State of the Art Paper 1

A framework for landslide risk assessment and management

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ABSTRACT: This paper provides a framework for landslide risk assessment and management. It outlines the processes of hazard analysis, including characterization of the landslide (the danger); frequency analysis; the risk estimation calculation; risk evaluation against risk tolerance criteria and value judgements. The paper discusses the benefits and limitations of quantitative and qualitative risk management, and gives simplified examples.

1 INTRODUCTION

Landslides and engineered slopes have always involved some form of risk assessment and management. This was often done by the use of “engineering judgement” by the Geotechnical Engineers or Engineering Geologists in consultation with owners and regulators.

The more formal applications of risk assessment and management principles, in a qualitative manner, have been practised for landslide hazard zoning for urban planning and highway slope management since the 1970’s. In the 1980’s, and particularly in the 1990’s, these have been extended to quantitative methods, and to management of individual slopes, pipeline routes, submarine slopes and more global slope risk management.

These developments are described by Varnes (1984), Whitman (1984), Einstein (1988, 1997), Fell (1994), Leroi (1996), Wu, *et al.* (1996), Fell and Hartford (1997), Nadim and Lacasse (1999) Ho, *et al.* (2000) Kvalstad *et al.* (2001), Nadim *et al.* (2003), Nadim and Lacasse (2003, 2004), Hartford and Baecher, and (2004), and Lee and Jones (2004). Some guidelines have been developed (e.g. Australian Geomechanics Society, 2000).

At this time there exists a generic framework for the use of quantitative risk assessment (QRA) for engineered slopes and landslides; including individual slopes, groups of slopes (such as cuts and fills on a length of highway), land use planning and zoning for urban development and “global” or regional landslide risk management. This paper describes this framework.

This paper also discusses the advantages, disadvantages and limitations of QRA for engineered slopes and landslides. The other seven State of the Art (SOA) papers in this Conference provide the details of the methods that can be used. The invited and submitted papers in this volume deal with specific applications, case studies, research and development.

2 TERMINOLOGY

The International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) Technical Committee on Risk Assessment and Management (TC32) developed a Glossary of Terms for Risk Assessment, based on IUGS (1997), ICOLD (2003), and National Standards such as British Standard BS 8444, Australia-New Zealand Standard AS/NZS 4360, and Canadian Standard CAN/CSA – Q 634-91. The Glossary is attached to this volume and these terms are used throughout all the SOA papers.

Readers are encouraged to use these terms so that there is consistency across the international community. The most important terms and their definitions are:

Annual exceedance probability (AEP): The estimated probability that an event of specified magnitude will be exceeded in any year.

Consequence: In relation to risk analysis, the outcome or result of a hazard being realised.

Danger (Threat): The natural phenomenon that could lead to damage, described in terms of its geometry, mechanical and other characteristics. The danger can be an existing one (such as a creeping slope) or a potential one (such as a rockfall). The characterisation of a danger or threat does not include any forecasting.

Elements at risk: Population, buildings and engineering works, infrastructure, environmental features and economic activities in the area affected by a hazard.

Frequency: A measure of likelihood expressed as the number of occurrences of an event in a given time or in a given number of trials (see also likelihood and probability).

Hazard: Probability that a particular danger (threat) occurs within a given period of time.

Individual risk to life: The increment of risk imposed on a particular individual by the existence of a hazard. This increment of risk is an addition to the background risk to life, which the person would live with on a daily basis if the facility did not exist.

Likelihood: Conditional probability of an outcome given a set of data, assumptions and information. Also used as a qualitative description of probability and frequency.

Probability: A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the magnitude of the uncertain quantity, or the likelihood of the occurrence of the uncertain future event.

There are two main interpretations:

i) Statistical – frequency or fraction – The outcome of a repetitive experiment of some kind like flipping coins. It includes also the idea of population variability. Such a number is called an “objective” or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment.

ii) Subjective probability (degree of belief) – Quantified measure of belief, judgement, or confidence in the likelihood of an outcome, obtained by considering all available information honestly, fairly, and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation, or the quality and quantity of information. It may change over time as the state of knowledge changes.

Risk: Measure of the probability and severity of an adverse effect to life, health, property, or the environment. Quantitatively, Risk = Hazard x Potential Worth of Loss. This can be also expressed as “Probability of an adverse event times the consequences if the event occurs”.

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: definition of scope, danger (threat) identification, estimation of probability of occurrence to estimate hazard, evaluation of the vulnerability of the element(s) at risk, consequence identification, and risk estimation. Consistent with the common dictionary definition of analysis, viz. “A detailed examination of anything complex made in order to understand its nature or to determine its essential features”, risk analysis involves the disaggregation or decomposition of the system and sources of risk into their fundamental parts.

Qualitative risk analysis: An analysis which uses word form, descriptive or numeric rating scales to describe the magnitude of potential consequences and the likelihood that those consequences will occur.

Quantitative risk analysis: An analysis based on numerical values of the probability, vulnerability and consequences, and resulting in a numerical value of the risk.

Risk assessment: The process of making a decision recommendation on whether existing risks are tolerable and present risk control measures are adequate, and if not, whether alternative risk control measures are justified or will be implemented. Risk assessment incorporates the risk analysis and risk evaluation phases.

Risk control: The implementation and enforcement of actions to control risk, and the periodic re-evaluation of the effectiveness of these actions.

Risk evaluation: The stage at which values and judgement 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 the risks.

Risk management: The systematic application of management policies, procedures and practices to the tasks of identifying, analysing, assessing, mitigating and monitoring risk.

Risk mitigation: A selective application of appropriate techniques and management principles to reduce either likelihood of an occurrence or its adverse consequences, or both.

Societal risk: The risk of widespread or large scale detriment from the realisation of a defined risk, the implication being that the consequence would be on such a scale as to provoke a socio/political response.

Temporal (spatial) probability: The probability that the element at risk is in the area affected by the danger (threat) at the time of its occurrence.

Tolerable risk: A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if possible.

Vulnerability: The degree of loss to a given element or set of elements within the area affected by a hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss).

Also, a set of conditions and processes resulting from physical, social, economic, and environmental factors, which increase the susceptibility of a community to the impact of hazards.

Other terms to describe landslide classification, features and geometry are detailed in Appendix A of this volume.

3 THE RISK MANAGEMENT PROCESS

Figures 1, 2 and 3 describe the overall risk management process.

Hazard analysis involves characterising the landslide (classification, size, velocity, mechanics, location, travel distance), and the corresponding frequency (annual probability) of occurrence.

Risk analysis includes hazard analysis and consequence analyses. Consequence analysis includes identifying and quantifying the elements at risk (property, persons), their temporal spatial probability, their vulnerability either as conditional probability of damage to conditional probability of damage to property, or conditional probability of loss of life or injury.

Risk assessment takes the output from risk analysis and assesses these against values judgements, and risk acceptance criteria.

Risk management takes the output from the risk assessment, and considers risk mitigation, including accepting the risk, reducing the likelihood, reducing consequences e.g. by developing monitoring, warning and evacuation plans or transferring risk (e.g. to insurance), develops a risk mitigation plan and possibly implements regulatory controls. It also includes monitoring of the risk outcomes, feedback and iteration when needed.

The process is iterative within any one study, and should be up-dated periodically as monitoring results become available.

Landslide risk management involves a number of stakeholders including owners, occupiers, the affected public and regulatory authorities, as well as geotechnical professionals, and risk analysts.

It is an integral part of risk management that the estimated risks are compared to acceptance criteria (either quantitative or qualitative). Geotechnical professionals are likely to be involved as the risk analysts, and may help guide in the assessment and decision process, but ultimately it is for owners, regulators and governments to decide whether the calculated risks are acceptable or whether risk mitigation is required.

In some cases the absolute values of risk are not as important as the relative risks. This is often the case for risk assessments for cuts and fills on highways, where the risk assessment process is being used to prioritise the implementation of risk reduction measures.

The risk management process in Figure 1 can be divided in phases. Five of these are illustrated by the darker shades in Figure 2. The graphics illustrate that each new phase includes the previous one(s) and that the solution becomes more involved as one progresses through the different phases. The 5 phases together form an integrated framework schematically illustrated in the graphics in Figure 3.

4 LANDSLIDE RISK ANALYSIS

4.1 *Scope definition*

To ensure that the risk analysis addresses the relevant issues, satisfies the needs of those concerned, and to avoid misunderstandings, it is important to define the scope of the risk analysis:

(a) Is the analysis for a single site (e.g. a road cutting, or a building); a number of sites, (e.g. all the road cuttings on a length of road); hazard zoning for land-use planning; or "global risk assessment", where for example cut slopes on all roads in a local government area are being studied universally to formulate policies and prioritise mitigation actions?

(b) The geographic limits. Note that to be complete, the effects of landsliding up slope of a site, not confined to the site may need to be considered; and the impacts of the landsliding on sites downslope, e.g. of a road fill, may also need to be part of the analysis.

(c) Whether the analysis will be restricted to property loss or damage, or it will also include assessment of the potential for loss of life and injury.

(d) The extent of geotechnical engineering and geological studies which will form the basis of the analysis. These can control the overall standard of the risk analysis.

(e) The approach to be used to characterise the landslides, and assess the frequency of landsliding, and their consequences.

(f) Whether the analysis will be quantified or qualitative.

(g) How risk acceptance criteria will be determined, by whom, and through what process? The extent to which the stakeholders (owners, public, regulator, risk analyst) will be involved.

(h) Operational (e.g. land access) and financial constraints to the analysis.

(i) Legal responsibilities of all parties.

(j) The nature of the end product of the risk analysis – report, maps, and how these will be communicated to the interested parties.

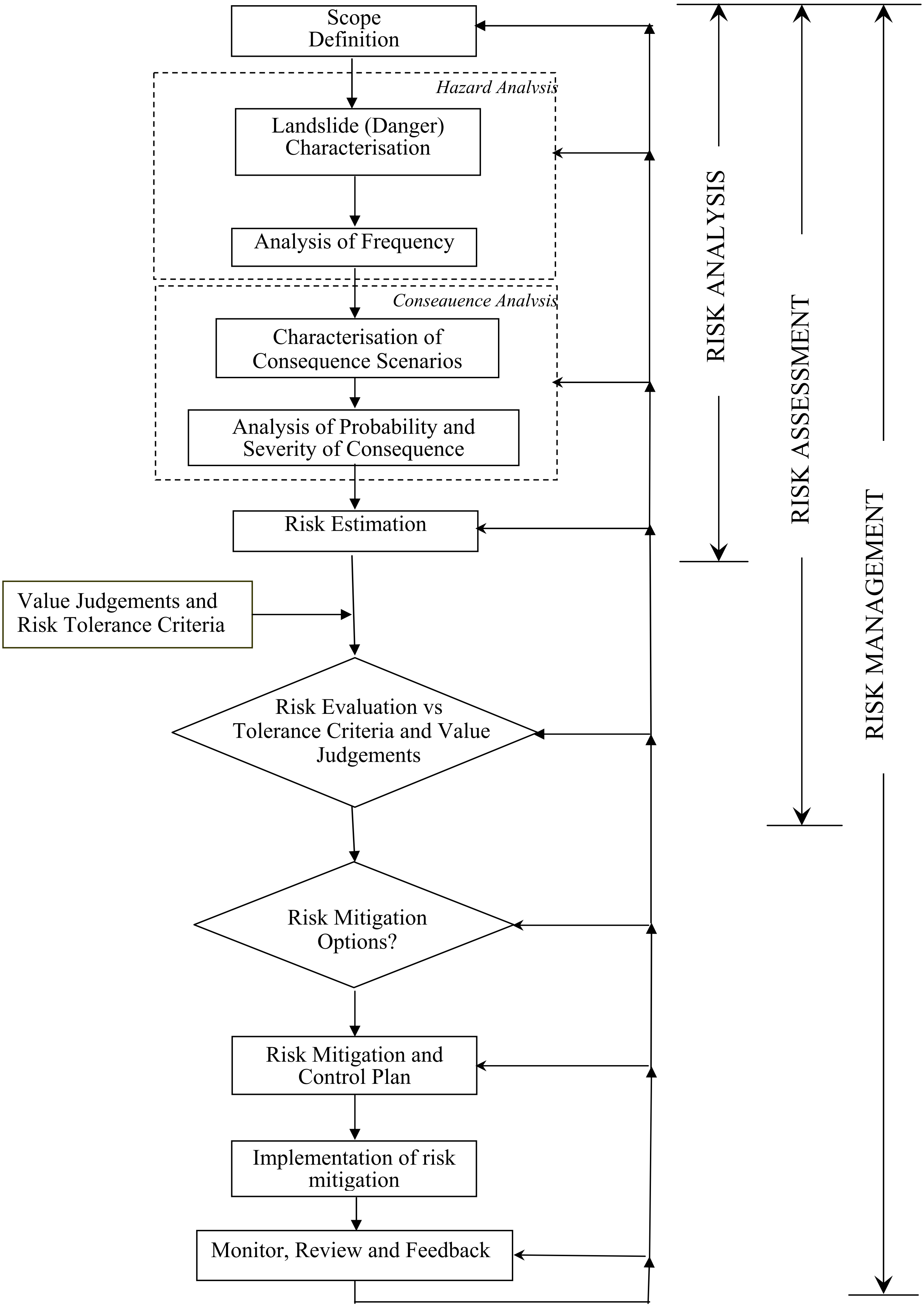
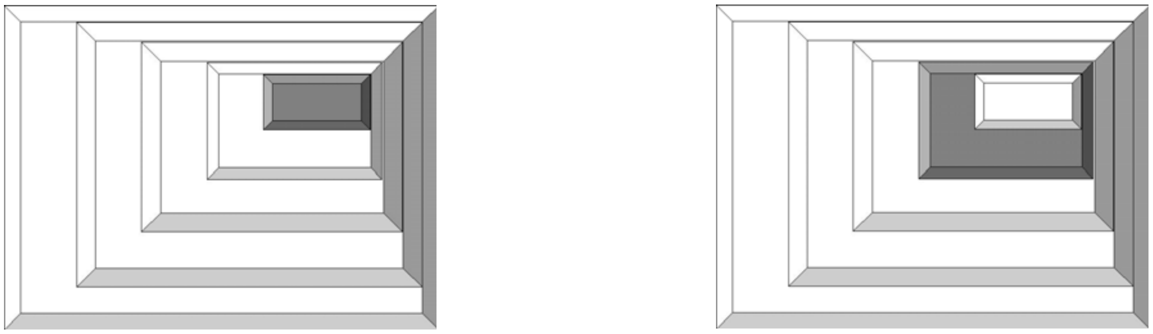


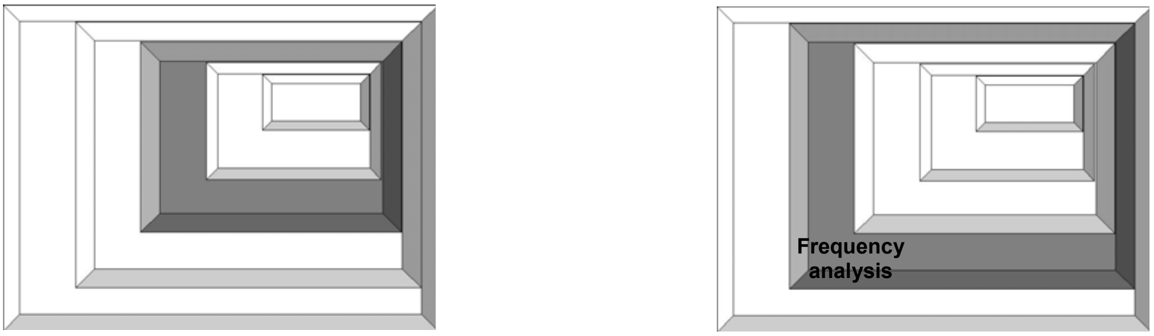
Figure 1 – Flow chart for landslide risk management.

Risk Evaluation vs



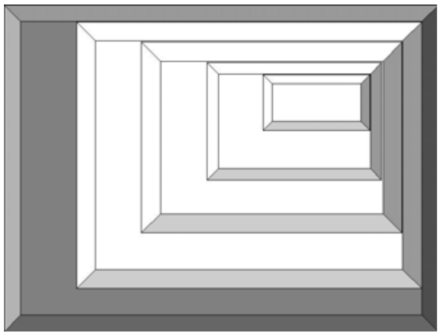
(a) Landslide (danger) characterisation

(b) Hazard analysis



(c) Risk analysis

(d) Risk evaluation



(e) Risk mitigation and control

Figure 2 –Representation of 5 phases of the Risk Management Process

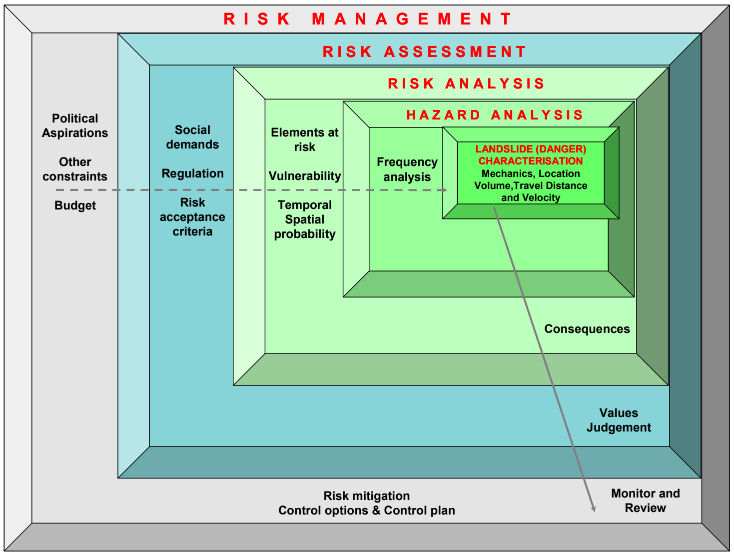


Figure 3 – Schematic representation of the integrated risk management process.

4.2 *Hazard analysis*

Hazard analysis is the process of identification and characterisation of the potential landslides together with evaluation of their corresponding frequency of occurrence.

4.2.1 *Landslide (Danger) characterisation*

Landslide (danger) characterisation requires an understanding of the slope processes and the relationship of those processes to geomorphology, geology, hydrogeology, failure and slide mechanics, climate and vegetation. From this understanding it will be possible to:

- Classify the types of potential landsliding: the classification system as proposed by Varnes (1984) or modified by Cruden & Varnes (1996) forms suitable systems. A site may be affected by more than one type of landslide hazard e.g., slow rotational earth slides on the site, and very rapid rockfall and debris flows from above the site.
- Assess the physical extent of each potential landslide,including the location, areal extent and volume involved.
- Assess the likely initiating event(s), the physical characteristics of the materials involved, such as shear strength, pore pressures; and the slide mechanics. The latter is critical to understanding the pre and post failure behaviour of the landslide.
- Estimate the resulting anticipated travel distance, travel path, depth and velocity of movement if failure occurs, taking account of the slide mechanics, and estimating the probability that the land slide will affect the area in which the element at risk is located ($P_{T:L}$)
- Identify possible pre-failure warning signs which may be monitored.

A list of possible landslides (dangers) should be developed. Consideration must be given to hazards located off site as well as within the site as it is possible for landslides both upslope and downslope to affect the elements at risk. It is vital that the full range of hazards (e.g. from small, high frequency events to large, low frequency events) be properly characterised and considered in the risk analysis. Often the risk is dominated by the smaller, more frequent landslides. The effects of proposed development in an area should also be considered, as these effects may alter the nature and frequency of potential hazards.

It is important that geotechnical professionals with training and experience in landsliding and slope processes are involved in this stage of the analysis because the omission or under/over estimation of the effects of different landslides often can control the outcomes of the analysis.

4.2.2 *Frequency analysis*

The frequency of landsliding can be expressed in terms of (IUGS 1997):

- The number of landslides of a certain characteristic that may occur in a study area per year.
- The probability of a particular slope experiencing landsliding in a given period, e.g. a year.
- The driving forces exceeding the resistant forces in probability or reliability terms, with the frequency of occurrence being determined by considering the annual probability of the critical pore water pressures being exceeded in the analysis.
- This should be done for each type of landslide which has been identified and characterised as affecting the analysis.

There are several ways of calculating frequency (IUGS 1997):

(1) Historic data within the area of study, or areas with similar characteristics, e.g. geology, geomorphology.

(2) Empirical methods based on correlations in accordance with slope instability ranking systems.

(3) Use of geomorphological evidence (coupled with historical data), or based on expert judgement.

(4) Relationship to the frequency and intensity of the triggering event, e.g. rainfall, earthquake.

(5) Direct assessment based on expert judgement, which may be undertaken with reference to a conceptual model, e.g. use of a fault tree methodology.

(6) Modelling the primary variable, e.g. piezometric pressures versus the triggering event, coupled with varying levels of knowledge of geometry and shear strength.

(7) Application of probabilistic methods, taking into account the uncertainty in slope geometry, shear strength, failure mechanism, and piezometric pressures. This may be done either in a reliability framework, or taking into account the frequency of failure (for example by considering pore pressures on a frequency basis).

(8) Combinations of the above methods.

In practice it may be appropriate and advisable to use more than one method for the analysis.

Details of the methods and their applicability are given in SOA Paper 2 in this volume. It is important to express the probability of sliding in frequency (per annum) terms, because quantitative risk acceptance criteria for loss of life are usually expressed in per annum terms. Financial analysis of damage also usually requires frequency as an input.

The authors have a preference for estimating frequencies quantitatively. This gives a uniformity of outcomes in quantified terms (rather than using ill-defined subjective terms such as likely, unlikely etc.), allows risk to be compared with quantitative acceptance criteria, and allows comparison with risks from other hazards with which the parties involved may be able to associate. However it is recognised that many practitioners are not familiar with quantifying landslide frequencies, and it is important there are "sanity checks" on the results against historical performance data, and for more important analyses, reviews by persons who are experienced in landslide risk analysis.

For most hazard analyses, the estimation of frequency based on historical data, geomorphological evidence, relationship to trigger event frequencies etc. are typically more reliable than the apparently more rigorous and detailed probabilistic analyses because of the many uncertainties involved and data constraints. Also, some of the causes or contributory factors to slope instability may not be amenable to conventional limit equilibrium analysis, e.g. effects of topography on surface water flows.

This is particularly true for smaller slopes, and for landslides on natural hillsides, where it is very difficult to estimate pore water pressures, and where small variations in strengths, and geometry and geological anomalies have large effects on the outcomes. There is also seldom sufficient data to properly model such factors as auto-correlation of parameters, so reliance is often placed on published generalised information which may not be applicable to the site under consideration.

4.3 *Consequence analysis*

Consequence analysis involves:

(a) Identifying and quantifying the elements at risk including property and persons.

(b) Assessing temporal spatial probabilities for the elements at risk ($P_{S:T}$).

(c) Assessing vulnerability of the elements at risk, in terms of property damage ($V_{prop:T}$) and loss of life/injury ($V_{D:T}$) as appropriate.

This has to be done for each of the landslide hazards.

The consequences may not be limited to property damage and loss of life/injury. Other consequences may include loss of reputation of the owner and geotechnical engineers, consequential costs (e.g. a road is closed for some time affecting businesses along the road), litigation from those injured or the relatives of those killed, potential criminal charges for those involved, political repercussions, adverse social and environmental effects. Most of these may not be readily quantifiable, but may need to be systematically considered, in consultation with owners and factored into the decision-making process as appropriate, at least for comprehensive risk analysis studies.

4.3.1 *Elements at risk*

The elements at risk include the population, buildings, engineering works, infrastructure, vehicles, environmental features and economic activities which are in the area affected by the hazard. In practical terms, this usually means on the landslide, and/or in the area onto which the landslide may travel if it occurs. It may also include property immediately adjacent to or upslope of the landslide, if the property or its value would be affected by landsliding and infrastructure which may include powerlines, water supply, sewage, drainage, roads, communication facilities. The population at risk includes persons who live, work, or travel through the area affected by the hazard.

It would be usual to categorise vehicles into cars, trucks and buses, because of the different number of persons likely to be in the vehicles.

The elements at risk are likely to be dependent on the nature of the landslide hazard e.g. for a boulder fall, or debris flow at a given site.

4.3.2 *Probability of landslide reaching the element at risk ($P_{T:L}$)*

The probability of the landslide reaching the element at risk depends on the relative location of the element at risk and the landslide source, together with the path the landslide is likely to travel below the source. It is a conditional probability between 0 and 1.

(a) For buildings which are located on the source landslide $P_{T:L} = 1$.

(b) For buildings or persons located below the source landslide and in the path of the resulting travel of the landslide, $P_{T:L}$ is calculated taking account of the travel distance of the landslide, the location of the source landslide, and the element at risk.

(c) For vehicles or persons in vehicles, or persons walking in the area below the source landslide in the path of the resulting travel (runout) of the landslide, $P_{T:L}$ is calculated taking account of the travel distance of the landslide, and the path to be followed by the vehicle or person. Whether the vehicle or person is in the path at the time of the landslide is taken account through the temporal spatial probability ($P_{S:T}$).

The methods for estimation of travel distance are described in SOA 4 of this volume. This involves some uncertainty which should be taken determinded.

4.3.3 *Temporal spatial probability ($P_{S:T}$)*

The temporal spatial probability is the probability that the element at risk is in the area affected by the hazard at the time of its occurrence. It is a conditional probability, and is between 0 and 1.

(a) For buildings on or in the path of the landslide, the temporal spatial probability is 1.

(b) For a single vehicle which passes below a single landslide, it is the proportion of time in a year when it will be in the path of the landslide.

(c) For all the vehicles which pass below a single landslide, it is the proportion of time in a year when a vehicle will be in the path of the landslide. Where there are a number of potential landslides in any year, e.g. rockfalls, the calculation is somewhat more complicated as described in SOA 5 in this volume.

(d) For persons in a building, it is the proportion of time in a year which the persons occupy the building (0 to 1.0). This is likely to be different for each person.

For persons in vehicles, the temporal spatial probability will be as for (b) and (c). However it may vary for say one person in a car, and four persons in a car.

The range of credible consequence scenarios will need to be considered in societal risk calculations. Details of how to calculate temporal spatial probability are given in SOA 5 of this volume.

For some situations it will be necessary to build into the calculation of temporal spatial probability, whether the person(s) at risk may have sufficient warning to evacuate from the area affected by the hazard. Persons on a landslide are more likely to observe the initiation of movement and move off the slide than those who are below a slide falling or flowing onto them.

Each case should take into account the nature of the landslide including its volume, and velocity, monitoring results, warning signs, evacuation systems, the elements at risk, and the mobility of the persons.

4.3.4 *Vulnerability ($V_{prop:T}$ and $V_{D:T}$)*

Vulnerability is the degree of loss (or damage) to a given element, or set of elements, within the area affected by the hazard. It is a conditional probability, given the landslide occurs and the element at risk is on or in the path of the landslide. For property, it is expressed on a scale of 0 (no loss or damage) to 1 (total loss or damage) for property.

For persons it is usually the probability (between 0 and 1) that given the person is on or in the path of the landslide, the person is killed. It may also include the probability of injury.

Factors that most affect vulnerability of property include:

- The volume of the landslide in relation to the element at risk
- The position of the element at risk, e.g. on the landslide, or immediately downslope
- The magnitude of landslide displacement, and relative displacements within the landslide (for elements located on the landslide)
- The velocity of landslide movement.

Landslides which move slowly (particularly those with a nearly planar, horizontal surface of rupture) may cause little damage, other than to structures which are on the boundaries of the landslide and hence experience differential displacement.

The rate of movement is less important for structures than it is for loss of life, except in so far as it affects the time rate of damage, i.e. buildings on a slow moving slide (which moves intermittently every year) can be expected to have a lower vulnerability than those on a fast moving one.

Factors which most affect the vulnerability of persons include:

- The velocity of landsliding. Persons are more likely to be killed by a rapid landslide than slow regardless of the landslide volume.
- Landslide volume – persons are more likely to be buried or crushed by large landslides than small.
- Whether the person(s) are in the open, or in a vehicle or building (ie. a function of the degree of protection the person(s) has from the landslide impact).
- If they are in a building, whether the building collapses upon impact by the landslide, and the nature of the collapse.

Persons who are buried by a landsliding mass have a high vulnerability. Death is more likely to result from asphyxia than from crushing or impact. SOA 5 in this volume gives detailed information on the assessment of vulnerability.

4.4 *Risk estimation*

4.4.1 *Risk calculation*

The risk can be presented in a number of ways:

(a) The annual risk (expected value) in which the probability of occurrence of the danger is multiplied by the consequences summed over all the hazards. This is expressed as \$x damage per annum; or potential loss of lives per annum.

(b) Frequency – consequence (f – N) pairs – for example for property, the annual probability of minor (\$x) damage; medium (\$y) damage and major (\$z) damage; and for risk to life, the annual probability of loss of 1 life, 5 lives, 100 lives etc.

(c) Cumulative frequency – consequence plots (F – N plots), for example a plot of the annual probability of N or more lives being lost (see section 5.2 and Figure 4).

It is often useful to calculate all three. The annual risk for property can be calculated from:

$$R_{(prop)} = P_{(L)} \text{ x } P_{(T:L)} \text{ x } P_{(S:T)} \text{ x } V_{(prop:S)} \text{ x } E \qquad (1)$$

where

$R_{(prop)}$ is the annual loss of property value
$P_{(L)}$ is the frequency of the landsliding

$P_{(T:L)}$ is the probability of the landslide reaching the element at risk

$P_{(S:T)}$ is the temporal spatial probability of the element at risk

$V_{(prop:S)}$ is the vulnerability of the element at risk to the landslide event

E is the element at risk (e.g. the value or net present value of the property)

The annual probability that a particular person may lose his/her life can be calculated from:

$$P_{(LOL)} = P_{(L)} \text{ x } P_{(T:L)} \text{ x } P_{(S:T)} \text{ x } V_{(D:T)} \qquad (2)$$

where

($P_{(LOL)}$ is the annual probability that the person will be killed

$V_{(D:T)}$ is the vulnerability of the person to the landslide event

and $P_{(L)}$, $P_{(T:L)}$ and $P_{(S:T)}$ are as defined above

To estimate annual loss of life risk, equation (3) is expanded to be as for equation (2) with E being the number of persons at risk.

There are a number of situations where the risks from a number of landslide hazards have to be summed to give the total risk. These include:

- Where the element at risk is exposed to a number of types of landsliding e.g. boulder fall, debris flows, and translational sliding
- Where the landsliding may be triggered by more than one phenomena e.g. rainfall, earthquake, human activity.
- Where the element at risk is exposed to a number of different sizes of landslide of the same classification e.g. debris flows of $50m^3$, 5,000 m^3 and $100,000m^3$ volume.
- Where the element at risk is exposed to a number of slopes on which landsliding can occur e.g. a vehicle driving along a road in which there are 20 cut slopes each of which is a potential source of boulder falls.

In these cases, equations (1) and (2) should be written as:

$$R_{(prop)} = \sum_{1}^{n} (P_{(L)} \text{ x } P_{(T:L)} \text{ x } P_{(S:T)} \text{ x } V_{(prop:S)} \text{ x } E) \qquad (3)$$

and

$$P_{(LOL)} = \sum_{1}^{n} (P_{(L)} \text{ x } P_{(T:L)} \text{ x } P_{(S:T)} \text{ x } V_{D:T}) \qquad (4)$$

where n is the number of landslide hazards.

This assumes that the hazards are independent of each other, which may often not be correct. If one or more of the hazards may result from the same causative event e.g. a single rain event, or earthquake, then the probabilities should be estimated using the theory of uni-modal bounds as follows:

(i) The upper bound

From de Morgan's rule, the estimated upper bound conditional probability is

$$P_{UB} = 1 - (1 - P_1)(1 - P_2) \ldots\ldots(1 - P_n) \qquad (5)$$

where

P_{UB} = estimated upper bound conditional probability

P_1 to P_n = the estimate of several individual hazard conditional probabilities.

This calculation should be done before applying the annual probability of the common causative event. If all the conditional probabilities P_1 to P_n are small (<0.01), equation 5 yields the same value, within acceptable accuracy, as obtained by adding all the estimated conditional probabilities.

(ii) The lower bound

The lower bound estimate is the maximum individual conditional probability.

4.4.2 *Uncertainty and sensitivity analysis*

The inputs into the risk estimation are not precise, usually involving a large contribution from engineering judgement, or uncertainty in input parameters (e.g. for formal probabilistic analysis) (Lacasse *et al.* 2003; 2004). Uncertainty describes any situation without certainty, whether or described by a probability distribution. Uncertainty is caused by natural variation and/or incomplete knowledge (lack of understanding or insufficient data). In the context of structural safety, uncertainty can be either aleatory (inherent variability in natural properties and events) or epistemic (incomplete knowledge of parameters and the relationships between input and output values).

Often for landslide risk assessments, it is not practical to model uncertainties formally e.g. by assigning probability distributions to each input and using Monte Carlo type analysis (e.g. Morgan and Henrion, 1990). However, it is possible to do sensitivity analysis by considering the effects of different assumed values for the inputs. It should be recognised that the use of upper or lower limits of input variables in order to estimate upper and lower bound results gives extremely low likelihood values, and that the analysis may be almost meaningless.

4.4.3 *Qualitative risk estimation*

Qualitative risk analysis uses descriptors to describe the frequency of landsliding and the consequences. This may comprise tools such as risk rating systems, risk scoring schemes, and risk ranking matries (e.g. Stewart, *et al.* 2002). These can serve a useful role in landslide risk management in providing a relative comparison of risks of different sites and prioritisation of follow-up actions in addressing the risk portfolio posed by a large number of sites. In some cases, a hybrid approach may be adopted whereby qualitative risk analysis can facilitate a ‘first-pass’ screening of the more dominant hazards in a given site so that attention can be focused on the more deserving areas or hazards, which can be evaluated in detail using quantitative methods. Qualitative risk assessment may also be used, coupled with engineering judgement, to examine whether a given landslide hazard is posing a significant risk to life (e.g. a precariously perched boulder above a busy highway with signs of distress) and the need for prompt risk reduction measures (e.g. boulder removal) in order to safeguard public safety, without the need for elaborate quantitative analysis. In general, qualitative risk assessment must be undertaken critically and preferably subject to expert review to avoid spurious outcomes and for it to be value-adding.

Table 1 gives an example adapted from AGS (2000). In this case, the “likelihood” incorporates the frequency of landsliding, the probability of the landslide reaching the element at risk, and temporal spatial probability. The consequences incorporate the vulnerability and the value of the element at risk.

Table 1. Example of qualitative terminology for use in assessing risk to property – adapted from AGS (2000)

Qualitative Measures of Likelihood of landsliding

Level	Descriptor	Description
A	Almost certain	The event is expected to occur
B	Likely	The event will probably occur under adverse conditions
C	Possible	The event could occur under adverse conditions
D	Unlikely	The event could occur under very adverse circumstances
D	Rare	The event is conceivable but only under exceptional circumstances
E	Not credible	The event is inconceivable or fanciful

Qualitative Measures of Consequences to Property

Level	Descriptor	Description
1	Catastrophic	Structure completely destroyed or large scale damage requiring major engineering works for stabilisation.
2	Major	Extensive damage to most of structure, or extending beyond site boundaries requiring significant stabilisation works.
3	Medium	Moderate damage to some of structure, or significant part of site requiring large stabilisation works.
4	Minor	Limited damage to part of structure, or part of site requiring some reinstatement/stabilisation works.
5	Insignificant	Little damage

Qualitative Risk Analysis Matrix –Classes of Risk to Property

Likelihood	Consequences to property				
	Catastrophic	Major	Medium	Minor	Insignificant
Almost certain	VH	VH	H	H	M
Likely	VH	H	H	M	L-M
Possible	H	H	M	L-M	VL-L
Unlikely	M-H	M	L-M	VL-L	VL
Rare	M-L	L-M	VL-L	VL	VL
Not credible	VL	VL	VL	VL	VL

Legend: VH – very high risk
H – high risk
M – moderate risk
L – low risk
VL – very low risk

Combining likelihood with consequence results in a risk matrix divided into 5 classes from very low risk (VL) to very high risk (VH).

Other schemes may be developed by the geotechnical risk analyst in consultation with the owners or other stakeholders where appropriate, to best suit a given problem.

Qualitative risk assessment is subject to limitations, which include potentially imprecise and subjective description of the likelihood term, for example “adverse or “could occur” and hence are liable to result in wide differences in the estimated risks, together with lack of risk acceptance criteria against which the qualitatively assessed risks can be evaluated.

AGS (2000) recommended that schemes such as that shown in Table 1 are only applicable to consideration of risks to property. Extreme care must be exercised where qualitative risk assessment approaches are used for estimating risk of loss of life and decision-making on site-specific basis, especially for marginal cases, because of the associated shortcomings

5 LANDSLIDE RISK ASSESSMENT

5.1 *Risk assessment process*

Risk assessment involves taking the outputs from the risk analysis and comparing them against values judgements and risk tolerance criteria to determine if the risks are low enough to be tolerable.

The process is one of making judgements, taking account of political, legal, environmental, regulatory and societal factors. The decision is usually the responsibility of the owner and regulator, sometimes consulting with the affected public or stakeholders. Non-technical clients may seek guidance from the risk analyst on whether to accept the risk, but from a legal viewpoint it is important that the owner and regulator make the final decision.

Assessment of the risk may involve consideration of values such as:

(a) Property or financial loss

- Annualised risk cost
- Financial capability
- Impact on corporate reputations
- Insurance available
- For railways and roads; accidents per million tonnes of freight hauled, frequency of accidents
- Indirect costs e.g. loss of road access
- When mitigation measures are being considered, cost benefit ratio.

(b) Loss of life

- Individual risk to life.
- Societal risk e.g. as a frequency versus number of deaths (known as f – N) or cumulative frequency versus number of deaths (known as F – N) criteria.
- Annualised potential loss of life
- When mitigation measures are being considered, cost per statistical life saved.

5.2 *Risk acceptance criteria*

It is important to recognise the difference between acceptable and tolerable risks:

Acceptable risk: A risk which everyone impacted is prepared to accept. Action to further reduce such risk is usually not required unless reasonably practicable measures are available at low cost in terms of money, time and effort.

Tolerable risk: A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible, and needing to be kept under review and reduced further if possible.

Factors that affect an individual's attitude to acceptable or tolerable risk will include (adapted from AGS 2000):

- Resources available to reduce the risk.
- Whether there is a real choice, e.g. can the person afford to vacate a house despite the high risk?
- The individual’s commitment to the property and its value relative to the individuals income.
- Age and character of the individual.
- Exposure the individual has experienced in the past, especially with regards to risk associated with landslides.
- Availability of insurance.
- Regulatory or policy requirements.
- Whether the risk analysis is perceived to be reliable.

There are some common general principles that can be applied when considering tolerable risk to loss of life criteria (IUGS 1997):

- The incremental risk from a hazard to an individual should not be significant compared to other risks to which a person is exposed in everyday life.
- The incremental risk from a hazard should, wherever reasonably practicable, be reduced, i.e. The As Low As Reasonably Practicable (ALARP) principle should apply.
- If the possible loss of life from a landslide incident is high, the likelihood that the incident might actually occur should be low. This accounts for society’s particular intolerance to incidents that cause many simultaneous casualties, and is embodied in societal tolerable risk criteria.
- Persons in society will tolerate higher risks than they regard as acceptable, when they are unable to control or reduce the risk because of financial or other limitations.
- Higher risks are likely to be tolerated for existing slopes than for planned projects, and for workers in industries with hazardous slopes, e.g. mines, than for society as a whole.

These principles are common with other dangers such as Potentially Hazardous Industries (PHI) and dams. (IUGS 1997) considered that there are other principles that are applicable to risk from slopes and landslides:

- Tolerable risks are higher for landslides on natural hillsides than those from engineered slopes.
- Once a natural slope has been placed under monitoring, or risk mitigation measures have been executed, the tolerable risks approach those of engineered slopes.
- Tolerable risks may vary from country to country, as well as within a country, depending on historic exposure to landslide hazard, and the system of ownership and control of slopes and natural landslides hazards.

There are no universally established individual or societal risk acceptance criteria for loss of life due to landslides. Guidance on what has been accepted in various countries is given in SOA 6 in this volume.

The following are some examples:

(i) Individual risk

AGS (2000) suggested that, based on criteria adopted for Potentially Hazardous Industries, Australian National Committee on Large Dams (ANCOLD 1994, which were also adopted in ANCOLD 2003); and the review in Fell and Hartford (1997) the tolerable risk criteria shown in Table 2 “might reasonably be concluded to apply to engineered slopes”. They suggested that acceptable risks are usually considered to be one order of magnitude smaller than these tolerable risks.

It should be noted the AGS (2000) guidelines do not represent a regulatory position. ANCOLD (2003) deleted reference to the “average of persons at risk", taking account only of the person most at risk.

Table 2. AGS (2000) suggested tolerable risk criteria

Situation	Suggested tolerable risk for loss of life
Existing engineered slopes	10^{-4}/annum person most at risk 10^{-5}/annum average of persons at risk
New engineered slopes	10^{-5}/annum person most at risk 10^{-6}/annum average of the persons at risk

(ii) Societal risk

The application of societal risk to life criteria is to reflect the reality that society is less tolerant of events in which a large number of lives are lost in a single event, than of the same number of lives are lost in a large number of separate events. Examples are public concern to the loss of large numbers of lives in airlines crashes, compared to the many more lives lost in small aircraft accidents.

The use of cumulative F-N curves to reflect this is not universal. An example which has been trialled on an interim basis to assist landslide risk management of natural hillside hazards is shown in Figure 4.

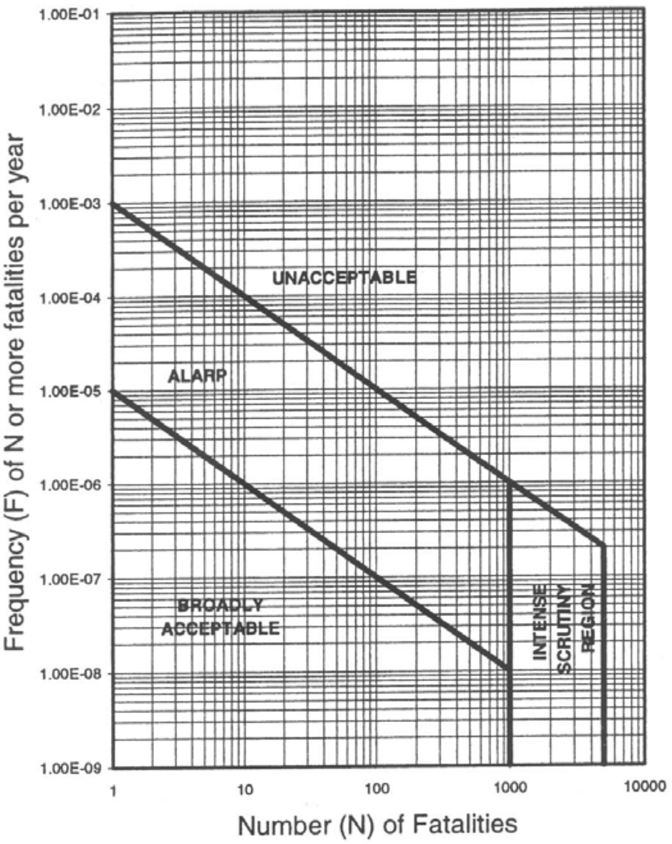


Figure 4 – Interim societal risk tolerance criteria (Geotechnical Engineering Office, 1998).

Christian (2004) also discusses the use of F-N criteria. He suggests that using the output of probabilistic analyses is hindered by the well-established fact that people, including engineers, have a lot of trouble understanding small probabilities and that in recent years, the *f-N* and *F-N* diagrams have proven to be useful tools for describing the meaning of probabilities and risks in the context of other risks with which society is familiar. He points out that computed absolute probabilities may not include all contributions; an effective approach is to compare probabilities of different options or alternatives. Probabilistic methodologies also provide insight into the relative contributions of different parameters to the uncertainty of the result and thus give guidance for where further investigations will be most fruitful.

Whether such quantitative criteria as the examples given are acceptable in principle will depend on the country and legal system in which the landsliding is being considered. In some societies, e.g. Australia, Hong Kong, and the United Kingdom, the use of such criteria for Potentially Hazardous Industries, and to a lesser extent dams and landslides is gaining acceptance. In others, such as France, the legal framework currently precludes the use at least in absolute terms. This is discussed further in SOA6.

As pointed out in IUGS (1997), those who use QRA for slopes and landslides should keep the following in mind when analysing, assessing and managing risk:

(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 the risk analysis outcomes.

(b) Tolerable risk criteria 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.

(c) It is often useful to use several measures of tolerable risk criteria, e.g. f-N pairs, individual and societal risk, and measures such as cost to save a life and maximum justifiable cost if risk mitigation is being considered.

(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, e.g. 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 the landslide and the consequences. Sometimes it is the smaller, more frequent, landslides that contribute most to risk, not the low frequency very large event.

6 LANDSLIDE RISK MANAGEMENT

6.1 *Risk management process*

The outcomes of the Risk Assessment will be either:

(a) The risks are tolerable, or even acceptable and no mitigation options need be considered.

or

(b) The risks are intolerable, and risk mitigation options need to be considered.

The risk management process is iterative, requiring consideration of the risk mitigation options and the results of the implementation of the mitigation measures and of the monitoring.

Examples of options for mitigation of risks for a slope or group of slopes would include:

- Reduce the frequency of landsliding – by stabilization measures such as groundwater drainage, slope modification, anchors; or by scaling loose rocks,
- Reduce the probability of the landslide reaching the element at risk – e.g. for rockfalls, construct rock catch fences; for debris flows construct catch dams;
- Reduce the temporal spatial probability of the element at risk e.g. by installing monitoring and warning systems so persons can evacuate; relocation of buildings to be further from the landslide;

Other risk management options may include:

- Avoid the risk – e.g. abandon the project, seeking an alternative site or form of development such that the risk will be tolerable
- Transfer the risk, by requiring another authority to accept the risk, or to compensate for the risk such as by insurance (for property)
- Postpone the decision if there is sufficient uncertainty, awaiting the outcomes of further investigations, assessment of mitigation options, and monitoring. This would usually only be a temporary measure.

Finally a risk mitigation plan will be decided upon. There may be elements of control in this plan – i.e. regulations imposed by local or other governments.

For hazard analysis for land use planning, the emphasis may be on limiting building development to those areas where risks are assessed as likely to be acceptable, and using the higher hazard areas for low occupancy use such as sports field or passive recreation. In some cases mitigation measures as outlined above may be appropriate.

Apart from the consideration of risk mitigation using engineering measures, landslide risk management also consists of the use of ‘soft’ (or non-engineering) options, such as public education campaigns, public information services, etc. to address the issue of risk tolerance by the general public or the stakeholders and avoid unduly high expectations of the level of safety that can be achieved in practice. Risk tolerance is related, in part, to the perception and understanding of landslide risk. Risk communication to lay people forms a key element of the landslide risk management process in facilitating a better understanding of the nature and reality of landslide risk, and promoting the build-up of trust in, and credibility of, the risk analyst. Geotechnical professionals involved in landslide risk assessment and risk management have an important role to play in risk communication, which is best done using languages and means that can be easily comprehensible by the general public.

7 THE BENEFITS AND LIMITATIONS OF LANDSLIDE RISK MANAGEMENT

Some of the benefits of the use of quantitative risk assessment in landslide risk management include:

(a) It encourages a rational, systematic approach to assessing the safety of natural and engineered slopes, by requiring an assessment of the characteristics of the landslides, their travel distance and velocity, frequency of sliding, the elements at risk, their temporal spatial probability and vulnerability.

(b) It can be applied to situations which are not amenable to conventional deterministic analysis e.g. rockfalls, small landslides in cut slopes, shallow landslides and resulting debris flows on steep natural slopes.

(c) It can be applied to land-use planning, with specific loss of life acceptance criteria used to determine the zoning where building is acceptable.

(d) It allows comparison of risks across an owner’s portfolio of slopes e.g. cut slopes on highways, and thereby allows prioritisation of remedial works, and potentially setting of risk-based standards for acceptable designs.

(e) Some local and regional government planners are familiar with risk management principles, and welcome landslide risk management being presented in terms they can relate to other hazards.

(f) The process requires consideration of risks for all levels of loading, rather than relying on “extreme event” loadings. Often failure paths will be identified in the analysis which have been overlooked.

(g) It focuses attention or what happens if the slope fails, including the possibility of the slide travelling rapidly onto buildings below, causing damage and loss of life.

(h) It focuses attention on liabilities and responsibilities if the parties involved.

(i) It provides a framework to put uncertainties and engineering judgement into a system. This results in an enhanced awareness of the need to consider uncertainties, and insight on what can go wrong, and their potential consequences, together with how the uncertainties and risks can be best managed

(j) It provides an open and transparent process on the nature and key contributors of landslide risk and the corresponding uncertainty for discussion with the regulators, owners, stakeholders, etc.

(k) It allows systematic consideration of risk mitigation options and cost benefit ratios, consistent with the As Low As Reasonably Practical (ALARP) principles, thus encouraging optimisation and enhancing cost benefit.

Some of the challenges and perceived limitations include (adapted from IUGS 1997):

(a) The potential uncertainty in estimating frequencies, travel distance and vulnerability. However these uncertainties can be modelled in the analysis, or sensitivity studies done to get a feel for their influence.

(b) The variety of approaches, and the need for expert judgement to assess frequency of landsliding in many cases. This requires those doing the analysis to be trained, and "calibrated". Baynes et al (2002) give a good example of how this can be achieved.

(c) Revisiting an assessment can lead to a significant change in the assessed risk due to increased data, or development of more advanced methods. This however is common to a "conventional deterministic" approach.

(d) Poor estimates of risk because significant hazards have been overlooked. This is a problem whichever approach is used, and can only be overcome by using well trained and experienced geotechnical professionals to do the analyses.

(e) Results of an assessment are seldom verifiable. A possible approach to overcome this is to use systematic peer review by individuals or for larger projects, panels. The first author has seen how successful this can be in risk assessment for dams. For slopes, where budgets are often smaller, peer review while still essential, is more likely to be done on a sample of the slopes being assessed, but it still should be done.

(f) Acceptable and tolerable loss of life criteria for slopes and landslides are not well established. This is an issue which has to be overcome at the country, state or local government level. It will not be practical to establish universal guidelines, although inevitably people will refer to what it is being done in societies with similar legal and social values.

(g) Some over rely on the results of risk assessments – and do not understand the uncertainty in the probabilities calculated. This is for the analyst to understand, and convey in the reporting process and when communicating with the public.

(h) The authors' experience is that many experienced practitioners are reluctant to use quantitative approaches to estimating landslide frequencies, because of their lack of experience in doing this. This needs to be addressed by systematic, on the site training and review by experienced professionals.

(i) There is still a lack of general acceptance of the method by the profession. It should be recognised that QRA is an engineering tool that may be used for an appropriate problem or to supplement other conventional tools for landslide risk management

8 EXAMPLES OF LANDSLIDE RISK ASSESSMENT

Figures 5, 6 and 7 give examples of certain elements of landslides risk assessment. These are simplified to illustrate the basic principles involved. Note that for convenience it has been assumed that the tolerable risk criteria in Table 2 and Figure 4 apply to the cases considered. Other examples can be found in Lee and Jones (2004), Lacasse (1998), Ho et al (2000), and Fell and Hartford (1997).

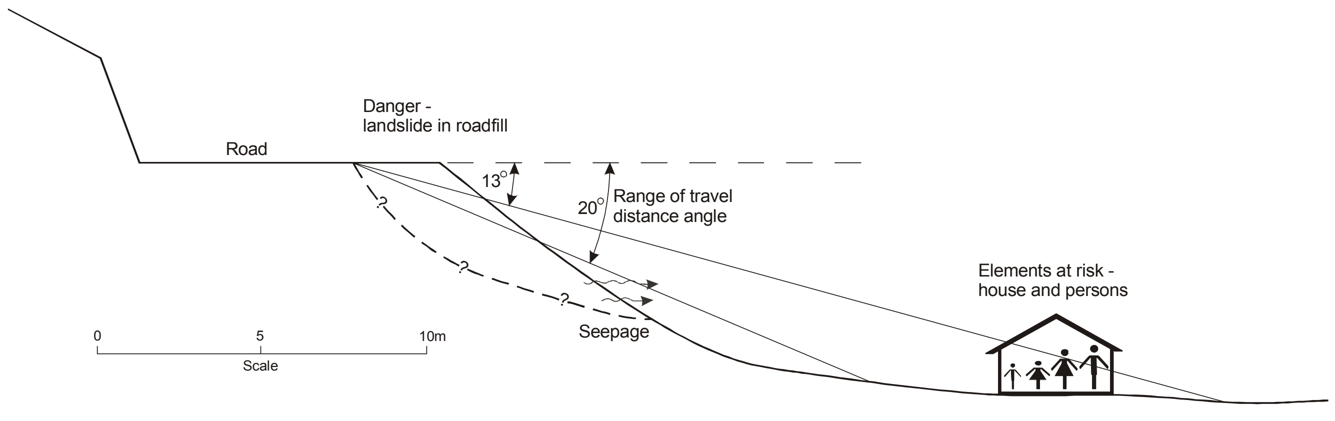
9 CONCLUDING REMARKS

(a) The risk management framework presented in this paper has been successfully used in landslide risk assessment and management for engineered and natural slopes. The framework may be adapted to suit a variety of problems, with due regard to the nature of the issues involved.

(b) Recent developments have included more widespread use of quantitative methods; more refined hazard and risk zoning which often involves use of digital technologies; improved rainfall-landslide incidence correlation models; and improved methods for assessing travel distances and travel paths.

(c) While the emphasis in this paper is on quantitative methods, current practice also involves the use of risk-based qualitative methods in many applications, including management of landslide risks for roads and railways, and in land use planning. These are valuable in that the landslide processes are systematically studied, and can lead to

FIGURE 5 –EXAMPLE I – LANDSLIDING IN ROAD FILL



1. Scope definition

Calculate the risk to persons living in the house below a road as shown in the figure. Assess the tolerability of this risk against the tolerable risk criteria shown in Table 1 and Figure 4.

2. Risk analysis

(i) Danger (Landslide) characterisation

The road was built 50 years ago, by cut and fill with a bulldozer. There was no proper compaction of the fill. The site is underlain by granitic rocks, and the fill is derived from residual soils and completely weathered granite which classifies as a silty sand. A thorough search of records has indicated that over the length of this road, which is all in similar topography, geology and climatic conditions to this fill, there have been 4 landslides in a total of 60 fills.

Based on the geometry of the fill, and the landslides which have occurred, it is assessed that the likely volume of the slide is about 1000m^3. Because of the loose, saturated nature of the fill it is anticipated that there may be a large loss of undrained shear strength on sliding ("static liquefaction") and the movement after failure is likely to be rapid.

Using empirical methods, it is estimated that the travel distance angle will be between 13^o and 20^o. Based on this estimate, and the geometry of the slope, it is estimated that the probability of the landslide reaching the element at risk (the house and its occupants) $P_{T:L} = 0.4$.

(ii) Frequency analysis

Assuming this fill is similar to the other 60 fills on the road and that the 50 years of the road's performance road is representative of the future, the frequency of sliding of the fill is:

$$P_L = \frac{4}{60 \times 50} = 1.33 \times 10^{-3} \,/\, \text{annum}$$

(iii) Consequence analysis

<u>(a) Temporal spatial probability ($P_{(S:T)}$) of the persons</u>

Four persons live in the house. One of those persons is in the house 20 hours per day, 7 days per week; while the other three are in the house 12 hours per day, 2 days per week.

For the person most at risk:

$$P_{(S:T)} = \frac{20}{24} = 0.83$$

For the other three persons:

$$P_{(S:T)} = \frac{12}{24} \times \frac{2}{7} = 0.14$$

$$P_{(S:T)} = \frac{12}{24} \times \frac{2}{7} = 0.14 \quad \text{assuming no warning.}$$

<u>(b) Vulnerability (of the persons ($V_{(D:T)}$)</u>

Based on the volume of landsliding, its likely velocity when it hits the house, it is estimated that the vulnerability of the persons to being killed if they are in the house when the landslides hits is 0.4.

FIGURE 5 continued

(iv) Risk estimation

The annual probability of the person most at risk losing his/her life is

$$P_{(LOL)} = P_{(L)} \text{ x } P_{(T:L)} \text{ x } P_{(S:T)} \text{ x } V_{(D:T)}$$

$$= (1.33 \text{x} 10^{-3}) \text{ x } (0.4) \text{ x } (0.83) \text{ x } (0.4) / \text{annum}$$

$$= 1.7 \text{x} 10^{-4} / \text{annum}$$

The annual probability of four persons being in the house where it is hit by the slide (assuming the time they spend in the house overlap)

$$= (1.33 \text{ x } 10^{-3}) \text{ x } (0.4) \text{ x } (0.14)$$

$$= 0.74 \text{ x } 10^{-4} / \text{annum}$$

Since their vulnerability is 0.4, so 1.6 persons (say 1 to 2) would be killed.

3. Risk assessment

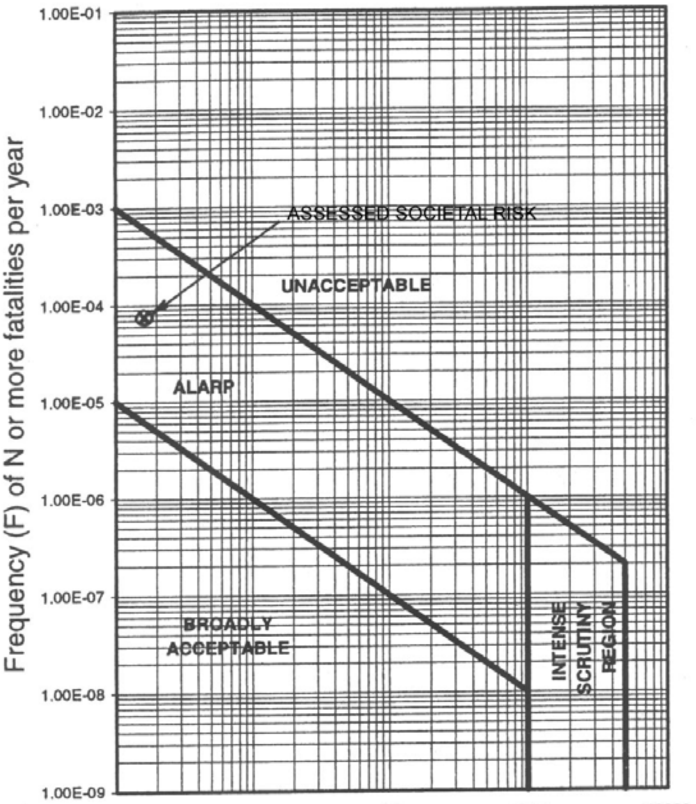
(i) Risk evaluation

(a) Individual Risk

From Table 2, the tolerable individual risk for an existing slope is 1 x 10^{-4}/annum; so for the individual most at risk, with $P_{(LOL)} = 1.7 \text{ x } 10^{-4}$, the risk is just in the intolerable range.

(b) Societal Risk

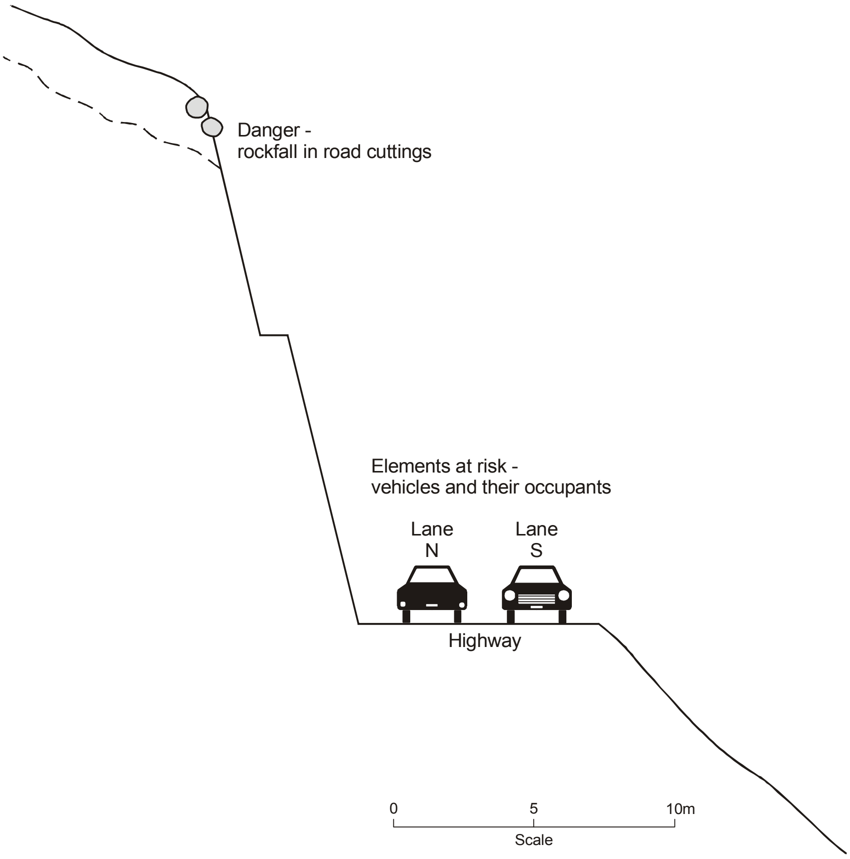
From Figure 4 reproduced below, the societal risk is below the limit of tolerability line, but in the ALARP region.



(ii) Comment

At this time, possible risk mitigation options would be considered, and the risks re-calculated. The ALARP principle might be used along with values judgements to determine a risk mitigation and/or monitoring plan, or to consider doing more geotechnical investigations to get an improved more accurate assessment of the risk.

FIGURE 6 –EXAMPLE II – ROCKFALLS FROM CUTTINGS ON A HIGHWAY



1. Scope definition

Calculate the risk to persons travelling on the highway as shown in the figure. Assess the tolerability of this risk against the tolerable risk criteria shown in Table 1 and Figure 4. Only consider direct impact falls.

2. Risk analysis

(i) Danger (landslide) characterisation

The road to a ski resort is privately owned and was built 10 years ago. The 50 cuts in the road were constructed at relatively steep slopes, and without treatment to control weathering, erosion and shallow instability leading to rockfalls.

A thorough search of the maintenance records and observations of boulder impacts on the road surface indicated that for the average cutting on the road, there have been 2 rockfalls per annum, with boulders ranging in size from 0.5m dia to 1m dia. The cuttings are in similar topography, geology and climatic conditions. Based on the recorded boulder impacts on the road surface, and the use of rockfall simulation programs, it is assessed that 60% of rocks falling from the slope will impact on Lane N which is closest to the cut, and 10% on Lane S.

(ii) Frequency analysis

The average frequency of rockfalls for each cutting is 2 per annum. There are a total of 50 cuts along the road, giving a total of 100 rockfalls per annum or 0.27/day, the average frequency of rockfalls (N_R) onto lane, N = 0.6 x 0.27 = 0.16/day, and on Lane S, = 0.1 x 0.27 = 0.027/day.

(iii) Consequence analysis

(a) Temporal spatial probability ($P_{(S:T)}$) of vehicles

The probability of a vehicle occupying the length of road onto which the rock falls is given by

$$P_{(S:T)} = \frac{N_V}{24} \bullet \frac{L}{1000} \bullet \frac{1}{V_V}$$

where N_V = average number of vehicles/day

FIGURE 6 continued

L = average length of vehicle (metres)
V_V = velocity of vehicle (km/hour)

For each lane, the average number of vehicles per day over the year is 2000, the average length of the vehicles is 6 metres, and they are travelling at 60 km/hr, ignoring the width of the boulder:

For each lane

$$P_{(S:T)} = \frac{2000}{24} \bullet \frac{6}{1000} \bullet \frac{1}{60}$$

$$= 0.0083$$

For a particular vehicle travelling once each day in one direction

$$P_{(S:T)} = \frac{1}{24} \bullet \frac{6}{1000} \bullet \frac{1}{60}$$

$$= 0.0000042$$

<u>(b) Vulnerability of the persons in the vehicles $V_{(D:T)}$</u>

Based on published information and judgement, it is estimated that the vulnerability of persons in vehicles in lane N is 0.3 and in lane S, 0.15.

(iv) Risk estimation

The annual probability of the person most at risk losing his/her life by driving along the road is:

<u>(a) For lane N</u>

$$P_{(LOL)} = P_{(S)}\ x\ V_{D:T} = (1 - (1 - P_{(S:T)})^{N_R})\ x\ V_{D:T}$$
$$= (1 - (1 - 0.0000042)^{0.16})\ x\ 0.3$$
$$= 2.0\ x\ 10^{-7}\ /\ annum$$

<u>(b) For lane S</u>

$$P_{(LOL)} = (1 - (1 - 0.0000084)^{0.027}\ x\ 0.15$$
$$= 0.3\ x\ 10^{-7}\ /\ annum$$

The total probability of death for the person most at risk is 2.3 x 10^{-7}/annum. For a person who only travels on the road once per year in each direction, $P_{(LOL)}$ = 6.3 x 10^{-10}/annum (2.3 x 10^{-7}/365). The total annual risk assuming each of the 2000 vehicles/day carries an average of 3 persons is 2000 x 365 x 3 x 6.3 x 10^{-10}/annum = 0.0014 persons/annum. The F-N plot has not been determined in this case.

3. Risk assessment

(i) Risk evaluation

(a) Individual risk

From Table 1, the tolerable individual risk for existing slopes is 1 x 10^{-4}/annum. So for the individual most at risk, with $P_{(LOL)}$ = 2.3 x 10^{-7}/annum, the risks are within the tolerable limit. For an individual who drives on the road only once per year, the risk is 6.3 x 10^{-10}/annum, which would be acceptable. The societal risk limit of tolerability for one life lost is 10^{-3}/annum (see Figure 4). The estimated probability of one or more lives lost is about 5 x 10^{-4}/annum, near the tolerable limit.

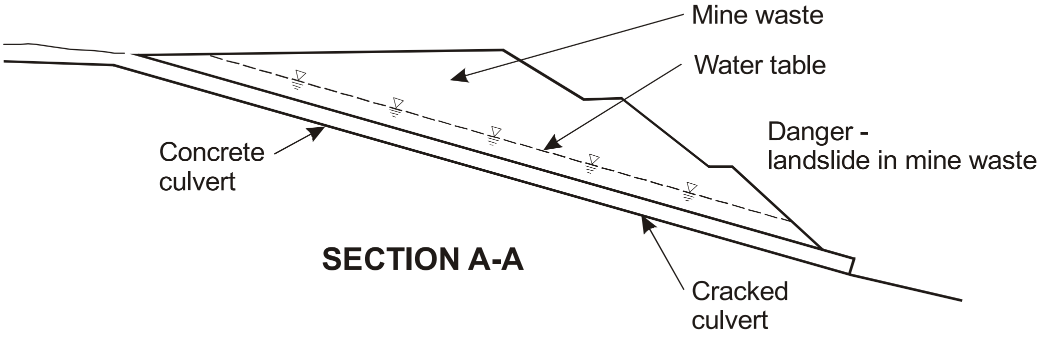
(ii) Comment

(a) It is considered reasonable to sum the risks for all the road cuttings because the road is the responsibility of one organization.

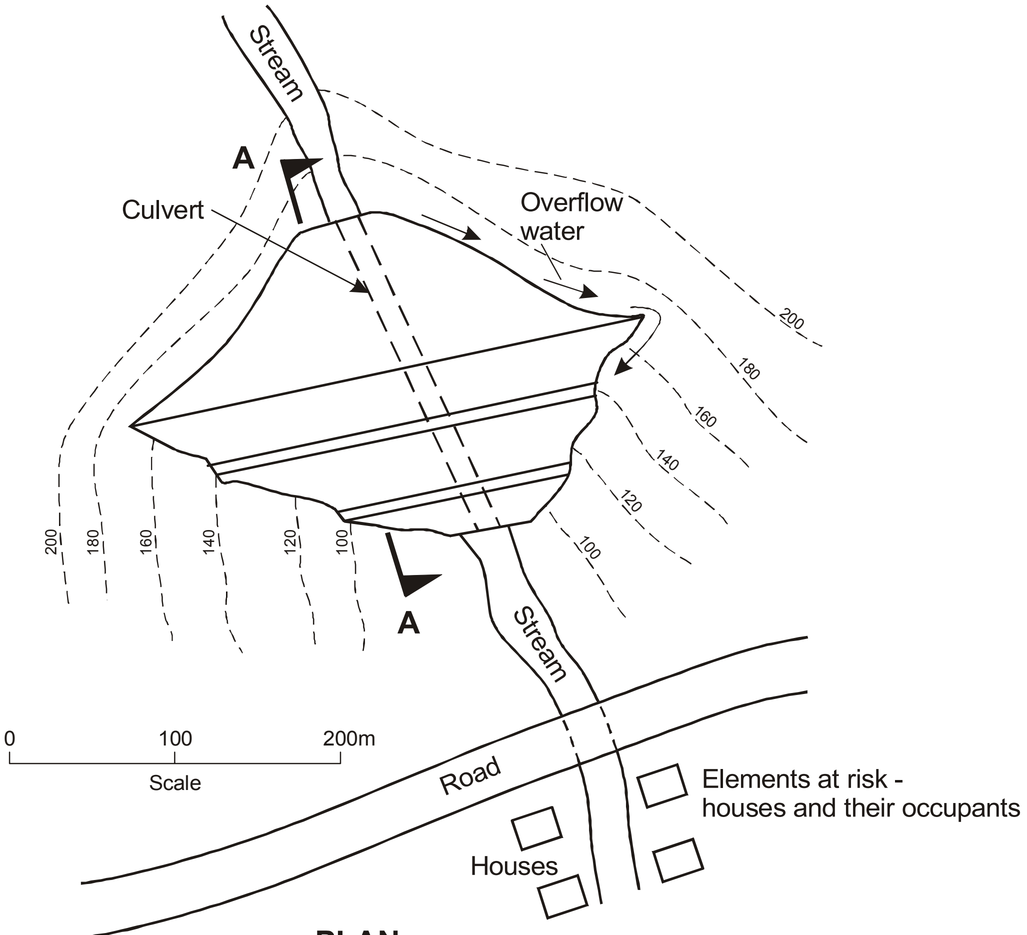
(b) At this time, risk mitigation options would be considered. These could include engineering option to reduce the frequency of rockfalls (rock-bolting, shotcreting, scaling of loose rocks in a regulated manner); reducing the probability the rocks will fall onto the road (e.g. mesh protection over the slope, catch drain); or reducing the probability of vehicles being below a rockfall when it occurs (e.g. closing the road in periods of heavy rain if it could be demonstrated that is when most rockfalls occurred).

(c) See SOA Paper 5 for the equations for estimating risk.

FIGURE 7 –EXAMPLE III– LANDSLIDING OF MINE WASTE DUMP



SECTION A-A



PLAN

1. Scope definition

Calculate the risk to persons living in the houses and travelling on the road below the mine waste dump. Assess the tolerability of these risks against individual and societal tolerable risk criteria.

2. Risk analysis

(i) Danger (landslide) characterisation

The mine waste is silty sandy gravel and gravelly silty sand coarse reject from a coal washing. It was deposited over 50 years by end tipping. Geotechnical site investigations, hydrological and engineering analyses have shown that:

(a) The waste is loose, and the lower part is saturated.

(b) The waste is likely to liquefy and flow liquefaction occurs for earthquakes loadings larger than 10^{-3} AEP

(c) The culvert through the waste dump exceeds its capacity and runs full for floods greater than 0.1 AEP. For floods larger than this water flows over the sides of the waste dump and leaks onto the waste material through cracks in the culvert, increasing the pore pressures in the waste.

FIGURE 7 continued

(d) The factor of safety of the dump under static loading is about 1.2 for water table levels which are reached annually.

(e) If the dump slides even under static loading, it is likely to flow because of its loose, saturated granular nature. The probability of this occurring given sliding occurs and the resultant debris flow reaching the houses is 0.5 based on post liquefaction shear strengths, and empirical methods for estimating travel distance.

(f) The volume of the anticipated landslide and resulting debris flow is about 100,000m^3 and the debris flows are likely to be travelling at a high velocity when they reaches the road and houses.

(ii) Frequency analysis

The potential failure modes are:

(a) Culvert runs full, water leaks, saturates downstream toe, causes slide.
(b) As for (a), but a smaller slide, blocks/shears culvert, causes slide.
(c) Culvert collapses, flow saturates downstream toe, causes slide.
(d) A bigger flood, causes the culvert overflow, saturates fill, causes slide.
(e) As for (d), but scour of flowing water at toe of fill initiates slide.
(f) Rainfall infiltration, remobilizes slide.
(g) Earthquake causes liquefaction.

Based on the hydrology of the catchment, the hydraulics of the culvert, stability analyses and engineering judgement, it is estimated that the frequency of landsliding of the waste for modes (a) to (f) is 0.01/annum.

Based on an analysis of liquefaction using a Youd et al (2001) approach, and post liquefaction stability analysis, it is estimated that the frequency of landsliding for mode G is 0.005/annum.

Hence the total $P_{(L)} = 0.015$/annum.

(iii) Consequence analysis

(a) Temporal spatial probability ($P_{(S:T)}$) of the persons in the houses, and on the road

A survey of occupancy of the houses shows that the person most at risk in one of the houses is in the house on average 18 hours/day, 365 days per year, so $P_{(S:T)} = 0.75$.

Each house is occupied by a further 4 persons, for 10 hours/day, 325 days/year. Assuming they are all in the houses at the same time. So:

$$P_{(S:T)} \text{ for 16 persons} = \frac{10}{24} \text{ x } \frac{325}{365}$$
$$= 0.36$$

Vehicles on the road travel at an average velocity of 30 km/hour as they pass by the 100 metres of road potentially affected by the debris flow. So for each time the vehicle drives along the road,

$$P_{(S:T)} = \frac{100}{30{,}000 \text{ x } 365 \text{ x } 24}$$
$$= 3.8 \text{ x } 10^{-7}$$

If a vehicle travels along the road 250 times a year (such as the school bus)

$$P_{(S:T)} = 250 \text{ x } 3.8 \text{ x } 10^{-7} = 9.5 \text{ x } 10^{-5}$$

The critical vehicles for risk assessment are buses which travel 250 days/year.

(b) Vulnerability of persons ($V_{(D:T)}$

Bases on the likely high velocity of sliding and large volume, it is estimated that the vulnerability of persons in the houses is 0.9, and in a bus, 0.8.

(iv) Risk estimation

The annual probability of the person most at risk losing his or her life is

$$P_{LOL} = p_{(L)} \ x \ P_{(T:L)} \ x \ P_{(S:T)} \ x \ V_{(D:T)}$$

$$P_{LOL} = (0.015) \text{ x } (0.5) \text{ x } (0.75) \text{ x } 0.9/\text{annum}$$
$$= 5 \ x \ 10^{-3} / annum$$

FIGURE 7 continued

If all four houses are hit by the landslide, 0.9 x 16 or say 14 of the 16 persons would be killed. The annual probability that this would happen is:

$$= 0.015 \text{ x } 0.5 \text{ x } 0.36/\text{annum}$$

$$= 2.7 \text{ x } 10^{-3}/\text{annum}$$

If a bus with 40 persons on it is hit by the landslide, 0.8 x 40 = 32 persons would be killed. The annual probability this would happen is:

$$= 0.015 \text{ x } 0.5 \text{ x } 9.5 \text{ x } 10^{-5}/\text{annum}$$

$$= 7.1 \text{ x } 10^{-7}/\text{annum}$$

So if loss of life of persons in other vehicles on the road is ignored, the cumulative F-N pair are:

$$\text{One or more lives } F = 5 \text{ x } 10^{-3} + 2.7\ x\ 10^{-3} + 7.1\ x\ 10^{-7} = 7.7\ x\ 10^{-3} / annum$$

$$15 \textit{ or more lives} = 2.7\ x\ 10^{-3} + 7.1\ x\ 10^{-7} = 2.7\ x\ 10^{-3} / annum$$

$$33 \textit{ lives } F = 7.1\ x\ 10^{-7} / annum$$

3. Risk assessment

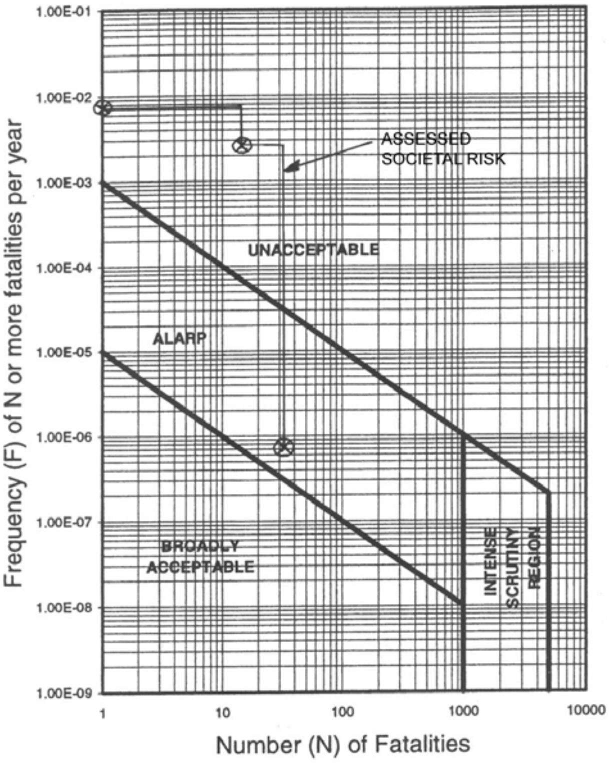
(i) Risk evaluation

(a) Individual risk.

The risk for the person most at risk is 5 x 10^{-3}/annum which is well in excess of the tolerable individual risk in Table 1.

(b) Societal risk

The three points on the F-N curve are shown below. It can be seen that the risks are well in excess of the tolerable for 1 and 15 lives, but in the ALARP range for 33 lives lost in a bus.



(ii) Comment

At this point, possible risk mitigation options would be considered, and the risks recalculated. The mitigation options could include reducing the probability of sliding by repairing the cracks in the culvert, controlling water which overflows when the culvert capacity is exceeded; removing and replacing the outer waste well compacted so it will not flow if it fails; adding a stabilizing berm; installing a warning system so persons in the houses can be evacuated and the road blocked to traffic when movement is detected in the waste.

uniform classification of hazards and risks, which can be understood by those responsible for risk management. Qualitative approaches are better if they are underpinned by quantitative studies particularly where loss of life is an issue. RTA(2001) is an example of this for risk management of landsliding affecting highways. Other examples include the design event approach for assessing mitigation measures for natural hillside landslide hazards (Ho, 2004).

(d) Adoption of quantitative methods is likely to assist in risk communication in many cases because regulators, politicians and managers of larger organizations are often familiar with quantifying risks within other parts of their responsibilities. Quantifying landslide risks allows these people to assess them in perspective with those from other hazards. In some cases the use of quantitative risk assessment is stipulated by the regulator or owner.

(e) While the nature of the problem and available methods for many studies always involve some degree of uncertainty in the risk estimates, this is not to say they should not be estimated, provided the limitations are acknowledged. Decisions have to be made despite the uncertainties, and it is better to have an approximate estimate of the risks, than none at all. The level of sophistication to be adopted in risk estimation for a particular problem only needs to be sufficient to facilitate an informed decision.

(f) There is often an overemphasis on the risk analysis, and not enough attention put on the risk assessment and management. It is important that Geotechnical Professionals involve themselves in the assessment and management process because they often have the best understanding of the nature of the hazard and the risk. However the final decisions on tolerable risks lie with owners, regulators and politicians.

(g) The authors cannot over-emphasise the need for proper geotechnical inputs to the risk analysis, particularly with respect to the hazard identification and quantification. Risk assessment is not a substitute for good geotechnical engineering knowledge and judgement. It enhances it by adding insight.

10 ACKNOWLEDGEMENTS

This paper is published with the permission of the Head of the Geotechnical Engineering Office and the Director of Civil Engineering and Development, Government of the Hong Kong Special Administrative Region.

11 REFERENCES

ANCOLD 1994. *Guidelines on risk assessment.* Australian Committee on Large Dams.

ANCOLD 2003. *Guidelines on risk assessment.* Australian National Committee on Large Dams.

AS/NZS 4360:1999. Australian/New Zealand Standard, Risk Management Standards Australia, Standards New Zealand.

Australian Geomechanics Society 2000. "*Landslide risk management concepts and guidelines"*. Australian Geomechanics Society, Sub-Committee on Landslide Risk Management, Australian Geomechanics, 35: 49-92.

Baynes, F.J., Lee, I.K. and Stewart, I.E. 2002. A study of the accuracy and precision of some landslide risk analyses. Australian Geomechanics, Vol.37, No.2, 149-156.

Canadian Standards Association 1991. "Risk analysis requirements and guidelines". CAN/CSA-Q634-91, Canadian Standards Association, Toronto, Canada, 42.

Christian, J.T. 2004. Geotechnical Engineering reliability: how well do we know what we are doing? *Journal Geotechnical and Geoenvironmental Engineering,* Vol.130, No.10, 985-1003.

Cruden, D.M. & Varnes, D.J. 1996. Landslide types and processes: in "Landslides Investigation and Mitigation". In K. Turner, R.L. Schuster (eds), *Transportation Research Board Special Report 247,* National Research Council, Washington, D.C.

Einstein, H.H. 1988. Special lecture, landslide risk assessment. *Proc. 5th Int. Symp. On Landslides, Lausanne, Switzerland*. A.A. Balkema, Rotterdam, The Netherlands, 2: 1075-1090.

Einstein, H.H. 1997. Landslide risk – systematic approaches to assessment and management in *Landslide Risk Assessment*, Cruden and Fell (eds), Balkema, Rotterdam, 25-50.

Fell, R. & Hartford, D. (1997). Landslide risk management; in "*Landslide Risk Aassessment"*, Cruden and Fell (eds), Balkema, Rotterdam, 51-110.

Fell, R. 1994. Landslide risk assessment and acceptable risk, *Canadian Geotechnical Journal*, 31: 261-272.

Geotechnical Engineering Office 1998. Landslides and Boulder Falls from Natural Terrain: Interim Risk Guidelines. GEO Report No.75, Geotechnical Engineering Office, The Government of the Hong Kong Special Administrative Region.

Hartford, D.N.D. & Baecher, G.S. 2004. Risk and uncertainty in Dam Safety. Thomas Telford, London.

Ho, K.K.S. 2004. Recent advances in geotechnology for slope stabilization and landslide mitigation – perspective from Hong Kong, in Landslides: evaluation and stabilization. Lacerda, Ehrlich, Fontoura and Sayão (eds). Taylor and Francis Group, London, 1507-1560.

Ho, K., Leroi, E. & Roberds, B. 2000. Quantitative risk assessment. *Application, myths and future directions*. GeoEng 2000, Technomic Publishing, 269-312.

ICOLD 2003. Risk assessment in dam safety management, Draft ICOLD Bulletin. International Commission on Large Dams, Paris.

IUGS 1997. Quantitative risk assessment for slopes and landslides – the State of the Art. IUGS Working Group on Landsldies, Committee on Risk Assessment, in *Landslide risk assessment*, Cruden and Fell (eds), Balkema, Rotterdam, 3-12.

Kvalstad, T.J., F. Nadim, and C.B. Harbitz 2001. Deepwater geohazards: Geotechnical concerns and solutions. Offshore Technology Conference, OTC '01, Houston, Texas, 30 April – 3 May, Paper OTC 12958., 11 p

Lacasse, S. 1998. Risk and Reliability in Geotechnical Engineering. State-of-the-Art paper. Fourth International Conference on Case Histories in Geotechnical Engineering, St-Louis, Missouri, USA. March 1998. (NGI Report 594000-4.)

Lacasse, S. 2004. Risk Assessment for Geotechnical Solutions Offshore. Keynote Paper. OMAE2004-51144. Proc. of OMAE 2004 -23rd International Conference on Offshore Mechanics and Arctic Engineering. Vancouver, Canada. June 2004, 16 p.

Lacasse, S., Nadim, F. and Høeg, K. 2003. Risk Assessment in Soil and Rock Engineering. PanAm Conference, SARA, June 2003, pp. 2743-2750

Lacasse, S., Nadim, F., Høeg, K. and Gregersen, O. 2004. Risk Assessment in Geotechnical Engineering: The Importance of Engineering Judgement. The Skempton Conference, Proc. London UK. Vol.2, pp 856-867.

Lee, E.M. and Jones, D.K.C. 2004. Landslide Risk Assessment. Thomas Tilford Publishing, London.

Leroi, E. 1996. Landslide hazard – risk maps at different scales: objectives, tools and developments. In *Landslides Proc. Int. Symp. On Landslides,* Trondheim, 17-21 June, K. Senneset (ed), 35-52.

Morgan, M.G. and Henrion, M. 1990. Uncertainty – a guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge University Press.

Nadim, F. 2002. Probabilistic methods for geohazard problems: State-of-the-Art. Probabilistics in GeoTechnics: Technical and Economic Risk Estimation, Graz, Austria, September 15 -19, pp. 333-350

Nadim, F. and Lacasse, S. 2004. Mapping of landslide hazard and risk along the pipeline route. GeoPipe 2004. Terrain and Geohazard Challenges facing Onshore Oil and Gas Pipelines. Proc. (loose leaf binder), London, June 2004.

Nadim, F. and S. Lacasse (1999). Probabilistic Slope Stability Evaluation. Proc. "Geotechnical Risk Management", Hong Kong Institution of Engineers, Hong Kong, 177-186.

Nadim, F. and S. Lacasse 2003. Review of probabilistic methods for quantification and mapping of geohazards. Geohazards 2003, Edmonton, June 2003, pp. 279-286

Nadim, F., D. Krunic, and P. Jeanjean 2003. Probabilistic slope stability analyses of the Sigsbee Escarpment. Procs, OTC 15203, Offshore Technology Conference ’03, Houston, Texas, May 2003, OTC paper 15203, 8 p.

RTA 2001. Guide to slope risk analysis version 3.1. Roads and Traffic Authority, Sydney.

Stewart, I.E., Baynes, F.J. and Lee, I.K. 2002. The RTA guide to slope risk analysis version 3.1. Australian Geomechanics, Volume 37, No.2, 115-149.

Varnes, D.J. & The International Association of Engineering Geology Commission on Landslides and Other Mass Movements 1984. *Landslide hazard zonation: A review of principles and practice.* Natural Hazards, 3: 63. Paris, France. UNESCO.

Whitman, R.V. 1984. Evaluating calculated risk in geotechnical engineering, J. Geotech. Eng., ASCE, Vol.110, No.2, 145-188.

Wu, T.H., Tang, W.H. and Einstein, H.H. (1996). Landslide hazard and risk assessment; in landslides investigations and mitigation, Transportation Research Board Special Report 247, national Research Council Washington DC.

Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian J.T., Dobry, R., Finn, W.D.L., Harder, L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcuson, W.F., Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, MS., Robertson, P.K., Seed, R.B., and Stokoe, K.H. 2001. Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF Workshops on evaluation of liquefaction resistance of soils. *J. Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 127, No. 10, 817-834.