that failure impinges on element, V.		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Annual ***Risk*** of *Consequence* occuring to *Element at Risk*, Risk = P(F) x P(T) x P(S) x V					1.68E-08	1.68E-08	1.68E-08	1.68E-08	1.68E-08	1.68E-08	
Expected *frequency of occurrence* of *Consequence* (years)					*5.96E+07*	*5.96E+07*	*5.96E+07*	*5.96E+07*	*5.96E+07*	*5.96E+07*	
Expected annual cost of *Consequence*					0	0	0	0	0	0	

RA4

Project Title: Argillite Cut, BC, Bunce et al, (1997)

		Existing Situation				Effectiveness of Remedial Programmes					
Risk of:	*(Consequence)*	Vehicle hitting fallen rock				Not used	Not used	Not used	Not used	Not used	Not used
To:	*(Element at Risk)*	Any vehicle									
Due to:	*(Failure Mode)*	Rockfall (reported)									
		Probability Distributions									
		Min	ML	Max	Exp. Value						
Cost of *Consequence* ($)		0	0	0	0						
Annual *Probability of Failure*, P(F)		2.20E+00	2.20E+00	2.20E+00	2.20E+00	0.00	0.00	0.00	0.00	0.00	
Temporal Probability that *Element at Risk* is present within the potential area of influence of the failure, P(T)		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Spatial Probability that *Element at Risk* and failure will coincide in space given that element is present and failure has occurred, P(S).		3.13E-01	3.13E-01	3.13E-01	3.13E-01	0.00	0.00	0.00	0.00	0.00	
Vulnerability to *Element at Risk* given that failure impinges on element, V.		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Annual ***Risk*** of *Consequence* occuring to *Element at Risk*, Risk = P(F) x P(T) x P(S) x V					5.62E-01	5.62E-01	5.62E-01	5.62E-01	5.62E-01	5.62E-01	
Expected *frequency of occurrence* of *Consequence* (years)					*1.78E+00*	*1.78E+00*	*1.78E+00*	*1.78E+00*	*1.78E+00*	*1.78E+00*	
Expected annual cost of *Consequence*					0	0	0	0	0	0	

RA5

Project Title: Argillite Cut, BC, Bunce et al, (1997)

		Existing Situation				Effectiveness of Remedial Programmes					
Risk of:	*(Consequence)*	Vehicle hitting fallen rock				Not used	Not used	Not used	Not used	Not used	Not used
To:	*(Element at Risk)*	Individual vehicle									
Due to:	*(Failure Mode)*	Rockfall (reported)									
		Probability Distributions									
		Min	ML	Max	Exp. Value						
Cost of *Consequence* ($)		0	0	0	0						
Annual *Probability of Failure*, P(F)		2.20E+00	2.20E+00	2.20E+00	2.20E+00	0.00	0.00	0.00	0.00	0.00	
Temporal Probability that *Element at Risk* is present within the potential area of influence of the failure, P(T)		5.70E-07	5.70E-07	5.70E-07	5.70E-07	0.00	0.00	0.00	0.00	0.00	
Spatial Probability that *Element at Risk* and failure will coincide in space given that element is present and failure has occurred, P(S).		3.10E-01	3.10E-01	3.10E-01	3.10E-01	0.00	0.00	0.00	0.00	0.00	
Vulnerability to *Element at Risk* given that failure impinges on element, V.		1.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00	0.00	0.00	0.00	0.00	
Annual ***Risk*** of *Consequence* occuring to *Element at Risk*, Risk = P(F) x P(T) x P(S) x V					3.18E-07	3.18E-07	3.18E-07	3.18E-07	3.18E-07	3.18E-07	
Expected *frequency of occurrence* of *Consequence* (years)					*3.14E+06*	*3.14E+06*	*3.14E+06*	*3.14E+06*	*3.14E+06*	*3.14E+06*	
Expected annual cost of *Consequence*					0	0	0	0	0	0	

RA6

Project Title: Argillite Cut, BC. Bunce et al. (1997)

Individually Assessed Risks

Individually Assessed Risks	Existing Situation	Remedial Programmes / Mitigated Risks: Not used	Not used	Not used	Not used	Not used	Not used	Risk Acceptance Threshold
2 Risk of Rock hitting stat vhcl to Any vehicle due to Rockfall (reported)	5.50E-05	5.50E-05	5.50E-05	5.50E-05	5.50E-05	5.50E-05		
3 Risk of Rock hitting stat vhcl to Individual vehicle due to Rockfall (reported)	1.37E-06	1.37E-06	1.37E-06	1.37E-06	1.37E-06	1.37E-06		
4 Risk of Falling rock hitting moving veh. to Any vehicle due to Rockfall (reported)	2.84E-02	2.84E-02	2.84E-02	2.84E-02	2.84E-02	2.84E-02		
5 Risk of Falling rock hitting moving veh. to Individual vehicle due to Rockfall (reported)	1.68E-08	1.68E-08	1.68E-08	1.68E-08	1.68E-08	1.68E-08		
6 Risk of Vehicle hitting fallen rock to Any vehicle due to Rockfall (reported)	5.62E-01	5.62E-01	5.62E-01	5.62E-01	5.62E-01	5.62E-01		
7 Risk of Vehicle hitting fallen rock to Individual vehicle due to Rockfall (reported)	3.18E-07	3.18E-07	3.18E-07	3.18E-07	3.18E-07	3.18E-07		
8 Risk of to due to	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
9 Risk of to due to	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
10 Risk of to due to	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
11 Risk of to due to	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
12 Risk of to due to	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
13 Risk of to due to	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	