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Date: March 1999

BRANZ
THE RESOURCE CENTRE FOR BUILDING EXCELLENCE

STUDY REPORT

No. 83 (1999)

Quantitative Assessment Methods for Determining Slope Stability Risk in the Building Industry

Riddolls & Grocott Ltd

The work reported here was funded by the
Building Research Levy.

ISSN: 0113-3675

Preface

The Building Research Association of New Zealand (BRANZ) commissioned this report to assist with the development of improved procedures for assessing the risk of instability of sloping land intended for development, particularly residential building sites. The views represented are not necessarily those of BRANZ.

Acknowledgments

Riddolls & Grocott Ltd wishes to acknowledge the help and financial support of BRANZ, particularly Dr J.R. Duncan in his capacity as Manager, Building Industry Research, and Mr A. King, who was responsible for technical liaison with BRANZ for this project. Dr L. Richards, consulting geotechnical engineer, and Mr G. Farquhar, Worley Consultants Ltd. geotechnical engineer, were responsible for technical audits of the report. The report was prepared by Mr Guy Grocott, Mr Paul Horrey and Dr Bruce Riddolls.

Note

This report is intended mainly to provide New Zealand geotechnical practitioners with guidelines for the use of quantitative risk assessment techniques for assessing the risks associated with the potential instability of sloping ground. The report will also be of use to local authority building consent officers in assessing the acceptability of slope stability risk if this risk is expressed quantitatively by geotechnical practitioners in their reports to Regional and District Councils in support of subdivision and building consent approvals.

QUANTITATIVE RISK ASSESSMENT METHODS FOR DETERMINING SLOPE STABILITY RISK IN THE BUILDING INDUSTRY

BRANZ Study Report SR 83 **Riddolls & Grocott Ltd**

REFERENCE

Riddolls & Grocott Ltd, 1999. Quantitative Risk Assessment Methods for Determining Slope Stability Risk in the Building Industry. Building Research Association of New Zealand, Study Report SR 83, Judgeford.

KEYWORDS

From Construction Industry Thesaurus – BRANZ Edition: Building regulations; Codes of practice; Development plans; Site; Slope; Stability; Evaluating; Investigation; Analysis; Risk.

ABSTRACT

Local authorities require a favourable report on the stability of sloping land before issuing either subdivision or building consents. Traditionally geotechnical practitioners have relied heavily on experience-based judgement to assess whether the stability of a slope is adequate to allow development, complemented by the use of numerical techniques such as the factor of safety concept to provide reassurance. New techniques, which have arisen out of other areas such as the nuclear and hazardous waste industries and dam safety, are now available to assist geotechnical practitioners in quantifying the uncertainty associated with the stability of slopes. These techniques use both numerical methods and/or subjective judgement to assist in quantifying the uncertainties inherent in any system such as a slope, and are collectively referred to as Quantitative Risk Assessment (QRA).

QRA provides relatively simple but powerful tools for numerically expressing the risk of slope instability. The main benefit of QRA is that all cause and effect relationships associated with slope instability can be taken account of, which is not the case with conventional analyses that emphasise the probability of failure rather than the consequences. QRA also facilitates a structured approach to understanding slope processes and the consequences of failure.

The application of QRA is limited by the difficulty in accurately determining input parameters. However, the numerical expression of risk allows the best estimate of the stability of a slope to be communicated in terms readily understood by lay personnel so that land owners, developers and regulators are able to understand the risks on which to base their development and planning decisions.

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1. INTRODUCTION

1.1 General

Traditionally geotechnical practitioners have relied heavily on experience-based judgement to assess whether the stability of a slope is adequate to allow development, complemented by the use of numerical techniques, such as the factor of safety concept, to provide reassurance. New techniques, which have arisen out of other areas such as the nuclear and hazardous waste industries and dam safety, are now available to assist geotechnical practitioners in quantifying the uncertainty associated with the stability of slopes. These techniques use both numerical methods and/or subjective judgement to assist in quantifying the uncertainties, or the risk inherent in any system such as a slope, and are collectively referred to as Quantitative Risk Assessment (QRA).

Assessment of the stability of sloping land involves considerable uncertainty. This arises from the variability of soil, rock and groundwater conditions across a site (referred to as spatial variability), the selection of appropriate engineering properties representative of slope materials (termed parameter uncertainty), and uncertainty in the way the slope will perform in terms of its stability (referred to as model uncertainty). Failure to recognise potentially adverse features may further complicate the matter, referred to as human uncertainty. There is also uncertainty about the consequences of slope failure on people and property.

QRA can be used in the context of slope stability to provide alternative procedures for formalising the process of engineering judgement. QRA consists of two components; assessment of the probability of slope failure and identification of the consequences of failure.

QRA may be used to assess the risk of failure of engineered slopes such as cuts, fills and retaining walls and of land that has already been affected by slope instability. It is more difficult to assess the risk of first time sliding of natural slopes. Many of the input parameters required to quantify the risk for these slopes are difficult to accurately assess, or require considerable expense to obtain by means of detailed site investigations.

1.2 Objectives

In 1987, comprehensive guidelines for carrying out geotechnical investigations were published in order to provide New Zealand practitioners with a uniform approach to the assessment of slope stability for building sites (Worley Consultants Ltd, 1987). At the time, this document represented the ‘state of the art’ for site investigation and evaluation techniques, and still remains the basis for most geotechnical investigations.

The use of QRA methods is not intended to replace those established and accepted procedures. Rather, it offers the possibility of expressing numerically the risk attached to any particular slope, compared with terms which are currently expressed qualitatively using such phrases as ‘safe’ and ‘unsafe’.

Although procedures are well established, the use of QRA to evaluate slope stability risk is very much an emerging concept overseas and still in its infancy in New Zealand. The objective of this publication is to raise awareness amongst New Zealand geotechnical practitioners of the use of QRA methods, to highlight the procedures for its use including guidelines for acceptable risk, and to describe its advantages and limitations.

1.3 Scope

The framework of QRA for evaluation of slope stability is reviewed in Section 2, including a summary of common definitions. Comparisons are also made with traditional methods of slope stability analysis based on the factor of safety approach.

The output from QRA is the numerical expression of risk, and methods of determining risk are summarised in Section 3. Risk acceptance criteria for landslides and other hazards such as dams that have been promulgated overseas are summarised, and suggestions for risk acceptance guidelines are offered.

Section 4 summarises the legislative framework in New Zealand in the context of the influence of slope instability on land development. The value of QRA for New Zealand conditions and practitioners is reviewed, and guidelines are provided for its use in slope work.

Finally, the document highlights a number of areas where it is considered there is scope for additional work. These mainly relate to providing the geotechnical practitioner with a greater awareness of QRA methods and capabilities.

2. FRAMEWORK FOR QUANTITATIVE RISK ASSESSMENT

2.1 Background

At a recent (1997) international workshop, the state-of-the-art quantitative risk assessment of landsliding was examined (Cruden & Fell (eds), 1997). The workshop presented the results of a Working Party composed of various international technical organisations and societies under the auspices of the International Union of Geological Sciences (IUGS). At its meeting in Trondheim in June 1996, the IUGS Working Party formed a technical committee on the Assessment of the Risk of Landsliding under the Chairmanship of Professor Robin Fell of the School of Civil and Environmental Engineering, The University of New South Wales, Australia. The objectives of the Working Party included:

- to review terminology and to propose internationally acceptable definitions of terms used in assessing the risks of landslides
- to review national standards of acceptable and tolerable risk and suggest methods of applying these to landslide risk
- to review methods of predicting vulnerability of property and life to landslides.

The Working Party identified some limitations to QRA, including the variety of valid approaches available, which can lead to significant differences in outcome, and the difficulty of verifying results. However, it concluded “that adequate methods for QRA exist for use in practice, but that it is necessary to explain the philosophy, application, and limitation to the professional potentially involved, and their clients” (IUGS Working Group on Landslides, 1997).

2.2 Definitions

Risk assessment in general and landslide risk assessment in particular has resulted in a plethora of different definitions by a range of different authors, resulting in confusion, misinterpretation and misuse of terminology. ‘Risk’ means different things to different people.

Definitions provided by a recent publication (Fell & Hartford, 1997), which have been promulgated for use with landslide QRA, appear to be gaining wider acceptance, and are used in this document. The original sources are also referenced:

Acceptable risk: a risk for which, for the purposes of life or work, we are prepared to take pretty well as it is with no regard to its management. Society does not generally consider expenditure in further reducing such risks (Health and Safety Executive, 1992; ANCOLD, 1994).

Hazard: a condition with the potential for causing an undesirable consequence. Descriptions of landslide hazard, particularly for zoning purposes, should include the volume or area of the landslide, and the probability of its occurrence. There may also be value in describing the velocity, and the differential velocity of the landslide (Varnes, 1984; Fell, 1994; United Nations, 1991).

Elements at risk (E): meaning the population, buildings and engineering works, economic activities, public services utilities and infrastructure in the area potentially affected by landslides (Varnes, 1984; Fell, 1994; United Nations, 1991).

Hazard identification: the recognition that a hazard exists and the definition of its characteristics (Canadian Standards Association, 1991).

Individual risk: the risk to any identifiable (named) individual who lives within the zone impacted by the slope failure; or who follows a particular pattern of life that might subject him or her to consequences of slope failure (Fell & Hartford, 1997).

Probability (P): the likelihood of a specific outcome, measured by the ratio of specific outcomes to the total number of possible outcomes. Probability is expressed as a number between 0 and 1, with 0 indicating an impossible outcome and 1 indicating an outcome is certain (Standards Australia and Standards New Zealand, 1995).

Risk: a measure of the probability and severity of an adverse effect to health, property or the environment (Canadian Standards Association 1991).

Risk is often estimated by the mathematical expectation of the consequences of an adverse event occurring (i.e. the product of ‘probability x consequences’). However, a more general interpretation of risk involves probability and consequences in a non-product form. This presentation is sometimes useful in that a spectrum of consequences, with each magnitude having its own corresponding occurrence, is outlined. For landslides, both representations are useful, the latter being used initially with the intangible consequences identified, with subsequent expected value calculations for those consequences where ‘risk costs’ can be estimated and compared with quantitative decision criteria (Canadian Standards Association 1991).

Risk analysis: the use of available information to estimate the risk to individuals or populations, property or the environment, from hazards. Risk analyses generally contain the following steps: scope definition, hazard definition and risk estimation (Canadian Standards Association 1991).

Risk assessment: the process of risk analysis and risk evaluation (Canadian Standards Association 1991).

Risk control: the process of decision-making for managing risk, and the implementation, enforcement, and re-evaluation of its effectiveness from time to time, using the results of risk assessment as one input (Canadian Standards Association 1991).

Risk estimation: the process used to produce a measure of the level of health, property, or environmental risk being analysed. Risk estimation contains the following steps: frequency analysis, consequence analysis, and their integration (Canadian Standards Association 1991).

Risk evaluation: the stage at which values and judgements enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing risks (Canadian Standards Association 1991).

Risk management: the complete process of risk analysis and risk evaluation (Fell & Hartford, 1997)

Safe: free from harm or risk (Standards Australia and Standards New Zealand, 1995).

Safe slope: one which is sufficiently stable as not to impose unacceptable risks to the public by its presence (adapted from US Bureau of Reclamation, 1989).

Societal risk: the risk to society as a whole: one where society would have to carry the burden of a landslide accident causing a number of deaths, injuries, financial, environmental and other losses (Fell & Hartford, 1997).

Specific risk (R_S): probability x vulnerability for a given element (Varnes, 1984; Fell, 1994; United Nations, 1991):

$$R_S = P \times V$$

System: a bounded, physical entity that achieves in its environment a defined objective through interaction of its parts. This definition implies that:

(a) the system is identifiable

(b) the system is made up of interacting parts or subsystems

(c) all of the parts are identifiable, and

(d) the boundary of the system can be identified (Canadian Standards Association, 1991).

For a risk-based safety evaluation, the system will generally comprise two sub-systems, the potentially unstable slope and anything impacted by partial or complete failure of the slope. Some hazards are internal to the system (internal weaknesses); others, such as extreme rainfall and earthquakes, are external hazards which cross the boundary of the system.

Tolerable risk: a risk that we are willing to live with so as to secure certain net benefits in the confidence that it is being properly controlled, kept under review and further reduced as and when possible (Fell & Hartford, 1997).

In some situations risk may be tolerated because the individuals at risk cannot afford to reduce risk even though they recognise it is not being properly controlled.

Total risk (R_t): the expected number of lives lost, persons injured, damage to property and disruption of economic activity. It is the product of specific risk (R_s) and elements at risk (E) over all landslides and potential landslides in the study area,

$$R_t = \Sigma (E \text{ x } R_s)$$

$$= \Sigma (ExPxV) \text{ (Fell \& Hartford, 1997)}$$

Vulnerability: the degree of loss to a given element or set of elements within the study area affected by the landslide(s). It is expressed on a scale of 0 (no damage) to 1 (total loss) (Varnes, 1984; Fell, 1994).

For a property, the loss will be the value of the property; for persons, it will be the probability that a particular life (the element at risk) will be lost, given the person(s) affected by the landslide.

2.3 The Quantitative Risk Assessment Process

The QRA process includes risk analysis, risk assessment and risk management, as illustrated by the flow chart in Figure 1, which is based on work presented by Fell & Hartford (1997) and the IUGS Working Group on Landslides (1997).

Risk analysis involves acquiring knowledge of the slope stability hazards, as well as consideration of the consequences of landsliding if persons and/or property are impacted by failure. Firstly a thorough assessment of the types, characteristics and frequency of landslides in a given study area is carried out in order to identify the hazard. Where the frequency of landslides cannot be determined directly from field evidence, or where engineered slopes are involved, analytical or numerical techniques are required to evaluate the probability of failure.

Secondly consequence analysis is carried out to establish the elements at risk (persons and/or property) which could be impacted by any failure and to determine their vulnerability in the event of failure.

Risk analysis is the product of hazard and consequence analysis, and the output is a mathematical expression of risk given by the general term *risk estimation.* Risk estimation can be expressed in a number of ways, such as the cost to save a life (not to be confused with the value placed on life), the probability of life loss (or injury), cost of damage, or the extent of environmental impact.

Risk assessment is risk analysis considered together with *risk evaluation* (Figure 1). Risk evaluation requires risk estimation (see above) to be compared against risk-based acceptance criteria for the reference slope under study, in order to determine the importance of the numerical value. This could include comparison with levels of acceptable death for other activities, or the economic, social and environmental consequences were failure to occur. Typically, the decision as to whether to accept the calculated risk is made by the client, owner or regulators, rather than their technical advisers, whose role is primarily to determine the risk.

Risk management, is risk analysis and risk assessment considered together with *risk control.* Risk control involves the evaluation of options for risk treatment, including risk mitigation, risk acceptance, and risk avoidance.

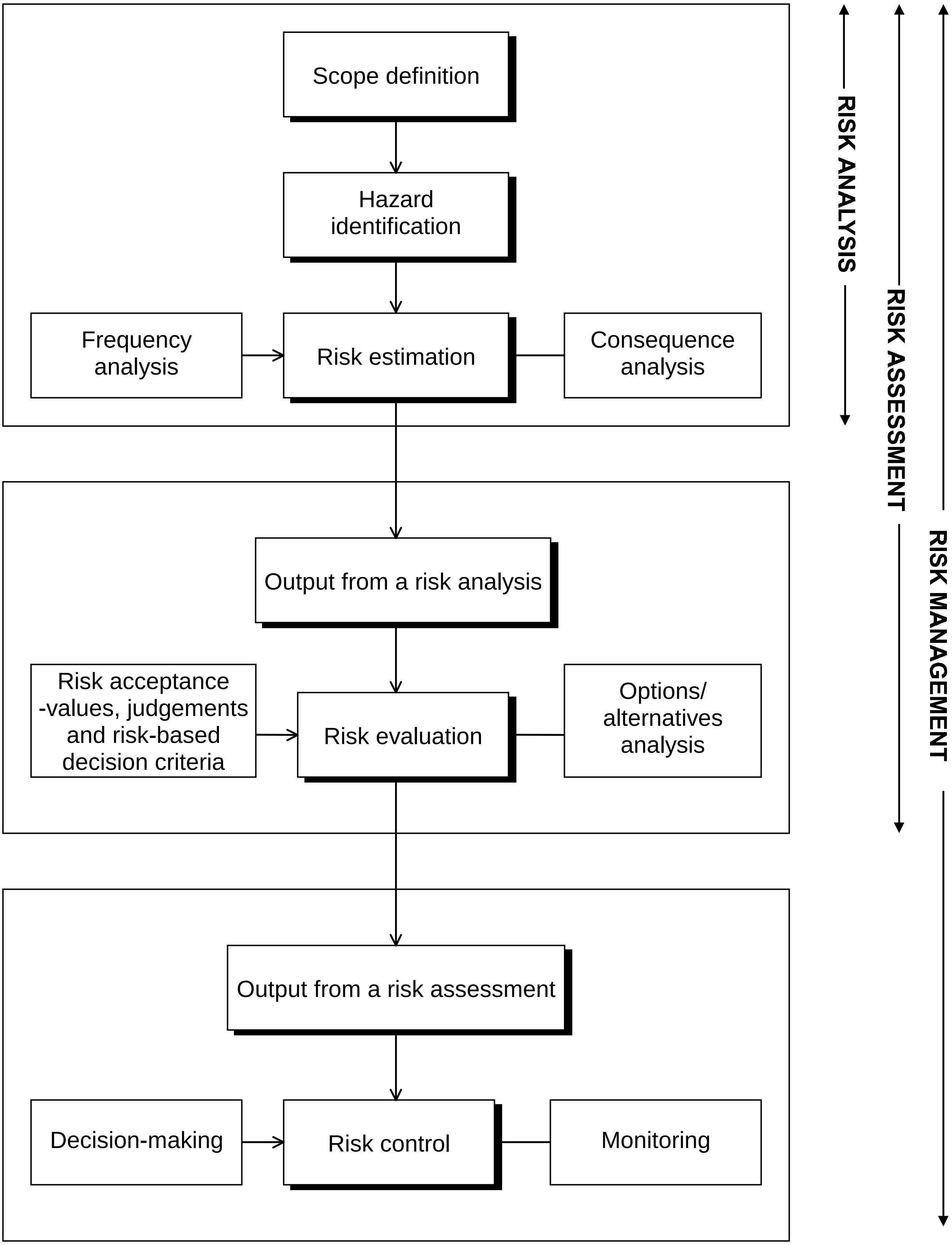


Figure 1: Quantitative risk assessment (based on Fell & Hartford, 1997; IUGS, 1997)

2.4 What Is Wrong With Factors Of Safety?

The numerical analysis of the stability of slopes has traditionally been (and still is) based on a deterministic approach in terms of the factor of safety (FS). The FS of a slope may be defined as the ratio of the available shear strength along the critical failure surface to the shear stresses acting on the surface. Put another way, the FS measures the proportion by which the shear strength would have to be reduced in order to bring the slope to the point of imminent failure. The FS is therefore an indication of the performance function of a particular slope. If the condition of theoretical failure of a slope (termed the ultimate limit state) is taken as being 1.0, then the level by which the FS exceeds the ultimate limit state is taken as an indication of the safety of that slope.

In New Zealand, the generally accepted minimum FS for a permanent slope in terms of its suitability for residential development is 1.5 (New Zealand Building Code via Verification Method B1/VM4), which is also accepted by most territorial authorities. However, the Building Code places no qualifications on the conditions under which the FS should be calculated, such as the use of 'mean' or 'expected' values of shear strength parameters, the groundwater conditions originating from a particular return period rain storm event, or the need for earthquake assessment, all of which have significant influences on slope stability.

It has long been recognised that the value of FS does not necessarily provide an indication of the general 'well being' of the stability of a slope. Worley Consultants Ltd (1987) succinctly summarise one of the main limitations with the use of the FS: "There is generally some uncertainty attached to all of the various input data used in an analysis. The soil strength parameters are the major source of uncertainty... Even where laboratory testing is carried out, errors in measuring these important properties may arise due to sample disturbance, testing errors or inappropriate test conditions." Similarly, groundwater conditions within a slope provide an additional source of uncertainty as these vary in response to specific climatic events.

If one can define the variability of the input parameters for a stability analysis, such as the cohesion and friction angle in terms of a probability distribution, the FS of the slope also takes the form of a probability distribution rather than a single value as is the case with a simple deterministic analysis. These concepts are illustrated by means of Figure 2 for two different slopes where, because of the relative differences in the variability of the input parameters, two distinct probability distributions for the factor of safety are obtained. The conventional deterministic approach would regard the slope with the higher mean FS = 2.0 as safer than that with the lower mean FS = 1.55. However, inspection of Figure 2 demonstrates that the slope with the higher mean FS has a much higher probability of failure (represented by the shaded area under the probability curve) compared with the latter.

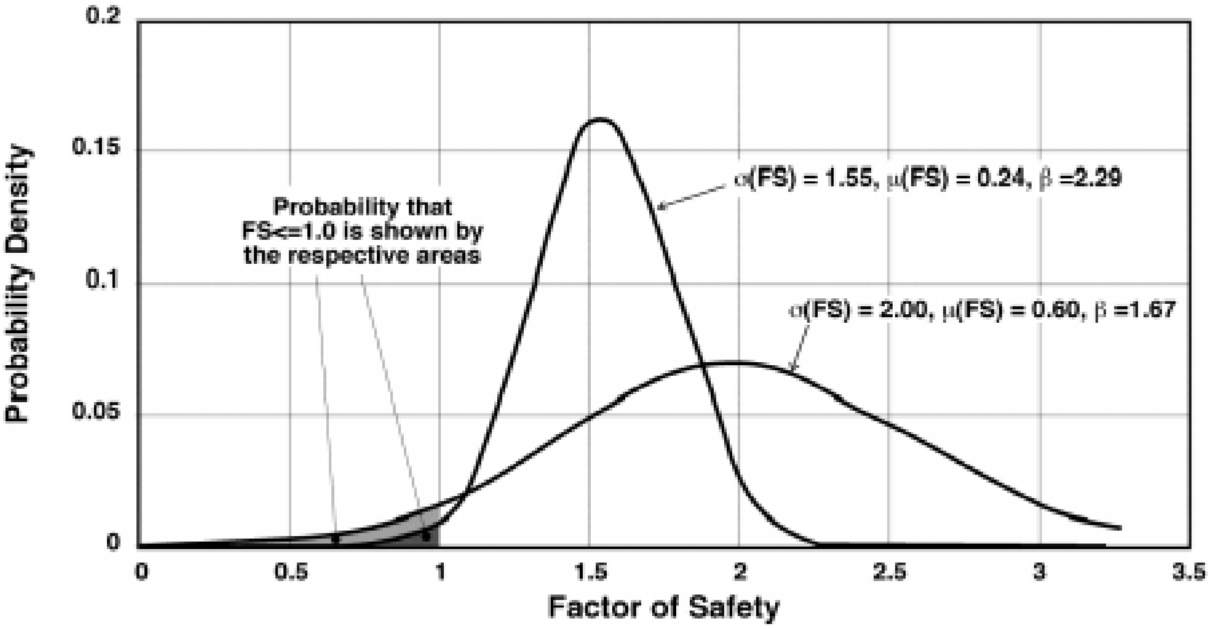


Figure 2: Two slopes with different distributions of factor of safety (modified from Christian, 1996)

In practice it is difficult to accurately construct probability distributions for the input parameters required to carry out numerical stability analyses, as the degree of variability or uncertainty is not known. Approximate distributions can however be obtained from laboratory testing and from an understanding of the soil properties. Regardless of these limitations, consideration of slope stability in terms of the probability of failure such as described here has advantages over the conventional factor of safety approach in that probabilistic analysis allows parameter uncertainty to be accounted for and permits the practitioner to "quantify and visualise the effects of that uncertainty" (Wolff, 1996).

3. PROCEDURE FOR QUANTITATIVE RISK ASSESSMENT

3.1 Risk Analysis

3.1.1 Introduction

Reference should be made to the flow chart provided as Figure 3 which is a summary of the components of slope stability risk analysis.

3.1.2 Hazard analysis

Identification of a landslide, its classification and an indication of the volume of unstable ground can readily be carried out. Much more difficult is the assessment of the probability of failure, P(F), which in many cases will be subjectively determined and approximate due to data inadequacies. The probability of failure can be determined in a number of ways including:

i) *Precedence information.* This could involve direct evidence of landslide activity from geomorphic and geotechnical mapping or historic data, from which the probability of failure can be estimated. Case histories with details of this approach are provided by Morgan et al., (1992) in British Columbia and Moon et al. (1992) in Australia. A New Zealand example of determining the rainfall threshold for the onset of debris flow activity is provided by Grocott & Olsen (1992).

   In many cases however, there will be no historic record on landslide activity and alternative means such as the relationship between rainfall triggers and slope failure, or modelling of the relationship between groundwater triggers and rainfall, will be required. Fell et al. (1988) and Fell et al. (1991) provide examples of these approaches.

ii) *Probabilistic modelling and reliability analysis.* There is a considerable amount of literature on the use of probabilistic modelling, which treats one or more of the input parameters for conventional deterministic slope stability analysis (such as shear strength, bulk density, groundwater pressure, earthquake acceleration etc.) as probability distributions.

   Three methods may be used to calculate the probability distribution of the FS:

   - **The Point Estimate Method** (Harr, 1987; Mostyn & Li, 1993) assumes the analysis input parameters such as shear strength, bulk density, groundwater pressures etc are normally distributed. Two values are arbitrarily chosen for each parameter, one greater than the mean value, and one less by an equal amount. The FS calculation is then repeated for all combinations of each of the random variables (the calculation will need to be repeated 2^n times where n is the number of random variables). The mean and standard deviation of the distribution of the resulting FS values may then be determined, together with the probability of failure, P(F). The Point Estimate Method has the advantage of being able to incorporate a degree of correlation between input parameters.

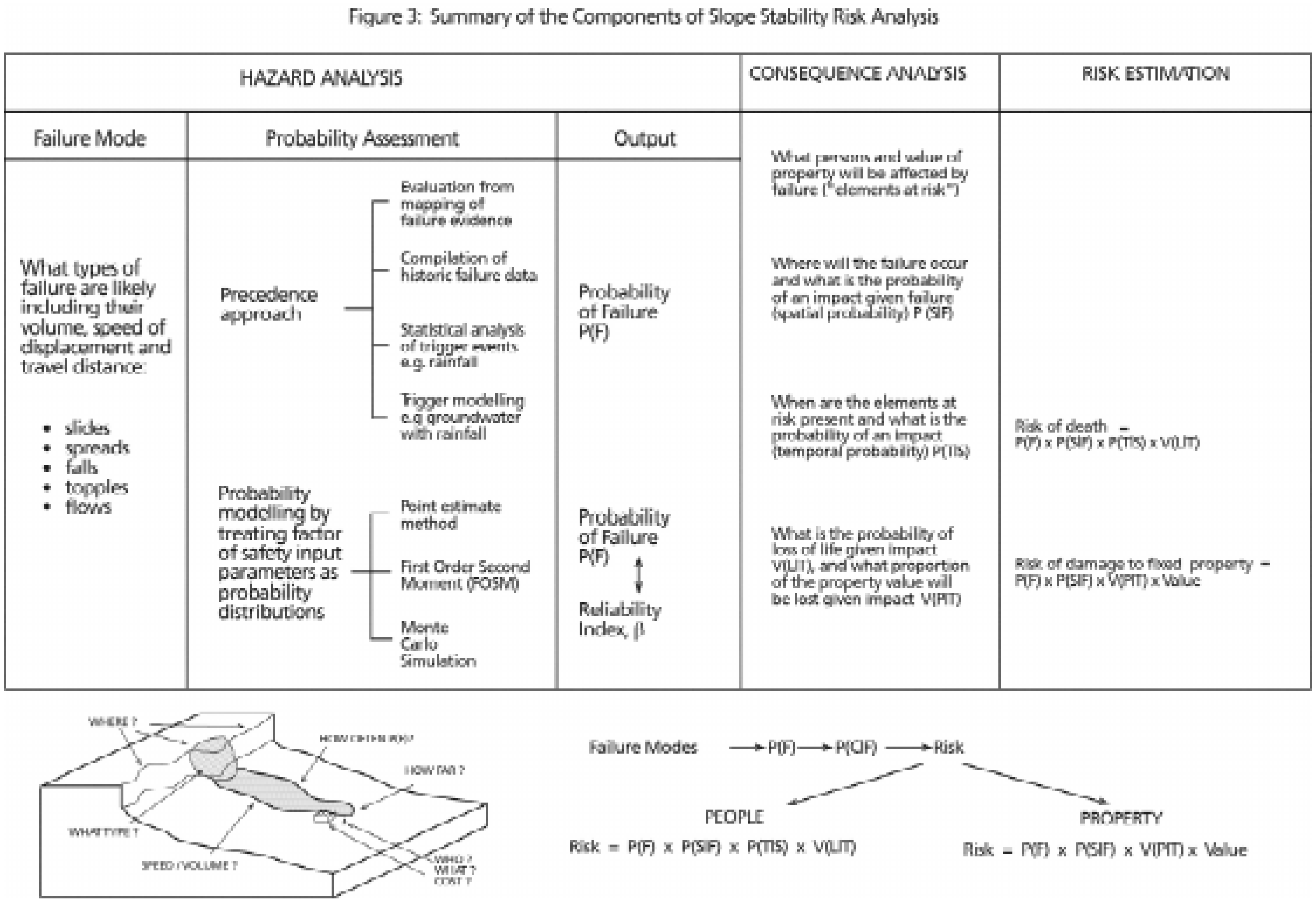


Figure 3: Summary of the Components of Slope Stability Risk Analysis

HAZARD ANALYSIS			CONSEQUENCE ANALYSIS	RISK ESTIMATION
Failure Mode	Probability Assessment	Output		
What types of failure are likely including their volume, speed of displacement and travel distance: • slides • spreads • falls • topples • flows	Precedence approach – Evaluation from mapping of failure evidence – Compilation of historic failure data – Statistical analysis of trigger events e.g. rainfall – Trigger modelling e.g groundwater with rainfall	Probability of Failure P(F)	What persons and value of property will be affected by failure ("elements at risk") Where will the failure occur and what is the probability of an impact given failure (spatial probability) P (S|F) When are the elements at risk present and what is the probability of an impact (temporal probability) P(T|S)	Risk of death = P(F) x P(S|F) x P(T|S) x V(L|T)
	Probability modelling by treating factor of safety input parameters as probability distributions – Point estimate method – First Order Second Moment (FOSM) – Monte Carlo Simulation	Probability of Failure P(F) ↕ Reliability Index, β	What is the probability of loss of life given impact V(L|T), and what proportion of the property value will be lost given impact V(P|T)	Risk of damage to fixed property = P(F) x P(S|F) x V(P|T) x Value

Failure Modes → P(F) → P(C|F) → Risk

PEOPLE

Risk = P(F) x P(S|F) x P(T|S) x V(L|T)

PROPERTY

Risk = P(F) x P(S|F) x V(P|T) x Value

Figure 3: Summary of the components of slope stability risk analysis

- **The First Order Second Moment Extrapolation (FOSM)** technique, in its simplest form, involves the following steps (modified after Christian, 1996):

  i) Identify those input parameters to be treated as probability distributions.

  ii) Determine the mean and standard deviation for each input parameter identified in (i).

  iii) Compute the FS using mean values for each input parameter to obtain a mean FS.

  iv) Repeat FS calculation applying a small increment to each input parameter in turn while holding the others constant. Use the results to estimate the derivative of FS with respect to each of the input parameters.

  v) Obtain the variance of FS, $V[FS]_x$ with respect to each input parameter from the equation:

  $$V[FS]x = \Delta FS/\Delta x \text{ x } V[x] \qquad \textbf{(1)}$$

  Where: ΔFS is the change in FS which results from a small change in input parameter x

  and: V[x] is the variance of input parameter x, being the square root of the standard deviation.

  vi) Sum the individual variances to get a total variance (and hence the standard deviation) of FS.

  vii) Once the mean and standard deviation of FS are known, P(F) may be calculated.

- **Monte Carlo simulation** requires input parameters to a stability analysis to be expressed as probability distributions. Many different types of probability distribution may be used depending on the nature of the input parameter. Monte Carlo simulation involves repeating the calculation of FS many times using input parameters generated from their associated probability distributions. The resulting FS values will gradually build up their own probability distribution as the simulation is repeated. The advantage of Monte Carlo simulation is its simplicity and ability to cope with complex calculations with a large number of input parameters.

  An example of the use of each of these methods based on a simple infinite slope analysis and using a common data set (after Mostyn, 1998) is provided in Appendix A, with results summarised in Table 1.

Table 1: Summary of probabilistic slope stability analyses by three different methods

	Factor of Safety		**Probability of Failure**	**Reliability Index**
	Mean	**Standard Deviation**		
	σ	μ	**P(F)**	β
• Point Estimate Method	1.47	0.25	0.033	1.84
• First Order Second Moment Extrapolation	1.46	0.23	0.024	1.97
• Monte Carlo Simulation	1.46	0.21	0.014	2.19

Table 1 indicates that the three different methods provide similar results for the simple example given.

Whereas values of FS, calculated by means of a deterministic analysis, are commonly used as the basis for stability acceptability criteria of slopes (eg. Geotechnical Control Office, 1984), there are few guidelines on the use of probabilities of failure as indices for slope stability criteria. Christian (1996) and Wolff (1996) have provided some commentaries on this.

As a complementary approach to determination of failure probability, P(F), the reliability index, ß, has been developed as an index of the degree of uncertainty in the distribution of the FS determined from a probabilistic analysis. The reliability index, ß is defined as:

$$\text{ß} = \frac{\underline{\sigma(FS) - 1.0}}{\mu(FS)} \qquad \mathbf{(2)}$$

where $\sigma(FS)$ is the best estimate (mean) of the probability distribution of the FS, and $\mu(FS)$ is the standard deviation of the probability distribution of the FS.

In this case, the factor of safety is calculated by means of an appropriate algorithm, and $\mu[FS]$ includes contributions due to uncertainty or randomness in the slope stability analysis input parameters.

An illustration of this is given previously in Figure 2 (Section 2.4) for two slopes having differing probability distributions for their respective factors of safety, with variation attributable to uncertainty in the analysis input parameters. The numerator of equation (1) is the distance along the abscissa (Figure 2) which represents the difference between the mean safety factor $\sigma(FS)$ and failure at FS = 1 (termed the ultimate limit state). This difference is equivalent to a ‘margin of safety’. When this difference is divided by $\mu(FS)$, the ‘margin of safety’ becomes relative to the uncertainty about the safety factor. This value, ß, termed the reliability index, is a measure of safety while taking into account the magnitude of the uncertainties involved. Clearly, when the uncertainty is large, large safety factors are required to maintain the same level of safety, while the converse is true when the uncertainty is small.

For the example given in Figure 2, σ(FS) for one slope is 2.0, and μ(FS) of 0.6, giving ß = 1.67. In the case of the other slope, σ(FS) is 1.55, and μ(FS) of 0.24, giving a ß = 2.29. Although the first slope has a considerably higher factor of safety compared to the second, its much lower reliability index indicates considerable uncertainty in the input parameters, and therefore much higher probability of failure.

Christian (1996) states. "The reliability index therefore provides a better indication of how close the slope is to failure than does the factor of safety. Slopes with large values of ß are farther from failure than slopes with small values of ß, regardless of the value of the best estimate of the factor of safety". If the form of the probability distribution of the factor of safety is known, then it is possible to relate the reliability index ß to the probability of failure. It is commonly assumed that the FS is normally distributed, although this will not always be the case. For a normally distributed factor of safety, the relationship between reliability index ß and the probability of failure P(F) is shown in Figure 4.

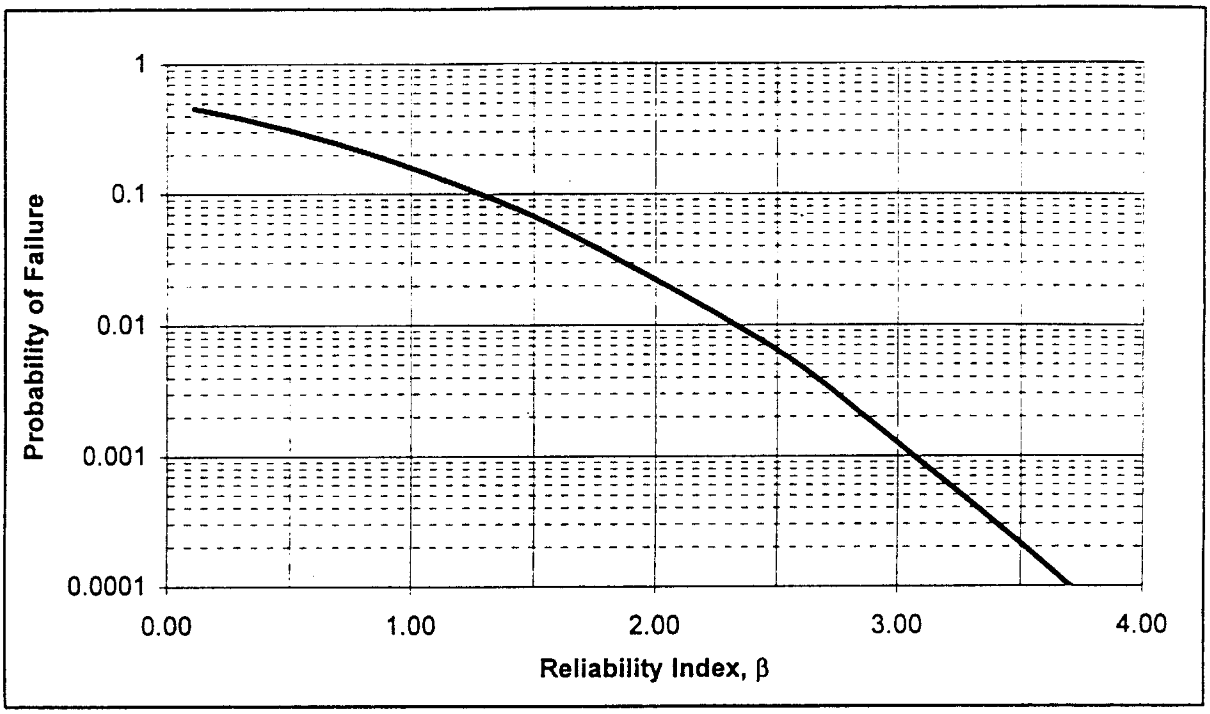


Figure 4: Relationship between the probability of failure and reliability index for a normally distributed factor of safety

3.1.3 Consequence analysis

Consequence analysis requires the elements at risk from landslide activity to be identified, and consideration of the vulnerability of those elements at risk in the event of failure. Consequence analysis is therefore an assessment of the conditional probability of the consequences occurring given failure to have occurred.

The elements at risk are relatively easy to identify in terms of the population and the value of the property potentially exposed to the landslide hazard.

Assessment of the probability of a consequence occurring to the elements at risk is much more difficult to quantify and traditionally has been based mainly on subjective judgement. Consequence analysis requires consideration of:

- where will the landslide occur and what will be the probability of the element at risk being impacted by the failure, termed the spatial probability, P(S|F)?

- what is the probability of the element at risk being present at the time of impact, termed the temporal impact, P(T|S)? Normally this conditional probability would not apply to property due to it being fixed in space, other than to moving vehicles on transportation routes, where the proportion of time the vehicle is exposed to the hazard would need to be allowed for

- what is the probability of loss of life, or what proportion of the property value will be damaged, given impact by the failure, and given as V(L|T) for the vulnerability of an individual and V(P|T) for the proportion of the property value lost.

The above conditional probabilities P(S|F), P(T|S), V(L|T) and V(P|T) are all expressed as values from 0 to 1. By assessing consequences in this manner, allowance can be made for the location of an element at risk in relation to the landslide and the length of time of exposure to the hazard. Wong et al. (1997) presented values for the conditional probability functions V(L|T) and V(P|T) for death from landslide impact, based on historical data from Hong Kong (Table 2).

The results given in Table 2 have been extracted from studies carried out by Finlay et al. 1997. They have been established directly by reference to historical landslide data, but without consideration of the various components influencing consequence analysis, such as the scale of the failures under consideration.

Table 2: Summary of Hong Kong vulnerability ranges and recommended values for death from landslide debris (from Wong et al., 1997, extracted from Finlay et al., 1997)

Vulnerability of Person in Open Space			
Case	**Range in Data**	**Recommended Value**	**Comments**
If struck by a rockfall	0.1 - 0.7	0.5	May be injured but unlikely to cause death
If buried by debris	0.8 - 1.0	1.0	Death by asphyxia
If not buried	0.1 - 0.5	0.1	High chance of survival

Vulnerability of Person in a Vehicle			
Case	**Range in Data**	**Recommended Value**	**Comments**
If the vehicle is buried/crushed	0.9 -1.0	1.0	Death is almost certain
If the vehicle is damaged only	0 - 0.3	0.3	High chance of survival

Vulnerability of Person in a Building			
Case	**Range in Data**	**Recommended Value**	**Comments**
If the building collapses	0.9 - 1.0	1.0	Death is almost certain
If the building is inundated with debris and the person buried	0.8 - 1/0	1.0	Death is highly likely
If the building is inundated with debris and the person not buried	0 - 0.5	0.2	High chance of survival
If the debris strikes the building only	0 - 0.1	0.05	Virtually no danger

Consequence analysis (P(C|F)) is the product of the above conditional probabilities in the form of:

$$P(C|F) = P(S|F) \times P(T|S) \times V(L|T), \text{ for people} \qquad \textbf{(3)}$$

and:

$$P(C|F) = P(S|F) \times V(P|T) \times \text{value, for fixed property} \qquad \textbf{(4)}$$

In assessing the consequences, allowance should be taken of the population density, location of any facility on the slope, degree of protection offered to persons by the type of facility they are housed in, and the degree of warning available.

Consequence analysis requires the scale (ie volume), travel distance and velocity of failure to be taken account of. The travel distance and velocity of debris depend critically on the scale and mechanisms of failure as well as the mobility of debris. The extent of the accumulation zone of the failure material at the slope toe and the velocity of the failure material are collectively an indication of the relative damage potential of landslide failure (Wong et al., 1997).

The techniques for assessment of travel distance and failure velocity are not well developed, as differences in slope morphology and slope-forming materials do not easily allow general rules to be developed. Empirical methods, using measured data to assess travel distance with due regard to the mechanisms of failure, have been attempted. Finlay et al. (1997) provide an example of this approach for Hong Kong cuts and fills using slope height and runout distance relationships (Appendix B).

Wong et al. (1997) have developed relationships between debris travel distance and failure volume for different failure mechanisms for Hong Kong examples. The relationship is described in terms of the travel angle, which is defined as the inclination of the line joining the far end of the debris to the crest of the landslide scarp (Appendix B). They found that the travel of landslide debris is affected by the gradient downslope of the failure and that the travel angle better accounts for such effects than slope height and runout relationships.

The debris travel distance relationships provided by Wong et al. (1997) are likely to differ significantly from those in New Zealand because of different rainfall characteristics and slope materials, but are indicative of the type of empirical relationships that it may be possible to develop in this country given enough data.

3.1.4 Risk estimation

The calculation of risk is essentially a mathematical manipulation of the probability of failure, P(F), the elements at risk, and the consequences of failure. Numerically, this can be expressed as:

$$\text{Risk} = P(F) \times P(C|F) \qquad \textbf{(5)}$$

where: P(F) = probability of failure

and P(C|F) = the conditional probability of a consequence occurring given failure has occurred.

Based on the definitions of the conditional probability, P(C|F), provided in Section 3.1.3 (formulas 3 and 4), risk can be expressed as (Figure 3):

Risk = P(F) x P(S|F) x P(T|S) x V(L|T), for people **(6)**

and

Risk = P(F) x P(S|F) x V(P|T) x value, for fixed property **(7)**

There are a number of ways that the various components of risk can be determined including:

i) *Subjective judgement.* In many cases, there will be a degree of subjectivity in the estimation of either the probability or the consequences of failure. Alternatively, for many situations such as those involving relatively small developments such as residential subdivisions, it will not be economically feasible to carry out detailed geotechnical investigations to accurately quantify the probability of failure, and a more qualitative risk assessment can be completed. This is usually achieved by means of ranked attributes on the basis of subjective judgement, using descriptive terms for the magnitude of the hazard, the probability of failure and the consequences.

An example of this approach has been proposed by Fell (1994), and the assessment terminology definitions are summarised in Table 3. By assigning ranges to the factors used to calculate the risk (i.e. probability of failure, and consequences), the investigator can allow for uncertainty in the assumptions, and test for those factors which are likely to have the greatest affect on risk. For example, the probability of failure is generally the one aspect of the risk estimation calculation which has the greatest uncertainty, and by assigning a range for this factor, one can determine how sensitive the resulting estimate of risk is to this aspect.

The results of a risk assessment based on subjective judgement should not be taken as representing the absolute risk, but rather as an indicator of the relative risk between different parts of the landslide, and as an indicator of whether a greater degree of investigation is required in estimating the risk. It also allows for the effect of proposed mitigation measures to be considered.

The definitions provided in Table 3 have some limitations in that the terminology used to describe the hazard magnitude is relevant for large scale instability, but is unlikely to be appropriate at the level of the building site where small scale events are more likely. Accordingly, in the New Zealand context, there is a need to develop more relevant qualitative risk assessment terminology.

Table 3: Qualitative risk assessment terminology definitions, from Fell (1994)

Magnitude M			**Probability** P			**Hazard** $H = M \chi P$		**Vulnerability** V *		**Specific Risk** R *	
M	**Description**	**Volume** (m^3)	P	**Description**	**Annual** P	H	**Description**	V	**Description**	R	**Description**
7	Extremely large	>5,000,000	12	Extremely high	-1	30	Extremely high	0.9	Very high	0.1	Very high
6	Very large	>1,000,000, <5,000,000	8	Very High	-0.2	20, <30	Very high	0.5, <0.9	High	0.02, <0.1	High
5	Medium-large	>250,000, <1,000,000	5	High	-0.05	10, <20	Low	0.1, <0.5	Medium	0.005, <0.02	Medium
4	Medium	>50,000, <250,000	3	Medium	-0.01	7, <10	Medium	0.05, <0.01	Low	0.001, <0.05	Low
3	Small	>5,000, <50,000	2	Low	-0.001	3, <7	Low	<0.05	Very Low	0.0001, <0.001	Very Low
2.5	Very small	>500, <5,000	1	Very Low	-0.0001	2	Very Low				
2	Extremely small	<500									

* For property loss, not loss of life

ii) *Event tree method.* This method uses probabilistic algebra to trace the various component events of the landslide failure using ‘event tree’ analysis to show the relationship between events in time or logical sequence. Only components that could cause landslide failure are fully developed. Some component probabilities of event tree construction are developed solely from subjective judgement while others are based on analysed probabilities and/or available statistics relating to the failure trigger mechanisms.

An example of an event tree construction for the case of an assessment of the effectiveness of various landslide mitigation measures is provided in Appendix C.

iii) *Consequence model.* This method involves the use of a rational framework based on the factors which affect failure probability and failure consequences, judged to be relevant to the particular hazard under consideration. It requires a high level of understanding of each of the specific risk estimation components and can be applied to one or two hazards or collectively across a wide range of hazards. An assessment of the risk to motorists from rockfall hazard on British Columbia highway provided by Bunce et al. (1996) is an example of this approach. A New Zealand example of this approach is provided by Riddolls & Grocott (in press) where the optimum road maintenance strategy was identified for a stretch of highway subject to rock fall, taking into account the tradeoff between the risk to road users and the cost of maintenance implementation.

There are a number of ways by which the estimate of risk from a risk analysis can be expressed. These relate to loss of life, financial, and socio-economic values (IUGS, 1997):

Loss of life:

- risk of death to an individual
- risk of death to any member of the population, referred to as societal risk, and expressed as frequency versus number of fatalities (f-N charts) or F-N or frequency of N or more fatalities (F-N charts)
- annualised potential loss of life (PLL)
- cost to save a life (which is not the same as the cost society places on a life)

Financial:

- cost benefit ratio
- financial capability
- annualised cost
- frequency of accidents

The calculation of risk for any particular landslide is based on the summation of the full range of landslide hazards taking account of their respective trigger mechanisms, volumes, runout distances, velocities, and positions on the slope, as well as the respective vulnerabilities for each type of hazard. Commonly, it is the smaller, more frequently occurring hazards which dominate the risk equation, rather than the extreme magnitude but very low probability event (Fell & Hartford, 1997).

3.1.5 Limitations of risk analysis

There are a number of well known limitations attached to risk analysis, which have been summarised by IUGS (1997):

- the judgement content of the inputs may well result in values of assessed risks with considerable inherent uncertainty
- the variety of approaches that can reasonably be adopted to assess risk can result in significant differences in outcome if the same problem is considered separately by different practitioners
- revisiting an assessment can lead to significant changes due to improved levels of data, a different method, or changing circumstances
- the inability to recognise a significant hazard and the consequential underestimation of the risk
- the results of an assessment are seldom verifiable, though peer review can be useful
- the methodology is currently not widely accepted, and thus there sometimes is an aversion to its application
- it is quite possible that the costs of an assessment may outweigh the benefit of the techniques in making a decision, especially where complex sets of data are required
- it is difficult to accurately assess risk for low probability events.

3.2 Risk Assessment

3.2.1 Concepts of risk assessment

The objective of risk assessment is to help define the limits of acceptable risk that are placed on members of the population, either as individuals or collectively, through exposure to hazards such as landslides. The limits of acceptable risk can be defined in a number of ways including loss of life, financial, and socio-economic values (Section 3.1.4).

The use of financial criteria for defining acceptable risk is often contentious, as they require a value to be placed on human life, and therefore encounter ethical and moral problems. Socio-economic values are usually employed where significant adverse environmental effects are possible, as they help to identify the tradeoffs between the benefits of a project and the potential adverse costs associated with the risk of failure.

More commonly, risk acceptance criteria are defined within a legal framework and the values and expectations of the society within which they operate. In the context of our legal framework, risk is commonly given in terms of the probability of a life lost, expressed as either risk of death to an individual, or the risk of death to any member of the population, termed societal risk. It is this concept of the probability of a life lost which is generally adopted as a measure of determining the risk to the population from unstable slopes, and has been adopted in other engineering disciplines such as industrial hazards and dam construction.

The concept of societal risk is based on the demand by society for a higher level of protection (or lower risk) as the number of lives that would be lost from a ‘failure’ (of any kind) increases. This is normally depicted by means of an F-N chart, whereby the vertical axis contains F, the probability of incremental loss of life exceeding the value N, which is given on the horizontal axis. In contrast, the individual risk is based on the risk to the identified individual who has the highest probability of life lost due to failure. Typically, the objective values of acceptable risk of life loss for this most critically exposed identifiable individual would be lower than those at N = 1 for societal life loss for a random individual.

The United Kingdom Health and Safety Executive (HSE, 1988) have promulgated the use of the terms ‘tolerable risk’ and ‘negligible risk’ (Figure 5). The lower limit of tolerable risk is the level below which the risk is considered to be so small that it is ‘de minimis’ or too small to be worth dealing with or to be held responsible for (Shortreed et al., 1995). However, the point at which a risk becomes a ‘de minimis’ risk will depend on the benefits which are being realised and the practicality and the cost of reducing the risk.

The upper limit of the ‘tolerable risk’ range is a level above which the risk is viewed as unjustified due to the benefits of accepting the risk being simply not high enough. However, this upper level is only tolerated if risk reduction is impracticable or the cost of doing so is very high relative to the benefits gained. This requires the owner/developer to demonstrate the level at which the risk has been reduced to the point at which the risk is considered to be as low as reasonably practicable (ALARP) (Figure 5). The ALARP principle is one at which the risk has been reduced to a level when most (but not all) of the public are satisfied (Health & Safety Executive, 1988).

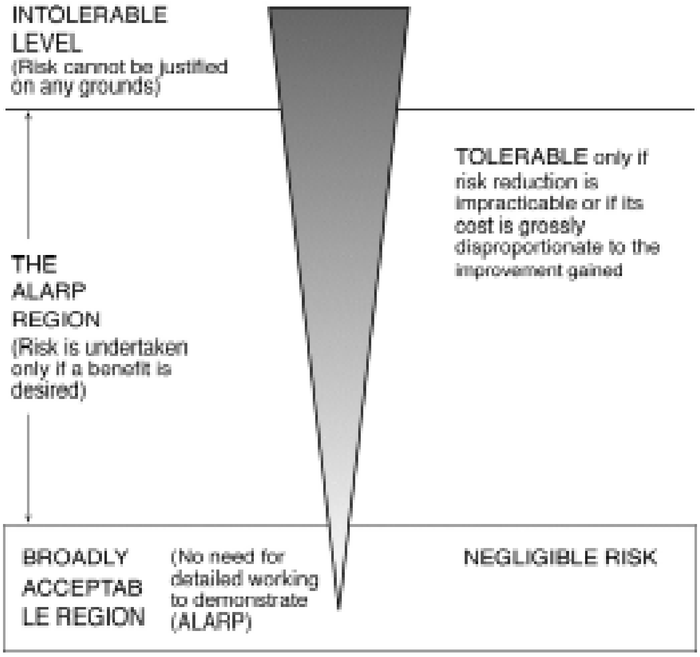


Figure 5: Levels of risk and the ‘ALARP’ principle (from Health & Safety Executive, 1998)

In defining acceptable and tolerable levels of risk, a distinction is also made between voluntary risk which we assume ourselves and involuntary risk which is imposed on us. In the context of risk acceptance criteria, it is generally accepted that the risk levels are based on involuntary risk as we are “loathe to let others do unto us what we happily do to ourselves” (Starr, 1969).

3.2.2 Existing risk acceptability criteria

The calculation of risk is merely an academic exercise and has no relevance unless the results are compared against acceptability criteria. In the context of landslide risk assessment to date, there are no accepted risk criteria which have been adopted anywhere by a government or national or international technical society (Fell & Hartford, 1997).

Societal risk acceptance criteria have been promulgated for a range of other engineering disciplines such as potentially hazardous industries and dam safety. Risk acceptance criteria for these and other non-landslide hazards have been detailed and described by numerous sources of which several of the most widely referenced include Whitman (1984), BC Hydro (1993), Health & Safety Executive (1988, 1989), Hong Kong Government Planning Department (1994), the New South Wales Department of Planning (1992), Salmon & Hartford (1995), ANCOLD (1994), Nielson et al. (1994) and USBR (1989) (Appendix D).

Morgan (1991) summarised the occurrence of fatalities from landslides in Japan, the European Alps and Canada, from which he developed a “suggested threshold of acceptability for individual landslides for Canada” (Appendix E). Cave (1992) produced hazard acceptability thresholds for development approvals for the Fraser-Cheam Regional District of British Columbia, Canada (Appendix E). This encompassed flooding, debris flows/debris torrents, erosion, small scale localised landslip, major catastrophic landslip, rockfall, and snow avalanche. Hungr et al. (1993) and Sobkowicz (1996) discuss tolerable risk criteria for a study of natural landslides on a potential site at the Cheekeye Fan, British Columbia (Appendix E).

Fell & Hartford (1997) provide a summary of societal risk criteria promulgated by many of those detailed above (Appendix E). The significance of this summary chart is mainly at the high number of fatalities (high N) end of the F-N plot, where there would appear to be an acceptance that the probability of life loss cannot realistically be reduced below about 10^{-5} to 10^{-6} per annum, regardless of the population at risk.

Fell & Hartford (1997) also summarise the risk of death to a single identifiable individual in a specified location based on criteria provided by those detailed above and others (Table 4):

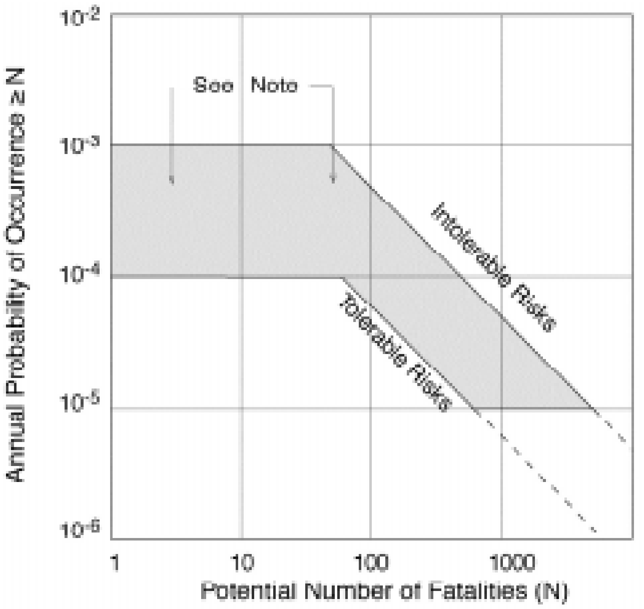
Table 4 : Summary of the risk of death to an individual (from Fell & Hartford, 1997)

Organisation	Acceptable and Tolerable Risk Criteria - per year	
	Lower bound (acceptable)	**Upper bound (tolerable)**
Health and Safety Executive (1989)	10^{-6} of dangerous dose equivalent to 0.33 x 10^{-6}	10^{-5} of dangerous dose equivalent to 0.33 x 10^{-5}
Health and Safety Executive (1988)	10^{-6} broadly acceptable	10^{-3}, divide between just tolerable and intolerable 10^{-4} any individual member of public from large scale industrial hazard
New South Wales Department of Planning (1992)		10^{-6} residential 5 x 10^{-5} industrial
Hong Kong Government Planning (1994)	Not defined	10^{-5}
BC Hydro (1993)		10^{-4}
ANCOLD (1994) New and upgraded dams		10^{-6} average 10^{-5} person most at risk
ANCOLD (1994) Existing dams		10^{-5} average 10^{-4} person most at risk
Finlay & Fell (1997)	10^{-5} to 10^{-6} 10^{-3} to 10^{-4} acceptable for property	10^{-3} tolerated

3.2.3 Acceptable and tolerable risk guidelines for landsliding

Several authors at the 1997 international workshop on the state-of-the-art QRA of landsliding have presented proposed guidelines for assessing the risks of life loss from landsliding. Morgan (1997) presented guidelines for societal risk criteria from naturally occurring slope hazards in Canada (Figure 6). The guidelines were based on documented landslide events within Canada and elsewhere and on published guidelines on the risk of life loss by others. However, Morgan pointed out that “since country-wide landslide occurrence models vary throughout the world, tolerable risk criteria can also be expected to vary”, meaning that countries which have a history of life loss from landslides can expect to have different acceptable risk criteria compared to those where deaths are less common from slope hazards.

The criteria in Figure 6 have been compiled on the basis of a wide range of data and we suggest that they could be used by New Zealand practitioners as a guideline for acceptable risk.



Note: Risks should be reduced in accordance with the ALARP principle with emphasis on those risks falling within the shaded area. The expected annual fatalities should not exceed 5×10^{-3} without justification.

Figure 6 : Proposed guidelines for assessing risks to life from naturally occurring slope hazards (from Morgan, 1997)

Fell & Hartford (1997) provide suggested tolerable risk criteria for the case of the specific identifiable individual at risk from landsliding involving engineered slopes (Table 5):

Table 5: Possible tolerable individual risk criteria for landsliding (for engineered slopes) (from Fell & Hartford, 1997)

Situation	Tolerable risk for loss of life
Existing slopes	10^{-4} person most at risk 10^{-6} average of persons at risk
New slopes	10^{-5} person most at risk 10^{-6} average of persons at risk

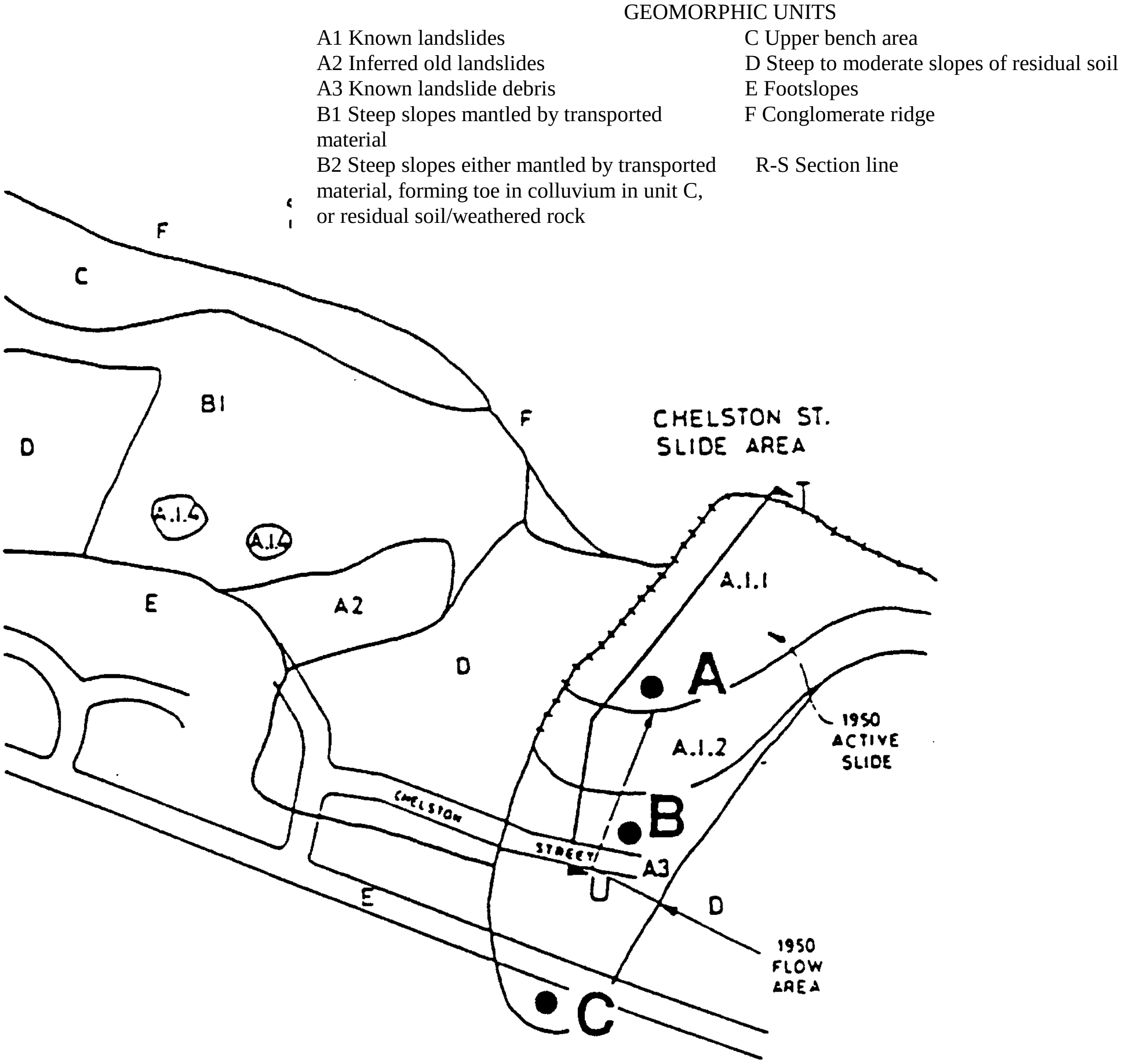
Fell & Hartford (1997) consider that the situation for natural slopes affected by landsliding is less clear, but that the general public will tolerate much higher individual risks from natural slopes (compared with engineered slopes), possibly of the order of 10^{-3}.

3.3 Examples of Slope Stability Quantitative Risk Assessment

3.3.1 Example 1

Fell (1994) provides an example of the use of QRA methods for residential housing threatened by debris flows at Speers Point, Newcastle. This is reproduced here to illustrate the methodology.

"Figure (7) is a plan of landsliding at Speers Point, Newcastle. The landslide area is in coal-measure rocks and is described in Fell et al. (1987). The landslide has been investigated and monitored in some detail, and the annual probability of landsliding has been assessed by relating piezometric levels to rainfall (Fell et al., 1991). Landsliding of the area shown as A.1.1 occurred in 1930 (poor records), 1950, 1951 (when a debris flow resulted, flowing down slope about 250 m into area A3), and again in 1988. As detailed in Fell et al. (1991) the estimated probability of landsliding was between 0.1 and 0.04 (say 0.05). The probability that, given landsliding occurs, a debris flow occurs is, say, 0.5. The landslide has shown itself to be slow moving in the source area (A.1.1) but is likely to flow rapidly in the steep slope below (A.1.2) slowing in the debris deposit area (A3)."



GEOMORPHIC UNITS

A1 Known landslides
A2 Inferred old landslides
A3 Known landslide debris
B1 Steep slopes mantled by transported material
B2 Steep slopes either mantled by transported material, forming toe in colluvium in unit C, or residual soil/weathered rock

C Upper bench area
D Steep to moderate slopes of residual soil
E Footslopes
F Conglomerate ridge

R-S Section line

Figure 7: Plan of landsliding at Chelston Street, Speers Point

The risk of damage to houses sited at A, B and C, and the risk of death to an individual occupying houses A, B and C have been determined by Fell (1994). The risk analysis calculations presented in the original paper by Fell (1994) have been modified to reflect the definitions for QRA analysis presented in Figure 3. The risk analysis presented in Fell (1994) for death to an individual has also been modified to include temporal probability which was not considered in the original analysis. Results of the modified risk analysis for this case history are presented in Tables 6 and 7.

Table 6: Chelston Street, Speers Point landslide, specific risk of death to an individual house occupant (adapted from Fell et al., 1987)

Element at Risk	Probability of Failure P(F)	Spatial Probability P(S|F)	Temporal Probability P(T|S)	Vulnerability V(L|T)	Specific Risk to Life S_r
House A Occupant	0.05	1.0	0.6	0.05	0.0015
House B Occupant	0.05	0.5	0.6	0.3	0.0045
House C Occupant	0.05	0.5	0.6	0.01	0.00015

Table 7: Chelston Street, Speers Point landslide, specific risk of damage to house (adapted from Fell et al., 1987)

Element at Risk	Probability of Failure P(F)	Spatial Probability P(S|F)	Temporal Probability P(T|S)	Vulnerability V(L|T)	Specific Risk of House Damage S_r
House A	0.05	1.0	1.0	1.0	0.05
House B	0.05	0.5	1.0	0.9	0.0225
House C	0.05	0.5	1.0	0.05	0.00125

It can be seen that the same landslide has a wide range of specific risk depending on the proximity of the house to the landslide, and whether one is considering loss of life or damage.

3.3.2 Example 2

This is a hypothetical example based on the cross section shown in Figure 8 (extracted from Figure B4 of Worley Consultants Ltd (1987)). An assessment is made of the risk of death to the most exposed individual occupant of a house which is subject to possible failure of a cut slope and foundation fill.

Stability analyses indicate that the probability of failure, P(F), of the cut slope adjoining the house for a 50 year return period storm event is 0.02, while a figure of 0.05 is indicated for failure of the fill for the same storm event. Consequence analyses indicate that failure of the cut slope will result in rapid movement of a small volume of material, causing severe impact to one side of the house. Failure of the fill is considered to occur as deformation of the ground surface over a period of hours rather than rapid movement, causing significant distress to the house. While the possibility of rapid displacement of the fill causing loss of life to the house occupants cannot be dismissed, this scenario is judged less likely. In both cases, the spatial probability, P(S|F), has been determined by assessing the probable dimensions of the failures as a proportion of the side of the house likely to be affected by failure.

Analyses of the risk of death to the most exposed house occupant for both cut slope and foundation failure are provided for in Table 8.

Table 8: Specific risk of death to the most exposed individual house occupant for the conditions given in Figure 8

Element at Risk	**Probability of Failure P(F)**	**Spatial Probability P(S|F)**	**Temporal Probability P(T|S)**	**Vulnerability V(L|T)**	**Specific Risk to Life S_r**
House Occupant, cut slope failure	0.02	0.35	0.6	0.5	0.0021
House Occupant, fill failure	0.05	0.9	0.6	0.01	0.00027

Even though the house is potentially affected by failure of fill over a much larger area, the specific risk of death to an individual is considered to be much less for this hazard, compared to failure of the cut slope, due to differences in the assessed vulnerability of the individual to the probability of death.

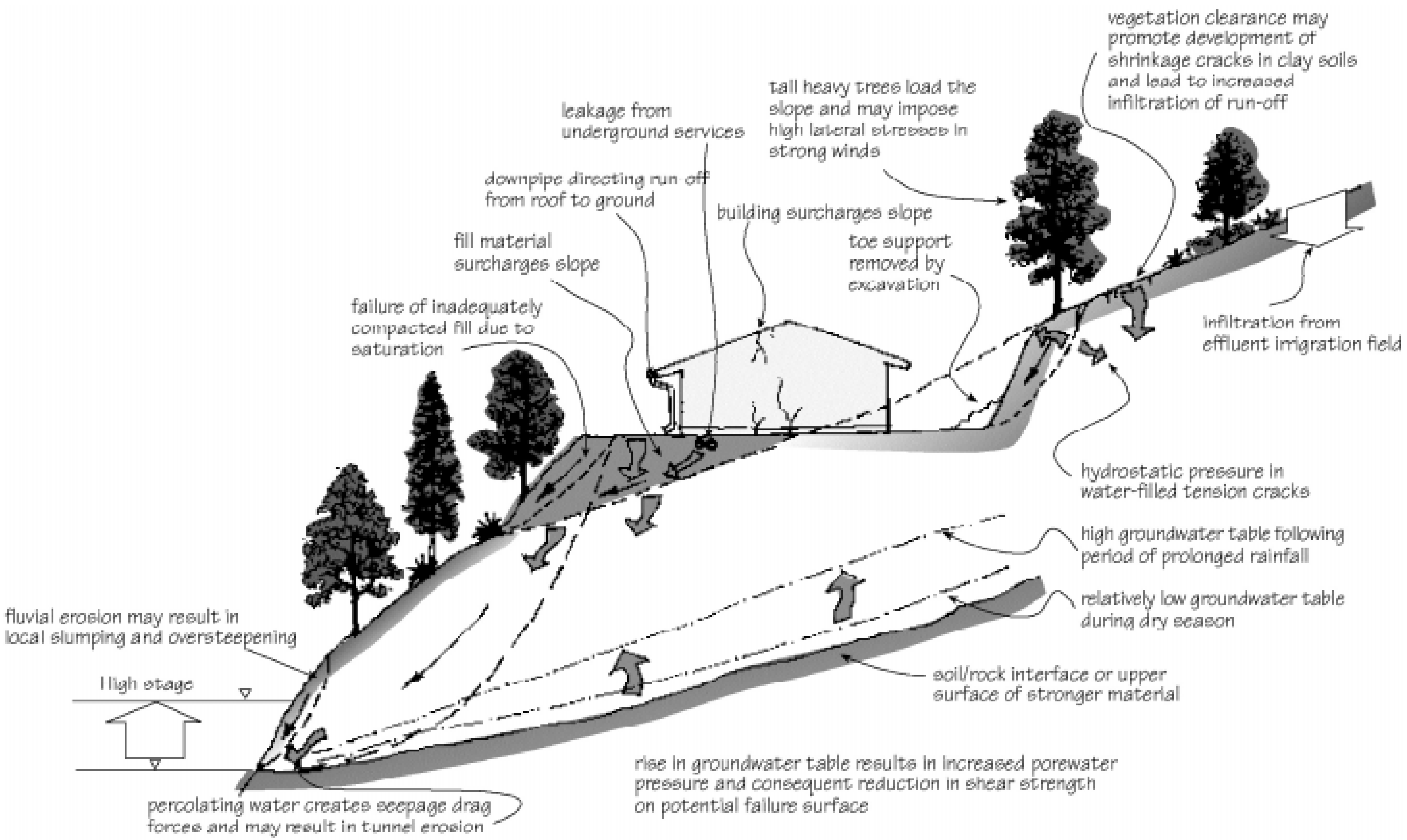


Figure 8: Cross section illustrating Hypothetical QRA Example (extracted from Figure B4 of Worley Consultants Ltd., 1987)

4. SUGGESTIONS FOR USE OF QUANTITATIVE RISK ASSESSMENT METHODS IN NEW ZEALAND

4.1 Relevant Legislation

The development of land subject to slope instability hazards is governed by several pieces of legislation.

The Resource Management Act (RMA) 1991, under section 106 provides for the refusal of subdivision consent by a territorial authority where it is not satisfied that adequate provision has been made for the protection of land/or buildings against *erosion, falling debris, subsidence, slippage, or inundation* from any source. Where land is subject to any of these hazards, section 220 of the Act provides an issuing authority with some flexibility to grant subdivision consent subject to conditions requiring that the land be protected from *erosion, falling debris, subsidence, slippage, or inundation*.

Section 104 of the RMA requires the issuing authority to have regard to any actual and potential effects on the environment when issuing subdivision consents, land use consents and water permits, which could include the effects of land stability on both the land to be subdivided and adjoining land.

Building consents for any work are issued under the Building Act 1991 (unless the work is specifically excluded under Clause 5(2) or listed in the Third Schedule of the Act), while legal requirements for building construction are contained in the New Zealand Building Code, which appears in the legislation as the First Schedule of the Building Regulations 1992.

A key provision of the Building Act 1991 is Section 36 (1) which states that the issuing authority shall refuse to grant a building consent where the land could be subject to instability (*erosion, avulsion*[1]*, alluvion*[2]*, falling debris, subsidence, inundation or slippage*) unless it is satisfied that adequate provision is made to protect the land/or building or to restore damage.

In situations where the building work will not accelerate, worsen, or result in any of the specified hazards identified above, Section 36(2) of the Act allows an issuing authority to grant a building consent subject to an entry being entered on the Certificate of Title by the District Land Registrar which details the hazard the particular site may be subject to.

The Building Code, contains slope stability performance guidelines within Verification Method B1/VM4, Foundations, ie:

- Clause 2.1.1 The preliminary site assessment must address:
  (a) General landform, geology, and any conditions likely to facilitate landslip, soil creep etc.

---

[1] erosion arising from water (river, sea) processes

[2] deposition arising from water (river, water) processes

- Clause 3.2.1 Slope stability shall be analysed using unfactored loads. Slopes include unsupported earth face, banks and vertical ground profiles.

- Clause 3.2.2 Permanent slopes shall have a factor of safety against instability of no less than 1.5.

- Clause 3.2.3 The factor of safety for temporary slopes shall be evaluated for each specific case, having regard to confidence in the soil and rock data and the consequence of failure.

There is ongoing debate amongst New Zealand geotechnical practitioners as to the appropriateness of Verification Method B1/VM4 with respect to the requirement for the adoption of a minimum factor of safety for permanent slopes of 1.5. This is because many slopes which have been and are presently being developed are known to have factors of safety less than 1.5, yet have performed adequately. Furthermore, there is no qualification on the load conditions under which an analysis is required to be carried out, on the selection of the appropriate shear strength and groundwater conditions, or on selection of the appropriate type of analysis.

Territorial authorities have responsibility for administering the Building Act & Regulations in response to applications for building consent. Where building proposals involve consideration of slope stability, some issuing authorities have developed in-house procedures for the minimum requirements for investigation and suitability of sloping land for development, in order to comply with the requirements of the Building Act. One such authority is the Christchurch City Council which, amongst other criteria, has adopted the following criteria for the assessment of risk from rockfall and debris slide risk:

> **General**
>
> The Council believes it is important for designers/geotechnical engineers to be clear on what standard the Council expect the work to protect the land/or building work from erosion, falling debris, subsidence, inundation or slippage is being designed to.
>
> **Rock Fall Risk Assessment**
>
> Council believe it is reasonable that the design should be based on protection from the size of earthquake (a ~450yr AEP event) as used to develop the Design Spectra for buildings in NZS 4203 1992 (see also clause 2.2.2 commentary). The appropriate seismic hazard acceleration coefficients should be used to assess the likelihood of falling debris being generated and the design of mitigation measures and subsequent certification should be based on this.
>
> **Debris Slide Risk Assessment**
>
> The slopes of the Port Hills in Christchurch are prone to forming storm generated debris slides which can and historically have caused major damage to dwellings. These erosive/damaging events normally occur after long duration low intensity rainfall, especially when followed by a short burst of moderate rainfall on steep slopes.
>
> Designers/certifying engineers attention is drawn to s(7) & s(36) of the Building Act and the Building Code Clauses B1.2, B1.3.1, B1.3.3, B1.3.7, B2.3, E1.2 & E1.3.2.
>
> (To satisfy the CCC that the dwellings Building Consent is able to be released without a section (36)2 Building Act erosion title notice with respect to Debris slide risks and Inundation risks, the investigating/certifying geotechnical engineer is to confirm that: In his/her professional opinion, the new structure/dwelling is not likely to be damaged from both:

> (A debris slide generated by a low intensity four day long duration 2% return period storm (ie ~2.7 mm/hr constantly for four days or 265 mm in four days) followed sometime within the next four days by another short duration 15 minute 10% return period rainfall event (ie another 16 mm of rain in 15 minutes).

Other than the Christchurch City Council, we are not aware of any legislation either at national or local government level where the suitability of land development with regard to slope stability hazards has been couched in probabilistic terms.

4.2 Usefulness to New Zealand

It is unlikely that QRA methods will be a panacea for resolving all risks associated with the development of sloping land. This is not because New Zealand's geologic and topographic conditions render its application to be unsuitable; rather, not all slopes will be amenable to resolution of the critical factors for application of QRA, such as determination of the probability of failure for slopes where first time failure is under consideration.

However, there are many instances where development occurs on or close to land affected by slope stability where QRA methods could be usefully employed. This ranges from development on known major landslides (e.g. Tahunanui slip, Nelson), or on land judged to be of marginal stability where there is a recognised history of repeated slope instability such as shallow debris flows.

Similarly, QRA methods could be employed for the evaluation of risk associated with engineered slopes such as cuts and fills, where sufficient levels of investigation can allow issues of failure probability and failure consequences to be assessed.

Accordingly, it is considered there is considerable scope for implementation of QRA by New Zealand practitioners as a complementary method of geotechnical investigation to more conventional methods, such as the factor of safety approach. Furthermore, given the increasingly litigious society in which we live, geotechnical practitioners, in common with other professionals, are increasingly being asked to quantify how safe a particular slope is, and the techniques of QRA provide the appropriate tools.

4.3 Guidelines for Use of Quantitative Risk Assessment for Determining Slope Stability Risk

IUGS (1997) has developed a series of guidelines for QRA use including risk acceptance criteria, which are summarised as:

“(a) Estimates of risk are inevitably approximate, and should not be considered as absolute values. This is best understood by allowing for the uncertainty in the input parameters, and in reporting risk analysis outcomes.

(b) Tolerable risk criteria, such as those published for dams and potentially hazardous industries are themselves not absolute boundaries. Society shows a wide range of tolerance to risk, and the risk criteria are only a mathematical expression of the assessment of general societal opinion.

There may be cases where risks higher than the upper limit tolerable risk criteria are adopted, because the As Low As Reasonably Practicable (ALARP) principle, indicates it is not practicable to further reduce risk.

(c) It is often useful to use several tolerable risk criteria, eg. individual and societal risk, cost, to save a life.

(d) It must be recognised that QRA is only one input to the decision process. Owners, society and regulators will also consider political, social and legal issues in their assessments and may consult the public affected by the hazard.

(e) The risk can change with time because of natural processes and development. For example:

  - depletion of debris from slopes can lead to a reduction in risk with time
  - removal of vegetation by natural processes, eg. fire or human intervention, can lead to an increase in risk
  - construction of roads on a slope may increase the probability of landsliding and/or the elements at risk, and hence the risk.

(f) Extreme events should be considered as part of the spectrum of events. This is relevant to the triggering events (landslides, earthquake), the size of landslide and the consequences. Sometimes it is the smaller, more frequent, landslides that contribute most to risk, not the extreme event.

(g) Care needs to be taken when assessing risk from individual slopes, to take into account whether the risk needs to be considered along with the risk from other slopes to which the public is exposed. For example, it is probably more relevant to sum the risk from all landslides for persons travelling on a highway between their home and destination, than only to consider the risk from one slope.”

5. FUTURE WORK

The IUGS (1997) has identified a number of areas requiring further investigation in order to improve the awareness and capability of QRA methods for slopes and landslides. Those which are relevant from the view of improving the awareness and capabilities of QRA methods in the New Zealand context include:

- Case histories of the use of QRA that illustrate the process, with emphasis on the probabilistic characterisation of landslide hazard and quantification of the risk.
- Development of geomorphological methods and the use of historic landslide data for quantifying the probability of landsliding. These techniques would appear to offer scope for assessing the potential for first time slope failures.

- Collecting historic data on landslide consequences, such as property damage and injury/death to individuals, so that these can be used to determine the public's tolerance to historic risk from landsliding. This should include data from natural and engineered slopes, and from a range of environments such as transportation routes and urban settings.

- Research on the consequences of potentially destructive fast moving landslides. In the New Zealand context, this would involve assessment of local conditions affecting the travel distance and velocity of rainfall initiated, shallow debris flow-type landslides mainly of colluvial origin, as well as the vulnerability of different types of structures to being impacted.

6. CONCLUSIONS

QRA methods provide a relatively simple but powerful means of numerically expressing the risk of instability associated with development of sloping land. Their main benefit is that all cause and effect relationships associated with slope instability can be taken account of, which is not the case with conventional analysis where emphasis is on the probability of failure rather than its consequences. They also facilitate a structured approach to the understanding of slope processes and the consequences of failure.

The methodology has a number of limitations, principally that reliance on the absolute value of the calculated risk may not always be possible. However, when this is so, QRA allows the stability of a slope to be communicated in terms of guidelines understood by lay personnel so that land owners, developers and regulators are able to understand the risks on which to base their development and planning decisions. QRA methods are likely to become more important in the future as geotechnical practitioners become increasingly required to quantify how safe a slope is.

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Appendices

Appendix A: Examples of methods of calculating probability distributions of factors of safety for slope stability analysis.

Appendix B: Empirical methods for determining travel distance of debris flow.

Appendix C: Example of estimation of risk using event tree methods.

Appendix D: Suggested risk acceptance criteria for non-slope stability related hazards.

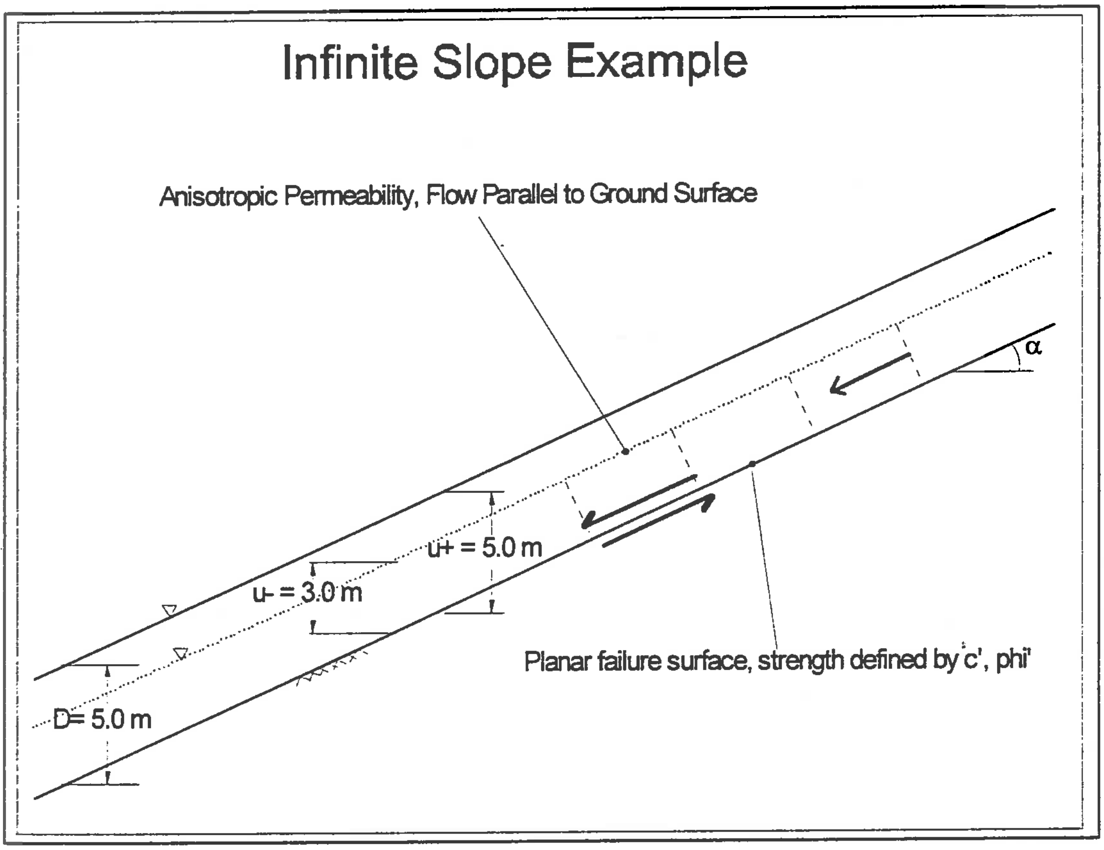
Appendix E: Suggested risk acceptance criteria for slope stability hazards.

NB The appendices for this report are only available in the printed version of the study report. This can be purchased from BRANZ by contacting them on telephone ++64 4 235 7600. Or by mail at *BRANZ Publications*, *Private Bag 50-908*, *Porirua City*, *New Zealand.* The price for this report is NZ$18.

Appendix A: Examples of methods of calculating probability distributions of factors of safety for slope stability analysis.

Probabilistic Slope Stability Analysis by Point Estimate Method, First Order Second Moment Extrapolation and Monte Carlo Simulation

The following illustrations are based on a simple infinite slope failure model as shown below.



Example after G Mostyn, Short Course on QRA for Soil and Rock Slopes, University of NSW, June, 1998

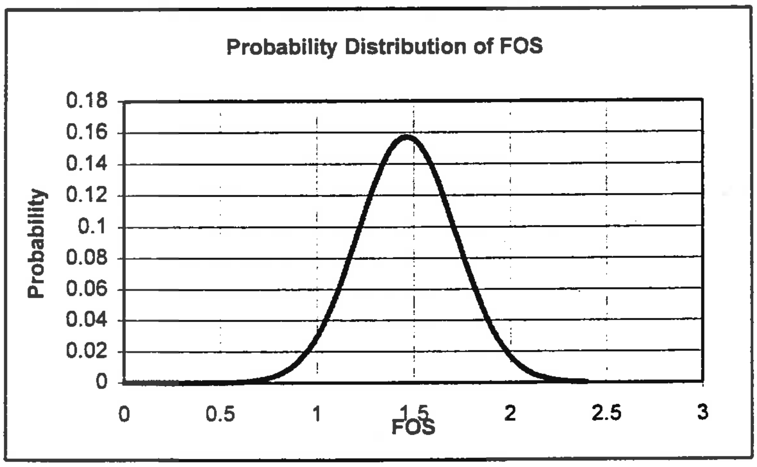
Probabilistic Slope Analysis by Point Estimate Method - Example.

Parameter	Symbol	Unit	Mean	Std Dv	Mean+	Mean-
Random variables (ie variables treated as probability distributions)						
soil internal friction angle	ϕ	deg	28	3	31	25
	Tanϕ		0.53	0.05	0.60	0.47
soil cohesion	c	kPa	10	5	15	5
slope angle	α	deg	20	1	21	19
		radians	0.349	0.017	0.37	0.33
pore water pressure	pwp				2.61	1.26
Other input variables						
soil bulk density	γ	kN/m3	20			
density of water	γω	kN/m3	9.8			
soil permeability anisotropy (kh/kv)	n				1	25
depth to failure plane	d	m	5.00			
depth of groundwater	dw	m			3.00	5.00
intermediate cal parameter	α"				*0.37*	*1.04*

Calculation

Tanϕ	c	pwp	α	FOS	
0.60	15	25.62	0.37	1.55	
0.60	15	25.62	0.33	1.73	
0.60	15	12.36	0.37	1.79	
0.60	15	12.36	0.33	1.99	
0.60	5	25.62	0.37	1.25	
0.60	5	25.62	0.33	1.41	
0.60	5	12.36	0.37	1.49	
0.60	5	12.36	0.33	1.67	
0.47	15	25.62	0.37	1.31	
0.47	15	25.62	0.33	1.45	
0.47	15	12.36	0.37	1.49	
0.47	15	12.36	0.33	1.65	
0.47	5	25.62	0.37	1.01	
0.47	5	25.62	0.33	1.13	
0.47	5	12.36	0.37	1.19	
0.47	5	12.36	0.33	1.33	
				1.47	sum

Probability distribution of FOS



Statistics of FOS distribution

Mean	μ	**1.47**
Std Dev	σ	**0.25**
Probability of failure	**P(F)**	**0.033**
Reliability Index	β	**1.84**

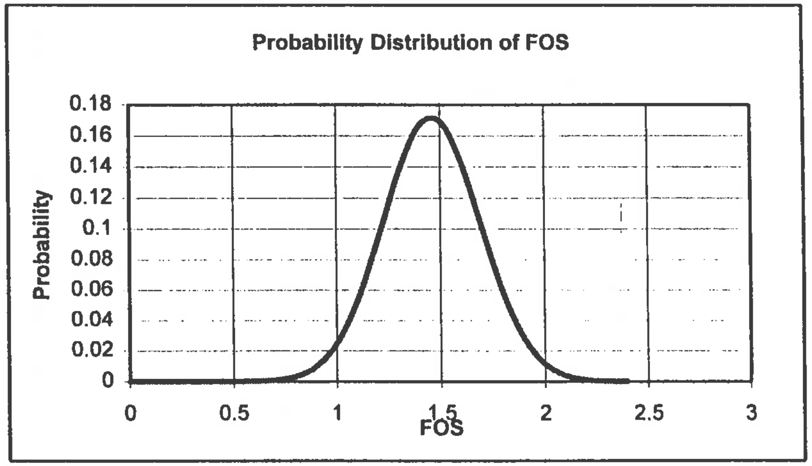
Example after G Mostyn, Short Course on QRA for Soil and Rock Slopes, University of NSW, June, 1998

Probabilistic Slope Analysis by First Order Second Moment Extrapolation - Example

Parameter	Sybmbol	Unit	Mean	Std Dv

Random variables (ie variables treated as probability distributions)

Soil internal friction angle	ϕ	deg	28	3
	Tanϕ		0.53	0.05
Soil cohesion	c	kPa	10	5
Slope angle	α	deg	20	1
		radians	0.349	0.017
Pore water pressure	pwp		18.99	6.63
Other input variables				
Soil bulk density	γ	kN/m3	20	
Density of water	$\gamma\omega$	kN/m3	9.8	
Soil permeability anisotropy **(kh/kv)**	n			
Depth to failure suface	d	m	5.00	
Depth to water	dw			



Random variable	μ_{xi}	σ_{xi}	μ_{xi} + 1%	Δ_{xi}	FOS(μ_{xi})	FOS(μ_{xi} +1%)	ΔF	Variance V[xi]	$(\Delta F/\Delta xi)^2$- V[xi]	% contributions
Tanϕ	0.532	0.050	0.537	0.005	1.458	1.469	0.0115	0.0025	0.0116	21.53
c	10.000	5.000	10.100	0.100	1.458	1.461	0.0031	25.0000	0.0242	44.81
pwp	18.990	6.630	19.180	0.190	1.458	1.455	-0.0031	43.9569	0.0120	22.27
α(rads)	0.349	0.017	0.353	0.003	1.458	1.442	-0.0157	0.0003	0.0062	11.39

Statistics of FOS distribution

	Total V[F]	**0.0540**
Mean	**μ**	**1.46**
Std Dev	**σ**	**0.23**
Probability of failure	**P(F)**	**0.024**
Reliability Index	**β**	**1.97**

Probabilistic Slope Analysis by Monte Carlo Simulation - Example

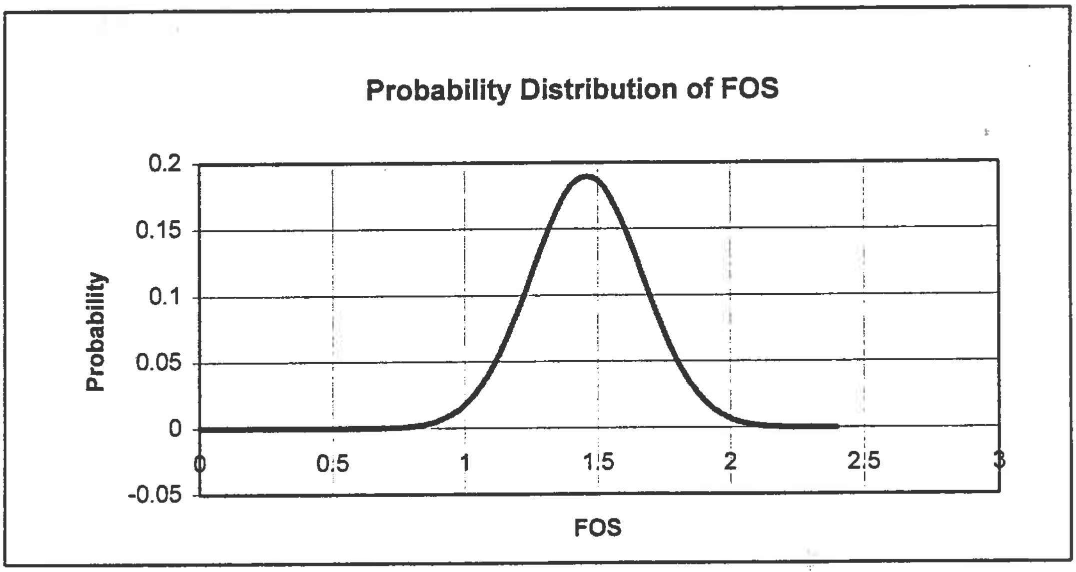
Parameter	Symbol	Unit	Mean	Std Dv	@risk probability function
Random variables (ie variables treated as probability distributions)					
soil internal friction angle	ϕ	deg	28	3	
	Tanϕ		0.53	0.05	0.53
soil cohesion	c	kPa	10	5	10.00
pore water pressure	pwp		18.99	6.63	18.99
soil bulk density	γ	kN/m3	20		
slope angle	α	deg	20	1	
		radians	0.349	0.017	0.35
Other input variables					
density of water	γω	kN/m3	9.8		
soil permeability anisotropy	n				
depth to failure plane	d	m	5.00		
depth of groundwater	dw		3.00	5.00	

Calculation

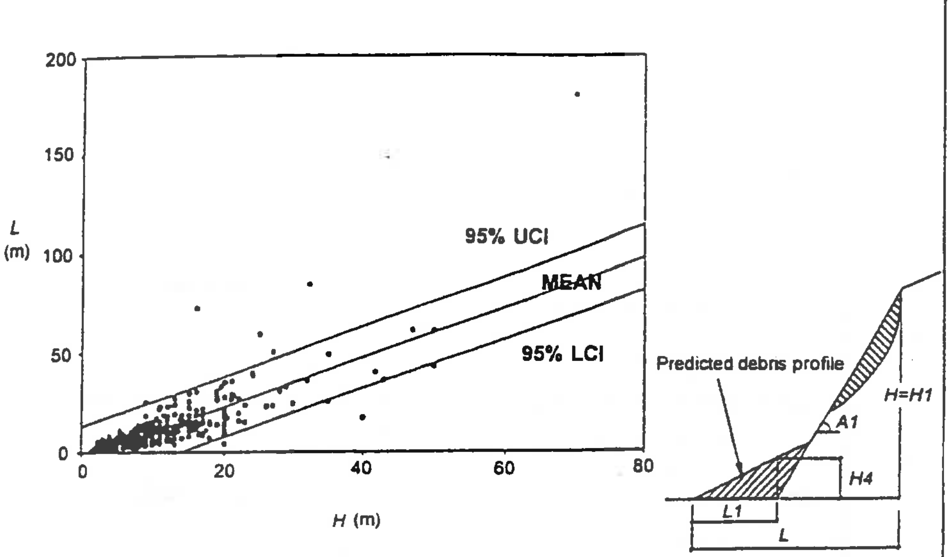
E(FOS)	**1.46**

Statistics of FOS distribution

Mean	μ	**1.46**
Std Dev	σ	**0.21**
Probability of failure	P(F)	**0.014**
Reliability Index	β	**2.19**

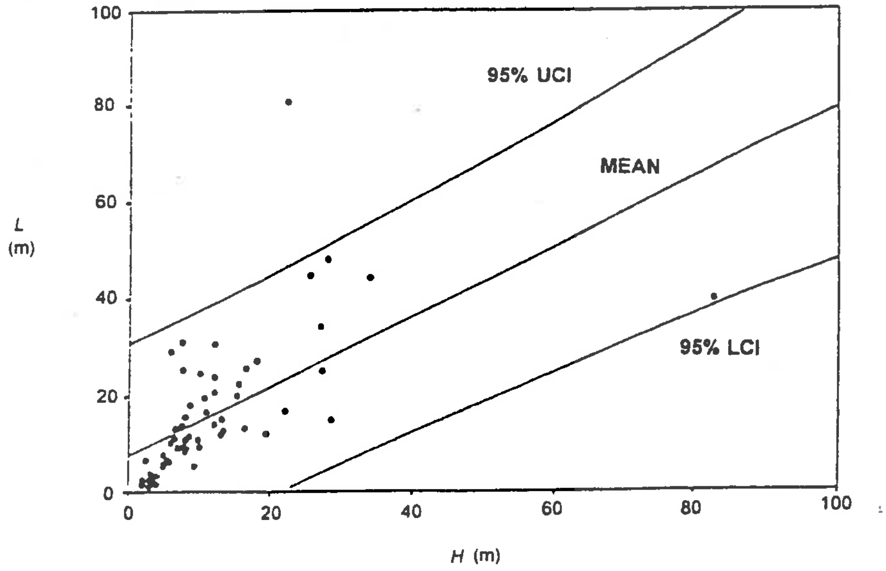


Appendix B: Empirical methods for determining travel distance of debris flow.



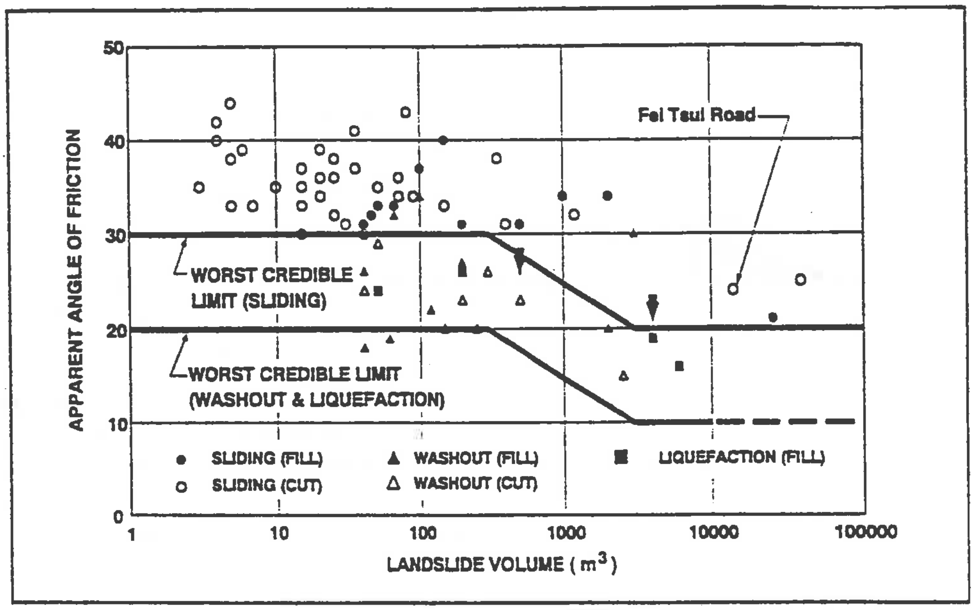
Problem definition for a cut slope runout distance prediction.

(a) Correlation between H and L for Hong Kong Cuts, $R^2 = 0.64$



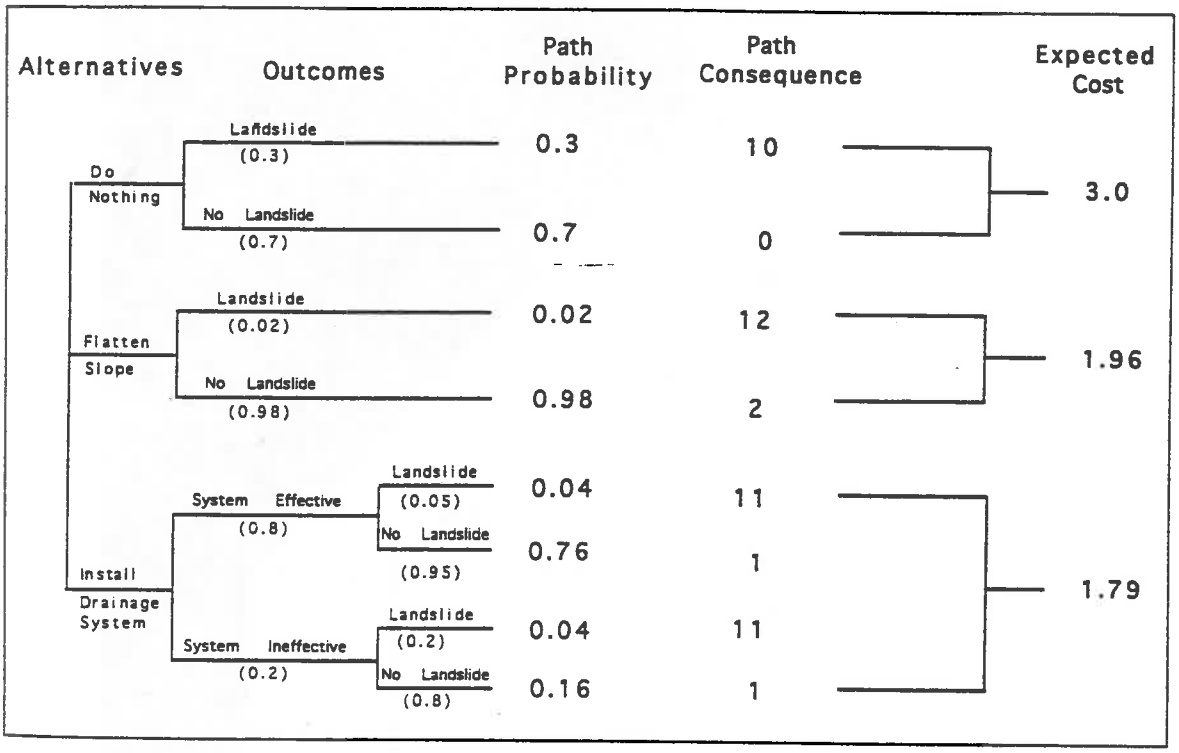
(b) Correlation between H and L for Hong Kong Fills, $R^2 = 0.36$

Empirical Correlations for Travel Distance of Debris
(Extracted from Finlay et al, 1997)



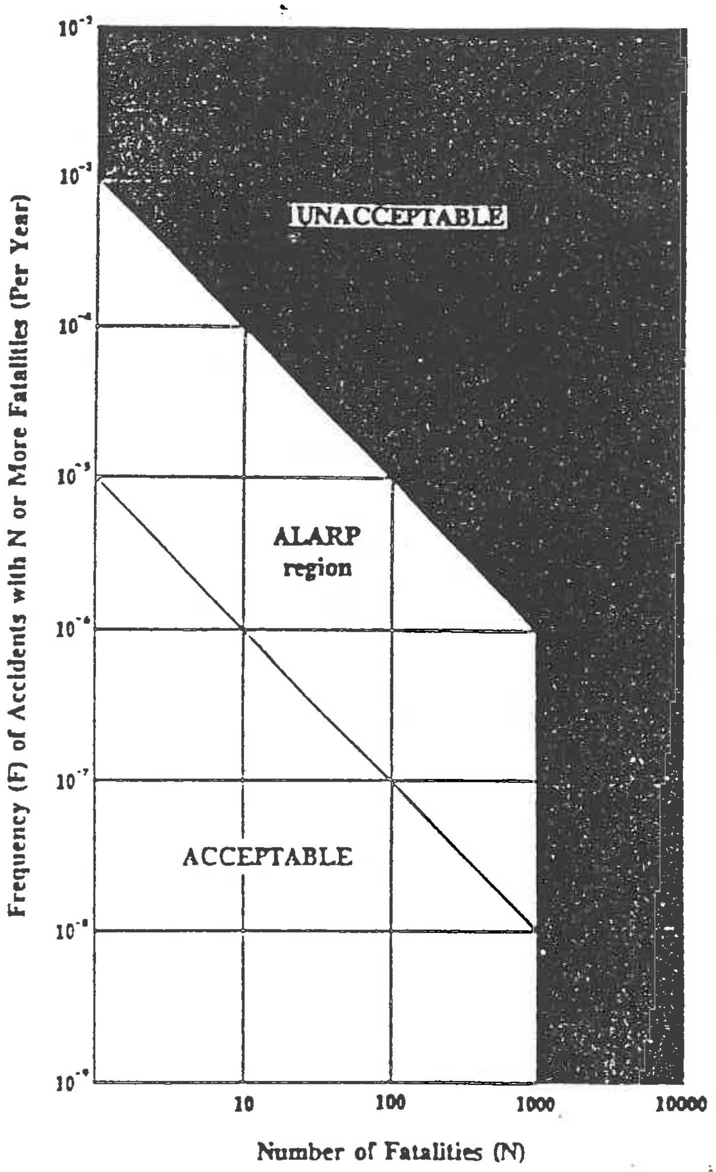
Data on Debris Mobility for Different Mechanisms and Scales of Landslides in Hong Kong (From Wong et al., 1997)

Appendix C: Example of Estimation of Risk Using Event Tree Methods

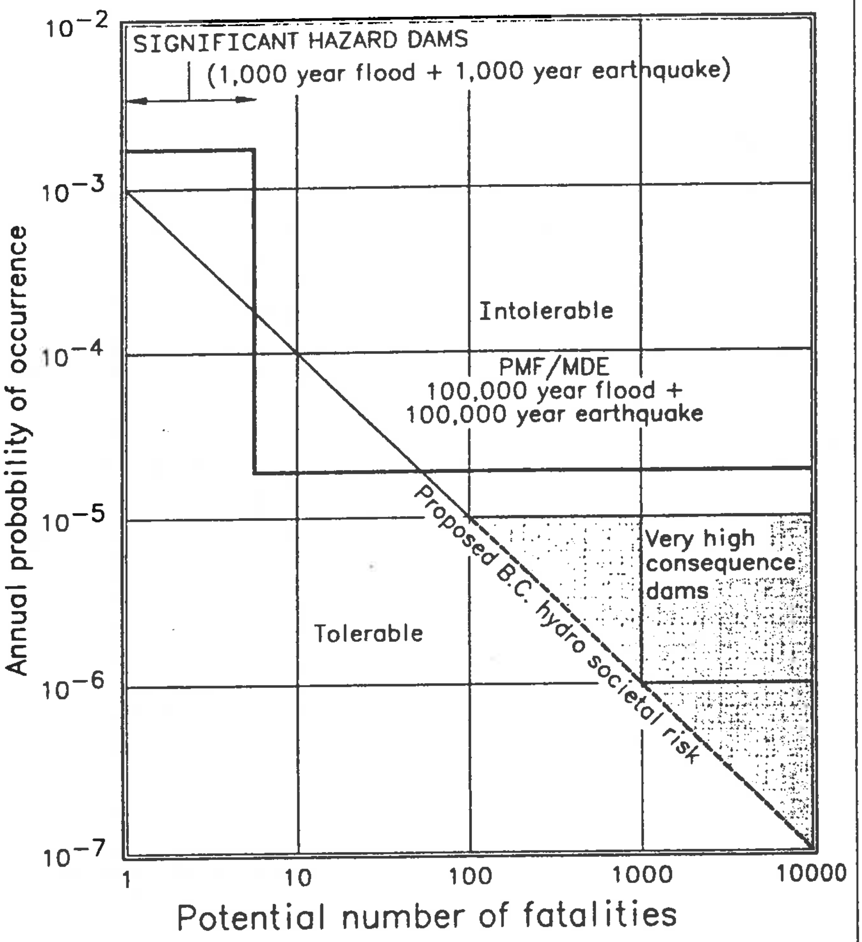


(From Turner & Schuster, 1996)

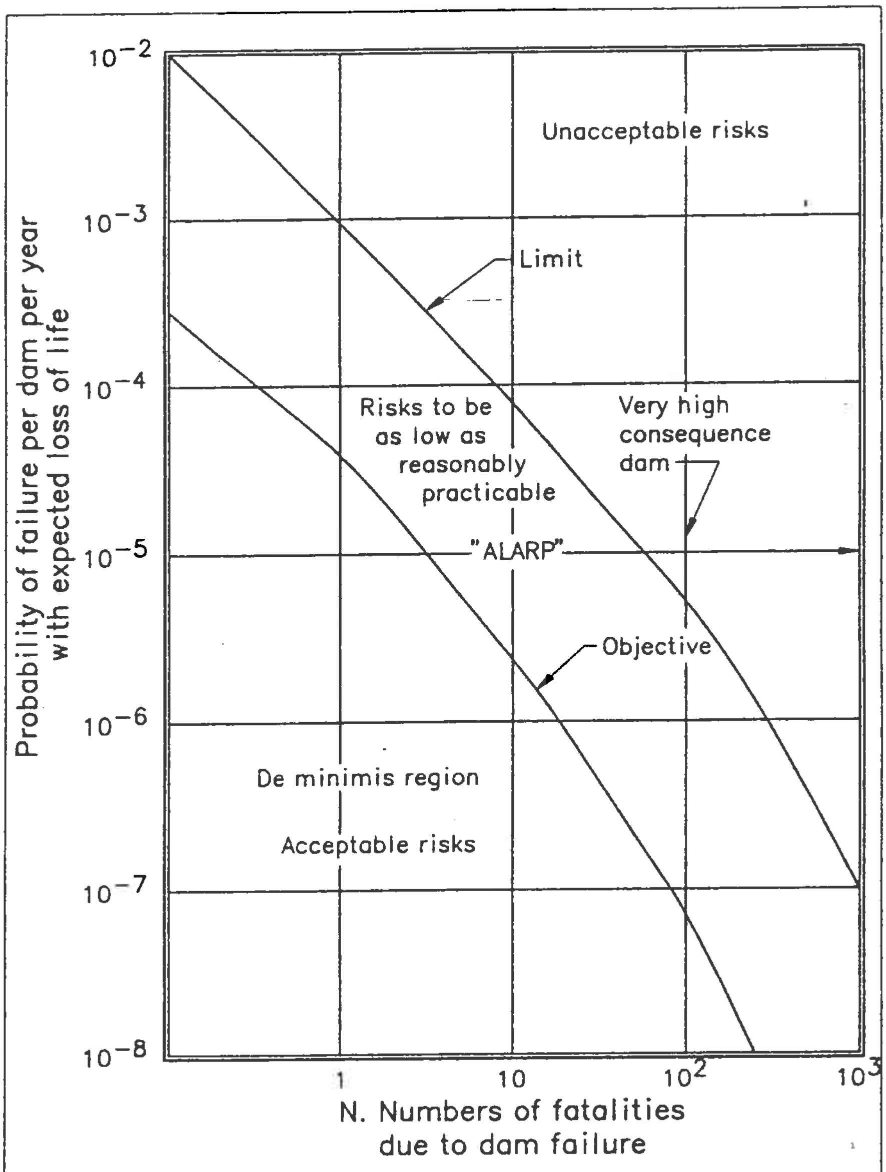
Appendix D: Suggested risk acceptance criteria for non-slope stability related hazards.



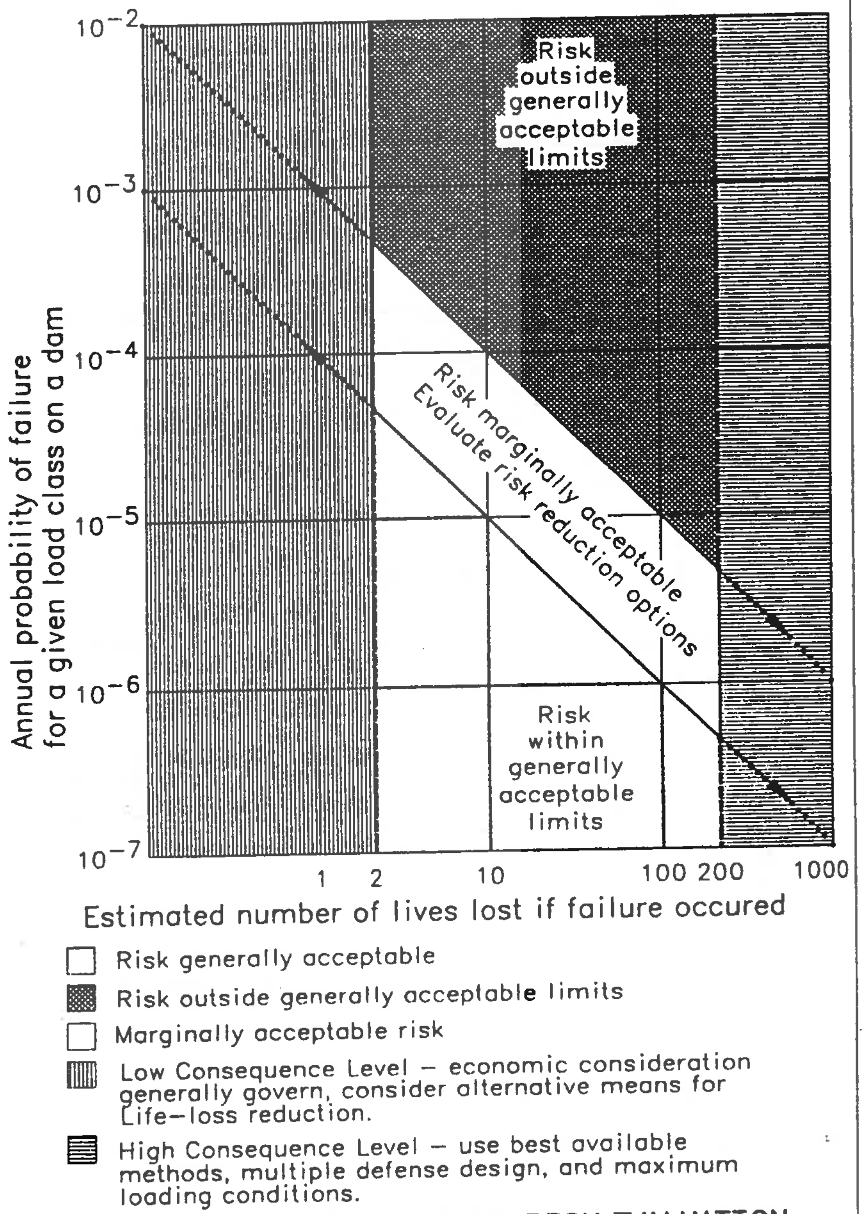
Hong Kong Government Planning Department (1994) societal risk criteria.



PROPOSED B.C. HYDRO SOCIETAL RISK CRITERIA

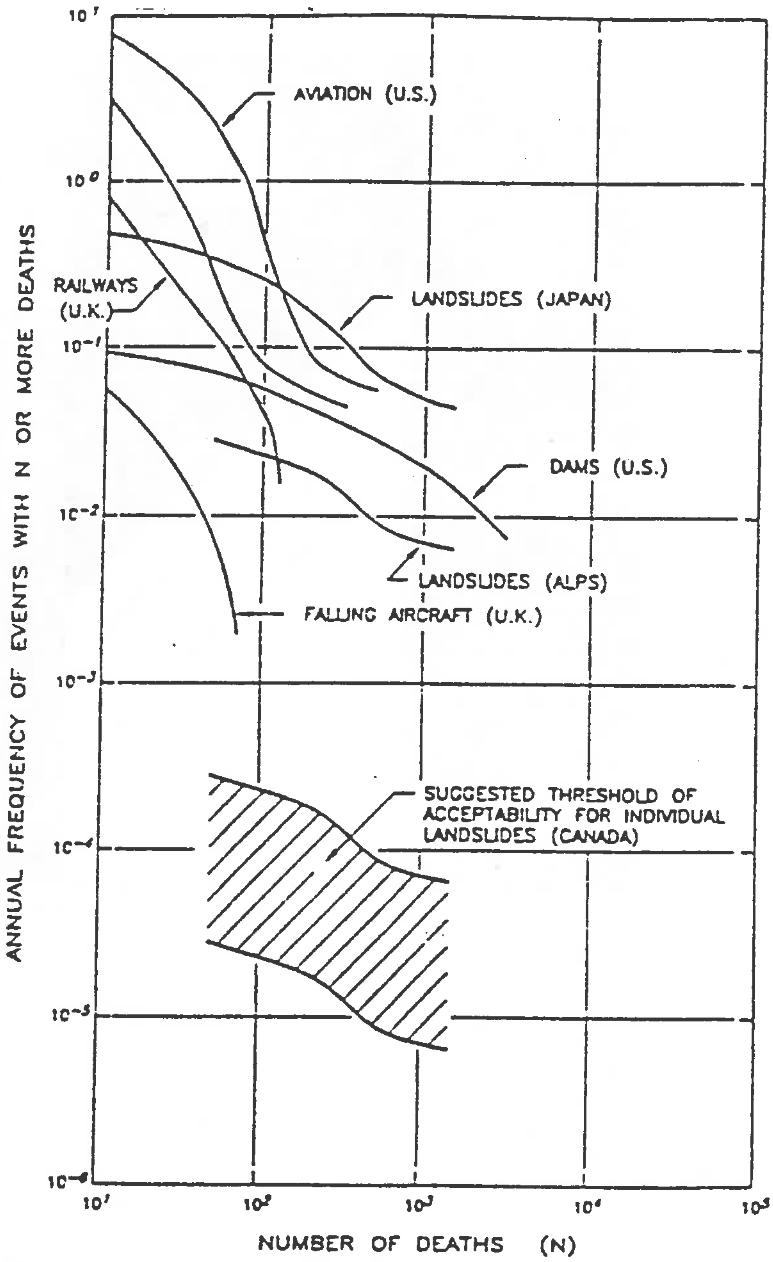


INTERIM ANCOLD SOCIETAL RISK CRITERIA



USBR PROPOSED RISK EVALUATION CRITERIA AND GUIDELINES

Appendix E: Suggested risk acceptance criteria for slope stability hazards.



Probability and frequency of multiple deaths for various natural and man-made sources based on reported occurrences (Morgan, 1991).

From Cave (1992)

Hazard-Related Responses to Development Approval Applications

1. Approval without conditions relating to hazards.
2. Approval, without siting conditions or protective works conditions, but with a covenant including "save harmless" conditions.
3. Approval, but with siting requirements to avoid the hazard, or with requirements for protective works to mitigate the hazard.
4. Approval as (3) above, but with a covenant including "save harmless" conditions as well as siting conditions, protective works or both.
5. Not approvable.

Inundation[1] by Floor Waters from Fraser River & Tributaries[2]

	1:40	1:40-1:200	<1:200
Minor Repair (<25%)	2	1	1
Major Repair (>25%)	4	3	1
Reconstruction	4	3	1
Extension	4	3	1
New Building	4	3	1
Subdivision (infill/extend)	5	4	1
Rezoning (for new community)	5	5	1

[1] Flooding Hazard involves both inundation and erosion/avulsion. Hazard acceptability thresholds must therefore involve assessment of both types of hazards at a given site.

[2] Revised 7/21/92.

Figure 4

Debris Flow/Debris Torrent

	1:50	1:50-1:200	1:200-1:500	1:500-1:10,000
Minor Repair (<25%)	2	2	1	1
Major Repair (>25%)	4	4	1	1
Reconstruction	4	4	3	1
Extension	4	4	3	1
New Building	4	4	3	1
Subdivision (infill/extend)	5	5	4	2
Rezoning (for new community)	5	5	5	3

From Cave (1992)

Mountain Stream
Erosion or Avulsion[1]

	1:10	1:10-1:100	1:100-1:200	1:200-1:500	<1:500
Minor Repair (<25%)	5	2	1	1	1
Major Repair (>25%)	5	4	2	1	1
Reconstruction	5	5	2	2	1
Extension	5	5	2	2	1
New Building	5	5	4	2	1
Subdivision (infill/extend)	5	5	5	4	1
Rezoning (for new community)	5	5	5	5	1

[1] Revised 7/21/92

Figure 6.

Debris Flow/Debris Torrent

	1:50	1:50-1:200	1:200-1:500	1:500-1:10,000	<1:10,000
Minor Repair (<25%)	5	2	2	1	1
Major Repair (>25%)	5	4	2	1	1
Reconstruction	5	5	4	3	1
Extension	5	5	4	2	1
New Building	5	5	4	3	1
Subdivision (infill/extend)	5	5	5	4	1
Rezoning (for new community)	5	5	5	5	1

From Cave 1992

Small-Scale Localised Landslip					
	1:50	1:50-1:200	1:200-1:500	1:500-1:10,000	<1:10,000
Minor Repair (<25%)	5	2	2	1	1
Major Repair (>25%)	5	4	4	1	1
Reconstruction	5	4	4	3	1
Extension	5	4	4	3	1
New Building	5	4	4	3	1
Subdivision (infill/extend)	5	5	5	4	1
Rezoning (for new community)	5	5	5	5	1

Figure 8

Snow Avalanche					
	1:30	1:30-1:100	1:100-1:500	1:500-1:10,000	<1:10,000
Minor Repair (<25%)	5	4	4	4	1
Major Repair (>25%)	5	4	4	4	1
Reconstruction	5	4	4	4	1
Extension	5	4	4	4	1
New Building	5	4	4	4	1
Subdivision (infill/extend)	5	5	5	4	1
Rezoning (for new community)	5	5	5	5	1

From Cave (1992)

Rockfall

Small-Scale Detachment

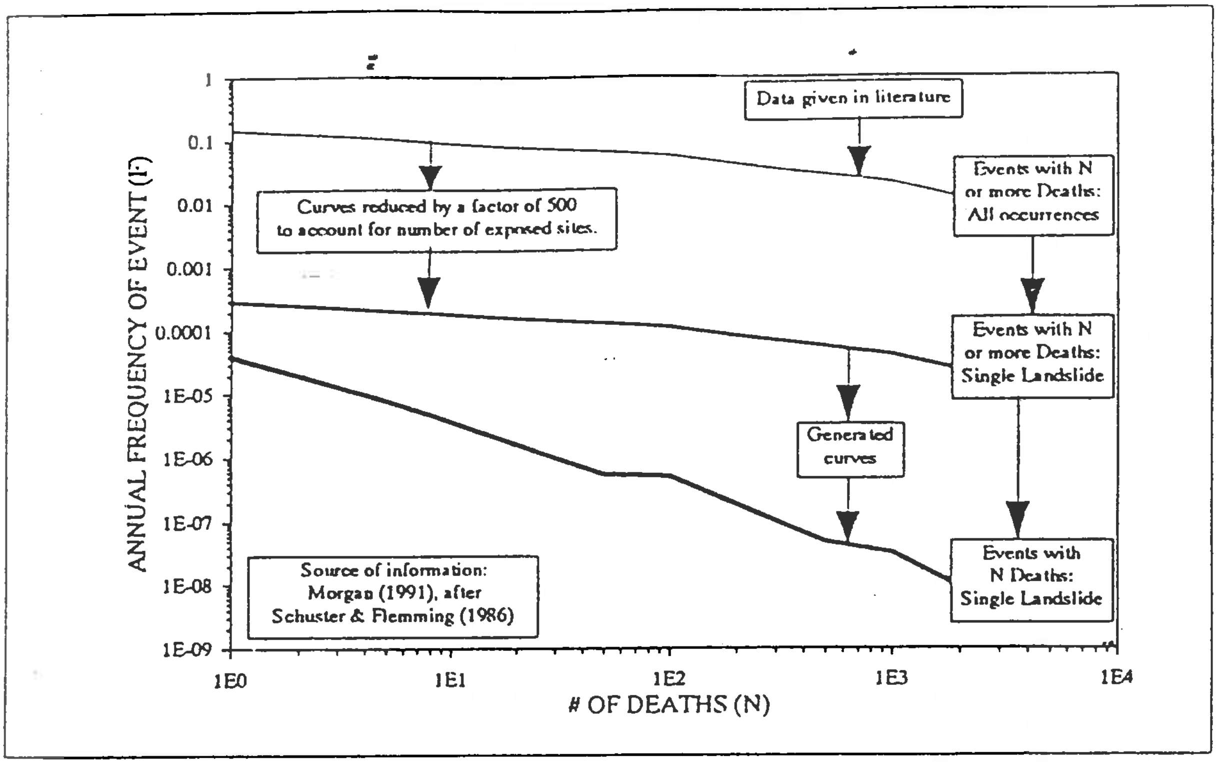
	1:100	1:100-1:500	1:500-1:1,000	1:1,000-1:10,000	<1:10,000
Minor Repair (<25%)	5	2	1	1	1
Major Repair (>25%)	5	4	2	1	1
Reconstruction	5	4	2	1	1
Extension	5	5	4	1	1
New Building	5	5	4	1	1
Subdivision (infill/extend)	5	5	5	4	1
Rezoning (for new community)	5	5	5	5	1

Figure 10

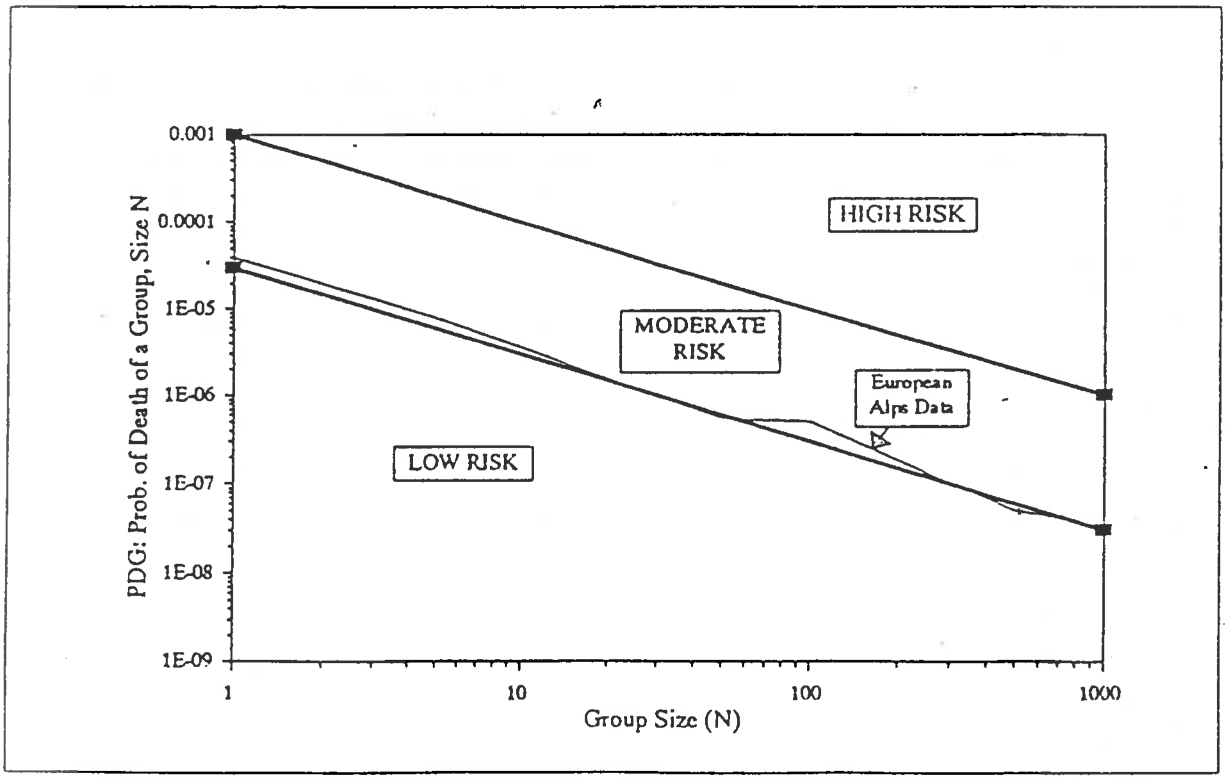
Major Catastrophic Landslide

	1:200	1:200-1:500	1:500-1:1,000	1:1,000-1:10,000	<1:10,000
Minor Repair (<25%)	5	2	1	1	1
Major Repair (>25%)	5	5	2	1	1
Reconstruction	5	5	5	1	1
Extension	5	5	5	1	1
New Building	5	5	5	1	1
Subdivision (infill/extend)	5	5	5	5	1
Rezoning (for new community)	5	5	5	5	5

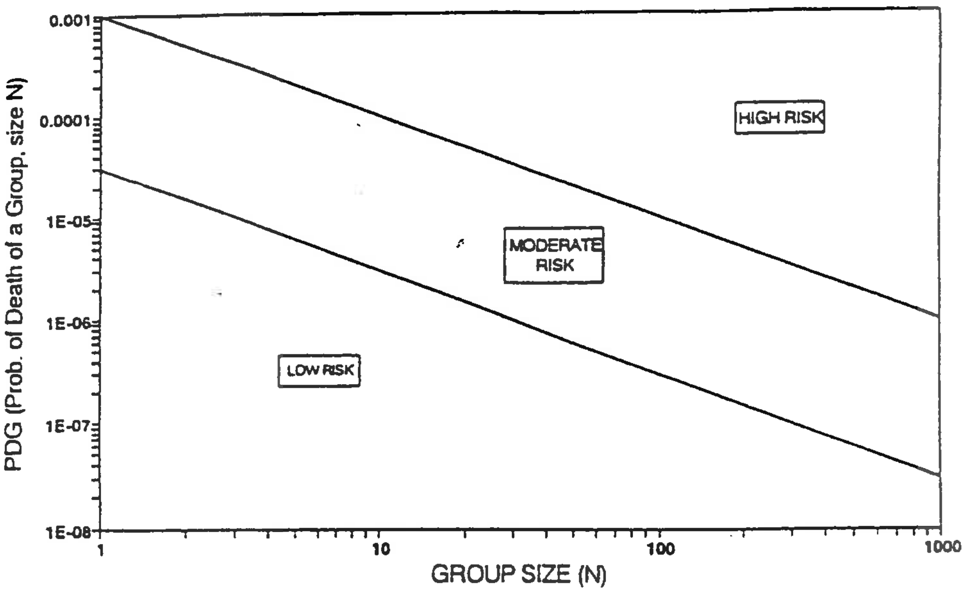
From Cave (1992)



Derivation of Landslide Risk Acceptability Criterion



Risk Acceptance Criteria for non-selected Groups in a single Community
From Sobkowicz (1996)



Cheekeye Fan risk assessment – proposed group risk acceptance criteria (Hungr et al, 1993)