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Quantitative Risk Assessment: Application, Myths and Future Direction

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Abstract: The development of quantitative risk assessment (QRA) methodologies has advanced to such a state that it is now a practical risk management tool in geotechnical engineering. Pilot applications of QRA have shown great promise and it has contributed to addressing questions that would otherwise be very difficult to answer using conventional techniques. Resistance against the more widespread use of QRA is real and this is partly due to myths about the technique. The essence is risk-based thinking, be it under a quantitative or qualitative framework. The geotechnical community stands to gain by integrating risk-based thinking and methodologies into current geotechnical practice. This integration will better align the geotechnical profession with many of the other engineering fields that practise risk management in a more explicit manner.

1 INTRODUCTION

In geotechnical engineering, empirical rules based on precedents are commonly relied upon to solve practical problems. Modelling the full range of factors involved in a real problem in detail is, nearly always, too complicated and not credible. Fortunately, only some of the factors tend to be major in a given problem and these can usually be characterized by indices from standard tests. It is generally deemed that one can obtain a good enough estimate for engineering purposes by discounting the minor factors as unimportant and the extreme factors as unlikely.

This pragmatic approach has generally served the geotechnical profession well. However, unpleasant surprises do occur from time to time. “Minor” factors can turn out to be major, and “extreme” events can occur more frequently than expected. Geotechnical failures are not a rarity, and sometimes occur in a disastrous manner. What was judged to be unimportant may actually be very important, at least for the combination of circumstances at hand which might not have been foreseen (but were not necessarily unforeseeable). Another more subtle reason for unpleasant surprises is that designers sometimes wishfully classify those factors which they cannot confidently characterize as being of minor importance, or hope that such imponderables would be compensated by conservatism built in the system elsewhere.

The standard defense against non-performance in geotechnical engineering is to allow for a safety margin based on a deterministic approach (e.g. designing for a certain Factor of Safety, or factor of ignorance). The Factor of Safety is an experience-based index, intended to aid judgement and decision-making. The design Factor of Safety will vary with situations and considers risk implicitly. Although it is intended to cover the uncertainties involved, it does not consider damages or consequences directly or explicitly. There may be a standard design safety factor for particular types of problems that would be considered the minimum acceptable. However, because of the cost involved, it is frequently difficult to justify a higher design safety factor to the client even for more critical cases.

Whilst the conventional deterministic approach is, by and large, adequate for routine problems, it also has limitations. Over-designing costs money and often mitigates against achieving an elegant solution. There needs to be a balance between the degree of over-conservatism and the uncertainties it is to cover. However, standard Factors of Safety will not ensure performance if the key factors are overlooked. Excessively mechanical use of Codes of Practice is liable to result in unsatisfactory performance in the hands of a professional lacking the experience to appreciate and allow for the peculiarities involved. For example, over-conservatism in the assessment of natural hillsides could prohibit new developments, result in loss of land value or raise serious questions about whether actions should be taken to reduce the risk posed to existing developments. On the other hand, lack of recognition of significant hazards posed by natural hillsides could result in dire consequences. Alternative, or supplementary, approaches to conventional assessment techniques may be called

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for, at least in certain situations. The integrated risk management approach is one. Risk assessment is a risk management tool. In risk assessment, the consideration of uncertainties is done explicitly in a systematic and comprehensive way, whereas traditional approaches tend to consider uncertainties implicitly using sensitivity analyses on assumptions, generally in an ad-hoc manner.

Risk is the combination of the probability of some unfavourable scenarios happening and the likely damage they can cause. It is assessed through focused examination of how factors can interact, what scenarios can result, and what damage the scenarios can cause. This process is conducive to the identification of how uncertainties may combine and how unfavourable scenarios may come about even given incomplete knowledge. Depending on the assessed outcome, one may manage the risk by increasing the safety margin, improving the reliability of critical components, modifying the design concepts, reducing the consequence of failure or risk-sharing amongst the stakeholders. In the real world, there is obviously a need to balance risk against both cost and responsibility.

Based on fairly intense development work in the past few years, the knowledge and experience gained in applying QRA in geotechnical engineering have advanced significantly. The early results of QRA have met with mixed responses from the geotechnical profession (i.e. geotechnical engineers, geologists, etc.): those who see its value are keen to seize the opportunity and push it further (but may not exactly know how best to), whilst those in the opposite camp remain sceptical. The future of QRA appears to be in an acute situation in that the early impetus and enthusiasm in risk assessments may well be fading out in view of the indifference or even opposition shared by the 'traditionalists'.

In this paper, the concepts of QRA as applied to geotechnical engineering and land-use management are discussed, with special reference to landslide problems. Case studies covering a range of problems are described to illustrate practical applications of QRA. Critical issues at stake are highlighted, myths concerning QRA are diagnosed and the future direction is discussed. The readers should refer to other literature for classification of landslides and landslide hazard assessment (e.g. Hansen, 1984; Hutchinson, 1988 & 1992; Fell et al, 2000).

2 WHERE DO WE STAND WITH QRA?

Hazard and risk assessments are well-developed techniques that have been established practice for quite some time in many other engineering fields, such as oil and gas, chemical, nuclear, etc. Traditionally in these industries, quantification of risk by means of QRA methodology involves the identification of possible accidents (or failure modes) and incorporates an analysis based primarily on historical records of performance to determine the occurrence and consequences of such mishaps. QRA is not new to the arena of slope stability. The mining industry cannot afford to operate some of its major pits with conventional Factors of Safety, and methods of evaluating the probability of failure of large pit slopes have been used. Similarly, the assessment of dam safety, notably in Canada, Australia and Europe (e.g. France and Spain), has applied QRA techniques, with qualified success.

Geotechnical engineering is fundamentally about managing risk. If we accept that management requires measurement ('what you cannot measure, you cannot manage'), how should we set about measuring risk for risk management purposes? QRA can be such a tool.

The use of a risk-based framework has been applied to selected geotechnical problems in recent years, e.g. hazard of methane gas from landfills (O'Riordan & Milloy, 1994), migration of leachate from landfills (O'Brien, 1998), development over abandoned mines (Cole, 1993), geotechnical assessment in association with flood control and flood reduction studies (US Army Corps, 1996), assessment of natural hazards (Garry & Graszk, 1997), etc. However, the majority of the above work has not advanced to the formal detailed quantification of risk in the traditional sense as compared with, for example, the chemical industry.

In the past few years, formal QRA has been applied to quantify the risk of slope failures, notably in Australia (Fell, 1994; Australian Geomechanics Society, 2000), Hong Kong (e.g. Wong et al, 1997) and France (Mornpelat, 1994 & Rezig, 1998). Most of this work involved primarily pilot studies to develop a suitable framework and test the methodology, but QRA has also been applied to specific sites on an ad-hoc basis to tackle real problems. This reflects the fact that the adoption of QRA techniques in the geotechnical field is still in its early stages of development as an emerging concept. The above studies have yielded promising results and provided much insight on the usefulness and limitations of QRA.

In Hong Kong, for example, there has been a move towards the development of a risk-based approach to supplement the conventional approach for certain classes of problems. This may be attributed to the following considerations:

(a) There is a growing realization that there are considerable uncertainties associated with the ground and groundwater conditions, especially given the inherent variability of weathered profiles and tropical rainstorm characteristics; even slopes or other geotechnical structures which have previously been assessed as being up to the required standards can have a fairly high failure rate (e.g. Whitman, 1984 & 1997; Wong & Ho, 2000; Morgenstern, 2000).

(b) A risk-based approach assists in the prioritization of the retrofitting of smaller-sized slopes with less serious failure consequences and the development of a rational strategy to deal with such a category of slopes.

(c) A risk-based approach facilitates the communication of the realities of landslide risk to the public.

In some jurisdictions, risk criteria have been established for which compliance must be demonstrated. In Switzerland and France, the development of statutory risk mapping has prompted legislators to ask for more quantitative methodologies.

3 QRA IN THE CONTEXT OF RISK MANAGEMENT

Uncertainty is a fact of life and risk cannot be totally eliminated. A useful discussion of the background and nature of risk is given in Royal Society (1983 & 1992) and Engineering Council (1993).

Risk management comprises the estimation of the level of risk (which may be done qualitatively or quantitatively), deciding whether or not it is tolerable, and exercising appropriate control measures to reduce the risk where the risk level cannot be tolerated. To choose between risk mitigation measures, it is necessary to weigh costs against benefit in the broad sense, including social and political considerations. The essence of risk management and the role of QRA within the context of risk management are shown in Figure 1.

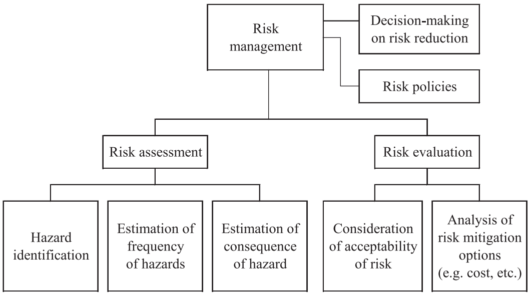

Figure 1. Framework for risk management

Risk may be defined as a measure of the chance of an adverse event (e.g. landslide) causing a certain amount of harm (e.g. fatalities, economic loss, social disruption, environmental damage, etc.) within a given time period. For practical purposes, risk may be taken to be the "expected value" (probability weighted average) of uncertain, adverse consequences due to all potential problems, i.e. the product of the probability (e.g. a chance of 1 in 10,000 per year) or, for multiple events, the frequency (e.g. 10 per year) of failure and the consequence (e.g. fatalities, damages to buildings, loss of service, political impact, etc.) each time the failure occurs, summed over all the different types of failures. Risk therefore comprises two main components, viz. probability (or frequency) of occurrence and consequence of failure.

In terms of conditional probability, the risk to a given individual may be defined as follows (Morgan et al, 1992):

$$R(IN) = P(H) \ \times \ P(S|H) \ \times P(T|S) \ \times V(L|T) \qquad (1)$$

where R(IN) is the risk to an individual (i.e. annual probability of loss of life)
P(H) is the annual probability of the hazard occurring (e.g. landslide)
P(S|H) is the probability of spatial impact (e.g. landslide impacting a building)
P(T|S) is the probability of temporal impact (e.g. presence of people at time of landslide impact)
V(L|T) is the vulnerability of individual given landslide impact (e.g. probability of loss of life)

Risk can be quantified using standard tools such as QRA technique, which is a method of quantifying risk through a systematic examination of the factors contributing to the hazard and the severity of consequence, and establishing probabilities for the various factors.

The following key questions are addressed systematically under a risk-based framework:

(a) What can cause harm? [Hazard Identification]
(b) How often? [Frequency Assessment]
(c) What can go wrong and how bad? [Consequence Assessment]
(d) What is the likelihood of damage? [Risk Quantification]
(e) So what? [Risk Acceptability]
(f) What should be done? [Risk Management]

As an example, the principal components and factors to consider in a landslide risk assessment are depicted in Figure 2.

One of the key steps in QRA is the formulation of a suitable hazard model. The hazard model should aim to classify the different types of hazard. For example, the classification may be in terms of different mechanisms and scales of failure, each with a corresponding frequency and consequence of failure. The hazard model should be comprehensive (i.e. covering the range of key hazards) and the classification suitably refined (but not unduly complicated) so as to be compatible with the resolution of the available data. The adequacy and appropriateness of the hazard model will greatly affect the accuracy of the subsequent frequency and consequence assessments.

It is important to bear in mind that QRA is a tool intended to aid (but not dictate) decision-making.

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Apart from the assessed risk levels and related technical considerations, the decision-making process will also need to give due consideration to other relevant factors and non-technical issues, such as land issues, political factors, social factors, programme, etc. Suitable tradeoffs are often necessary. By defining the fundamental questions to be answered and decisions to be made, the quantified and non-quantified information can be kept in balance in arriving at an informed decision.

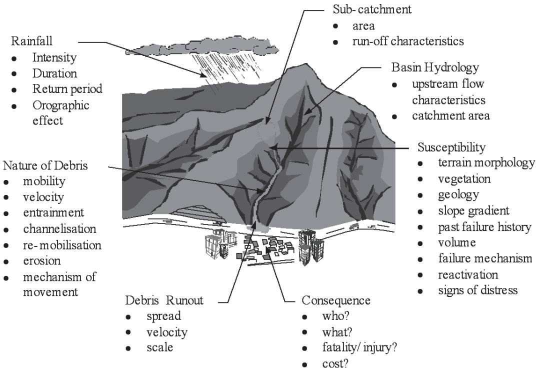

Figure 2. Factors to be considered in natural terrain landslide risk assessment

4 IMPETUS FOR QRA IN SLOPE PROBLEMS

For slope stability problems, the conventional approach is to carry out a limit equilibrium analysis to determine the Factor of Safety (i.e. deterministic analysis). Target factors of safety are stipulated primarily through experience and observations of past performance, together with an implicit judgement on the consequence of failure without explicit evaluation. By and large, the prime focus has been on how to prevent slope failures. The deterministic approach has been codified and its extensive use has been calibrated against experience over the years. This simplified approach can generally cope with routine problems given appropriate engineering judgement and adequate geological and geotechnical characterisation of the sites. However, examples can be cited whereby conventional stability analysis with traditional Factors of Safety are not always capable of averting undesirable performance (Morgenstern, 1991).

In contrast, conventional probabilistic methods have tended to find favour and application in more specialised problems (such as stability of oil platforms under wave or earthquake loading) although the technique can in principle serve as a more formal approach to other more common problems, e.g. probabilistic site characterisation (NRC, 1995; Lacasse & Nadim, 1996).

The main difference between a conventional probabilistic approach and QRA is that the former considers only the likelihood of failure, and is only one component of risk-based thinking. In contrast, QRA addresses the totality of the problem, i.e. both probability and consequence of failure, and it deals directly with risk issues. The assessment of landslide risk, for instance, can be related to other types of risks posed by other activities, whereas the assessment of what is the acceptable probability of failure is comparatively more open-ended because this will depend on what the consequences are for the given circumstances.

The problem of landslides is dominated by uncertainties. Morgenstern (1995) suggested that it would suffice for engineering purposes to distinguish three sources of uncertainties, namely, parameter uncertainty, model uncertainty and human uncertainty. QRA provides a numerical measure of the risk posed by a hazard, taking cognizance of the uncertainties involved.

There has been growing pressure on the geotechnical community to apply risk concepts or QRA, arising from the following sources:

(a) wish of the clients who want to know their exposure to risk and assign priorities,
(b) regulatory requirements by governments (e.g. Cave, 1992; Besson et al, 1999; DRM, 1990; Garry & Graszk, 1997; Graszk & Toulemont, 1996), and
(c) concern expressed by public bodies about adequacy of safety systems or measures, especially after a landslide disaster.

In reality, the main impetus for QRA is its potential to answer pertinent questions (either imposed externally or generated internally as part of emergency preparedness and crisis management programmes) that cannot be satisfactorily addressed by conventional means.

The risk concept is attractive in principle because it is rational, systematic and transparent in the quantification of risk and diagnosis of the areas requiring attention. It also provides a formal and consistent basis for judging risk acceptability and a common, definitive basis for evaluating the cost-benefit of alternative risk mitigation strategies to optimise design.

QRA can be an effective means of communicating the realities of landslide risk to the community and the authorities. It can have a major bearing on the legal profession in respect of assessing the question of liability. The concept of residual landslide risk, which can be compared with risks from other hazards to which the public are exposed in their daily lives (taking cognizance of the nature of the risk, i.e. voluntary or involuntary), is important in coming up with strategies to get the public to effectively buy into a residual risk (Malone, 1998).

It is important not to give a false impression that achieving a certain Factor of Safety at a cost will buy total safety (or zero risk). In fact, many students or even younger professionals may have been lured into

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believing that Factors of Safety are the essence of slope engineering and lack a fundamental understanding of risk-related issues. This is a worrying trend.

Historical fatalities do not necessarily reflect the actual level of landslide risk involved, because of the influence of near-miss events, changing scenarios such as population growth and continued urban development, rainfall conditions over a relatively short observation period that may not be representative, etc. It is international, state-of-the-art, practice in the formal risk management field to quantify the 'theoretical' risk using QRA techniques.

5 TYPES OF QRA AND PRESENTATION OF RISK RESULTS

Risk concepts and QRA can be applied in a number of areas. These include:

(a) Global risk assessment - to examine the scale of a problem and define the relative contribution of the different components to facilitate formulation of risk management policies and consideration of optimal resources allocation.
(b) Relative risk assessment - to determine the priority for follow-up action.
(c) Site-specific risk assessment - to evaluate the hazards and level of risk in terms of fatality (or economic or other loss) at a given site.
(d) Preparation of hazard or risk mapping - for hazard zoning or planning control of a region or an area.

Global QRA results will be of interest to policy makers or major organizations involved in determining risk tolerability levels. Detailed site-specific data are not normally required for a global QRA.

Site-specific QRA will be of interest to designers and slope owners. This facilitates the assessment of whether the risk levels at a specific site are acceptable and assists in the determination of whether a proposed development should be permitted, identification of constraints on the design layout, evaluation of cost-effectiveness of mitigation measures, etc. Site-specific risk assessment may also provide a benchmark for calibrating the results of global risk assessment. The application of a site-specific QRA will need to be supported by the detailed examination of landslide trigger factors, mechanisms and mode of failure and debris runout for the results to be sufficiently accurate.

In a formal QRA, the findings of a risk analysis with respect to public safety are often presented in the following format:

(a) individual risk (which relates to the risk posed to the most exposed and vulnerable and can be compared to other everyday risks), and
(b) societal risk (which relates to the risk posed to the affected population as a whole).

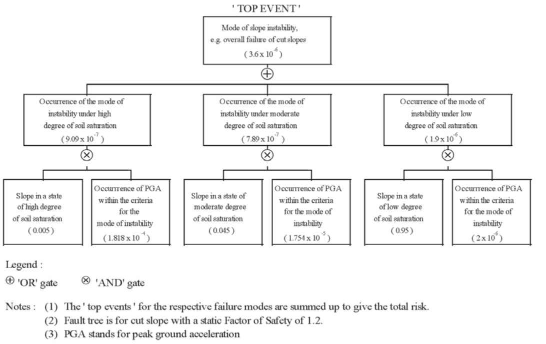
The concept of societal risk is based on society's aversion to high-fatality incidents. Traditionally, societal risk is expressed in terms of an F-N curve, i.e. a graphical representation of the number of fatalities (N) plotted against the cumulative frequency (F) of N or more fatalities, on a log-log scale. An F-N curve will provide information on the full range of credible fatal scenarios and the corresponding likelihood of occurrence. Alternatively, the societal risk results can be expressed in the form of a risk index known as potential loss of life (PLL), i.e. PLL = $\Sigma(f_i \times N_i)$ where f_i is the frequency of landslide incident i with N_i fatalities (note that this is the corresponding failure frequency and not the cumulative failure frequency) and N_i is the estimated number of fatalities for landslide incident i. In essence, PLL may be taken as the expected value (or mean of the probability distribution) of the total number of fatalities per year and it corresponds to the area under the plot of frequency of occurrence (i.e. f) against N.

Criteria are usually set against both individual risk and societal risk. Where this is done, both criteria need to be satisfied. Decisions regarding other types of risks (e.g. damage, loss of service, etc.) are typically based on cost-benefit analysis.

6 TOOLS FOR FREQUENCY ASSESSMENT

The main tools for assessment of failure frequency are:

(a) precedence data (including past performance and correlation between the cause-effect function, such as rainfall-landslide correlations and probability of exceedance of rainfall of different duration and intensity).
(b) fault trees techniques,
(c) probabilistic modelling (e.g. Mostyn & Li, 1993), and
(d) direct subjective assessment.



Notes : (1) The ' top events ' for the respective failure modes are summed up to give the total risk.
(2) Fault tree is for cut slope with a static Factor of Safety of 1.2.
(3) PGA stands for peak ground acceleration

Figure 3. Example of a fault tree analysis for earthquake-induced landsliding

These tools are fairly well developed, and more discussions are given in Riddolls & Grocott (1999), IUGS Working Group on Landslides (1997) and Australian Geomechanics Society (2000).

Great care is needed in analysing past historical performance of slopes and in establishing correlations between rainfall trigger and landsliding. Some of the common pitfalls are discussed in later sections of this paper and by Wong & Ho (2000) in relation to natural terrain landslides.

Fault trees are used to display and analyse the logical structure of events and situations which can combine to lead to failures. An example of this is given in Figure 3. The symbol ⊗ denotes an 'AND' gate which means that the event will not occur unless the sub-events all occur at the same time. The symbol ⊕ denotes an 'OR' gate which means that the event will occur when any combination of the sub-events occurs. Fault trees can facilitate the examination of the effect of certain actions to reduce the chance of occurrence of a sub-event on the probability of occurrence of the 'Top Event', i.e. slope failure.

Tang et al (1999) cautioned against the incorrect use of fault trees where there exists strong correlation between the different branches of the tree as this can result in significant errors. This cross-correlation effect in a fault tree model can be accommodated by the Monte Carlo simulation technique (Ang & tang, 1975). Li (1992) cautioned against the use of the single random variable approach and the gross over-estimation of the probability of failure of slopes if the reduction in variance of the key soil properties that will occur with spatial averaging, such as along a potential failure surface, is not taken into account.

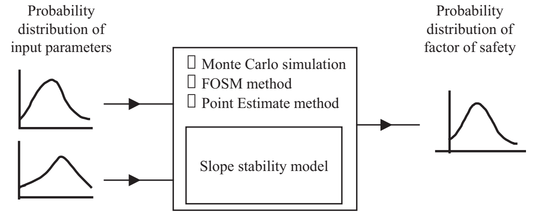


Figure 4. Concept of probabilistic slope stability analysis

Probabilistic modelling can be useful, particularly where site-specific historical failure data are inadequate or not available. In probabilistic analyses, the input parameters are treated in an assessment model as variables instead of unique numbers. The concept is illustrated in Figure 4. Simplified analytical techniques have been developed, e.g. Point Estimate Method (Li, 1992), First Order Second Moment (FOSM) Method (Duncan, 2000), etc. to assist in the calculation of the probabilistic distribution of the factor of safety in a probabilistic assessment of slope stability.

If an unbiased probability distribution function of the Factor of Safety has been assessed, the reliability index β may be computed (i.e. $\beta=\{\mu_F - 1.0\}/\sigma_F$, where μ_F is the mean value of the Factor of Safety, and σ_F is the standard deviation of the Factor of Safety). β may be regarded as an index of the degree of uncertainty and it can be related to the probability of failure if the form of the frequency distribution of the performance function is known. A higher factor of safety may not necessarily correspond to a lower probability of failure because the latter is also dependent on the degree of uncertainty of the parameters (Figure 5), as well as the accuracy of the analysis model. If the probability distribution for the Factor of Safety is conservatively biased (e.g. by using conservative input assumptions), then the associated probability of failure will be conservative. The unbiased probability of failure can be derived if the degree of bias is known.

The formulation of specific probabilistic models for landslide risk assessment of natural hillside is discussed by Roberds et al (1997). Probabilistic analyses of slope failure require a suitable slope stability analysis model, e.g. slip circle analysis. There are failure modes which are not directly amenable to analysis (e.g. washout failure due to erosion by concentrated surface water flow) and hence probabilistic assessment cannot be undertaken. Theoretical advances have been made in probabilistic site characterisation and in the assessment of geological anomalies (e.g. Tang, 1993). Techniques are available for updating the estimate of probability of failure given additional information based on Bayes Theorem. Tang et al (1999) cautioned about the common pitfalls in the assessment of statistical parameters on soil properties from test specimens, and the development of correlations through regression analysis.

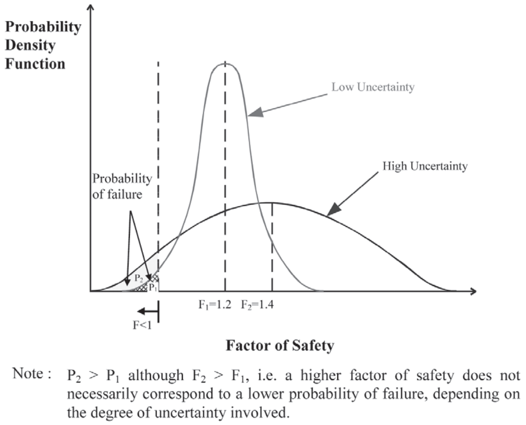


Figure 5. Illustration of relationship between Factor of Safety and probability of failure (after Lacasse & Nadim, 1998)

Simulation techniques (e.g. Monte Carlo simulation) involve a computerised sampling procedure used to approximate the probability distribution of the factor of safety by repeating the analysis many times, especially if the target reliability

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to be evaluated is small. A set of random numbers is generated for the random variables according to the chosen frequency distributions of the input parameters. It should be noted that the value of reliability estimated by simulation may not be unique, depending on the number of simulations. Commercial software packages such as @RISK can perform Monte Carlo simulations for most routine problems. For low probability events, a more efficient simulation technique known as importance sampling (Ang & Tang, 1984) may be used.

It should be remembered that formal probabilistic analysis which gives a notional probability of failure may not necessarily be realistic, depending on how well the assumed model resembles actual field conditions. It is important that all the relevant key processes and uncertainties in the set of major contributing factors for each process be adequately considered. In principle, this should include possible relationships amongst processes and events, as well as different sources of parameter uncertainties (natural spatial and temporal variability as well as ignorance) and correlations in parameter values (both intra-parameter at different times and locations, and inter-parameter at the same time and location). Poor quantification of uncertainties (especially regarding combinations of factors), sometimes inconsistent with available information, is a major problem, which may be difficult to detect and may produce misleading results.

7 TOOLS FOR CONSEQUENCE ASSESSMENT

Practical tools for consequence assessment have been reviewed in detail by Leone et al (1996) and Wong et al (1997). These include direct assessment based on subjective judgement, event tree approach, consequence model and probabilistic approach (with relevant models constructed with the aid of influence diagrams). It should be pointed out that historical fatality statistics are not adequate for assessing the potential consequence because of the dependence on vulnerability (which varies significantly with time and location) and lack of sufficient representative data (Leone, 1996).

The need to formally evaluate failure consequences in QRA poses a great challenge to the geotechnical profession because this is a relatively unfamiliar area. Conventionally, the assessment is done either implicitly (through judicious choice of factors of safety for different scenarios), or qualitatively via subjective judgement. The recent advances in the understanding of factors controlling mobility of landslide debris (e.g. Wong & Ho, 1996) permitted the development of a more generalised consequence model for QRA, as described by Wong et al (1997).

This consequence model incorporates the key factors that affect debris mobility and vulnerability of the affected facility, including scale and mechanism of failure, nature and proximity of the affected facilities, debris mobility and degree of protection afforded by the facility.

In this approach, the consequence of a given hazard (that corresponds to a specific mechanism and scale of failure for a certain feature), expressed in terms of PLL, is a function of the following key parameters:

$$\begin{matrix}\text{Expected no. of}\\ \text{landslide fatalities for}\\ \text{a given facility}\end{matrix} = f\left\{\begin{matrix}\text{Expected no. of fatalities}\\ \text{given direct impact}\\ \text{by reference landslide}\end{matrix}\right\}\left\{\begin{matrix}\text{Scale of}\\ \text{failure}\end{matrix}\right\}\left\{\begin{matrix}\text{Vulnerability}\\ \text{factor}\end{matrix}\right\} \tag{2}$$

The above model involves consideration of the consequence of a reference landslide of a standard size directly affecting a given type of facility (i.e. located right at the toe of a slope or near the edge of the slope crest), assuming occupation of the facility under average conditions. The consequence is then scaled with respect to the size of the actual failure relative to that of the reference landslide and the vulnerability of the facility given its actual location relative to the influence zone of the landslide.

The first term relates to the type of facility that is directly affected by the reference landslide (taken to be a 10 m wide failure of 50 m^3 in volume, based on experience in Hong Kong). The expected numbers of fatalities for different types of facilities directly affected by the reference landslide can be derived from formal QRA methodology (Table 1).

The size of the actual failure serves to scale up, or down, the consequence with respect to that expected of the reference landslide. The scaling is based on the ratio of the width of the actual landslide to the width of the reference landslide, taking due account of the width of the affected facility (e.g. consideration of spatial impact).

The vulnerability factor corresponds to the probability of loss of life given the impact and is influenced by a number of factors, including the nature, proximity and spatial distribution of the facilities, debris mobility, scale of failure, and the degree of protection afforded to people by the facility.

The above consequence model has been shown to give reasonable estimates through application to case studies (Wong et al, 1997).

The assessment of debris mobility is an integral part of consequence assessment. Wong & Ho (1996) suggested that an empirical approach developed by reference to good quality landslide data and based on a proper classification of the mechanisms of failure and debris movement will offer a practical and realistic means for the assessment of travel distance of landslide debris. The use of the travel angle as defined by Cruden & Varnes (1996) has been found to be

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Table 1. Grouping of Facilities for Hong Kong Global QRA Study

Group No.	Facilities	Expected No. of Fatality Given Reference Landslide
1	(a) Buildings with a high density of occupation or heavily used - residential building, commercial office, store and shop, hotel, factory, school, power station, ambulance depot, market, hospital/polyclinic/clinic, welfare centre	3
	(b) Others - bus shelter, railway platform and other sheltered public waiting area - cottage, licensed and squatter area - dangerous goods storage site (e.g. petrol station) - road with very heavy vehicular or pedestrian traffic density	3
2	(a) Buildings with a low density of occupation or lightly used - built-up area (e.g. indoor car park, building within barracks, abattoir, incinerator, indoor games sport hall, sewage treatment plant, refuse transfer station, church, temple, monastery, civic centre, manned substation)	2
	(b) Others - road with heavy vehicular or pedestrian traffic density - major infrastructure facility (e.g. railway, tramway, flyover, subway, tunnel portal, service reservoir) - construction sites	1
3	Roads and Open Space - densely-used open space and public waiting area (e.g. densely-used playground, open car park, densely-used sitting out area, horticulture garden) - quarry - road with moderate vehicular or pedestrian traffic density	0.25
4	Roads and Open Space - lightly-used open-aired recreation area (e.g. district open space, lightly-used playground, cemetery, columbarium) - non-dangerous goods storage site - road with low vehicular or pedestrian traffic density	0.03
5	Roads and Open Space - remote area (e.g. country park, undeveloped green belt, abandoned quarry) - road with very low vehicular or pedestrian traffic density	0.001

Notes :
(1) To account for the different types of building structure with different detailing of windows and other perforations, etc., a multiple fatality factor ranging from 1 to 5 is considered appropriate for Group No. 1(a) facilities to account for the possibility that some incidents may result in a disproportionately larger number of fatalities than that envisaged. For global QRA, an average value of 3 is taken for the multiple fatality factor.
(2) The expected number of fatalities was derived on the basis of formal consequence assessment in a risk-based framework, taking into account the type of facility, density of occupation or degree of usage, and vulnerability to death under direct impact (Wong et al, 1997).

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useful for consequence assessment (Coronminas, 1995; Wong & Ho, 1996). Typical data on debris runout for different mechanisms and scale of landslides in Hong Kong are given in Figure 6. For realistic consequence assessments, it is not sufficient to assume the worst credible limit of debris runout. Instead, the likely distribution (or frequency of occurrence) of debris runout distances needs to be considered.

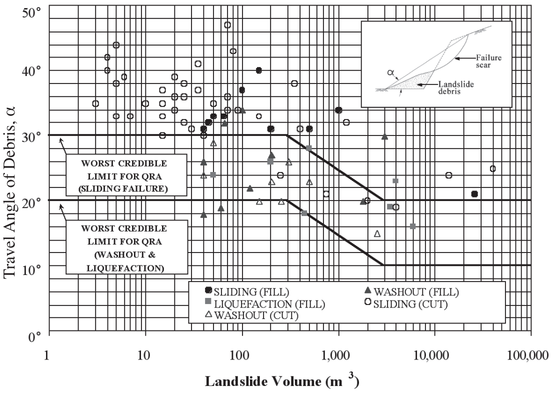

Figure 6. Data on debris mobility for different mechanisms and scales of landslides in Hong Kong

8 TOLERABILITY AND COMMUNICATION OF RISK

In applying QRA techniques, the acceptable (or tolerable) level of risk will have to be decided upon and there is no established precedence in this area for landsliding problems (Fell, 1994; Fell & Hatford, 1997). Some risk tolerability criteria have been suggested for evaluation of dam safety (e.g. ANCOLD, 1997; BC Hydro, 1993). However, these may not necessarily be amenable for direct adoption in other geotechnical problems.

Establishing appropriate risk criteria is by no means a scientific matter alone. In practice, this involves socio-political considerations. Public response to disasters and hazards is typically emotional and subjective, and can be disproportionate to the risk involved. Risk tolerability is a delicate matter that touches on value and perception of risk and is fundamentally different compared to the objective analysis of risk by QRA. Multiple fatality or major-consequence incidents tend to be subject to media sensationalism and one such failure is, quite simply, one failure too many. The real question is what is the "willingness to pay" to reduce the risk of a particular activity as opposed to expending the limited resources elsewhere.

Tolerability of risk is at the heart of all engineering design and any professional judgement, because zero risk is unachievable given the uncertainties. For instance, all design codes carry with the methodology a finite, but low, risk of failure. However, the actual level of risk is not stated, simply because it is generally not known. What this means in effect is that engineers have decided what level of risk society ought to carry without calculating it and without getting community endorsement. Of course, to state the actual risk level would be no easy task, given the human factors involved in the implementation of the codes.

Recently the HKSAR Government has published interim risk guidelines for natural terrain landslide hazards for trial use (ERM, 1998a; Reeves et al, 1999). These criteria are couched in terms of individual and societal risks (in the form of F-N curves). The criteria are based on benchmarking against the yardsticks which have been adopted by the HKSAR Government for risk assessment of Potentially Hazardous Installations (PHI) since the late 1980's. The PHI criteria were determined following a review of worldwide practice in the hazardous industries and are essentially based on international norms.

Under the above interim risk guidelines in Hong Kong, the limits on individual risk for the most vulnerable person affected by the landslide hazard is as follows:

Type of development	Maximum allowable individual risk
New	1×10^{-5}
Existing	1×10^{-4}

In terms of societal risk, two options are offered (Figure 7).

The first option involves a 3-tier system which is the conventional approach incorporating an unacceptable region, a broadly acceptable region and an "As Low As Reasonably Practicable (ALARP)" region.

The second option involves a 2-tier system comprising an unacceptable region and an ALARP region. When the risk level is assessed to be within the ALARP region, cost benefit calculations need to be carried out to demonstrate that all cost-effective and practicable risk mitigation measures are undertaken. The 2-tier system is consistent with the public expectation that the best will be done in all respects to reduce risk. There may be concerns that this approach will lead to an apparently open-ended requirement for expenditure on risk mitigation. However, if the assessed risk is small, so will the calculated justifiable expenditure on risk mitigation. The practicality of this option is to be further assessed in trial applications.

Careful thought is needed in the implementation of the societal risk criteria. In the case of an PHI, the risk criteria are applied principally to the PHI itself, i.e. assessing the tolerability of the risk posed by a proposed or existing PHI to the community. In the case of landslides, however, the criteria need to be applied to the development site that may be affected, i.e. assessing the tolerability of risk for a specific site

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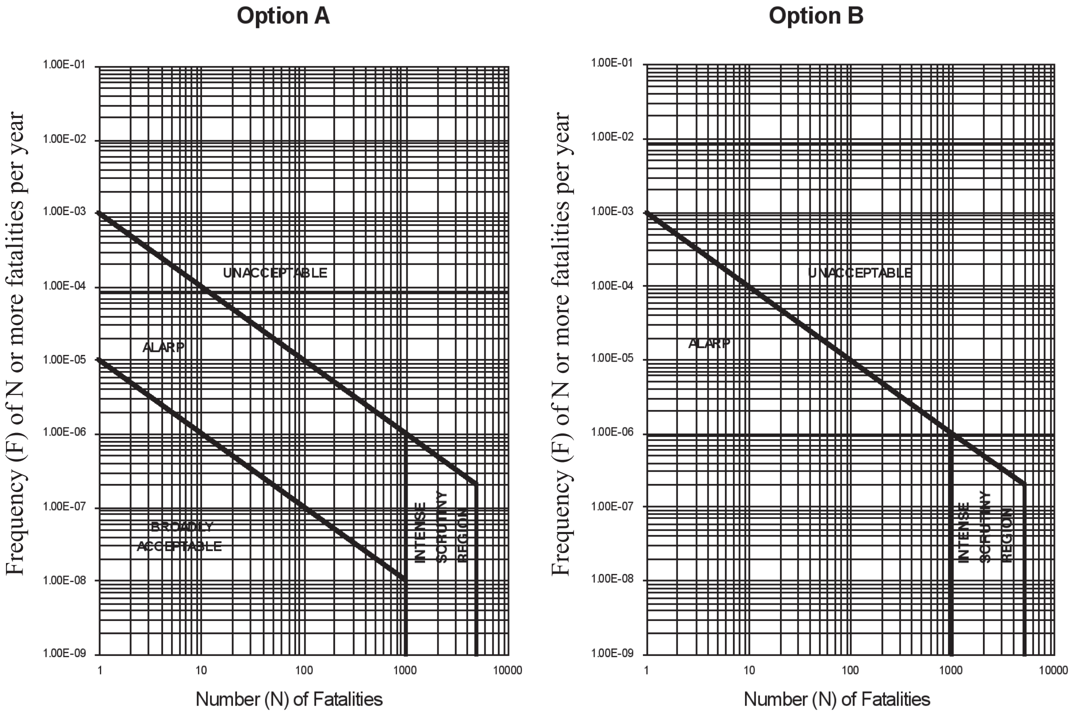

Notes:
(1) The above societal risk criteria are to be used in conjunction with a reference toe length of the natural hillside of 500 m (Reeves et al, 1999).
(2) If a development is affected by more than 500m toe length of natural terrain, an appropriate linear scaling factor should be used to scale up the risk criteria. For example, in the case of a large development affected by natural terrain with a toe length of 5km, then the above societal risk criteria should be increased by one order of magnitude.
(3) If the development is affected by less than 500m toe length of natural terrain, then the same criteria as proposed above are taken to apply (i.e. the criteria will not be scaled down).
(4) The societal risk criteria are intended to aid decision-making and not intended to be mandatory.

Figure 7. Proposed societal risk criteria for landslides and boulder falls from natural terrain in Hong Kong

posed by the natural terrain and not to the natural terrain (which is equivalent to the PHI) itself. In order to apply the risk criteria, it is necessary to define a unit area that is liable to be affected by the natural terrain landslides for consideration in the QRA. This is a complex issue as the size of the 'consultation zone' is an integral part of the risk criteria in the case of natural terrain, unlike in the case of PHI where the 'consultation zone' is only a technical aspect of the risk assessment and not related to the risk criteria.

There is a danger that in practice too much reliance is placed upon the numbers. This is not desirable bearing in mind that the confidence limits associated with risk assessment can vary depending on circumstances. The risk criteria are strictly intended to be used as guidelines only and not mandatory requirements. Sensitivity analyses should always be an integral part of risk assessment.

Risk tolerability is intrinsically related to public perception of risk which can be influenced by public education, provision of information and building up of confidence and trust in the adequacy of the safety system in place (Malone, 1997). This is all part of risk communication, which is an integral element of risk management. It may also be possible to assess risk tolerability by social science techniques.

Morgenstern (1997) suggested the use of a case history approach (legal precedents or otherwise) to synthesize current societal perspectives on the tolerable level of landslide risk. This would preclude

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the practice of the geotechnical profession from being circumscribed by allowable risk criteria set wholly by others. However, the complicated context of the individual cases and the different social values prevailing in different countries at different times are likely to render this approach very difficult to apply. For instance, memory of a particular landslide disaster may not last very long, so that public perception and tolerability of risk could be dependent on the timing relative to major landslide disasters (e.g. whether there have been a number of uneventful years).

QRA provides a framework to directly deal with the risk issues. Factors of Safety from conventional deterministic assessments are at best an experience-based index but they tend to give the unfortunate impression that the assessment is precise, whereas it is really linked to an arbitrary degree of conservatism implicit in the input parameters which varies amongst designers. Risk is actually a continuous spectrum. The searching question is what is the residual risk level and whether it is acceptable.

Risk communication is a delicate area but the geotechnical community must not shy away from it. However, risk and probability are difficult concepts for many engineers, let alone laymen. There is much to learn from other industries heavily engaged in the risk management business, such as the oil and gas profession, in this respect (e.g. Royal Society, 1983 & 1992; Health and Safety Executive, 1988 & 1999; Brinded, 2000). There is also much scope for the engineers to work together with social scientists and media experts to communicate the realities of landslide risk to the general public.

A recent trend that is of some concern is the impact of the increasingly litigious society. The evaluation of risk is connected to the legal responsibility of the citizen as well as to organizations. The court has to decide whether "on the balance of probabilities" a citizen or organization created a risk whose consequences are reasonably foreseeable. The evaluation of this risk and its foreseeability are determined by the Judge on the evidence available, and that evidence rarely includes a quantitative risk assessment. Whether a more systematic approach to risk in such cases would produce better justice is difficult to say, due to its often emotive (rather than logical) nature. Even more uncertain is whether such an approach would lead to a greater sense of justice, bearing in mind the general level of public understanding of the statistics and science involved. The usefulness of QRA in support of a lawsuit is not proven.

Another perceived problem is that if the risk has been assessed, the owner effectively takes on added responsibility because he consciously accepted the risk and can no longer claim ignorance if something unfavourable does happen.

9 LIMITATIONS OF QRA - REAL OR APPARENT?

In the overview paper of the IUGS Working Group on Landslides (1997), a number of limitations of risk assessment are listed. Each limitation (presented in italics below) is discussed in turn to put the issues in context:

- *The judgement content of the inputs to any assessment may well result in values of assessed risks with considerable inherent uncertainty.*

The uncertainty associated with subjective judgmental input also applies to other forms of geotechnical engineering evaluation.

- *The variety of approaches that can reasonably be adopted to assess landslide risk can result in significant differences in outcome if the same problem is considered separately by different practitioners.*

The same can be true even for traditional problems. If the assessment is done by experienced and skilled assessors, the outcome may not vary significantly (but this is certainly no guarantee!). If the outcome does vary significantly, it may reflect lack of experience of the assessor or limited knowledge about the processes. With QRA, the judgement involved in assessing the sub-components would be made more transparent and this tends to greatly facilitate discussion of particular items with major differences in views. In fact, it is generally easier to achieve consensus on the uncertainties in a parameter than on what single value should be used for design. Relevant experience and a sound understanding of the mechanisms involved are essential for realistic QRA, or any assessments.

- *Re-visiting an assessment can lead to significant change due to increased data, a different method, or changing circumstances.*

This also applies to other forms of geotechnical engineering evaluations. Generally speaking, successive assessment will tend to produce better answers than earlier ones, particularly if the circumstances have changed. The above should not be regarded as a limitation of QRA. There are, in fact, formal methodologies to update risk assessment and determine the value of additional information.

- *The inability to recognize a significant hazard and the consequential underestimation of the risk.*

Significant hazards must be recognized irrespective of the forms of evaluation. QRA provides a framework to assist in identifying the range of hazards in a structured manner. If a significant hazard is missed in the QRA, this is a reflection of the assessor or the state-of-the-art knowledge, not the QRA technique itself.

- *The results of an assessment are seldom verifiable, though peer review can be useful.*

The omission of significant hazards should be apparent when vetting a QRA. QRA may sometimes supplement other approaches, in which case there

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is some kind of a cross-check. Peer review will assist in vetting the assessment, as for other forms of evaluation. Back analysis of well documented cases to test out the model, or part of it, can add confidence to the model and judgement made. Overall, this should not be a major limitation of QRA. If a QRA methodology is deemed to be the most appropriate tool for the particular problem at hand, then QRA would still represent best practice.

- *The methodology is currently not widely accepted, and thus there sometimes is an aversion to its application.*

This can be a constraint in further promulgating QRA, though it is not a limitation of the methodology itself.

- *It is quite possible that the cost of the assessment may outweigh the benefit of the technique in making a decision, especially where complex detailed sets of data are required.*

The essence is to have a reasoned approach to substantiate the assessment. It would not be appropriate to apply QRA to routine problems that can be adequately handled by conventional techniques. However, there are more complicated situations that warrant the use of QRA methodology to supplement the assessment, in which case the cost would be incidental to carrying out an appropriate assessment and deciding on the necessary course of actions. Whether the cost will outweigh the benefit is dependent on individual circumstances and the right balance needs to be struck. In assessing the cost-benefit, it may be necessary to consider the direct and indirect cost of failure (i.e. getting the assessment wrong), issue of accountability, reasonable defence, etc. Typically, the cost of analysis does not constitute the major cost. The major component of cost is usually in acquiring the necessary information which can be common to both traditional and risk assessments. Large amounts of data for statistical analysis are not required, and are often inappropriate, for QRA.

- *Acceptable and tolerable risk criteria for slopes and landslides are not well established.*

For problems that cannot be reasonably tackled by the Factor of Safety approach, e.g. boulder falls, natural hillside instability, etc., the conventional judgemental or qualitative approach implicitly incorporates some value judgement on what is acceptable and what is not. In fact, the target factors of safety also imply a certain degree of residual risk although this is not evaluated and could vary among engineers. Risk certain degree of residual risk although this is not evaluated and could vary among engineers. Risk guidelines have been developed for dam assessments in Australia and Canada, and interim guidelines have been formulated for natural terrain landslide hazards in Hong Kong.

- *It is difficult to accurately assess risk for low probability events.*

This limitation also applies to other forms of geotechnical engineering evaluation. However, tools are available in QRA to better address such events.

Overall, some of the alleged limitations of QRA may be regarded as apparent only. Most are not unique to the QRA methodology but are also common to other forms of geotechnical assessments. These perceived limitations must therefore be viewed in perspective to avoid unfair criticism of QRA.

In general, it is inevitable that any analysis, no matter how elaborate or simplified, will be invalidated by wrong assumptions, particularly for key factors such as inadequate or incorrect geological models (e.g. presence of adversely-orientated weak seams in the slope not accounted for). QRA is not immune from such defects.

If there is a serious lack of data and gross extrapolation of the experience database is necessitated, then the apparent accuracy implied by the outcome of QRA may do more damage than good and QRA may not be a good tool in these circumstances.

Morgenstern (1995) also cautioned about the influence of human errors. The subject of human errors has been studied extensively in the traditional risk assessment field, mainly in relation to operational aspects. If there are human errors involving the use of an incorrect retaining wall dimension for analysis or an inappropriate geological model, then these are potentially professional (and legal) issues but again these will affect any other forms of geotechnical engineering evaluations, not just QRA. The nub is, of course, whether the issues concerned are unforeseen or unforeseeable given the practical constraints, industry norms and state-of-the-art knowledge. In practice, guards against human errors include Quality Assurance systems, independent checking of design assumptions, supervision of critical procedures during construction by experienced personnel, adoption of appropriate construction specifications, use of appropriate contract procurement methods, etc.

10 CASE EXAMPLES

QRA has been applied to a number of areas in respect of landslides. These include:

(a) Global risk assessment to quantify the overall risk to facilitate measurement of performance of a system and determine optimal risk mitigation for different components.
(b) Site-specific risk assessment to evaluate the hazards and level of risk at a given site and examine the appropriate risk mitigation measures.
(c) Relative risk assessment involving determination of the priority for action.
(d) Development of a technical framework for assessing natural hillsides.

A number of case examples are presented in the following to illustrate the application of QRA techniques to tackle real-life problems.

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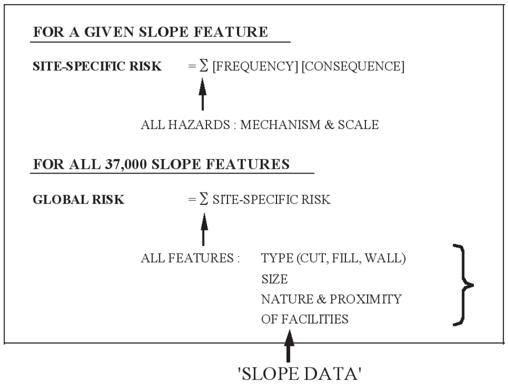

Figure 8. Global QRA framework for man-made slopes in Hong Kong

10.1 *Case No. 1 - Global QRA of failure of old man-made slopes in Hong Kong*

A global landslide QRA has been carried out to assess the overall risk posed by old man-made slopes (about 37,000 no.) to the community in Hong Kong. Details are described in Wong et al (1997) and Wong & Ho (1998a).

The hazard model adopted reflects the different types of slopes of differing heights, mechanisms and scale of failure. For example, in the case of old fill slopes constructed without proper geotechnical control, different mechanisms of failure (namely static liquefaction, washout and sliding) have been distinguished. The failure rates associated with the different hazards (a particular slope type with a given failure assessed by reference to the available failure statistics because Hong Kong is "data-rich" on landslides (Wong & Ho, 2000). The generalized consequence model as described above was formulated to assess the mobility of landslide debris and the vulnerability of affected facilities.

Details of the basic slope characteristics (including the type and proximity of facilities affected) can be obtained from the comprehensive catalogue on all the sizeable man-made slopes and retaining walls in Hong Kong. This information can be applied to the global QRA framework to evaluate the total risk as well as the risk components by integrating the hazard and consequence models (Figure 8).

The risk profile shown in Figure 9 shows that about half of the overall risk is derived from approximately 10% of the slope population that has a higher potential risk (Wong & Ho, 1998). This illustrates that upgrading of a relatively small proportion of the old slopes posing the highest potential risk would result in a major global risk reduction. It also emphasizes the importance of an appropriate risk-based ranking system for prioritizing landslide preventive actions to ensure that the risk reduction effort is expended in a cost-effective manner. Such information can be useful for making policy decisions on the necessary extent of upgrading works for old substandard slopes.

From the global assessment, different risk components can also be assessed, e.g. the percentage of total risk contributed by different types of slopes, certain types of facility such as roads, slopes of a given height range, etc. Such information can provide much insight on the make-up and distribution of the total risk, which cannot otherwise be obtained from a conventional limit equilibrium calculation.

With the above QRA techniques, the average theoretical annual fatalities can now be predicted sufficiently accurately to determine longer-term trends and predict future performance as well as to quantify the effectiveness of the risk mitigating actions over time.

The total landslide risk derived from the global QRA model is now used as a basic yardstick by which the HKSAR Government is measuring the long-term performance of its slope safety system. The global QRA calculations show that by the year 2000, the overall landslide risk from sizeable man-made slopes will have been reduced to about 50% of that which existed when the Geotechnical Engineering Office was established in 1977. The risk calculations also show that, with the slope safety system now in place, the risk from old man-made slopes would be reduced by the year 2010 to less than 25% of that in 1977.

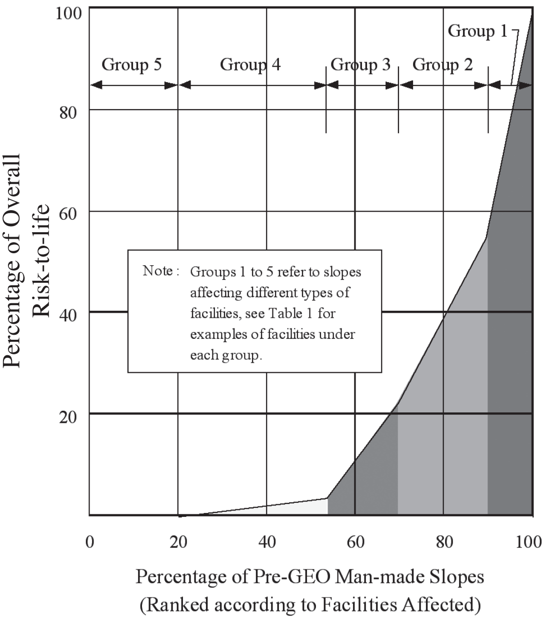

Figure 9. Risk Profile of 37,000 old man-made slopes and retaining walls in Hong Kong

Cost-benefit calculations indicate that the investment made relative to the projected number of lives saved as a result of the efforts of the slope safety

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system has been about HK$20 million (about US$2.5 million) per statistical life. This figure is near the lower end of the typical range of values used in risk management of potentially hazardous technological installations in current worldwide practice. On this basis, the slope safety investment may be regarded as cost effective.

10.2 *Case No. 2 - QRA of Earthquake-induced Failures of Man-made Slopes in Hong Kong*

The vast majority of landslides in cut and fill slopes in Hong Kong are triggered by heavy rainfall. In current geotechnical practice in Hong Kong, no explicit provision is made for earthquake loading in routine slope design. A preliminary assessment of the risk of earthquake-induced landslides in slopes designed to the current required standards has been carried out using standard QRA methodology (Wong & Ho, 1998b).

For the QRA study, a model needed to be set up to capture the likely slope behaviour under earthquake loading. The seismicity of Hong Kong was assessed based on the available macroseismic and instrumental earthquake data using a conventional seismic hazard analysis to determine the return periods for different peak ground accelerations (PGA) in bedrock. Based on dynamic response analysis, the magnification associated with local failures was taken to be 60%. Possible amplifications of ground motions due to possible site-response effects of the foundation material have not been considered in this study given that most man-made slopes within developed areas in Hong Kong are not underlain by soft soils.

The response of slopes when subjected to an earthquake was examined using the critical acceleration concept (i.e. determining the net acceleration under which the soil mass would be brought to a state of limit equilibrium according to a pseudo-static analysis). The relationships between critical acceleration and the static Factor of Safety (F_s) for typical soil cut and fill slopes in Hong Kong were derived analytically.

When the acceleration imposed on the soil mass exceeds its critical acceleration, displacement will result because the net disturbing force will be larger than the net resisting force. Published correlations were used to estimate the likely order of seismic-induced slope displacements.

Except in the case of very heavy rain, the degree of saturation of the majority of slopes in Hong Kong is generally fairly low and the prevailing unsaturated shear strength will provide an additional margin of safety compared to that computed assuming the fully saturated strength conventionally used in current slope design practice in Hong Kong. The likelihood of slopes having different degrees of saturation at the time of an earthquake, which occurs randomly in time and lasts only for a very short period, was examined using a simplified analysis based on the wetting band approach and consideration of the real-time rainfall data. In the assessment, the likely threshold rainfall required to bring a typical slope to a significant degree of soil saturation was predicted and the frequency of occurrence of rainfall exceeding the predicted threshold values was determined. The findings suggest that the likelihood of low, moderate and high degrees of soil saturation prevailing at the time of an earthquake in Hong Kong may be taken as 95%, 4.5% and 0.5% respectively. An assessment was also made of the additional margin of stability in typical unsaturated slopes in Hong Kong assuming soil suctions as measured in the field. The results suggest that the typical additional margin of stability due to suction may be taken to correspond to an increase in F_s of 0.3 and 0.15 for low and moderate degrees of saturation respectively.

Differing earthquake motions will affect slopes to a different degree and the corresponding consequences of slope failure will also vary. The range of earthquake-induced landslide hazards considered in the QRA are classified into four failure modes (Figure 10), as follows:

(a) overall slope failure (denoted as OF),
(b) overall slope deformation with localised slope failure (denoted as OD),
(c) localised slope failure (denoted as LF), and
(d) localised slope deformation (denoted as LD).

The criteria for triggering a failure can be expressed in terms of the ratio of PGA to the critical acceleration for each of the failure modes. The failure triggers were derived by reference to the dynamic response characteristics of the slope and the likely range of earthquake-induced slope displacements.

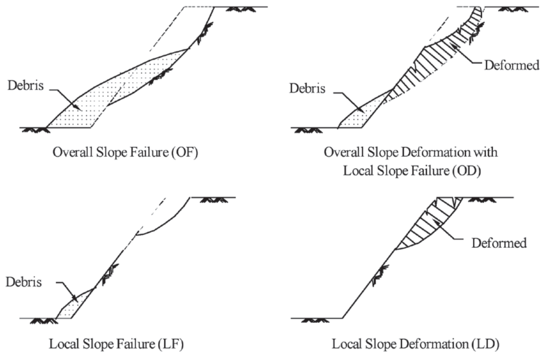

Figure 10. Mode of seismic-induced slope instability assumed in QRA

10.2.1 Frequency Assessment

The critical acceleration values will depend on the slope type and the prevailing factors of safety. Typical soil cut slopes and compacted fill slopes, with design

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F_s values of 1.4, 1.2 and 1.1 respectively which comply with current required safety standards for different facilities, are considered.

Based on the failure trigger criteria together with the peak ground acceleration-return period relationship, the annual frequencies of occurrence of the respective peak ground acceleration values triggering failure may be calculated (Table 2).

Simplified fault trees were used to account for the occurrence of the different modes of earthquake-induced failure for slopes with different degrees of saturation. An example of a fault tree is shown in Figure 3.

10.2.2 Consequence Assessments

In analysing the consequence of failures, reference is made to both the available historical landslide data as well as the generalised landslide consequence model and the results of the global QRA for failure of old man-made slopes in Hong Kong as described above.

10.2.3 Risk Calculations

The output of the frequency and consequence analyses for the different hazards can be combined to give the risk components, which can then be summed to give the overall risk associated with the different modes of failure.

To put the assessed risk of seismic-induced landslides in context, the calculated risk levels may be compared with the risk of rain-induced landslides of old substandard man-made slopes. The results shown in Table 3 suggest that the risk of earthquake-induced landslide for engineered slopes is only a small proportion of the risk posed by rain-induced failures of old slopes (i.e. not engineered to current safety standards). The quantified risk results lend support to the current approach by the HKSAR Government in directing efforts to studying and upgrading old man-made slopes, rather than to undertake further stability assessment and seismic retrofitting of slopes that comply with the current required safety standards.

The findings of the QRA indicate that the risk of earthquake-induced landslides at slopes that comply with current design standards is one to three orders of magnitude lower than the risk posed by rain-induced landslides at old slopes. It would therefore appear that the current design standards for slopes are generally adequate in maintaining the overall risk of earthquake-induced failures on new, or modified, slopes at a relatively low level, and efforts should continue to be directed to upgrading old man-made slopes that are susceptible to failures triggered by rainfall.

The QRA framework, which has extended beyond the conventional seismic hazard assessment, has provided additional insights that cannot otherwise be obtained from conventional assessments.

Table 2. Frequency of Occurrence of PGA Levels Triggering Different Failure Modes

Margin of Static Factor of Safety	Failure Mode	Range of PGA for Different Failure Modes (g)	Return Period, T (years)	Annual Frequency of Occurrence, f
10%	OF	> 0.084	> 500	$\leq 2.000 \times 10^{-3}$
	OD	0.06 - 0.084	150 - 500	4.667×10^{-3}
	LF	0.053 - 0.06	100 - 150	3.333×10^{-3}
	LD	0.038 - 0.053	30 -100	2.333×10^{-2}
20%	OF	> 0.168	> 5 500	$\leq 1.818 \times 10^{-4}$
	OD	0.12 - 0.168	1 600 - 5 500	4.432×10^{-4}
	LF	0.106 - 0.12	1 150 - 1 600	2.446×10^{-4}
	LD	0.076 - 0.106	350 - 1 150	1.988×10^{-3}
40%	OF	> 0.308	> 120 000	$\leq 8.333 \times 10^{-6}$
	OD	0.22 - 0.308	18 000 - 120 000	4.722×10^{-5}
	LF	0.194 - 0.22	10 000 - 18 000	4.444×10^{-5}
	LD	0.139 - 0.194	3 000 - 10 000	2.333×10^{-4}

Legend:
OF denotes overall failure
OD denotes overall deformation with local slope failure
LF denotes local failure
LD denotes local slope deformation
PGA denotes peak ground acceleration

$$f = \left(\frac{1}{T_1} - \frac{1}{T_2} \right)$$

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Table 3. Comparison of Risks of Landslides Caused by Rainfall and Earthquake Respectively

(a) Soil Cut Slopes

Factor of Safety	Buildings	Roads
1.4	2.862 x 10^{-7} (≈ 0.08%)	N/A
1.2	2.21 x 10^{-6} (≈ 0.7%)	1.66 x 10^{-6} (≈ 0.7%)
1.1	N/A	7.279 x 10^{-6} (≈ 2.9%)

Note: The figure shown in bracket is the ratio of the risk of earthquake-induced failure for engineered soil cut slopes to the risk of rain-induced failure for old substandard soil cut slopes.

(b) Fill Slopes

Factor of Safety	Buildings	Roads
1.4	1.721 x 10^{-6} (≈ 0.9%)	N/A
1.2	5.459 x 10^{-6} (≈ 2.9%)	7.278 x 10^{-7} (≈ 2.7%)
1.1	N/A	1. 903 x 10^{-6} (≈ 7%)

Note: The figure shown in bracket is the ratio of the risk of earthquake-induced failure for engineered fill slopes to the risk of rain-induced failure for old substandard fill slopes.

Figure 11. The August 1995 landslides affecting the Lei Yue Mun squatter villages

10.3 *Case No. 3 - Site-specific QRA for Lei Yue Mun Squatter Villages, Hong Kong*

The third example concerns a site-specific QRA which is described by Hardingham et al (1998).

The abandoned quarry faces of the slopes flanking the Lei Yue Mun squatter villages are between 20 m and 40 m high, typically at 65°- 80°. The granitic natural terrain is inclined at approximately 35° and rising some 200 m above the squatter huts. The abandoned quarry faces and the hillside (with a variable colluvial cover and signs of active sheet and gully erosion) have been subjected to a history of instability. A number of significant landslides occurred during a major rainstorm in August 1995 causing severe damage to the squatter dwellings and loss of life was narrowly avoided (Figure 11). The landslide risk was quantified to assist in decision-making with regard to the extent of rehousing of squatters. The approach adopted for the study is illustrated in Figure 12.

The work comprised two main parts: a geotechnical study and a risk assessment. The purpose of the geotechnical study was to determine the frequency of landslide events within the study area and to estimate the associated hazard. This involved three steps:

(a) establishing a database of 115 landslides at the site, compiled from aerial photographs, landslide records and field inspections,

(b) consideration of various types of landslides of different mechanisms and likely scales of failure, i.e. debris slides, rockfalls and squatter cut/fill failures and according to size as small (<50 m^3), medium (50-500 m^3), large (500-1,000 m^3), very large (1,000-5,000 m^3) and extremely large (>5,000 m^3), and

(c) determination of the frequency of each type of landslide.

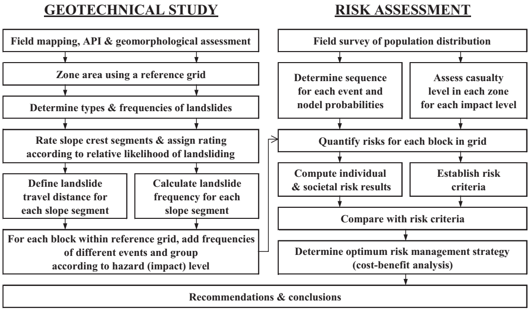

Figure 12. Overall approach to the QRA study at Lei Yue Mun

The frequency was mainly assessed from the history of failures, with ‘recognition factors’ applied to the small to medium debris slides, i.e. the numbers were adjusted to account for the fact that some of these smaller failures could have been missed by aerial photograph interpretation. The global failure frequencies were then spatially distributed to the slopes in the site in 20 m segments through a slope rating system (which took into account slope geometry, presence of drainage lines, slope-forming material and past performance) according to a relative weighting scheme.

The consequences of landslides were defined in terms of three different hazard groupings, each with

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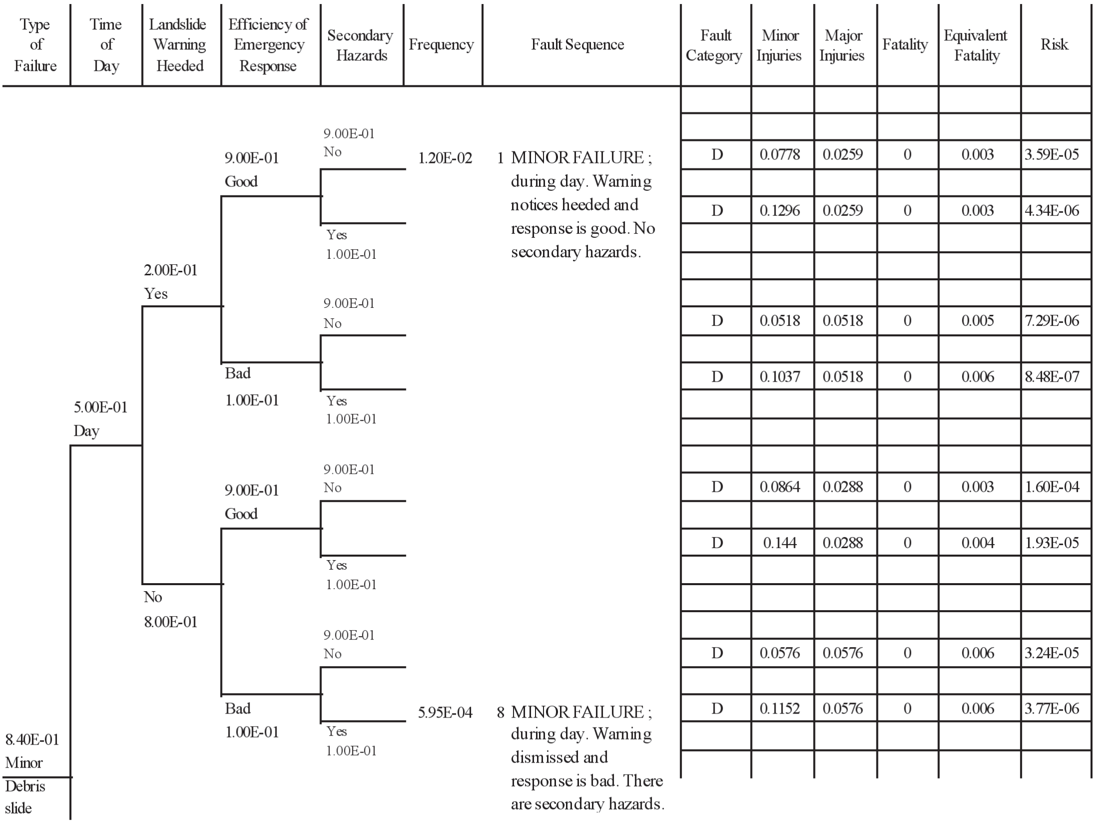

1 MINOR FAILURE ; during day. Warning notices heeded and response is good. No secondary hazards.

8 MINOR FAILURE ; during day. Warning dismissed and response is bad. There are secondary hazards.

Fault Category	Minor Injuries	Major Injuries	Fatality	Equivalent Fatality	Risk
D	0.0778	0.0259	0	0.003	3.59E-05
D	0.1296	0.0259	0	0.003	4.34E-06
D	0.0518	0.0518	0	0.005	7.29E-06
D	0.1037	0.0518	0	0.006	8.48E-07
D	0.0864	0.0288	0	0.003	1.60E-04
D	0.144	0.0288	0	0.004	1.93E-05
D	0.0576	0.0576	0	0.006	3.24E-05
D	0.1152	0.0576	0	0.006	3.77E-06

Note : The following rule is assumed : Equivalent fatalities = No. of fatalities + (0.1 x No. of major injuries) + (0.005 x No. of minor injuries)

Figure 13. Extract of an event tree for the Lei Yue Mun QRA

its own level of associated casualties. The hazard groupings took into account the type of landslides and debris travel distance as well as the proximity of the dwellings. Debris travel distances were evaluated from the landslide database using the travel angle concept (Wong & Ho, 1996).

The risk assessment utilised the geotechnical study data to calculate both the individual and societal risks to the squatter residents. For the purpose of risk calculation, the dwellings were grouped into 20 m by 20 m blocks according to a reference grid. The number of people and the temporal presence in each block were determined from a population survey, and an event tree was generated for each block using standard QRA techniques. A total of 130 slope segments, 5 frequencies for the relevant landslide hazards and 149 reference blocks were considered. An Event Tree was generated for each of the reference blocks, which traced the different credible scenarios considering the hazard grouping, timing of failure, responses to landslip warning, level of emergency services, secondary hazards, etc. (Figure 13). Sensitivity analyses were also carried out to consider the different assumptions in population distribution.

By integrating the hazard model, frequency assessment and consequence assessment, individual risk levels at different locations were computed and contoured. The site-specific risk acceptance criteria were determined through a review of different safety acceptance criteria and consideration of the situation involving squatters at Lei Yue Mun. The proposed individual risk criteria ranged from an upper boundary (unacceptable) of 1×10^{-4} to a lower boundary (acceptable) of 1×10^{-6}.

The results of the QRA indicate that a large area of the squatter area fell within the unacceptable region in terms of individual risk (Figure 14). The assessed societal risk (Figure 15) was also found to be unacceptable. Risk calculations further show that if the squatter residents within the area recommended for clearance are re-housed, the societal risk will reduce to the ALARP region. Cost-benefit calculations indicate that the residents in areas where the landslide risk was within the ALARP region did not justify immediate re-housing.

The quantification of risks associated with landslide hazards using a formal QRA framework provided a rational basis for decisions to be made on

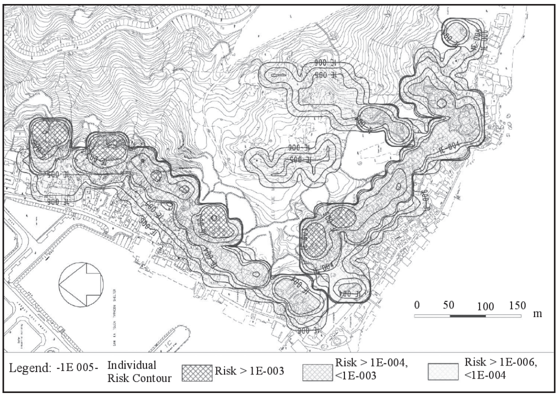

Figure 14. Individual risk contours for the Lei Yue Mun squatter villages

risk mitigation or clearance in this case. The QRA results allowed calibration of expert judgement on the extent of clearance required. The large number of past landslides in this study has provided a reasonable basis for assessing the frequency and consequence of potential failures for risk quantification, without the need for more sophisticated probabilistic analyses and detailed ground investigations.

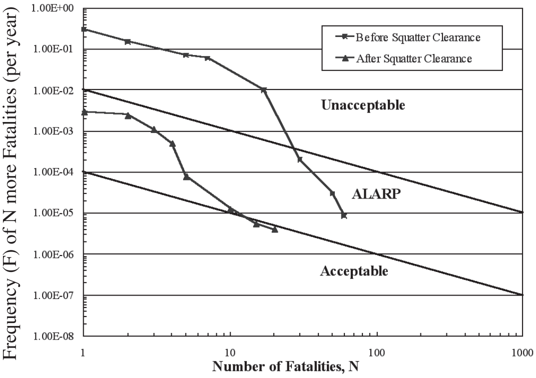

Figure 15. Societal risk for the Lei Yue Mun squatter villages

10.4 *Case No. 4 - Site-specific QRA of the 1995 Fei Tsui Road landslide, Hong Kong*

The fourth example concerns a site-specific QRA which is described by Wong et al (1997). The generalized consequence model developed by Wong et al (1997) was used to back analyse the theoretical consequence of the Fei Tsui Road landslide, which occurred in the early hours of 13 August 1995 with a failure volume of some 14,000 m^3 (Figure 16). The road in front of the slope was totally engulfed by landslide debris of up to about 6 m thick (Figure 17). The incident resulted in one fatality and one other person was injured. This failure is of significance in Hong Kong in that the slope (comprising weathered volcanics) was previously assessed by a number of professionals from different organisations at different times but the scale and mode of the failure that actually occurred, which was essentially controlled by an extensive and low strength, kaolinite-rich altered tuff layer, was not anticipated. It was also the largest cut slope failure since systematic landslide records began in Hong Kong in 1984.

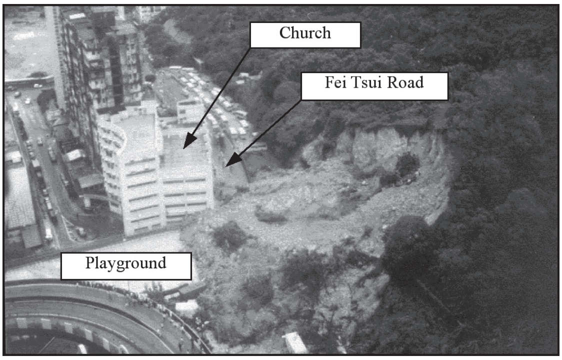

Figure 16. The 13 August 1995 landslide at Fei Tsui Road, Hong Kong

The theoretical consequence model predicts an average number of four fatalities arising from the

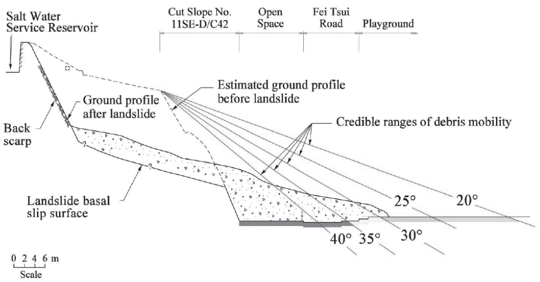

Figure 17. Cross-section through the 1995 Fei Tsui Road landslide

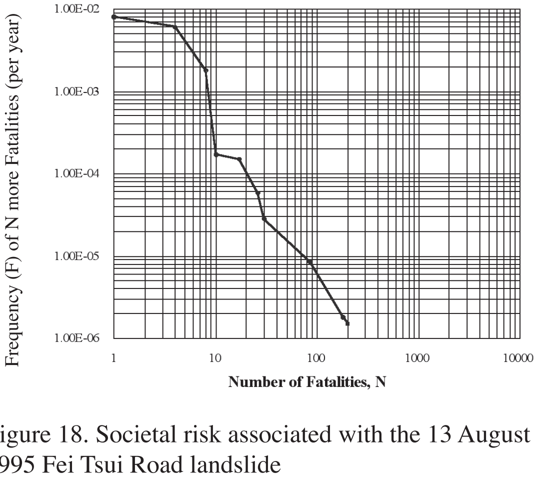

Figure 18. Societal risk associated with the 13 August 1995 Fei Tsui Road landslide

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given landslide. This assessment illustrates the "near-miss" nature of the incident in that if the landslide had occurred during day time, instead of at 1:15 a.m., with a lot more traffic on the road and possibly during classes in the kindergarten in the church's basement across the road, the fatality figures would have been much higher. This emphasizes the difficulty in extrapolating historical data in the absence of a rational framework. Consideration of the actual fatality figures on their own does not permit much progress to be made in the understanding of possible landslide consequences in a risk-based framework.

The level of societal risk posed to the affected community is reflected by the F-N curve for the landslide (Figure 18), based on assumptions made regarding the different credible scenarios and the associated temporal presence of population. Details on how the F-N curve was derived are explained in Wong et al (1997).

Using the generalised consequence model, it was possible to examine the predicted consequences if the same landslide were to occur alongside a road that is more heavily-used than Fei Tsui Road. The results are illustrated in Table 4 and illustrate the expected extent of damage for roads with differing degrees of traffic usage.

10.5 *Case No. 5 - Relative QRA for Ranking of Old Fill Slopes in Hong Kong*

The fifth example concerns the use of QRA concepts for risk-based priority ranking purposes. The new priority classification system for fill slopes developed by the Geotechnical Engineering Office is in the form of a scoring system (Figure 19) which reflects the relative risk posed by old fill slopes (Wong, 1998). The system is based on a detailed review of the available failure records with particular reference to the mechanisms of fill slope failure and factors affecting the likelihood and consequence of failure respectively. Three failure mechanisms are recognized, viz. sliding (or minor wash out), liquefaction and major washout (i.e. mobile failure involving concentrated discharge of surface water resulting in scouring and erosion). For each mechanism of failure, an Instability Score and a Consequence Score are derived for each slope. The Instability Score reflects the likelihood of occurrence of the mechanisms of failure, based on correlation with historical slope failure data. The Consequence Score is the potential loss of life (i.e. the estimated number of fatalities for a given failure) assessed by applying the consequence model described in Wong et al (1997) for the corresponding mechanism of failure.

Table 4. Results of Consequence Assessment for the 1995 Fei Tsui Road Landslide, Hong Kong

Facility Affected	Facility Group No. (Reference PLL)	Vulnerability to death in The event of debris impact	Scaling Factor for Actual Size of Landslide	PLL	Proportion of Total PLL
Open Space	Group 5 (0.001)	0.95	90 / 10 = 9	0.01	0.2%
Fei Tsui Road	Group 3 (0.25)	0.85	90 / 10 = 9	1.91	47.9%
Baptist Church (+kindergarten)	Group 1 (3 * 2)	0.17	20 / 10 = 2	2.04	51.4%
Playground	Group 4 (0.03)	0.15	50 / 10 = 5	0.02 Σ = 3.98	0.5%

Notes :
(1) The facility grouping and reference PLL are taken from Table 1.
(2) A multiple fatality factor of 2 is judged appropriate for the type of building under consideration.
(3) The vulnerability factors have been assessed using the framework described in Wong et al (1997).
(4) As an illustration, the calculated PLL for Fei Tsui Road is given as follows:
PLL = 0.25 * (90/10) * 0.85 = 1.9 (given that the width of the landslide was 90 m)
(5) If the road affected were a Group 2 road, then PLL = 1 * 9 * 0.85 = 7.6
[i.e. (reference PLL) (scaling for size of failure) (scaling for vulnerability)]
(6) If the road affected were a Group 1 road, then PLL = 3 * 9 * 0.85 = 23

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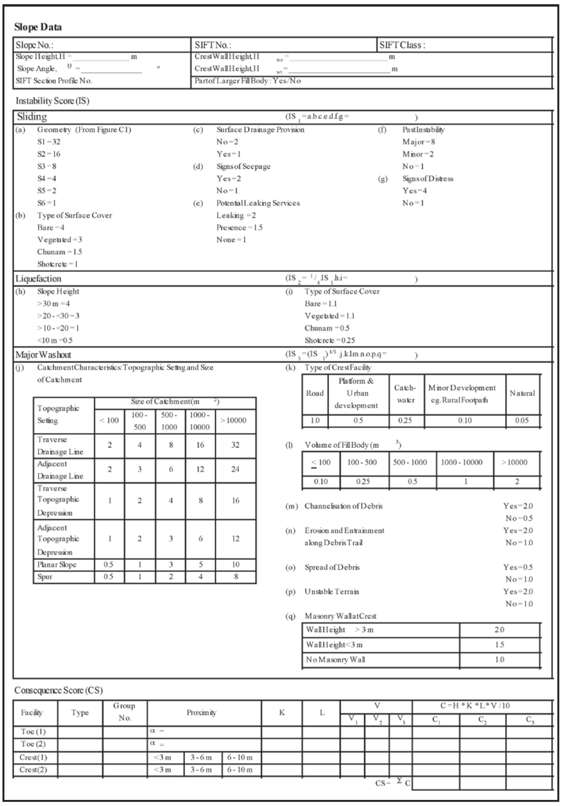

Slope Data

Slope No.:	SIFT No.:	SIFT Class :
Slope Height, H = ________ m Slope Angle, θ = ________ °	Crest Wall Height, H_{wc} = ________ m Crest Wall Height, H_{wt} = ________ m	
SIFT Section Profile No.	Part of Larger Fill Body : Yes/No	

Instability Score (IS)

Sliding (IS_1 = a.b.c.e.d.f.g =)

(a) Geometry (From Figure C1)
S1 = 32
S2 = 16
S3 = 8
S4 = 4
S5 = 2
S6 = 1

(b) Type of Surface Cover
Bare = 4
Vegetated = 3
Chunam = 1.5
Shotcrete = 1

(c) Surface Drainage Provision
No = 2
Yes = 1

(d) Signs of Seepage
Yes = 2
No = 1

(e) Potential Leaking Services
Leaking = 2
Presence = 1.5
None = 1

(f) Past Instability
Major = 8
Minor = 2
No = 1

(g) Signs of Distress
Yes = 4
No = 1

Liquefaction ($IS_2 = {}^1/_4 IS_1$.h.i =)

(h) Slope Height
>30 m = 4
>20 - <30 = 3
>10 - <20 = 1
<10 m = 0.5

(i) Type of Surface Cover
Bare = 1.1
Vegetated = 1.1
Chunam = 0.5
Shotcrete = 0.25

Major Washout ($IS_3 = (IS_1)^{1/3}$ j.k.l.m.n.o.p.q =)

(j) Catchment Characteristics: Topographic Setting and Size of Catchment

Topographic Setting	Size of Catchment (m^2)				
	< 100	100 - 500	500 - 1000	1000 - 10000	> 10000
Traverse Drainage Line	2	4	8	16	32
Adjacent Drainage Line	2	3	6	12	24
Traverse Topographic Depression	1	2	4	8	16
Adjacent Topographic Depression	1	2	3	6	12
Planar Slope	0.5	1	3	5	10
Spur	0.5	1	2	4	8

(k) Type of Crest Facility

Road	Platform & Urban development	Catch-water	Minor Development eg. Rural Footpath	Natural
1.0	0.5	0.25	0.10	0.05

(l) Volume of Fill Body (m^3)

≤ 100	100 - 500	500 - 1000	1000 - 10000	> 10000
0.10	0.25	0.5	1	2

(m) Channelisation of Debris Yes = 2.0
No = 0.5

(n) Erosion and Entrainment along Debris Trail Yes = 2.0
No = 1.0

(o) Spread of Debris Yes = 0.5
No = 1.0

(p) Unstable Terrain Yes = 2.0
No = 1.0

(q) Masonry Wall at Crest

Wall Height > 3 m	2.0
Wall Height < 3 m	1.5
No Masonry Wall	1.0

Consequence Score (CS)

Facility	Type	Group No.	Proximity			K	L	V			C = H * K * L * V / 10		
								V_1	V_2	V_3	C_1	C_2	C_3
Toe (1)			α =										
Toe (2)			α =										
Crest(1)			<3 m	3 - 6 m	6 - 10 m								
Crest(2)			<3 m	3 - 6 m	6 - 10 m								
										CS = Σ C			

Figure 19. Priority classification system for fill slopes in Hong Kong

The ranking order for further action is governed by the Total Score which is derived from the sum of the products of Instability and Consequence Scores for different failure mechanisms. The system is couched in such a way that the Total Score reflects directly the landslide risk posed by the slope to the community. The system has been benchmarked directly with case histories to examine if the priority assessment is sensible. The results of the calibration exercise (Wong & Ho, 2000) show that there is a good correlation between the predicted (i.e. Consequence Score) and the actual number of fatalities. The actual mechanism of failure is also consistent with that assessed by the Instability Scores. This risk-based ranking system has now been adopted in prioritising old fill slopes for stability study and upgrading works under the long-term slope retrofitting programme.

Similar risk-based priority ranking systems have been developed for soil cut slopes, rock cut slopes and retaining walls respectively (Wong, 1998). In fact, the results of the global QRA as described in the first case example above have been used to determine the appropriate adjustment factors for the different ranking systems to come up with an adjusted ranking score. This latter adjusted score, which takes account of the relative total risks posed by the different slope types, is used to determine the overall priority for systematic slope retrofitting.

Risk-based scoring systems have also been developed for boulder fields on natural hillsides (Maunsell Geotechnical Services, 1998). These have been calibrated against the available historical records and can be used for both priority ranking of different boulder fields or the quantification of risk for a given site.

10.6 *Case No. 6 - Relative QRA for Ranking of Roads with a History of Landslides*

The sixth example concerns the use of the QRA technique to examine the relative landslide risks posed by different sections of roads that have a history of landslides. Details of the assessment are given in ERM (1999). This risk management tool will provide a more rational basis for determining the priority for road upgrading programmes, in conjunction with other considerations such as traffic needs and road maintenance needs.

The classification of landslides (with respect to types and scales of instability for both uphill and downhill failures) and the assessment of failure frequencies were done primarily by reference to the historical data, with suitable adjustments made for any slope upgrading works over the years. The generalised consequence model as described above was used for assessing the consequence to life in the event of landslides. In addition, the economic costs associated with social disruption due to road closures as a result of landsliding were considered. The probability of two close-by roads affected simultaneously by landslides was also assessed.

Both the risk to life and economic risk due to landslides for each of about 40 road sections were evaluated, providing a basis for ranking of the roads with respect to landslide hazards.

10.7 *Case No. 7 - Risk-based Framework for Natural Terrain Hazard Study*

The last example relates to the semi-quantitative risk-based framework recently formulated for trial use in Hong Kong with respect to natural terrain hazard studies for new development sites (GEO, 2000).

The criteria for assessing whether a development site would require a natural terrain hazard study, based on the consideration of the potential debris runout distance, are depicted in Figure 20.

Under the technical framework for natural terrain hazard studies, the following approaches may be adopted:

(a) Factor of Safety Approach [This approach has been used in the study of natural terrain below development areas to check that the sites would not be adversely affected by failure of the hillsides. It has also been used to assess the stability of hillsides

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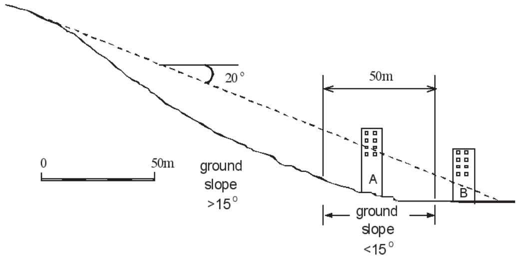
above development sites against major failures, particularly where signs of recent distress and slope movement are observed which are potentially indicative of the development of large-scale, deep-seated instability.]

(b) QRA Approach [This approach is relevant when designers opt for mitigation of landslide risk instead of relying solely on stabilization works at the source areas. In practice, stabilization works are subject to constraints, e.g. extensive nature of the hillside, major uncertainties of ground conditions and behaviour (e.g. mechanism of failure and debris travel, deterioration, etc.), difficult access, potential damage to the environment, long-term maintenance liability, etc.]

(c) Design Event Approach [Under this deterministic approach, the relevant design failure events are assessed for the different hazards and any necessary mitigation measures are evaluated.]

The QRA approach entails a detailed assessment of the probability and consequence of natural terrain landslides and determination of the necessary mitigation works by reference to the interim risk guidelines published by the HKSAR Government (ERM, 1998a). It calls for expert input and the assessment may be fairly involved and costly in having to address a large number of scenarios. However, it should be thought of as only a means of formalising the thought process and decision-making framework and couching it in a risk context.

The framework for the Design Event Approach is risk-based in that it takes account of the susceptibility (or likelihood of failure) of the terrain and failure consequence in a semi-quantitative manner. Under this framework, the susceptibility of the hillside to failure is categorised into 4 classes based on historical data and assessment of geomorphological features and other information (Table 5). The notional range of probability of occurrence indicated for each category serves as yardsticks to aid judgement in addition to the general guidance given in the assessment of relative susceptibilities.



Site	Natural Terrain Hazard Study Requirement Criteria		Natural Terrain Hazard Study Required ?
	Within 20 ° Angular Elevation of Natural Terrain ?	Within 50m of Ground Sloping at > 15 ° ?	
A	Yes	Yes	Yes
B	Yes	No	No

Notes:

(1) A natural terrain landslide hazard study may have to be undertaken for development sites which meet the following criteria: " Where there is natural terrain outside the site, but within the same catchment, which is at an angular elevation of 20° or more from the site and where there is natural terrain sloping at more than 15° within 50 m horizontally upslope of the site, provided that there is a credible debris flowpath to the site. 1:5,000 scale topographic maps shall be used to judge whether these criteria are met".

(2) For sites that fall outside the above criteria, if the professional responsible for the development considers that there is a reasonable chance that natural terrain hazards could affect the site, then a study will be required. A natural terrain landslide hazard study may be required for development sites which do not meet the above criteria, e.g. development sites which are either intersected by or adjacent to a natural drainage course.

Figure 20. Criteria for requiring natural terrain hazard study for new development sites in Hong Kong

The consequence of failure is categorised into 5 classes based on quantitative criteria (derived from systematic landslide studies in Hong Kong), considering the types of facilities affected and their proximity to the hillside (Table 6).

Under the framework, further studies are not required if the susceptibility of the hillside and the consequence of failure are insignificant. Otherwise, further studies should be carried out to establish the need for any mitigation measures to deal with the relevant design events. Depending on the susceptibility of the hillside to failure and failure consequence of the site, the required design event may be a 'conservative' event or a 'worst credible' event. The design requirements for mitigation measures should be evaluated based on Table 7.

For the purposes of calibration, the design requirements for the Design Event Approach have been applied to 17 cases (GEO, 2000). The framework was found to be relatively easy to apply and it gave reasonable results. This helps to benchmark the requirements for maintaining consistency and ensuring practicality.

The potential disadvantage of the Design Event Approach is that only one lumped assessment can be made in a deterministic manner. However, in practice, it may be perceived to be simplistic and provide less scope for disagreement. It is therefore projected that many designers may opt for the Design Event Approach, particularly where the required mitigation measures are not disproportionate to the scale of the development.

10.8 Other Case Studies

Some other case studies involving the use of QRA in assessing landslides have also been published in the literature, including:

- Site-specific QRA of landslides at Speers Point, Newcastle and debris flows at Montrose in Melbourne, Australia (Fell, 1994).
- Site-specific QRA of debris flow hazard affecting proposed developments at Cheekye Fan, British Columbia (Hungr & Rawlings, 1995; Sobkowicz et al, 1995).
- Site-specific QRA of boulder falls for a highway between Vancouver and Whistler, British Columbia (Bunce et al, 1996).

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Table 5. Natural Terrain Susceptibility Classes

Susceptibility Class	Description
A	The natural terrain is extremely susceptible to the type of failure under consideration, with a notional annual probability of occurrence in the order of 1/10 or higher. For example: there are signs of instability, continued movement, or records of repeated recent failures (say over the past 50 to 100 years as observed from aerial photographs) in the catchment and its relevant vicinity.
B	The natural terrain is highly susceptible to the type of failure under consideration, with a notional annual probability of occurrence within the order of 1/10 to 1/100. For example: there are records of occasional recent failures in the catchment and its relevant vicinity.
C	The natural terrain is moderately susceptible to the type of failure under consideration, with a notional annual probability of occurrence within the order of 1/100 to 1/1,000. For example: there are few records of recent failures, but there are indications of relic failures, or geomorphological evidence of potential problems in the catchment and its relevant vicinity, or any other evidence from similar terrain in Hong Kong.
D	The natural terrain is of low susceptibility to the type of failure under consideration, with a notional annual probability of occurrence less than 1/1,000. For example: there are no records of recent and relic failures, and little geomorphological and other evidence of potential problems in the catchment and its relevant vicinity, and little other evidence from similar terrain in Hong Kong.

Note: In assessing the susceptibility of the hillside to failure consideration should be taken of potential effects of changes in environmental factors e.g. any changes to the overall setting of the terrain such as hillfires and construction upslope and the relevance of the available historical landslide records

Table 6. Consequence Classes for Developments Adjacent to Natural Terrain

Proximity	Facility Group			
	1 & 2	3	4	5
Very Close (e.g. if angular elevation from the site is ≥ 30°)	I	II	III	IV
Moderately Close (e.g. if angular elevation from the site is ≥ 25° & < 30°)	II	III	IV	V
Far (e.g. if angular elevation from the site is < 25°)	III	IV	V	V

Notes:
(1) Facility groups are described in Table 1.
(2) For channelised debris flow, if the worst credible event affecting the site is judged to have a volume exceeding 2,000 m^3, the angular elevation given in the above examples should be reduced by 5°.
(3) The examples given above are for general guidance only. Other factors, such as credible debris path, topographical conditions and site-specific historical data, should also be taken into account in assessing the 'proximity' of the natural terrain to the site.
(4) This Table is not applicable to sites which do not require a Natural Terrain Hazard Study.

Table 7. Requirements for the Design Event Approach

Susceptibility Class (see Table 5)	Consequence Class (see Table 6)				
	I	II	III	IV	V
A	WCE	WCE	WCE	CE	N
B	WCE	WCE	CE	CE	N
C	WCE	CE	CE	N	N
D	N	N	N	N	N

Notes:

(1) The recommended minimum design requirements are given in this Table. The designer may adopt a more conservative design or provision of other precautionary/warning measures if he considers it necessary.

(2) This Table is to be applied to each type of hazard that may affect the site. In practice, this will be applied to each catchment and normally the predominant type of hazard will control the design requirements.

(3) WCE = Adopt a 'worst credible' event as the design event
CE = Adopt a 'conservative' event as the design event
N = Further study not required

(4) A 'conservative' event is a reasonably safe but not overly conservative estimate of the hazard that may affect the site, with a notional return period in the order of 100 years. It generally corresponds to a reasonably conservative estimate based on the worst of the historical failures over the past 50 to 100 years (i.e. that can be identified from the aerial photographs) in the catchment and its vicinity as appropriate.

(5) A 'worst credible' event is a very conservative estimate such that the occurrence of a more severe event is sufficiently unlikely. Its notional return period is in the order of 1,000 years. It generally corresponds to the largest credible event based on interpretation of historical landslide data, geomorphological evidence in the catchment and its vicinity as appropriate, and any other evidence from similar terrain in Hong Kong.

- Site-specific QRA of a proposed tailings dam in an urban environment in South Africa (Roberds et al, 1996).
- Site-specific QRA of natural terrain landslide hazards for a proposed housing estate development in Fanling, Hong Kong (Tse et al, 1999).
- Site-specific QRA of coastal landslides at Lyme Regis, UK (Lee et al, 2000).
- Formulation of a risk-based methodology for identifying and evaluating potential geotechnical problems during site selection and development for the Housing Authority in Hong Kong (Roberds et al, 1999).
- Development of a risk assessment methodology to assist in determining optimal slope maintenance programs for large networks of a remote forestry roads in Washington State (Burke et al, 1991).
- Regional QRA of shallow landslips and large debris flows at Cairns, Australia (Michael-Leiba et al, 2000).
- QRA of construction failure of deep excavations, Hong Kong (Ove Arup & Partners, 1999).
- Relative risk-based ranking relating to slope failures potentially induced by leakage from service reservoirs, Hong Kong (Hyder, 2000).

Other examples of application of QRA, which are unpublished, include:

- QRA of design options for widening of major highways in Hong Kong.
- QRA of stability of dykes containing hazardous waste adjacent to a river in Virginia
- Risk assessment of slope hazards for a gas pipeline route in Western Canada
- Development of probabilistic design procedures for long stretches of rock slopes alongside highways in mountainous terrain in North Carolina.
- Development of map of annual probability of maximum extent of slope debris for land-use decisions for city in BC Canada.
- Risk assessment of preventive slope maintenance programs for large inventory of rock slopes along railway alignment in Canada.
- QRA of rock slopes in Stanley Park in BC Canada.
- QRA of slope stability of open pit mines throughout North America.
- QRA of rockfalls along transportation routes in Australia and USA.

It is evident that there are quite a number of examples of successful application of QRA methodology to tackle specific practical problems.

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11 HAZARD AND RISK MAPS FOR LAND-USE MANAGEMENT AND DEVELOPMENT PLANNING

Risk concepts have been applied in a qualitative or semi-quantitative manner for land-use management and development planning purposes. For example, acceptance criteria have been published for natural terrain landslides and flooding for the Regional District of Fraser-Cheam in British Columbia (Cave, 1992). Under this framework, an application must be supported by an assessment of return period probabilities for events of different magnitudes. The application of regional landslide hazard assessment is discussed by Hutchinson (1992).

Where assessments are made over a large area, the results can be expressed in the form of landslide hazard or risk maps. Significant advances have been made in developing such maps and many have been published in different forms in many countries, such as Australia, Austria, Canada, China, France, Fuji, Italy, Jamaica, Japan, New Zealand, Papua New Guinea, Philippines, Switzerland, UK, USA, etc. For example, in the United States, Brabb et al (1972) produced the landslide susceptibility map for San Mateo County in California based on geomorphology, geology and past landslide activity. This map has been used as basic guideline in land-use planning. Other similar maps have evolved in other countries based on terrain evaluation techniques, such as the ZERMOS maps (Humbert, 1977; Champetier de Ribes, 1987), PER maps (DRM, 1990) and PPR maps (Besson et al, 1999; Garry & Graszk, 1997; Graszk & Toulemont, 1996) in France, and the GASP maps in Hong Kong (Brand, 1988). Some of the maps have been built into the regulatory framework in respect of “no-build” zones.

Leroi (1996 & 1997) gave an overview of the practical issues regarding the compilation of hazard maps or risk maps. He noted the importance of considering the various scales of the different maps and summarised the different approaches and tools (e.g. GIS) that can be used in compiling such maps.

Most of the published hazard maps are qualitative or semi-quantitative, e.g. based on multiple regression analysis, in nature(Fell, 1992). The majority of the current hazard maps are not risk maps in that the consequences of the hazards are not considered. Einstein (1997) suggested that hazard maps can in principle be overlaid on top of land-use maps to produce risk maps. In practice, the main difficulty is the resolution of the data, particularly in defining the runout distance and travel paths of landslide debris, notwithstanding recent developments in GIS-based modelling and calibration against real events (e.g. Leroi et al, 2000). In addition, there could potentially be political ramifications if the maps proved to be wrong. Some regional risk maps derived using GIS-based QRA based on the concept of hazard mapping and travel angle have recently been published for the Cairns City Council in Australia for planning and emergency management purposes (Michael-Leiba et al, 2000).

Even for landslide susceptibility maps (i.e. no consideration of the runout and vulnerability aspects), the large-scale nature of the regional or area maps means that the evaluations are generally fairly broad-brush and may not be able to account for site-specific conditions with sufficient resolution. The inherent limitations associated with regional hazard or risk maps must be recognized and they should strictly be used for overall land-use planning purposes and not for safety-critical site-specific assessments. Overall, these maps are valuable in general land-use planning and ‘first-pass’ screening and preliminary feasibility studies, provided they are not used out of context.

At the other end of the spectrum, detailed risk maps can be produced following a formal QRA for a given site, e.g. based on individual risk contours derived from QRA such as that shown in Figure 14. However, it should be cautioned that relatively crude assumptions could also be made in projects using QRA in preliminary studies and such rough assessments can similarly produce superficially attractive risk maps. The problem here is the accuracy or reliability of the assessment because poor quality data or data of inadequate resolution are used. This problem of course would be common to all types of analysis and can be a trap for the unwary.

12 SOME CURRENT ISSUES RELATED TO APPLICATION OF QRA

The pilot application of QRA has provided insight on its potential usefulness as an emerging concept. It has come a long way in progressing from a conceptual idea to a practical tool for real geotechnical engineering problems. However, the value of the technique does not appear to be widely accepted or appreciated by the geotechnical community. In fact, there are indications that QRA is beginning to lose momentum and enthusiasm is fading, because of an under-current of resistance against its recognition as a practical tool. This is partly related to some common misconceptions by the profession. The main issues at stake are discussed below.

12.1 *Issue 1: Probability Scares People Off*

The QRA technique provides a framework for systematic application of engineering judgement to quantify uncertainties in addressing a problem. The basic concept of QRA is fairly rudimentary and not difficult. The notion of probability threads through the various components of uncertainties. However, probability concepts have tended to scare off practitioners. Some ‘probabilists’ seem to favour developing complex mathematical techniques of formal probabilistic analysis. Consequently, an average

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geotechnical engineer will find it difficult to come to grips with the complicated probabilistic concepts and jargons such as normal-tail approximation, Rosenblatt's transformation, zero-upcrossing, etc., to name a few. The end result is obvious geotechnical practitioners become disinterested in using formal probabilistic methods.

Whilst risk assessment calls for a basic understanding of probability, practical applications do not necessarily need to invoke complicated probabilistic techniques. A conceptual risk assessment framework based on formal probabilistic approaches for natural hillside problems can be developed (e.g. Roberds et al, 1997), which comprised modules that have different interchangeable versions of varying complexity depending on the application. At the extreme, the outcome can be rather complicated and there could be genuine difficulties in applying the framework in practice because a lot of "guesses" on inputs (about which there is little feel) are called for, e.g. probability distribution of various input parameters. Moreover, a probabilistic approach cannot in itself make the outcome better or more reliable. The complications in the mathematics are conducive to losing a feel for the problem. Also, the approximation of the relevant processes using a mathematical model in order to facilitate formal probabilistic analysis may involve grossly simplified assumptions that may not be appropriate.

Duncan (2000) put forward a simplified framework for application of reliability analysis in routine geotechnical practice, which only requires modest extra effort compared to the conventional approach. Although the approach may not be very rigorous mathematically (Li & Lam, 2000), such pragmatic probabilistic analysis is useful in giving the designer an idea of the uncertainties associated with a design. Duncan (op cit) suggested that the Factor of Safety and reliability should be used together, as complementary measures of an acceptable design.

Overall, formal probabilistic techniques should only be regarded as an analysis tool but they do have a place in relevant situations. In principle, it is important to have a fundamental understanding of the key processes at work and the factors that have a major effect on the causes and consequence of the different failure modes. Complicated mathematics would have the shortcoming that the assessor is liable to lose a feel for the problem.

Key message: *QRA does not necessarily call for complicated mathematics or probabilistic methods, as demonstrated by many of the case studies. A complicated mathematical framework will tend to scare off practitioners. It is liable to result in the assessor losing a feel for the problem and the outcome may not necessarily be more reliable. However, if oversimplified, the results may not be very accurate or may even be misleading. One cannot rule out the need for more theoretical approaches which are more comprehensive and fundamental in modelling complex mechanisms and correlations.*

12.2 *Issue 2: Qualitative or Quantitative Assessment*

For problems that are not amenable to conventional limit equilibrium analysis, the traditional approach is to rely on qualitative assessment, followed by an implicit value judgement on whether the outcome of the assessment is acceptable or not. Such qualitative assessments could work well, depending on the nature of the problem and whether experienced assessors making soundly based judgement are involved.

Obviously, the type of analysis has to be organized to include the appropriate level of detail. Where the quality and quantity of the available data are too meager for formal uncertainty analysis (e.g. subjective data based on inference from geomorphological assessments and expert judgement), a detailed QRA may be "out of reach". In such circumstances, a less rigorous qualitative risk assessment may be more relevant.

Although qualitative assessment may be very useful in its own right and adequate for some problems, its limitations should be recognized. A qualitative approach is liable to be haphazard because it is often difficult to know the scale of the implied risk used by different assessors, the limits of acceptability assumed (i.e. what would be acceptable and what would not), how uncertainties have been accounted for, etc.. Imprecise definition of the potential problem can result in difficulty in communication between fellow professionals, and with the authority or the general public. It can also be difficult to assess logically as to whether the cost of mitigation is adequate or can be justified.

The traditional defense for such a lumped qualitative approach includes use of expert judgement. This may be debatable and will critically depend on the skill and experience of the assessor. Qualitative assessment is not readily transparent and the judgement made can be significantly affected by personal experiences and pre-occupations. Notwithstanding the above, if the assessor takes due cognizance of the potential constraints, qualitative risk assessment can play a useful role in thinking through the process from a risk perspective, particularly for preliminary assessments and identification of significant problem areas which warrant further attention.

Overall, whether qualitative or quantitative assessments are more suitable depends on the desired accuracy and resolution of the outcome, and the nature of the problem at hand. In some case, it is not

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necessarily useful to draw a clear line between these two types of approaches. Some of the parameters may be defined partly in a qualitative manner even in a QRA framework, especially where the input cannot be quantified easily.

Key message: *Both quantitative and qualitative risk assessment techniques have merits and de-merits. The main difference lies in the fact that QRA provides a more structured and explicit framework which would be conducive to improving the accuracy and resolution of the assessment. What is the most appropriate tool depends on the problems at hand. In some cases, they can be used to complement each other, e.g. in staged assessments.*

12.3 *Issue 3: Scepticism Towards New Techniques*

To set the scene, it is useful to recite the following statements made by Professor Ralph Peck during the 1995 US National Research Council's Workshop on Reliability Methods for Risk Mitigation in Geotechnical Engineering (NRC, 1995):

"We see geotechnical engineering as developing into two somewhat different entities: one part dealing with traditional problems such as foundations, dams, and slope stability, and another part dealing with earthquake problems; natural slopes; and, most recently, environmental geotechnics. Practitioners in the first part have not readily adopted reliability theory, largely because the traditional methods have been generally successful, and engineers are comfortable with them. In contrast, practitioners in environmental geotechnics and to some extent in offshore engineering require newer, more stringent assessments of reliability that call for a different approach. Therefore, we may expect reliability methods to be adopted increasingly rapidly in these areas as confidence is developed. It is not surprising that those engineers working in environmental and offshore problems should be more receptive to new approaches, and it should not be surprising that there may be spillback into the more traditional areas."

There would appear to be an inherent resistance against the more extensive use of QRA by the practitioners or the checking authority, although the techniques for QRA exist for use in practice. This is partly due to misconceptions about QRA or lack of understanding of the philosophy, application and limitations of quantitative risk-based methodology. However, it must be recognized that formal QRA will not be justified for all problems, particularly the more routine problems, and hence one should not expect QRA will bring about a major transformation of the existing practice. It is merely a tool in the engineer's toolkit ready to be deployed for the appropriate situations.

Additionally, there may also be complex human factors, possibly including vested personal or professional interests. Some practitioners may feel rather "insecure" with the relatively unfamiliar approach of QRA which appears to be much less straightforward than conventional deterministic approaches. Some may see QRA as hard work to learn and not practicable to apply in practice because it requires so many inputs (which is understandable if QRA is used inappropriately for a simple problem resulting in unnecessary complications). Some may even feel vulnerable in being left behind if the technique were to be widely adopted.

Many practitioners in the long-standing traditional areas based on extensive experience have seen little need and value to change from deterministic methods that have stood the test of time and apparently served the profession well, to new, and largely untried, methods of questionable potential benefit. There is a school of thought that QRA is complex and impractical (with seemingly complicated probabilities) and that the method should remain a research tool. The concern of some people in the checking authorities is that QRA is very difficult, or impossible, to check, because much judgement is involved which can be difficult to substantiate and that there is considerable room for disagreement. In practice, it is debatable as to whether it would be easier to agree on what the uncertainties are or to agree on appropriate assumptions for deterministic design, depending on the problem at hand.

The common objections against the use of QRA includes lack of data, poor data resolution, lack of suitable verification data, lack of systematic approach to decide on the amount of data to be collected, inadequate modelling knowledge, as well as other human factors and constraints. However, the above objections actually also affect the usefulness and quality of any geotechnical engineering evaluations. Other objections against QRA include unnecessary complications and the fact that it may be a costly undertaking. Whether these allegations are really valid depends on many factors, including the type of questions to be answered.

The above diagnosis of general resistance by the geotechnical profession because of prejudice and misconception may be controversial and a matter for debate. However, the worrying trend is that many practitioners have become entrenched in fairly superficial assessments following standard approaches, often based on generalised shear strength parameters, with inadequate insight and feel for the uncertainties involved. Risk-based thinking is the essence, whichever analysis tool is used.

Key message: *It is important for the profession to keep an open mind in examining the usefulness and limitations of new techniques. QRA is meant to assist in more complicated problems or*

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problems with difficult questions to answer (e.g. how safe is the slope?) and is not intended for general application.

12.4 *Issue 4: QRA Must Wait for Consensus Standards - Reasonable or Not?*

National standards providing general guidance on risk management and risk analysis are available, e.g. British Standard BS8444, Australian/New Zealand Standard AS/NZS4360, Canadian Standard CAN/CSA-Q634-91, French Standard (Besson et al, 1999; Garry & Graszk, 1997) and Swiss Standard (Lateltin, 1997). However, there is nothing specific for geotechnical QRA in these standards. Standards on risk assessment advocated by BC Hydro in Canada, the Australian National Committee on Large Dams and US Bureau of Reclamation are discussed by Fell & Hartford (1997).

Lack of standards on QRA defined by the geotechnical profession and accepted by the authorities in many countries, contrary to conventional approaches based on Factors of Safety, is sometimes cited as a reason for rejection of QRA. This is related to the level of acceptance in terms of residual risk and how the uncertainty of the assessed risk should be taken into account in decision-making. As discussed, risk guidelines can be formulated as a reference, but these should not be taken as absolute and flexibility is needed in practice. Given the nature of the assessment, it would not be credible to expect that many of the inputs can be codified.

Overall, pending consensus standards, situations where QRA could be useful may be judged on a case-by-case basis.

Key message: *Codification of judgement is not possible although the various QRA methodologies may be described in codes or standards, as could risk guidelines. Over-prescription of use of specific assessment techniques is not advisable. Pending agreed standards, scenarios for which QRA can prove to be a useful tool may be judged on a case-by-case basis.*

12.5 *Issue 5: Interpretation of Historical Data*

There are various ways to carry out a risk assessment, depending on the type of problem and the nature and amount of data. QRA does not necessarily hinge on the availability of a large amount of data. In principle, a risk assessment can involve judicious extrapolation of the available data, tempered with judgement and if necessary assisted by formal probabilistic techniques.

Where there is much data on past failures, this would in principle assist the QRA. However, much care is needed in interpreting the historical data.

The insight derived from the pilot development and application of QRA points to the importance of understanding mechanisms, e.g. mechanisms of failure and debris movement. This is tantamount to having a better understanding of the hazards and failure modes involved. The alternative of adopting a 'black-box' type approach and mixing together different data without proper classification can significantly affect the accuracy of the assessment and may sometimes even give rise to misleading results. Over reliance on statistical analysis of past data with inadequate appreciation of the data constraints will not be appropriate.

The growing popularity of the use of multi-variant regression analysis, with or without the use of GIS, in establishing correlations between parameters deserves some cautionary remarks. In principle, there is a potential danger that such statistical methods, when used in a black-box manner with inadequate consideration of the mechanics of the physical processes involved, coupled with the use of limited input or calibration data that may be of questionable quality, are liable to result in very coarse and even misleading regression correlations. Such derived correlations are prone to errors (e.g. apparent statistical fits that are contrary to accepted physical phenomena) and could be of doubtful validity, particularly when used as a predictive tool or for extrapolation. The numerical complexity and apparent statistical fit may in fact provide a false sense of accuracy.

In general, multi-variant regression analysis and GIS are potentially useful tools but they must be applied in an appropriate manner. What is important is to have quality data diagnosed in a suitable mechanistic framework. Simply having more data does not necessarily mean more accurate information or better correlations.

As explained by Wong & Ho (2000), systematic landslide studies have contributed significantly to the development and application of QRA by providing good quality data on failures as a source of information to quantify landslide risk. In addition, these studies have led to an improved understanding of the failure mechanisms which assist greatly in hazard identification and systematic analysis of failure data. For example, good quality data on debris travel distance have been obtained for different failure mechanisms and site settings (Wong & Ho, 1996). Such systematic diagnosis of empirical data is important in the development of failure frequency and consequence models for risk quantification.

Key message: *Historical data must be scrutinized and interpreted with care under a suitable framework for their value to be fully exploited. This will also affect the accuracy of inputs and predictions.*

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12.6 *Issue 6: Problem of Assessment of Extreme Events Generated by QRA - Fair or Not?*

With a more structured approach, QRA will serve to highlight some of the unknowns which may not be commonly addressed by routine approaches. An example of this is the low probability, high consequence events, or so-called extreme events. In principle, knowledge of engineering mechanics and a good understanding of the geological and geomorphological setting provide the means by which the experienced practitioner may go beyond the limits of personal experience. Assessing the probability and consequence of such extreme events can present practical problems because these do not allow data gathering through experience or trial and error learning, and the uncertainty about the non-linear nature of system behaviour. Schuster (1999) noted that the important point in trying to assess such low-probability events is not accuracy, but the bounds of likelihood and the degree of confidence that the likelihood is low and remains low.

Morgenstern (1996) suggested that the approach to deal with such events either involves an extrapolation of past practice or simply conducting relative studies amongst alternative mitigation measures. A possible alternative pragmatic approach might be to declare that such extreme events are excluded from the risk assessment by documenting the relevant assumptions and scope.

QRA provides a framework to handle uncertainties but it will not directly improve the accuracy of the input per se. However, in addressing the uncertainties associated with the hazards, QRA will help to focus on the key factors and can potentially result in better assessments. The difficulty associated with assessing accurately extreme events is real, and this is especially the case for direct assessments. With QRA, the assessment is facilitated to some extent by decomposing the problem down (e.g. using fault trees and event trees) into contributing factors that can be more reasonably assessed. The overall assessment will also tend to be less sensitive to the accuracy of the individual inputs in comparison with direct assessments.

It is important to realize that the difficulty in assessing extreme events is not an inherent defect of the QRA methodology and it is unfair to blame QRA for generating questions which cannot be satisfactorily answered, thus casting doubts on the overall assessment. In the conventional deterministic approach, similar considerations are also applicable simply because the same problem is being tackled, except that these are basically not explicitly considered in the assessment, or at least not done in a very rigorous manner. This could well give rise to a false sense of security but the problem exists, be it highlighted by the analysis or not. In highlighting them under the QRA framework, one stands a fighting chance of making a more reasoned assessment, or taking appropriate steps to mitigate the hazards. Fell & Hartford (1997) pointed out that although the risk assessment methodology appears to be considerably more complicated than the conventional deterministic approach, in reality it is only a means of structuring the thought processes and risk-based decision framework.

The QRA technique has also received a fair share of criticism for being unable to cope with certain events such as long-runout, channelised debris flows and deep-seated natural hillside failures. It is sometimes alleged that the uncertainties in the risk assessment process of these hazards are so great (principally because of lack of historical data) that the assessment results cannot be interpreted properly. If such assertion were correct and reflected the current state of knowledge with such processes, then surely the basis of making subjective judgement in accordance with the conventional deterministic approach, without the use of a structured framework like QRA, is equally, if not more, questionable.

Key Message: *One should not blame and condemn QRA for generic problems (such as difficulty in assessing extreme events) that are not a result of the QRA methodology. Particularly for more complex or less familiar problems, QRA can have merits over the conventional deterministic approach.*

12.7 *Issue 7: Role of Subjective Judgement in QRA*

The need to use imperfect knowledge and limited data, guided by judgement and experience, to tackle real problems is a fact of life with geotechnical engineering. QRA does not replace judgement; rather, it provides a framework for making systematic judgement. Indeed, judgement must continue to play an important role in setting up an appropriate hazard model, assessing the likelihood of the different scenarios and influencing the quality of input data.

One of the merits of QRA is that by breaking the problem down into smaller components associated with the different scenarios and considering the corresponding uncertainties, there is a better chance of making a more reasonable judgement, compared to making a lumped judgement which could be rather coarse. The transparency of the assessment and judgement made will provide a useful basis for discussion and refinement of the assessment.

On the other hand, the less soundly-based judgement could be exposed and open to question through the QRA process. In QRA, it would be more difficult to hide behind the notion of "overall expert judgement" based on personal experience and this may well be a threat to some individuals. It can be very difficult to weigh up the subjective judgement of different individuals, including issues such as consistency, etc. Roberds (1990) gave an overview

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of the possible techniques (including the use of expert panels to try to facilitate convergence of judgements) and their limitations in the geotechnical field. Baynes (1997) noted the difficulty in applying this approach where some individuals are reluctant to commit to such an experimental methodology and suggested that more guidelines on the approach should be promulgated.

Needless to say, judgement should be soundly based and this means an adequate understanding of the processes at work and the conditions that favour the different mechanisms. Knowledge of past performance and behaviour under a similar site setting is a great asset. It is important that the assessment should factor in the uncertainty and degree of confidence of the input data. The degree of understanding of the processes and the prevailing knowledge database will affect the resolution of the judgement made. Sensitivity analysis can be useful to guide the judgement and should be carried out.

Hoek (1999) discussed the essence of putting numbers to geology from an engineer's perspective. He noted that many geologists may be uncomfortable with the need to assign numbers to geology. The necessary simplifications involved in the process of quantifying geological complexity may also be a concern to geologists. Hoek (op cit) contended that a good engineering geologist and a good geotechnical engineer working together as a team can usually make realistic judgement, or educated guesses, for the input parameter to an engineering design, or risk assessment.

Judgmental input essentially represents the state of belief of the assessor. The QRA framework will allow for the maximum usage of the available information and expertise for the quantification of risk. It has always been the engineer's role to solve problems by maximising the use of all the available information, and certainly not to avoid the problem.

Key Message: *Judgement continues to play a very important part in QRA, especially when the data is inadequate. QRA provides a systematic framework for judgement. The need for judgement is not a limitation of QRA, nor is it unique to QRA.*

12.8 *Issue 8: QRA Cannot be a 'Cure' For All Problems!*

The lack of general acceptance of QRA and recognition of its usefulness may be related to the fact that some users may be expecting too much from the numerical values obtained. The mindset needs to be changed when compared with deterministic analysis, which may seem comparatively more straightforward.

It should be remembered that QRA is afterall only a tool and it cannot be expected to be a cure for all problems. It only serves to put the uncertainties and engineering judgement into a system to facilitate the assessment. The technique itself will not add to the fundamental understanding of the operating mechanisms, nor is it a crystal ball that will predict exactly what will happen. Decisions still have to be made based on uncertain scenarios and competing consequences, and QRA provides a structured process to accomplish this in a more rational and defensible way.

Inadequate appreciation of what QRA can and cannot do is liable to result in disappointment or the perception that the problem may have been rendered unnecessarily complicated. The allegation that QRA is giving rise to more difficulties instead of solving problems is not uncommon.

Key Message: *Over-expectation of what QRA can offer is liable to lead to frustrations. The attributes and limitations of the technique must be viewed in perspective. Integrated risk assessment (if done correctly) is not perfect but may well be the best that can be done in the face of inherent uncertainties and limited resources for more defensible decisions.*

12.9 *Issue 9: Use of QRA for Relative Assessment*

It has been argued that the value of QRA in making relative risk assessment may have been underestimated in practice. The strength of risk-based thinking lies in the emphasis on uncertainty and the potential they offer to quantify the effects of uncertainty. This can be done in relative terms and not necessarily in absolute terms.

The structured approach of QRA can be applied to different sites, to different areas of a given site, or to examine the cost-benefit of different mitigation measures for relative or comparative assessments. If only a relative ranking is needed, then the demand for accuracy and resolution of the data will be less than that for absolute quantification of risk. If some kind of risk calibration is undertaken, then the risk-based ranking can be related to the order of risk.

However, if one were to address the question of whether risk mitigation works are needed at a given site or not, one inevitably has to apply some value judgement on the outcome of the assessment. In the Factor of Safety approach, an index is evaluated and compared against some reference points. If a purely qualitative assessment is made, the value judgement on the acceptability of the outcome of the assessment will be subjective and not transparent. In practice, this shortcoming may be improved by resorting to assessment by a panel of experts, or benchmarking against previous decisions for similar scenarios.

An alternative to detailed quantification of the risk levels is to adopt the percentage improvement concept. For instance, in the case of an existing man-made slope, this is akin to assuming the prevailing factor of safety is one and that measures are implemented to improve the safety margin by a certain percentage. This does mean that mitigation will be inevitable and the question becomes how much is needed.

Overall, there are merits in adopting a risk-based framework (even for qualitative assessments) for comparative purposes. Whether this will suffice will depend on the problem at hand.

Key Message: *The structured framework for QRA can be usefully employed to provide comparative assessments for certain classes of problems. However, quantitative risk assessment would still be needed for more definitive cost-benefit analysis.*

12.10 *Issue 10: Expertise in Geotechnical QRA - Issues of Quality and Recognition*

The risk assessment approach demands a range of additional skills and talents to those required for conventional geotechnical engineering problems. Collaboration across disciplines is useful. Geotechnical professionals should take the lead because they can describe the processes that form the risk assessment framework, exercise judgement and be responsible for the final solution adopted. Risk analysts may assist in examining the combination and interaction of scenarios and advising on vulnerability assessments given the impact upon different facilities, which tends to be one of the strengths of traditional risk analysts. Economists and social scientists can contribute to the evaluation of the costs of damage, cost-benefit calculations and consideration of risk acceptability.

The quality and skill of the assessor will have a major bearing on the accuracy of the QRA. This is related to the insight and judgement in formulating a suitable hazard model that considers the factors affecting the key processes involved. An over-simplified or inappropriate framework will affect the accuracy of the assessment and could even miss out key factors. On the other hand, an overly complicated framework will be unnecessarily taxing on the data input, possibly without significant improvement in the accuracy of the assessment.

It is vital to have an adequate understanding of the mechanisms involved in terms of what can go wrong. Hence, it is logical that geotechnical professionals with a basic understanding of risk concepts should take the lead in geotechnical QRA problems. However, expertise in geotechnical risk assessment is not formally recognized in practice. Such expertise is difficult to define at present. Thus, there is little control on the personnel undertaking the assessment, who may or may not have the required level of expertise and insight. Lack of suitable personnel with the requisite experience is partly related to the lukewarm reception of the QRA methodology by the geotechnical profession, which in turn means less opportunities for people to get involved and gain experience.

There is a danger that the apparent rigour underlying a QRA may mask the omission of key factors which would significantly affect the accuracy of the risk assessment, or even render it incorrect. Morgenstern (1995) highlighted the importance of model uncertainty and human errors which can overwhelm the accuracy of a risk assessment. Obviously, no amount of statistical manipulation could compensate for shortcomings of models that are fundamentally flawed. However, it should be remembered that such factors can overwhelm other types of assessments as well, not just risk assessment.

Morgenstern (1995) illustrated the point about model uncertainty by reference to the case study reported by Jackson & Fell (1993). This risk assessment did not take account of the static liquefaction potential of loose mine waste in an embankment that may collapse and fail in a brittle manner at much lower mobilised peak strengths than that corresponding to critical state conditions. Undrained collapse of such a loose metastable structure typically gives rise to a mobile failure, which has important bearing on debris runout, degree of warning and consequence of failure, and hence risk quantification.

Some people argue that it would be difficult to evaluate the quality of QRA or have the assessment verified. However, the above is a vivid example that a risk assessment (or any assessments), with erroneous assumptions on the key factors, can be noted. A lumped qualitative assessment might have masked such omission of key consideration but it is made more transparent in a QRA framework.

Whilst the quality of the assessor has an important bearing, the resolution of the assessment will be constrained by the state of knowledge on the mechanisms involved and the paucity of data. For example, there are correspondingly more uncertainties associated with risk assessment of natural hillsides because the factors that govern the initiation, mechanism, scale, transformation of different failure modes, mobility of landslide debris, etc. are less well understood than for man-made slope failures. Recognition of the complex and diverse range of hillside failures in the consideration of the hazard scenarios is important for meaningful risk assessments (Wong & Ho, 2000).

Key Message: *It is important to ensure that geotechnical professionals with adequate skills, knowledge and insight be deployed to carry out realistic risk assessments. There is no effective mechanism at present to distinguish between those who are capable and those who think they are capable (but are not).*

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13 *WHAT IS THE FUTURE FOR QRA?*

QRA is a powerful tool and the pilot applications of QRA have shown great promise. As an alternative or supplementary tool to the use of conventional techniques, it has provided considerable insight to certain problems and facilitated balanced decision-making, both on a site-specific level and corporate/organisational basis. The process can result in a much more complete understanding of the problem and its solution than merely arriving at a conventional Factor of Safety.

The relatively novel application of global QRA methodologies has served their intended purposes well. However, some breakthrough is probably needed in further refining and tuning the QRA methodology to improve the accuracy of site-specific QRA. Work is also needed in the area of hazard identification (Wong & Ho, 2000), as well as means to improve the accuracy of frequency and consequence assessments, especially for natural terrain problems.

It is fair to say that the majority of routine problems can be adequately dealt with by existing practice with the use of experienced-based approaches and there may be no need for elaborate risk assessments. For less familiar or more complicated problems (e.g. natural hillside failures, boulder falls, landfill, radioactive waste disposal, developments over abandoned mines, etc.), it is considered that QRA has a role in supplementing the conventional approaches, some of which may be judgmental and/or qualitative in nature.

QRA can be used to provide additional insight to a problem after one has developed a feel via conventional approaches. The key is to identify the most appropriate tool(s), or combination of tools, for the problem at hand. The choice may well be different even for the same class of problems, depending on the exact questions posed, the stakeholders concerned and the context of the answers needed (e.g. different stages of a project, accuracy, etc.). In examining the relevant approaches, one must not be unduly constrained by the more familiar (or popular) methods which may not be appropriate and could give rise to a false sense of security. On the other hand, it is important to ensure that the level of complexity of the analysis is compatible with the problem to be solved, and balance the additional cost and time involved in more elaborate analysis against the potential savings and other perceived benefits (e.g. political and social considerations). The challenge is to be able to choose the right tools for the right problems so that the full benefit can be realized.

There are problems which may be less conducive to QRA, e.g. when the uncertainties are substantial and sensitive, when the mechanisms involved are not well understood, or when the parameters of the analysis model are not well defined. However, the alternative of adopting more conventional approaches will similarly fall short of providing a satisfactory tool to such problems. With QRA or a risk-based framework, the more structured approach will stand a better chance of identifying the major risk components and highlighting key uncertainties to facilitate more reasonable decisions. Under this context, it is better to be ‘probably right’ (by explicitly considering the uncertainties) than to be ‘exactly wrong’ through a lumped assessment.

The inability to come up with accurate risk assessment is not necessarily an impediment to risk quantification. It is however necessary to examine the likely order of accuracy of the QRA and understand its sensitivity to input parameters. Where the uncertainties of the assessment are significant, suitably robust risk mitigation measures may be adopted to cater for those components principally giving rise to the uncertainty.

QRA involves a different mindset and approach in that uncertainties and failures have to be considered explicitly. As a process, it is more difficult to vet and verify because of lack of experience and/or data. This in turn means that it can be difficult to obtain acceptance by authorities and the extended time-scale involved in resolving queries can strongly discourage those who may opt for a risk-based approach.

The current resistance against QRA by the profession is by no means easy to resolve. Appropriate grounding of the basic concepts in university education and focused professional training are relevant. More promulgation through writing technical papers will be a step in the right direction and this will pave the way for the individuals to try out the technique in appropriate situations. Successful application of QRA as demonstrated by case histories will be a powerful message to the geotechnical community.

From a more global perspective, the usefulness of QRA must not be oversold. QRA must not be blindly applied to the wrong problems, in which case it is likely to do more harm than good. Although rigorous quantification of risk can be useful to put particular issues in context, this is not necessarily essential for effective risk management, depending on the nature of the problem at hand. Integrated risk management is the key, and this can include both direct engineering actions and soft approaches, such as public education and community emergency preparedness programmes based on social science techniques, as well as warning systems (Yim et al, 1999). A comprehensive safety risk management system should be based on a holistic approach, with the principal goals being to reduce risk (i.e. reduce probability or consequence of failure, or both), increase risk tolerance and maintain risk awareness (Malone, 1998).

The consideration of risk is essential to assure geotechnical performance and the process does not necessarily have to be quantitative for the majority of routine problems. Morgenstern (2000) suggested

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that Consequential Risk Analysis would be the appropriate process, coupled with other tools of qualitative risk analysis (such as preliminary hazard analysis (PHA), failure modes-effects analysis (FMEA) commonly used in the formal risk assessment field in other industries) to secure satisfactory performance of geotechnical structures. To translate the above into more down-to-earth terms, this is equivalent to thinking through the "what if's" scenarios, actions or measures to manage or mitigate the risk, contingency measures ("Plan B's"), etc.. This amounts to a more systematic application of the Observational Approach. Such an approach would be a useful pedagogic instrument for younger professionals to develop their feel and sensitivity for what can go wrong, how likely, with what consequences, and how the adverse events may interact. This could also provide a convenient framework for transferring a sense of judgement from the experienced to the inexperienced. In practice, the above assessment could be incorporated as part of the quality assurance system and carried out during the Option Assessment Stage collectively by the concerned stakeholders when the design options together with the uncertainties and project constraints are evaluated. The assessment should be re-appraised from time to time during the construction stage in accordance with standard good practice, with a view to minimizing mishaps.

14 CONCLUSIONS

Quantitative risk assessment (QRA) techniques should be recognized as an additional tool to conventional deterministic methods in the quantification of landslide risk. It provides a framework for anticipating problems, evaluating them, mitigating them in a cost effective manner and acceptance of the residual risk level. Risk assessment is not an end in itself but an input to risk management. It can be done in various ways, with the best way being dependent on the specific application.

QRA has been shown to provide considerable insight to old problems, and serve as solutions to new problems. It has the potential for wider applications in the various disciplines of geotechnical and geo-environmental engineering for selected problems. The risk-based methodology, whilst not a complete substitute for the traditional deterministic design and decision methods, offers a systematic approach to accounting for the uncertainties and quantifying the level of safety. QRA has proved very useful to addressing the question "How safe are the slopes?" or similar questions on quantification of the level of safety, in terms that can be meaningfully compared to other risks. Such questions are increasingly being asked by clients, resource allocators and the public alike. The profession is faced with the challenge of appreciating when and where risk-based decision-making is most applicable and judging the most appropriate risk analysis tools for the specific problems.

Many of the perceived limitations and reservations about risk assessment are not unique to QRA. Although QRA is able to solve some of the problems associated with traditional approaches, it shares some of the same problems. Misunderstandings about QRA have contributed to thwarting its more widespread use. The technique cannot be oversold as it will not necessarily tackle all problems satisfactorily and there are practical constraints associated with QRA, as with any other assessment tools. Obviously, the right engineering tool has to be applied to the right problem by skilled users for it to be a value-added process.

The risk assessment process is an important reminder to the profession that geotechnical engineering is essentially about managing uncertainties and risk. Engineering is about making decisions where the behaviour is uncertain but it is important that one knows enough to make reasoned and defensible decisions; perfect knowledge is not required. Routine practice nowadays tends to be largely dominated by standards and tried-and-tested solutions. Whilst this may be adequate for the majority of the routine and more familiar problems, an overly rigid and un-insightful approach that discourages lateral thinking is not conducive to improvement in engineering practice and may lead to unfavourable outcomes.

Having a risk-based mindset and adopting a more structured approach in the assessment of what can go wrong (be it quantitatively or qualitatively) is an important starting point, particularly when tackling more complex and/or less familiar problems. For important or sensitive projects, QRA can be a very valuable tool to complement existing techniques and facilitate decision-making. The use of a risk-based framework to integrate the consideration of potential consequences and identification of robust preventive or mitigation measures into the different stages of the geotechnical assessment process will greatly help to map out areas deserving attention and avoid surprises, embarrassments or disasters.

A better understanding of how geotechnical structures behave under normal and more extreme loading conditions would improve the accuracy of predictions, and good-quality databases are important in developing this understanding. Learning from geotechnical failures is essential in advancing fundamental understanding about failure mechanisms and what can go wrong in order to facilitate more realistic risk assessments.

Finally, our societies are becoming less and less tolerant of failures of engineered structures, including disasters brought about by natural phenomena affecting developed areas. Engineers tend to get blamed for their actions or inactions. There is pressure for increased accountability and more transparency. Practitioners can hardly hide behind "expert judgement" or esoteric explanations any more. Blind public confidence in "experts" is gradually being replaced by a sense of suspicion: "It should have been foreseen!". There is much scope for the geotechnical profession to work alongside other disciplines, such as social scientists, media consultants, etc., to contribute more to promoting improved communication with the stakeholders regarding the nature and realities of landslide risk using language and vocabulary that can be comprehended by laymen.

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