INTERIM REVIEW OF PILOT APPLICATIONS OF QUANTITATIVE RISK ASSESSMENT TO LANDSLIDE PROBLEMS IN HONG KONG

GEO REPORT No. 126

D.O.K. Lo

GEOTECHNICAL ENGINEERING OFFICE
CIVIL ENGINEERING DEPARTMENT
THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION
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PREFACE

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. A charge is made to cover the cost of printing.

The Geotechnical Engineering Office also publishes guidance documents as GEO Publications. These publications and the GEO Reports may be obtained from the Government’s Information Services Department. Information on how to purchase these documents is given on the last page of this report.

R.K.S. Chan
Head, Geotechnical Engineering Office
June 2002
The Geotechnical Engineering Office embarked on a programme of research and development studies on landslide risk management under the R & D theme on quantitative risk assessment (QRA) in 1993.

This Report reviews some of the pilot QRA applications to examine the usefulness of QRA in such work and to identify areas for further improvement. The review was carried out in 1999 by Dr D.O.K. Lo who was the Secretary of the Working Group on QRA at the time of the study. Comments and contributions from members of the Working Group have been incorporated in this Report. The Work Group comprises Mr Y.S. Au-yeung, Mr Y.C. Chan, Mr K.K.S. Ho, Mr K.W. Leung, Mr S.H. Mak, Dr R.P. Martin, Mr J.B. Massey, Mr P.G.D. Whiteside, Mr H.N. Wong and Mr K.M. Wong.

In this study, assistance was given by colleagues involved in carrying out or in reviewing the QRA projects. Mr S.H. Tse and Mr K.K.S. Ho reviewed a draft of this Report and provided useful comments. All assistance is gratefully acknowledged.

The subject of QRA as applied to landslide risk assessment is evolving. Readers should note that since this review was completed in 1999, a number of other QRA studies have been carried out and further experience gained. Interested parties should refer to the relevant documentation on these to obtain a more complete picture of the current state of development.

P.L.R. Pang
Chief Geotechnical Engineer/Special Projects
Chairman, Working Group on Quantitative Risk Assessment
ABSTRACT

In 1993, the Geotechnical Engineering Office (GEO) embarked on a programme of research and development studies on landslide risk management under the R & D theme on quantitative risk assessment (QRA). This has led to a number of pilot applications of QRA to landslide problems in Hong Kong.

In 1999, an interim review of some of the pilot applications of QRA to landslide problems in Hong Kong was carried out to examine the usefulness of QRA in such work and to identify the areas for further development. The review is documented in this Report.

While one may query about the details of some of the assumptions and methodologies in the pilot studies carried out, the studies have demonstrated that the QRA framework has been useful to help address issues that could not be tackled effectively by the conventional deterministic factor of safety approach. This interim review has shown that QRA can be a very valuable tool in landslide risk management. It has been applied to assess the cost of managing risk and the direct and indirect benefits, optimise the allocation of available resources, identify areas of concern for improvement, and measure and evaluate the effectiveness of the Slope Safety System. QRA can also be an effective vehicle for objective communication of risk amongst engineers, regulatory agencies, resources allocators and the public.

The interim review has identified factors that can affect the usefulness of QRA. These include scarcity of relevant or good quality data, low resolution of data for the purpose of assessment, lack of suitable verification data, insufficient knowledge about hazard and consequence modelling, influence of human factors, project constraints, etc. These are not specific to QRA itself but are identical to those that can affect the usefulness of any geotechnical engineering evaluation technique. Notwithstanding the above, QRA can provide valuable insights and perspectives beyond those that can be normally obtained from conventional deterministic methods. It helps to break down the problems into manageable sub-components to facilitate a better understanding of the critical elements. It provides a framework for evaluating uncertainties and exercising engineering judgement systematically. It also helps to identify effective solutions or to justify any acquisition of additional data prior to decision-making. Some areas of improvement to enhance the reliability of QRA that were identified during the course of the pilot studies are summarised in the Report.

The subject of QRA as applied to landslide risk assessment is evolving. Readers should note that since this interim review was completed in 1999, a number of other QRA studies have been carried out and further experience gained. Interested parties should refer to the relevant documentation on these to obtain a more complete picture of the current state of development.
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1. **INTRODUCTION**

Deterministic methods have commonly been used to tackle geotechnical problems. For example, for slope stability, it primarily involves the computation of a factor of safety for comparison with a selected minimum value. The acceptable design factor of safety generally varies with the type of problem and situations, e.g. a lower factor of safety will be accepted where the consequences of failure are low, and a higher factor of safety is required for high consequences of failure situations. The deterministic methods incorporate implicit value judgement as to what is an acceptable standard of practice, and are largely derived from an extension of past practice and experience. Although these methods are well developed and well understood in some geotechnical problems, they have their own limitations.

Geotechnical engineers are increasingly asked to tackle different types of problems for which there are no precedents and that cannot be answered in terms of factor of safety, e.g. frequency of boulder falls and natural terrain instabilities and their associated risk. At the same time, society also demands explicit assessment of risk related to new technological systems developed by engineers. There is a growing need for effective communication of risk amongst engineers, regulatory agencies and the public. The risk management approach can supplement the conventional deterministic methods in addressing some of these issues and help support decision-making.

In 1993, the Geotechnical Engineering Office (GEO) embarked on a programme of research and development studies on landslide risk management under the R & D theme on quantitative risk assessment. This has led to a number of pilot applications of quantitative risk assessment (QRA) to landslide problems in Hong Kong. This Report presents a review of some of the QRA applications to examine the usefulness of QRA and to identify the areas for further development.

2. **RISK CONCEPTS**

Risk is present in all human activities. It is a measure of the likelihood and severity of the consequence of an adverse event to health, property, or the environment. Risk is often estimated by the mathematical expectation of the consequence of an adverse event occurring (i.e. the product of 'probability and consequence'). A glossary of some risk terminology is given in Appendix A.

Risk needs to be analysed before it can be effectively managed. Risk analysis is a part of the risk assessment and management process as illustrated in Figure 1 and consists of scope identification, hazard identification and risk estimation (Stewart, 2000). Risk management is the process by which the results of risk assessments are integrated with other information, such as political, social, economic and engineering considerations to arrive at decisions about the need and methods for risk reductions. Methods for estimating risk to humans have evolved steadily over the last few decades. Risk assessment is not a single, fixed method of analysis. Rather, it is a systematic approach to organising and analysing scientific knowledge and information for the hazards that may pose risks under certain conditions.

Risk assessment can be qualitative or quantitative. The former is carried out using
ranking methods with varying degrees in detail and complexity primarily for relative ranking purposes. It involves acquiring knowledge of the hazards, the elements at risk and their vulnerabilities, and expressing that knowledge, typically as ranked attributes. The risk may then be ranked based on the consideration of the basic input of hazard, vulnerability and elements at risk. When there is increasing quantitative expression of the input parameters even though these may have a judgmental basis, it becomes a form of quantitative risk assessment. The type of risk analysis required depends on the objective and nature of the subject. Schuster (1999) and Stewart (2000) noted that engineers often tend to quantify issues too quickly and cautioned that some risk problems may best be handled as qualitatively.

QRA involves risk estimation, which incorporates frequency and consequence analysis to produce a measure of the level of risks being analysed, as well as risk evaluation to provide a basis for risk management action. The frequency analysis is commonly by means of statistical analysis of relevant historical data, analytical (or simulation) techniques and expert judgement. Consequence analysis is to estimate the consequence, both immediate consequence and knock-on effects that could result from the hazards, taking due account of any existing mitigation measures and conditions that could have an effect on the consequence.

The outcome of a QRA is an estimate of the frequency of occurrence of different types of adverse consequences, such as mortality of individuals (i.e. individual risk), statistical expected loss rate in terms of casualties (i.e. societal risk), economic cost (i.e. economic risk) or environmental damage. A more general interpretation of risk involves probability and consequence in a non-product form. This presentation, commonly referred to as the F-N curve, is sometimes useful in that a spectrum of consequences, with each magnitude having its own corresponding probability of occurrence, is outlined (Canada Standards Association, 1991).

Site-specific QRA serves to provide a systematic assessment of the hazards and level of risk at a given site. This facilitates the consideration of whether the risk levels are acceptable and the evaluation of different risk mitigation measures, usually on the basis of cost-benefit analysis. It may also serve as a benchmark for calibrating the results of global risk assessment.

Global QRA is aimed at assessing the overall risk of the hazards posed to the community. It also serves to define the relative contribution of various hazards to the total risk, which can provide a reference for landslide risk management and consideration of resources allocation and policy making. Detailed site-specific data are not normally required for a global QRA (Wong & Ho, 1998; Ho et al, 2000).

QRA techniques have been well established in the process industries, toxicology and some engineering fields such as dam, petrochemical, nuclear, transport, etc. Probabilistic methods have been used effectively in connection with exploration, mining and geo-environmental assessments. These methods, similar to QRA, are not a substitute for traditional deterministic design methods. They offer a systematic and quantitative way of accounting for uncertainties encountered by geotechnical engineers, and are most effective when used to organise and quantify these uncertainties for engineering design (National Research Council, 1995). However, unlike the probabilistic methods, which generally consider only the likelihood of failure, QRA addresses both the probability and consequence
of failure and deals directly with risk issues.

3. RESEARCH AND DEVELOPMENT FRAMEWORK FOR QRA

The research and development studies undertaken by GEO to develop QRA methods broadly follow the R & D framework shown in Table 1. The framework is composed of four separate, but related, initiatives as follows:

(a) **Data Collection** - This consists of compilation of relevant data and knowledge of the landslide processes to facilitate the formulation of various models for conducting frequency and consequence analysis.

(b) **Development of Methodology** - This consists of evaluation of factors affecting the frequency and consequence of landslides and classification of different types of geotechnical features and landslides. It provides the technical basis for risk assessment and risk management, and the formulation of methodology for the quantification of risk and determination of optimal risk mitigation options for different types of geotechnical hazards.

(c) **Risk Tolerability and Communication** - This consists of development of guidelines for assessment of the level of tolerable landslide risk. The work is carried out through a review of the actual and tolerable risks of different hazards and through consultation with the public and practitioners, which provides information for risk communication and determination of optimal risk mitigation options.

(d) **Applications** - This consists of quantification of the risk to aid decision making and formulation of risk management strategies and the determination of the optimal risk mitigation options for different types of landslide hazards.

Lists of relevant study reports and technical papers on QRA work carried out or initiated by the GEO are given in Appendices B and C respectively.

4. QRA REVIEW

4.1 General

The review outlined in this Report aims to examine the usefulness of QRA in relation to application to landslide studies and to identify the areas for further development. The review was carried out predominantly based on information contained in the summary sheets on individual QRA projects given in Appendix D. These sheets were prepared by persons who were either involved in carrying out or in reviewing the projects. The commentaries and the comments on the usefulness of the QRA given in the individual summaries were
made together with these persons. The assessment was based on the state of knowledge and information available at the time of the study.

4.2 Brief Outline of the Applications

Table 2 summarises the types of application that have been reviewed. In total, fourteen applications were reviewed, including six global assessments and eight site-specific assessments. Almost all the QRAs considered risk to life with only one included the consideration of economic loss. Among these assessments, only one of them was for a private project and the rest were for government projects.

The principal objectives of the global assessments are to:

(a) examine the relative risk of different geotechnical hazards (viz. pre-GCO slopes, natural terrain landslides, deep excavations and earthquake-induced landslides at engineered man-made slopes) posed to different communities for the formulation of landslide risk management strategies and consideration of resources allocation, and

(b) examine the feasibility of the application of QRA to landslide problems.

The main objectives of the site-specific assessments are to:

(a) supplement and calibrate engineering judgement,

(b) aid decision-making by:

(i) providing a framework to assess the need for mitigation action or works and to evaluate the cost-effectiveness of different risk mitigation options,

(ii) helping to establish priorities of works based on risk considerations, e.g. the prioritisation of road improvement/reconstruction schemes by adding the consideration of landslide risk other than consideration of traffic needs alone,

(iii) assisting to address some issues that are difficult to be answered in terms of conventional slope stability analysis, e.g. the extent of evacuation of squatters affected by landslides,

(iv) identifying (through breaking down the problem into small components) important risk contributors and weak links in the ‘system’,
(c) examine the feasibility of using QRA for land-use planning purposes, and

(d) highlight the detail of issues that need to be addressed in implementing QRA methods in practice.

4.3 Usefulness of the QRA Studies

4.3.1 General

Risk assessment is a multi-faceted process that relies on an assortment of methods, data and models. The overall accuracy of a risk assessment hinges on the validity of the various methods and models chosen, which in turn are governed by the scope and quality of data. The degree of confidence that one can place in a risk assessment depends on the reliability of the models chosen and their input parameters and on how well the boundaries of uncertainty have been quantified for the input parameters, for the models as a whole, and for the entire risk-assessment process (National Research Council, 1996).

The key input parameters in a QRA study can be split into two groups: those related to the hazard assessment (in particular, failure frequency) and those related to consequence assessment. The accuracy of consequence modelling and that achieved in the frequency of occurrence estimates should be comparable and both are equally important. The focus and degree of details required in data resolution and precision of risk results depend on the objective and nature of assessment to be carried out and the level of risk involved, as shown in Table 2, viz. global versus site-specific QRA. Detailed site-specific data are not normally required for global QRA. The output of global risk assessments is generally order-of-magnitude estimates of the risk due to a particular type of hazard and is less demanding on data resolution and consequence modelling. Furthermore, the study area involved is usually of a large extent where there is likely to have relatively abundance of historical data for formulating the failure frequency model.

Site-specific QRA studies that have been carried out are primarily for the determination of whether the prevailing risk due to different geotechnical hazards is acceptable and whether mitigation works are necessary. For these cases, risk acceptance criteria need to be established to allow such assessment. At present, interim risk criteria are available only for natural terrain landslide and boulder fall hazards (ERM-Hong Kong, 1998). When compared to global risk assessments, the risk estimates for site-specific QRA studies need to be fairly precise in order to allow meaningful evaluation of their acceptability. These site-specific assessments generally require detailed information on landslide triggering factors, modes of failure, and debris runout (Wong et al, 1997; Ho et al, 2000). The quality or reliability of the site-specific QRA studies is commonly hampered by lack of site-specific data. This problem accentuates for small sites or sites with no historical failure data for certain hazards. To fill in the data gaps, judgmental input was generally resorted to. Numerical techniques (e.g. Monte Carlo simulation) have not been attempted to address this problem in these pilot applications.

Some site-specific QRA studies have been carried out to determine the ranking of sites in terms of geotechnical risk, e.g. BRIL roads (busy roads with a history of landslips) and individual boulder fields. The demand for accuracy and data resolution for these studies is
comparatively less than that for other site-specific studies where more precise quantification of risk is needed for risk evaluation.

The factors that can affect the usefulness of QRA are discussed in the following Section.

### 4.3.2 Factors Which Can Affect the Usefulness of QRA

Based on the review of the QRA studies, the following factors are identified that have affected the usefulness of QRA in general and they are categorised into three groups, viz. data, modelling, and human factors and constraints, as suggested by Morgenstern (1995):

**Data**

(a) scarcity of data and poor data resolution, especially for site-specific studies, rendering it difficult to establish the bounds of possible risk levels with confidence, and

(b) lack of suitable data to verify the risk results, although in some instances the historical fatality figure may serve as a rough indicator of risk.

**Modelling**

(a) insufficient knowledge of the key factors affecting the initiation, mechanism, scale and mobility of landslides, in particular natural terrain landslides,

(b) insufficient knowledge on how to integrate information that is not readily quantifiable (e.g. geological, geomorphological and hydrogeological features) in the QRA hazard model,

(c) uncertainties in the modelling of the mobility of landslide debris, in particular, for natural terrain landslides, and

(d) uncertainties in the determination of the risk reduction associated with different mitigation options.

**Human Factors and Constraints**

(a) judgmental input may differ for different personnel and in particular between those with and without sufficient relevant experience and expertise,

(b) difficulties in finding suitable combination of personnel with experience in both landslide assessment and QRA work. The number of professional geotechnical engineers
in Hong Kong who have experience in the use of QRA is fairly small; some are more skilled than others,

(c) lack of a commonly-accepted methodology to achieve consistency in making judgmental input, and

(d) in some cases underestimation of resources and time for development work, especially when such work is done during actual works projects that have a tight programme.

It can be seen that most of these factors relate to the understanding of the landsliding process, mechanisms, debris mobility, etc., and are not specific to the QRA technique itself. Similar to other types of engineering assessment, relevant experience and a sound understanding of the mechanisms involved are essential for a realistic QRA. This also reinforces the merit of adopting the risk concept which is to provide a framework for breaking down a complex problem into sub-components to facilitate the understanding of the controlling critical elements and evaluating the sensitivity of the results to uncertainties, and hence the implications, of professional judgement in a rational, systematic and transparent manner. The accuracy of estimates of risk can then be progressively improved by selective attention to important areas of uncertainty. It is noteworthy that the significance of a given factor will also depend on the level of risk involved.

4.3.3 Presentation of QRA

A proper presentation of technical information involved in a QRA is a critical part of the risk assessment. According to BS 8444 (BSI, 1996) and Canadian Standards Association (1991), a risk analysis report should contain the following elements:

(a) objective and scope
(b) limitation, assumptions, and justification of hypothesis
(c) system description
(d) analysis methodology
(e) hazard identification results
(f) model description, including assumptions and validation
(g) data and their sources
(h) risk estimation results
(i) sensitivity and uncertainty analysis
(j) discussion of results
(k) conclusions and recommendations

(l) references

It is noted that in most of the QRAs reviewed, there seems to be a lack of documentation of the limitations and assumptions of the analysis, description of the strengths and limitation of the models used, data and their sources, and sensitivity and uncertainty analysis. The completeness and accuracy of the risk estimation need to be stated as fully as possible. Sources of uncertainty, both in relation to data and model, should be identified where possible, stating the parameters to which the analysis is sensitive. The very heart of QRA is to use, with judicious judgement, the information at hand or that can be generated to produce a number, a range, a probability distribution - whatever expresses best the present state of knowledge about the effects of certain hazards in specific setting.

4.4 Overall Comments on the Pilot Studies Examined

Expert judgement and judicious extrapolation of the available data have been made in some of the pilot studies to overcome gaps in knowledge and data at the time when the studies were carried out. This is inevitable given the nature of problems in practice and the scarcity of good quality data. Overall, the studies have:

(a) demonstrated the feasibility of applying QRA to landslide studies,

(b) provided order-of-magnitude estimates of risk for different landslide hazards for the first time, and allowed relative risk proportions to be derived, for the formulation of risk management strategies,

(c) provided a basis for relative ranking of facilities or slope features for prioritisation of Landslip Preventive Measures (LPM) works (i.e. the CNPCS score),

(d) provided a basis for justifying that mitigation measures were warranted to improve the prevailing conditions, and

(e) demonstrated that QRA may serve as a useful tool in communicating risk.

In broad terms, the pilot QRA studies met their intended objectives. Furthermore, these pilot studies resulted in considerable advances in the development of the QRA method and in the understanding of the difficulties and limitations of QRA for different geotechnical applications.

5. MEANS TO ENHANCE RELIABILITY OF QRA

Notwithstanding the difficulties associated with the application of QRA with current
knowledge and data, the usefulness of QRA as an engineering tool to aid slope safety management decision-making was clearly demonstrated. Further development of some areas to enhance the usefulness of QRA techniques is certainly needed. The areas worthy of further development depends on the added benefits that can be derived from QRA over existing approaches in the application, which will be problem and situation dependent (as shown in Table 4).

Conventional slope stability analysis will not facilitate global risk management of man-made slopes and natural terrain hazards. QRA appears to be a promising tool in this regard.

Site-specific QRA of landslides at natural terrain and man-made slopes, based on current knowledge and data, is more difficult in terms of achieving the accuracy required for the assessment and could be a resource-demanding undertaking which necessitates input from personnel with experience in both risk and geotechnical issues. As conventional design standards for man-made slopes are well established and calibrated against a wealth of experience, the development of QRA techniques for use in routine design of man-made slopes is not of high priority, except for specialised applications such as evaluation of dam safety. However, the increasing pressure for developments encroaching on natural terrain for which there are more uncertainties and much less experience in terms of assessment prompt the need for further developing site-specific QRA for natural terrain. However, one should always bear in mind that the reliability of a site-specific QRA will partly depend on the amount of data available and the accuracy and relevance of the data collected for the analysis. One should not be led into believing that the QRA can simply be a convenient panacea in circumstances where the deterministic approach does not appear to be feasible.

Some areas of improvement are summarised below. They are derived partly based on the above considerations and partly based on suggestions made by personnel involved in undertaking the pilot studies and members of the GEO’s Working Group on QRA.

Hazard Modelling

(a) continue to systematically obtain good quality data on man-made slope failures and natural terrain landslides for classification and analysis,

(b) study selected landslides to:

(i) further enhance the understanding of the mode, mechanism and causes of different types of landslide hazards together with their spatial and temporal distribution,

(ii) further enhance the understanding of mechanisms of landslide debris movement and improve runout modelling and assessment,

(c) systematically review and analyse historical landslide data and other relevant information to improve hazard
identification,
(d) examine the key factors that affect the susceptibility of natural terrain to landsliding, and
(e) improve the model for susceptibility assessment and zoning of natural terrain landslides.

Consequence Modelling
(a) development work to improve consequence modelling, especially for natural terrain hazards.

Risk Perception and Acceptability
(a) calibrate and refine the interim risk guidelines for natural terrain in the light of additional QRA studies, and
(b) regular survey of public perception and tolerability of landslide risk for different types of slopes in Hong Kong (e.g. squatters, natural terrain, old man-made slopes, etc), which will facilitate formulation of landslide risk management strategies and decision-making in slope safety policy, and assist to benchmark the risk guidelines.

Risk Assessment
(a) the estimation of risk is intended to be the best estimate and the calculated risk results should not necessarily be taken as absolute values. Suitable allowance should be made for the uncertainties in the hazard model and the input parameters, which should be made clear in the reporting of the risk analysis results. Discussion of limitations and error bounds of the QRA should where appropriate be included in giving recommendations on how best to manage the risk identified,
(b) development of generalised guidelines on situations that may warrant site-specific QRA, and
(c) development of a consistent process of judgmental input to hazard model formulation and assignment of data ranges in a QRA study.

It is noteworthy that some of the above suggested areas of improvement pertain to an improved understanding of failures, both for man-made slopes and natural hillsides, which is essential to the quantification of risk posed by these features. Steady headway has been made in this respect (e.g. Wong & Ho, 2000). The relative importance of these areas of improvement is dependent on the scope and rigour of the risk analysis required which in turn
relates to its purpose within the decision-making framework for the particular situations.

6. CONCLUSIONS

An interim review of some pilot applications of QRA to landslide problems in Hong Kong has been carried out. While one may query about the details of some of the assumptions and methodologies in the pilot studies, the studies have demonstrated that the QRA framework has been useful to help address issues that could not be tackled effectively by the conventional deterministic factor of safety approach. QRA can be a very valuable tool in landslide risk management. It has been applied to assess the cost of managing risk and the direct and indirect benefits, optimise the allocation of available resources, identify areas of concern for improvement, and measure and evaluate the effectiveness of the Slope Safety System. QRA can also be an effective vehicle for objective communication of risk amongst engineers, regulatory agencies, resources allocators and the public.

The factors that can affect the usefulness of QRA include scarcity of relevant or good quality data, low resolution of data for the purpose of assessment, lack of suitable verification data, insufficient knowledge about hazard and consequence modelling, influence of human factors, project constraints, etc. As outlined in Section 4, many of these factors are not specific to QRA itself but are identical to those that can affect the usefulness of any geotechnical engineering evaluation technique. Notwithstanding the above, QRA can provide valuable insights and perspectives beyond those that can be normally obtained from conventional deterministic methods. It helps to break down the problems into manageable sub-components to facilitate a better understanding of the critical elements. It provides a framework for evaluating uncertainties and exercising engineering judgement systematically. It also helps to identify effective solutions or to justify any acquisition of additional data prior to decision-making. Some areas of improvement to enhance the reliability of QRA identified in the pilot studies are summarised in Section 5.

The Slope Safety Technical Review Board (SSTRB) were presented with the outcome of this review in the November 1999 meeting. They opined that the apparent lack of acceptance of the QRA technique and recognition of its usefulness could partly be due to the fact that the users expect too much from the numerical values obtained (SSTRB, 1999). It is noteworthy that no matter how objectively a QRA has been carried out, some elements of subjectivity and/or uncertainty are unavoidable. Risk estimation is not a precise exercise but it should in principle represent a best estimate having regard to the uncertainties involved, if the appropriate expert input is provided. The accuracy of calculated values of risk should be viewed in the appropriate perspective and not taken out of context. The main benefit of estimating risk using QRA methodologies lies in the achievement of a detailed understanding of the processes involved and the implications of various risk mitigation options. QRA will not remove the need for the necessary investigation, engineering analyses and judgement. In many cases, the thought process, as opposed to the detailed calculations, contributes a more rational basis for making professional judgement. QRA could be a valuable enhancement to the present approaches when used properly, which require inter alia the following (Royal Society, 1992; SSTRB, 1999; Stewart, 2000):

(a) the problem be properly framed in terms of hazard modelling and consequence modelling,
(b) the nature and limitations of the risk assessment be understood,

(c) the results of the risk assessment be expressed in the form of value judgement as well as numbers, and

(d) the results of the risk assessment be used to facilitate, rather than to dictate, decisions and be only one of the factors to be taken into account in reaching a decision for the particular problem.

Since the completion of this review, a number of other QRA studies have been completed, e.g. Cheung & Shiu (2000), Sun & Evans (2001), FMSWJV (2001) and Maunsell Geotechnical Services Ltd (2001). Readers' attention is also drawn to the Issues Paper on this subject by Ho et al (2000) presented at the GeoEng2000 Conference held in Melbourne and the General Report by Kreuzer (2000) presented at the Twentieth International Congress on Large Dams in Beijing. Interested parties should refer to the relevant documentation on these for a more complete picture of the state of QRA development as applied to landslide risk assessment.

7. REFERENCES


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<td>• Pilot Studies</td>
</tr>
<tr>
<td>• Further Developmental Studies</td>
</tr>
<tr>
<td>• Development of Performance Measurement Indicators (CE’s Target-based Management Policy)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Risk Tolerability and Communication</th>
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<tbody>
<tr>
<td>• Risk Guidelines for:</td>
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<tr>
<td>• Public Opinion Surveys</td>
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<table>
<thead>
<tr>
<th>Application</th>
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<tbody>
<tr>
<td>• Landslide Risk Management</td>
</tr>
<tr>
<td>• Measurement of Effectiveness of the Slope Safety System</td>
</tr>
<tr>
<td>• Setting of Standards</td>
</tr>
</tbody>
</table>
## Table 2 - Types of QRA Applications Reviewed

<table>
<thead>
<tr>
<th>Application</th>
<th>Global Assessment</th>
<th>Area/Site-specific Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feasibility study</td>
<td>• Natural terrain landslides</td>
<td></td>
</tr>
<tr>
<td>Relative risk of landslide hazards</td>
<td>• Pre-GCO man-made slopes</td>
<td>• Boulder falls</td>
</tr>
<tr>
<td></td>
<td>• Natural terrain landslides</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Deep excavations</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Earthquake-induced landslides at engineered slopes</td>
<td></td>
</tr>
<tr>
<td>Land-use planning</td>
<td></td>
<td>• Area study (Tung Chung East &amp; Mount Johnston North)</td>
</tr>
<tr>
<td>Ranking of projects/facilities</td>
<td>• Consequence classification of mass transportation facilities</td>
<td>• BRIL roads</td>
</tr>
<tr>
<td>Evaluation of mitigation options</td>
<td></td>
<td>• Lei Yue Mun squatter villages</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Fanling Area 49A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Tuen Mun Road</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Castle Peak Road</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Slope below Aberdeen Catchwater</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Lok Sang Tong, Lantau</td>
</tr>
</tbody>
</table>
Table 3 - Comparison between Global and Site-specific QRAs

<table>
<thead>
<tr>
<th></th>
<th>Global Assessment</th>
<th>Site-specific Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objectives</strong></td>
<td>• quantification of relative risk</td>
<td>• supplement and calibrate judgement</td>
</tr>
<tr>
<td></td>
<td>• global prioritisation - resources allocation</td>
<td>• assessment of risk acceptability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• aid decision-making</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>• generally involves large number of slope features and data (e.g. failure</td>
<td>• involves smaller area and data are generally limited</td>
</tr>
<tr>
<td></td>
<td>frequency) are more abundant</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• less demanding on data resolution</td>
<td>• data resolution varies with project needs but generally requires higher</td>
</tr>
<tr>
<td></td>
<td></td>
<td>data resolution</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td>• order of magnitude estimates of risk for resources allocation</td>
<td>• risk estimates need to be fairly precise for meaningful evaluation of</td>
</tr>
<tr>
<td></td>
<td></td>
<td>acceptability and selection of appropriate mitigation measures</td>
</tr>
<tr>
<td><strong>Quality</strong></td>
<td>• failure frequency largely based on historical records</td>
<td>• historical failure data are generally scarce, considerable judgmental</td>
</tr>
<tr>
<td></td>
<td></td>
<td>input has been made</td>
</tr>
<tr>
<td></td>
<td>• risk results in broad agreement with historical fatality records</td>
<td>• numerical techniques such as Monte Carlo simulation have not been used</td>
</tr>
<tr>
<td></td>
<td>• generally reasonable results for man-made slopes, further understanding of</td>
<td>• site-specific historical fatality records are generally absent or lacking</td>
</tr>
<tr>
<td></td>
<td>natural terrain landsliding processes is needed</td>
<td>for comparison</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• generally large uncertainty in risk results, further development is needed</td>
</tr>
</tbody>
</table>
Table 4 - Potential Areas of Application of QRA

<table>
<thead>
<tr>
<th>Types of Application</th>
<th>Existing Approach</th>
<th>Potential Areas of Application of QRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Man-made Slopes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global Assessment</td>
<td>Nil</td>
<td>✓</td>
</tr>
<tr>
<td>Site-specific Assessment</td>
<td>• Conventional limit equilibrium slope stability analysis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Minimum factors of safety (FOS) dependent on the consequence category of the slope</td>
<td></td>
</tr>
<tr>
<td>Natural Terrain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global Assessment</td>
<td>Nil</td>
<td>✓</td>
</tr>
<tr>
<td>Site-specific Assessment</td>
<td>• Do not need to meet standards for man-made slopes if:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o the slope is undisturbed, and</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o no evidence of instability or severe erosion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Hazard assessment</td>
<td></td>
</tr>
</tbody>
</table>

Notes: (1) Global assessments are to assess relative risk of different hazards and hazard components and the size of the problem. (2) Site-specific assessments are to determine suitability of site for development, design and layout constraints, and cost-effectiveness of mitigation measures, and to highlight uncertainties in the assessment to help decide on how best to manage the risk.
## LIST OF FIGURES

<table>
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<th>Description</th>
<th>Page No.</th>
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<tbody>
<tr>
<td>1</td>
<td>Steps in Risk Management Decision-making (Stewart, 2000)</td>
<td>27</td>
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</tbody>
</table>
Initiation
- Define problem or opportunity and associated risk issue(s).
- Identify risk management team.
- Assign responsibility, authority, and resources.
- Identify potential stakeholders and begin to develop consultation process.

Preliminary Analysis
- Define scope of the decision(s).
- Identify hazards using risk scenarios.
- Begin Stakeholder Analysis.
- Start the risk information library.

Risk Estimation
- Define methodology for estimating frequency and consequences.
- Estimate frequency of risk scenarios.
- Estimate consequences of risk scenarios.
- Refine Stakeholder Analysis through dialogue.

Risk Evaluation
- Estimate and integrate benefits and costs.
- Assess stakeholder acceptance of risk.

Risk Control
- Identify feasible risk control options.
- Evaluate risk control options in terms of effectiveness, cost, and risks.
- Assess stakeholder acceptance of proposed action(s).
- Evaluate options for dealing with residual risk.
- Assess stakeholder acceptance of residual risk.

Action/Monitoring
- Develop an implementation plan.
- Implement chosen control, financing, and communication strategies.
- Evaluate effectiveness of risk management decision process.
- Establish a monitoring process, terminate as applicable.

Note: Risk communication with stakeholders is an important part of each step in the decision process.

Figure 1 - Steps in Risk Management Decision-making (Stewart, 2000)
APPENDIX A

GLOSSARY OF QRA TERMINOLOGY
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Acceptable Risk</td>
<td>A risk for which, for the purposes of life or work, society is prepared to accept as it is with no regard to its management. Society does not generally consider expenditure in further reducing such risk justifiable</td>
</tr>
<tr>
<td>ALARP (as low as reasonably practicable)</td>
<td>The risk is regarded as tolerable only if risk reduction is impracticable or if the cost is grossly disproportionate to the improvement gained</td>
</tr>
<tr>
<td>Harm</td>
<td>Physical injury or damage to health, property or the environment</td>
</tr>
<tr>
<td>Hazard</td>
<td>A condition with the potential for causing an undesirable consequence</td>
</tr>
<tr>
<td>Hazard Identification</td>
<td>The recognition that a hazard exists and the definition of its characteristics</td>
</tr>
<tr>
<td>Individual Risk</td>
<td>The risk or fatality and/or injury to any identifiable (named) individual who lives within the zone exposed to landslide, or who follows a particular pattern of life that might subject him or her to consequences of the landslide</td>
</tr>
<tr>
<td>Risk</td>
<td>A measure of the probability and severity of an adverse effect to health, property or the environment. (The concept of risk always has two elements: the frequency or probability with which a hazardous event occurs and the consequences of the hazardous event)</td>
</tr>
<tr>
<td>Risk Analysis</td>
<td>The use of available information to estimate the risk to individuals or populations, property, or the environment, from hazards. Risk analysis generally contains the following steps: scope definition, hazard identification, and risk estimation</td>
</tr>
<tr>
<td>Risk Control</td>
<td>The process of decision-making for managing risk, and the implementation, enforcement, and re-evaluation of its effectiveness from time to time, using the results of risk assessments as one input</td>
</tr>
<tr>
<td>Risk Assessment</td>
<td>The process of risk analysis and risk evaluation</td>
</tr>
<tr>
<td>Risk Estimation</td>
<td>The process used to produce a measure of the level of health, property, or environmental risks being analysed. Risk estimation contains the following steps: frequency analysis, consequence analysis, and their integration.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
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<td>--------------------------</td>
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</tr>
<tr>
<td>Risk Evaluation</td>
<td>The stage at which values and judgements enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks</td>
</tr>
<tr>
<td>Risk Management</td>
<td>The complete process of risk assessment and risk control</td>
</tr>
<tr>
<td>Societal Risk</td>
<td>The risk of multiple injuries or deaths to society as a whole: one where society would have to carry the burden of a landslide accident causing a number of deaths, injuries, financial, environmental, and other losses</td>
</tr>
<tr>
<td>Tolerable Risk</td>
<td>A risk that society is willing to live with so as to secure certain net benefits in the confidence that it is being properly controlled, kept under review and further reduced as and when possible</td>
</tr>
</tbody>
</table>
APPENDIX B

LIST OF RELEVANT STUDY REPORTS
Data Collection


Scott Wilson (Hong Kong) Ltd (1999). *Specialist API Services for the Natural Terrain Landslide Study for Agreement No. CE 39/98 (Interpretative Report, Factual Report and 8 other Technical Reports and Data Table Reports)* Report prepared for the Geotechnical Engineering Office, Hong Kong.


Development of Methodology


**Risk Tolerability and Communication**


**Application**


APPENDIX C

LIST OF RELEVANT TECHNICAL PAPERS ON GEO'S QRA WORK


APPENDIX D

SUMMARY SHEETS ON INDIVIDUAL QRA PROJECTS
Scoping Study for a Global Quantitative Risk Assessment of Natural Terrain Landslide in Hong Kong

Objective: To determine the feasibility of evaluating the risk from natural and quasi-natural landslides in Hong Kong using QRA techniques.

Background: Landslide risk reduction by the GEO has focused on man-made slopes, failures of which have caused many fatalities in the past. By contrast, landslides from natural terrain, while recognised as a potential hazard, have not resulted in any documented casualties. However, a number of natural terrain landslides have come close to developed areas in recent years and have highlighted the possible risks from these events. It is possible that risks of this nature are increasing as development encroaches on natural terrain. If QRA techniques could be used to evaluate the global risk from natural terrain landslides and compare it with that from failures of man-made slopes, it might be possible to allocate risk-reduction resources in the most cost-effective way.

Approach:
- reviewed QRA and natural terrain studies carried out in Hong Kong and internationally
- identified and classified the range of natural terrain landslide hazards in Hong Kong and the consequence scenarios necessary for a global QRA
- established a global QRA approach
- assessed the feasibility of applying a global QRA approach given currently available information

Input Data: Information on the QRA techniques and natural terrain hazards was derived from literature and the Natural Terrain Landslide Inventory (NTLI)

Results:
- The study team concluded that a global QRA for all possible types of natural and quasi-natural terrain landslides in Hong Kong is not feasible at present. However, the study team considered that a global QRA of the group of landslides comprising typical shallow debris slides and flows is feasible using existing data.
- The study team recommended that a pilot area or areas be investigated using a technique referred to as the Landslide Intensity Mapping Approach. Risk evaluations from the pilot area(s) could then be extrapolated using either a generalised consequence model or by classification of development and slope types along the development line defined in the NTLI.

Duration: Study commenced in February 1998 and completed in February 1999.

Commentary:
- Many of the conclusions and recommendations of this study are being acted on as part of the GEO's continuing studies of natural terrain hazard and risk.
- Site-specific studies are being carried out at two trial sites (Mount Johnston North and Tung Chung East).
- Further information on large-scale natural terrain failures was analysed within the Planning Division.
- A global QRA of typical shallow debris slides and flows has commenced.

**Usefulness:** The study has assisted in deciding the direction in which future natural terrain hazard and risk studies should proceed.

Quantitative Landslip Risk Assessment of Pre-GCO Man-made Slopes and Retaining Walls

Objective: To develop a rational framework for studying the global risk of failures of old man-made slope features and the relative risk proportions for different components of the population of pre-GCO slopes.

Background: An objective means of quantifying the landslide risk of old man-made slopes was needed for prioritisation of LPM actions.

Approach: • classified the landslide hazards according to types of slope features, and mechanisms and scale of failure
• assessed the landslide frequency of each hazard based on an interpretation of the historical landslide records
• developed a generalised landslide consequence model which involved the consideration of the consequence of a reference landslide of a standard size (taken to be a 10 m-wide failure of 50 m$^3$ in volume) directly affecting a given type of facility located at the worst possible spot (i.e. right at the toe of a slope or near the edge of the slope crest), assuming the occupation of the facility under average condition. This model accounted for the nature and proximity of the affected facilities, the mobility and the likely upslope extent of the influence zone of the landslide, the scale of failure and the degree of protection offered to persons by the facility in the consequence analysis
• expressed the consequence of each type of landslide hazard in terms of potential loss of life, which was a function of the expected number of fatalities for facilities directly affected by the landslide, the actual scale of failure and vulnerability factor

Input Data: • information on the failure frequencies of different types of slope features was obtained from the GEO landslide database (1984 - 1996)
• information on slope geometry, and types and proximity of the facilities affected by the slope feature was obtained from the Old Slope Catalogue and limited slope data in the New Slope Catalogue available at the time of the study (for estimating the size of the problem)

Results: The risk is unevenly distributed amongst the different types of features. Globally, the risk from cut slopes, fill slopes and retaining walls is in the ratio of 6:1:1. In terms of the average annual risk per feature, the corresponding ratios are approximately 3:1:1. About half of the global risk is derived from about 10% of the slope population.

Duration: Study commenced in 1995 and completed in 1996

Commentary: • One advantage of the model developed is that it can allow the consequence to be 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 consequence model may also be applied to site-specific QRA.
- The study was based on extrapolation of limited data on slopes. A re-assessment of the risk is necessary with the information available in the New Slope Catalogue.
- The determination of the vulnerability factors and grouping of some facilities was judgmental.

Usefulness:
- The results have indicated that about half of the global risk is derived from about 10% of the slope population. This suggests that the upgrading of a relatively small proportion of the old man-made features that pose the highest potential risk could result in major risk reduction.
- It forms the basis for the computation of CNPCS scores for the combined ranking of slopes.

Reference:
The Average Annual Global Risk from Natural Terrain Landslides in Hong Kong in 1994

Objective: To assess the approximate average annual potential loss of life (PLL) for natural terrain landslides in Hong Kong.

Background: As development in Hong Kong is getting closer to steep natural terrain, there has been increasing concern in recent years as to the possible risk from natural terrain landslides. This study is part of the work for evaluating the use of QRA techniques for natural terrain landslide risk assessment.

Approach: • used available data of 'recent' landslides in the NTLI that crossed the 1994 development line
• assessed the facilities affected by these landslides
• adapted the landslide consequence model developed by Wong et al (1997)
• expressed the consequence of each type of landslide hazard in terms of potential loss of life, which is a function of the expected number of fatalities for facilities directly affected by the landslide, the scale of failure and vulnerability factor

Input Data: • the number of landslides that crossed the development line of 1994 from the Natural Terrain Landslide Inventory and facilities affected
• landslide size (width and volume) distributions from previous field studies of natural terrain landslides

Results: • On average, approximately 12 natural terrain landslides would be expected to affect the developed areas every year (given the 1994 development situation).
• These landslides generated a best-estimated potential loss of life (PLL) of between 0.07 and 0.18, which equated to one fatality in every 5 to 14 years.

Duration: Study commenced in July 1999 and completed in October 1999.

Commentary: • This study did not consider hazards arising from rock or boulder falls, severe erosion, quasi-natural terrain landslides or high-magnitude low frequency deep-seated natural terrain landslides (no available record at the time of study).
• The landslide activity derived from the NTLI database was assumed to be representative of average annual landslide activity with respect to the 1994 development line.
• Sensitivity of the calculated risk with respect to the landslide size distribution was examined.

Usefulness: The results have indicated that the global risk to life of typical shallow natural terrain landslides is about an order of magnitude less than that
due to man-made slopes in recent years. This study helps to put in context the relative proportion of risk due to different types of landslide hazards.

QRA of Collapses and Excessive Displacements of Deep Excavations

Objective: To carry out a QRA study of collapses and excessive displacements of deep excavations associated with private building developments.

Background: The 31 incidents of collapses or excessive displacements of deep excavations between 1980 and 1992 gave rise to a concern about the potential risk of failure of deep excavations in Hong Kong. It was considered necessary to assess the risk rationally and to identify critical events and activities that lead to collapses and excessive displacements so that the overall effectiveness of the geotechnical control system can be reviewed and improved if necessary.

Approach: • reviewed the records and documents of collapses and excessive displacements of deep excavations
• carried out a hazard identification exercise and identified the principal causes and events leading to failures of deep excavations
• carried out frequency analysis for different types of supporting systems
• carried out consequence analysis using the event tree methodology to estimate the fatalities due to collapses and excessive displacements of deep excavations taking due account of site conditions, supporting systems and the types of facilities affected
• estimated the average annual risk of private deep excavations and presented the results in terms of potential loss of life (PLL) and F-N curves
• conducted sensitivity analysis for different input parameters

Input Data: • number and frequency of failure and excessive displacements of deep excavations with different supporting systems from past records of collapses and excessive deformations of deep excavations associated with private building developments
• expert judgement in the casualty figures for each scenario in the consequence assessment

Results: • The PLL of the annual average number of 100 private deep excavation sites was estimated to be between 0.015 and 0.03 per year. This level of risk was comparable to the annual risk posed by similar number of pre-GCO cut slopes of less than 20 m high with buildings at their crest. The overall annual risk of collapses of private deep excavations is much lower than that of pre-GCO man-slopes in HK as the number of pre-GCO man-made slopes is considerably larger.
• For the four common types of supporting systems, sheet pile walls contributed most to the total risk of private deep excavations in Hong Kong.
Study commenced in August 1998 and completed in October 1999.

- In the consequence assessment, considerable judgmental input was required in assigning the branch probabilities and casualty figures in each event tree as no private deep excavation failures involving fatality were recorded in the past 20 years.
- Broad assumptions were made in terms of the depth of excavation and the types of facilities affected.

The results of this QRA study give a rough indication of the risk level of deep excavations associated with private building developments in Hong Kong in comparison with that of pre-GCO man-made slopes.
- It helps to highlight the relative risk associated with different types of supporting systems and the relative importance of different factors contributing to failures.
- The maximum justifiable additional expenditure to reduce risk was estimated to be of the order of about HK$ 0.5M per annum assuming the annual average number of private deep excavation sites was 100. This may suggest that significant increase over the present resources spent on checking may not be warranted from a cost-benefit standpoint.

Preliminary Quantitative Risk Assessment of Earthquake-induced Landslides at Man-made Slopes in Hong Kong

Objectives: To explore the feasibility of using the QRA methodology to assist in the evaluation of the risk of earthquake-induced landslides at engineered slopes.

Background: The problem is to evaluate the risk of earthquake-induced landslides at engineered slopes as compared with the risk of rain-induced landslides at pre-1978 man-made slopes.

Decision Required from the QRA: Whether the current geotechnical standards are adequate in maintaining the overall risk of earthquake-induced landslides on engineered slopes at a relatively low level.

Approach: Standard QRA technique considering the seismicity of Hong Kong, critical acceleration and dynamic response characteristics of slopes, seismic-induced slope displacement, likelihood of different degrees of soil saturation at the time of earthquake and consequence of failure.

Input Data:
- hazard model (4 modes of instabilities considered)
- results of seismic hazard assessment (i.e. correlation between return period and peak bedrock ground acceleration)
- correlation between critical acceleration and factors of safety for typical cut and fill slopes
- correlation between seismic slope displacement and critical acceleration ratio
- likelihood of different degree of saturation based on rainfall analysis and simplified wetting band analysis
- unsaturated shear strength for different degree of saturation
- probability of fatality level for different failure modes

Results: The risk of earthquake-induced landslides at slopes designed or upgraded to current geotechnical standards is much smaller (about 0.1% to 3% depending on the minimum factor of safety adopted and slope type) than the risk of rain-induced landslides at pre-1978 man-made slopes that have not been upgraded to current standards.


Commentary:
- Although some of the data and correlations were not very precise and some simplifying assumptions had been made in the analysis, the assessment was considered to be sufficiently representative for the range of man-made slopes that prevail in Hong Kong.
- The successful application of QRA techniques to evaluate the risk of earthquake-induced landslides illustrates the usefulness
of this tool in such applications which provide more insight to the problem than the conventional seismic hazard assessment methodology.

- No sensitivity analysis was carried out to identify both the data and model uncertainties and to determine the variation of the results arising from the collective variations in the parameters involved in the analyses.

**Usefulness:** Without the QRA framework, one would not be able to demonstrate quantitatively that the risk of earthquake-induced landslides at engineered slopes is much smaller than the risk posed by rain-induced landslides at pre-1978 man-made slopes.

QRA of Boulder Fall Hazards in Hong Kong, Phase 2 Study

Objective: Conduct detailed pilot QRAs studies on selected representative areas exposed to boulder fall risk, and by appropriate factoring and weighting of the results, estimate the risk of boulder fall for the whole territory. Compare the boulder fall risk with risks posed by other hazards.

Background: As part of the landslide risk management system, the risk posed by boulder fall from natural terrain together with the size of the problem need to be assessed.

Approach:
- reviewed the boulder fall incidents reports and relevant information in GEO to identify major causes of boulder falls and the resultant damage
- carried out a literature survey on available overseas data on boulder falls, including studies on risk assessment and hazard analysis of boulder falls
- carried out a hazard identification exercise to determine the causes of boulder falls and the potential consequences
- selected 5 representative areas and map the boulders by API technique; 4 parameters were mapped, viz. % area covered by boulders, and type, size, & shape of boulders
- estimated frequency of boulder fall by correlating specific parameters (boulder density and slope gradient) with historical frequencies
- carried out event tree analysis to evaluate consequence of various damage scenarios
- determined societal risks, potential loss of life and individual risk
- calibrated the risk levels against historical incident records in Hong Kong, and compare with risk from natural and man-made slope hazards in Hong Kong

Input Data:
- boulder type, boulder shape, boulder density, & boulder size mapped by API technique
- slope gradient measured from 1:5000 topographical maps
- erosion from Terrain Classification Maps
- historical boulder fall data from the GEO landslide database and records
- frequency estimated by correlating historical frequency with boulder density and slope gradient
- velocity estimated using the computer simulation

Results:
- A QRA methodology is developed for the assessment of risk from boulder fall hazards.
- The derived boulder fall risk in terms of F-N curve is below the risk due to extreme weather conditions (e.g. typhoons), landslides at man-made slope features, and other natural
meteorological events (tornadoes and hurricanes in USA).

- The risk due to failure of man-made slopes is at least two orders of magnitude higher than the risk from boulder fall hazard.
- Pedestrian and squatter hut dwellers are the two largest contributors to PLL.
- The average individual risk from boulder falls is in the order of $10^{-5}$.

**Duration:**

The study commenced in December 1995 and completed in November 1996.

**Commentary:**

- Only an indication of the risks from boulder fall is obtained as the developed methodology and the input parameters are relatively crude.
- The frequency correlation using two parameters (boulder density & gradient) is crude; further refinement to identify the critical parameters that initiate or affect boulder fall is required, or alternatively, boulder fall frequency could be synthesised based on these critical parameters.
- Mapping of boulder fields by API technique is feasible. It is financially viable to carry out mapping at a scale of 1 in 20000. Mapping at a smaller scale (e.g. 1 in 5000) would be too costly.
- The consequence models can be refined by taking due account of slope gradient, vegetation, boulder size and density.
- Since pedestrian and squatter dwellers contribute significantly to the derived PLL, more accurate estimates of these two parameters will be required for subsequent studies.
- Sensitivity analyses are required to determine upper and lower bound risk values.

**Usefulness:**

- A feasible QRA methodology has been developed to assess boulder fall hazards.
- The study points out key parameters which should deserve more attention and areas of improvement in subsequent studies.

**Reference:**

Objective: To develop techniques for assessing the hazard and risk from natural terrain landslides. To evaluate methods of site reconnaissance and ground investigation for such assessments. To investigate the applicability of the Interim Risk Guidelines.

Background: Conventional site investigations and slope stability analyses as outlined in the various Geoguides are often not appropriate when assessing the probability and consequence of natural terrain failures. There is therefore a need to develop alternative techniques.

Approach: • used data derived from existing sources, API and walkover surveys compile area hazard models for the two areas (18 ha and 75 ha) and attempted to calculate risk on an area basis, quantifying uncertainties where necessary
• applied the area hazard models to a range of hypothetical developments affected by sub-areas of the natural terrain study areas
• carried out site investigation to attempt to reduce hazard model uncertainties
• formulated the site-specific hazard models using all available data and applied them to the hypothetical developments discussed above
• calculated risk where possible. Considered appropriate mitigation works and methods of optimising cost-benefit.

Input Data: existing information on topography, geology and natural terrain landslides. Additional data on existing landslides from API, site walk-over surveys and geological and geomorphological mapping. Landslide susceptibility estimates from regional NTIL data. Subsurface data from trial pits, boreholes, probes and geophysics.

Results: • Hazard models were conveniently separated for open hillside landslides, rock and boulder falls, channelised debris flows and deep-seated landslides. Hazard models for deep-seated natural terrain landslides are at present extremely crude and also available data cannot support QRA. Similar problems are present to a lesser degree with channelised debris flows and rock and boulder falls.
• Hazard and risk from the commonest type of natural terrain landslide (open hillside landslides) is restricted to within a short distance of the toe of steep natural terrain.
• The biggest uncertainty in natural terrain hazard models is the prediction of future event frequency. Confidence in estimates of future frequency was only high enough to permit QRA for open hillside landslides. Frequency estimates were not much improved by more detailed site investigation at the site-specific
• For channelised debris flows, an approach based on assessment of a ‘maximum credible event’ appears promising.
• The use of F-N curves for societal natural terrain risk assessment is difficult to support at present. The high frequency/low magnitude events which can be quantified do not cause high numbers of fatalities. Possible high magnitude/high N events cannot be quantified based on current state of knowledge. The study has recommended alternative societal PLL criteria.

Duration: Study commenced in September 1998 and completed in October 1999.

Usefulness: This study is the first attempt to critically assess the applicability of the interim risk guidelines. More QRA studies comprising a range of planning developments for different types of natural terrain using different QRA techniques would be needed to permit a well-balance assessment of the Interim Risk Guidelines.

Consequence Classification System of Mass Transportation Facilities

Objective: To formulate a methodology for the classification of mass transportation facilities in terms of the likely severity of consequence in the event of a landslide, based on quantitative risk assessment methodology and to review the current consequence category grouping of mass transportation facilities.

Background: In view of the landslide incidents in July 1997 that affected railway operation, the gradual modernisation of the passenger train system over the years and the potential escalation of failure consequence involving a high-speed train, there is a need to formulate a rational risk-based landslide consequence classification system for mass transportation facilities.

Approach: • identified the probable causes of train derailment
• identified probable scenarios in the event of a landslide adjacent to the railway track and estimated the corresponding casualties
• used the event tree methodology to estimate the consequence given the occurrence of a reference landslide (taken to be a 10 m-wide failure of 50 m$^3$ in volume)

Input Data: • input from local rail operators on operational matters
• landslide incidents affecting railway operation
• casualty figures from notable train derailment incidents

Results: Given the occurrence of a 50 m$^3$ landslide, the probable fatality figures vary from 0.5 to 1.8 for KCR and 0.4 to 0.9 for MTR. These results suggest that the current consequence category grouping for railways is adequate for both the KCR East Rail and MTR lines.


Commentary: • The derivation of many of the conditional probabilities, associated with the branch nodes of the event trees, is judgmental.
• This study focused on considerations of the consequence to life due to landslides. In terms of economic consequence and social disruption, the effects of landslides on mass transportation facilities are likely to be severe as a result of delay or suspension of services.

Usefulness: • This study illustrates the use of the event tree methodology to systematically assess the landslide consequence to operating rails.
• Notwithstanding the concerns over the derivation of the conditional probabilities, the availability of a transparent framework suitably broken down into small component parts.
facilitates the exercising of judgement and helps to ensure internal consistency of the judgement made for the different scenarios.

Although the probability and casualty figures could be subjective, the study yielded indicative probable fatality figures for the verification of the consequence category grouping of mass transportation facilities.

Objective: To formulate a methodology for ranking of selected busy roads with a history of landslides (BRIL Roads) based on a quantitative risk assessment of landslides with due regard given to the risk to life and economic losses.

Background: Traditionally, the selection of roads for improvement/reconstruction schemes is based on traffic needs. For roads with a history of landslides (BRIL roads), a risk based methodology may provide a basis for determining the priority of upgrading certain routes in road improvement/reconstruction schemes by adding the consideration of landslide risk to that of traffic needs.

Approach:

- collected information regarding the number of slopes and their geometry along each BRIL road section from the 1977/78 Slope Catalogue
- compiled a landslide frequency and debris volume relationship of slope failures along each BRIL road section from historical data, and suitably adjusted with territory-wide data when no road-specific data were available
- the consequence assessment was based on suitable adaptation of the approach developed by Wong et al (1997) for the global assessment of landslide risk of pre-GCO features
- the model for the assessment of economic loss due to road closure caused by landslides was adapted from that developed by an economist advisor in Government (Financial Services Bureau). The assessment involved the estimation of the increase in travelling time due to varying degree of road closure, the usage of each road section, the cost of travelling time and operating cost of vehicles
- ranked the road sections according to the landslide risk, economic loss due to road closure as well as potential fatalities, assuming the value of a statistical life saved was HK$24 million

Input Data:

- slope geometry data from the 1977/78 Slope Catalogue
- previous landslide incidents from the GEO landslide database
- cost data on travel time and vehicle operation, and traffic density along each road section from Traffic Census and traffic study reports

Results: 41 BRIL road sections are ranked based on potential loss of life per year and economic loss (due to traffic disruption caused by landslides). These road sections are also ranked in terms of the total economic loss considering both the cost of statistical life saved and economic loss due to road closure.

Duration: Study commenced in April 1997 and completed in November 1997.
Commentary: The estimated economic loss due to landslides was based on the premise that it resulted in an increase in travelling time for the public with a corresponding value for time costs. The economic loss in relation to social disruption and dread has not been directly accounted for.

Usefulness: This methodology provides a rational framework to assess the landslide risk on roads for possible elevation of the priority of selected roads for improvement based on geotechnical consideration in addition to traffic needs.

Quantitative Landslide Risk Assessment for the Squatter Villages in Lei Yue Mun

Objective: Carry out a QRA of the landslide risk to squatters within, and in the vicinity of the clearance zone recommended by the GEO and to delineate the area where the risk is unacceptable and to identify the optimal risk mitigation option.

Background: The Lei Yue Mun squatter villages are located adjacent to some abandoned quarry slopes which have a long history of instability. In August 1995 a number of significant landslides occurred after a major rainstorm causing severe damage to properties within the squatter villages. Loss of life was narrowly avoided during the rainstorm. Based on visual inspection and judgement, some squatters have been recommended for re-housing.

Decision required from the QRA: To identify if further squatter clearance was warranted.

Approach:
- collected information on previous landslide activities (e.g. scale and frequency) from desk study, aerial photograph interpretation and site reconnaissance
- divided the slope toe into 20-m long segments and apportioned the landslide frequency to each segment according to a slope instability rating which took due account of previous instability, slope angle and presence of colluvium
- the mobility of the debris was modelled using angles of reach compiled from data on man-made slopes
- the consequence model took due account of the scale of failure, debris mobility, proximity and number of the dwelling, temporal presence of residents, etc. It involved grouping the dwellings into a 20-m by 20-m block and calculating the landslide risk to the residents within each block using event tree methodology
- compared the computed risk with risk criteria suitably adapted from the CCPHI criteria to delineate zones for clearance

Input Data:
- landslide frequency and volume data from desk study, API and site reconnaissance
- distribution of dwellings and population within the study area derived from data from Housing Authority and population survey of selected squatters to determine the number of residents and their temporal movement
- potential casualty figures for each block

Results:
- Proposed the acceptable individual risk level to be $10^{-4}$ for Lei Yue Mun squatters.
- The results of the study indicated that there were a number of squatters living within areas of unacceptable individual risk ($>10^{-4}$) and the extent of this area was in general agreement
with the clearance zone recommended for re-housing by the GEO using guidelines based on engineering judgement.

- The prevailing societal risk was unacceptable; however, with the completion of re-housing, the societal risk would drop to within the ALARP and acceptable region.
- The cost-benefit calculations indicated that the landslide risk within the ALARP zone did not justify re-housing although it is Government's policy to offer re-housing to the residents in the squatter village as soon as alternative housing can be made available.

Duration: Urgent study commenced in September 1995 and took three and a half weeks to complete.

Commentary: This was one of the earliest geotechnical applications of QRA. Although there was significant judgmental input in the exercise, the QRA results appear to be reasonable and the assessment was fairly comprehensive.

Usefulness: This was a case history in which the QRA methodology has been used to supplement and calibrate engineering judgement in the delineation of the extent of squatter clearance.
- The process of carrying out the QRA has highlighted the factors that contribute to the landslide risks to the individual squatters.
- The QRA framework provides a rational and transparent basis for decision to be made on risk mitigation.

Geotechnical Assessment - Fanling Area 49A Phases 1 & 3 - Natural Slopes

**Objective:** Carry out a quantitative risk assessment of the natural terrain landslide hazards affecting a proposed housing development to evaluate the current landslide risk level and identify cost-effective mitigation measures.

**Background:** A housing development was proposed to be located at the foot of a natural terrain with landslide activities. The natural terrain has a plan catchment area of 10.7 ha and a toe length of about 400 m, and an average gradient of 25° to 35°. As mitigation works to the natural terrain were perceived to be prohibitively expensive, a QRA was carried out to determine the acceptability of the risk posed by the prevailing natural terrain landslide hazards and to identify cost-effective mitigation measures to reduce the landslide risk.

**Decision Required from the QRA:** Evaluate the acceptability of the prevailing landslide risk levels and put forward appropriate cost-effective mitigation measures.

**Approach:**
- estimated previous landslide activities from desk study, API and site reconnaissance
- classified the landslides according to types and sizes and assess the probability of occurrence with due assessment of the probability of the debris reaching the development
- divided the slope toe length abutting the development into a number of line segments and apportion the landslide frequency to these line segments according to a landslide hazard rating scheme, taking account of the slope gradient, topography and accumulation of colluvium
- used a vulnerability factor to account for protection, e.g. presence of buildings and barriers, offered to the individual
- used a lethality factor to account for proximity of the individual to the toe of slope
- determined the individual risk and societal risk

**Input Data:**
- the frequency, scale and age of different types of landslide
- the population distribution within the development
- judgement to assign the vulnerability factors and lethality factors and to apportion of the landslide frequency at the toe of slope

**Resources:**
- landslide frequency data from desk study, API and site reconnaissance (3 man-months and took 4 months to complete)
- 8 drillholes and 45 trial pits to obtain information for the development of the geological model and the hazard rating system (2 months to complete)
- population survey of adjacent housing development (2 man-months and took 1 month to complete)
Results: The QRA indicates that the prevailing individual risk is generally below $10^{-5}$ except at the periphery of the development. The societal risk is within the ALARP region. Proposed to build a reinforced concrete barrier at the toe of the slope to reduce the risk further. The barrier was designed against a debris volume of 1000 m$^3$ to 2225 m$^3$ and an impact velocity of 15 m/s which corresponds to a design event with an estimated return period of 300 years.


Commentary: Although the framework of the QRA appears to be reasonable and the assessment is fairly comprehensive, there was significant judgmental input to the assessment. The reliability of the QRA has not been examined. No sensitivity analysis was carried out to identify both the data and model uncertainties and to determine the variation of the results arising from the collective variations in the parameters involved in the analysis to facilitate effective interpretation of the risk values.

- The societal risk was estimated to be within the ALARP region and a barrier was recommended to be constructed at the toe of the slope to mitigate the landslide hazards. No cost-benefit analysis was carried out to determine whether the proposed mitigation measures were cost-effective, which was one of the original objectives of the study. It has, however, been estimated that the recurrent cost of maintenance of the works will only be a trivial sum (approximately $20 000 per month or ~ HK$5.5 per unit per month).

Usefulness: As the reliability of the QRA has not been established and that the application of the QRA technique to landslide problem is relatively new, little weight was placed on the numerical results of the assessment. However, the process of carrying out the QRA has helped to show that some kinds of mitigation measures are needed to reduce the landslide risk further.

- Although the landslide debris-resisting barrier has not been shown to be cost-effective, the QRA framework developed has indicated that such a mitigation measure could bring about a significant reduction in the landslide risk, through a reduction in vulnerability factor from 1.0 (without barrier) to 0.1 (with barrier).

Tuen Mun Road Widening at Tai Lam Section
Design and Construction Consultancy
Design Report: Risk-Based Slope Design

Objective: To carry out risk analysis to determine appropriate factors of safety for slope design such that the residual landslide risk will be within tolerable limits.

Background: The improvement of the Tuen Mun Road, Tai Lam Section, would involve slopes to be stabilised or formed. The Geotechnical Manual for Slopes recommends slopes to be designed to minimum factors of safety according to the consequence-to-life category. However, prevailing practice is such that these minimum factors of safety are adopted. Concerns arose regarding the residual risk resulting from such practice might be too high. It was proposed that instead of designing the slope to achieve the minimum factor of safety, the slope should be designed to achieve an acceptable risk level.

Decision Required from the QRA: To derive the factors of safety for slope design such that the residual landslide risk is within acceptable levels.

Approach:
- assuming a correlation between design factor of safety and probability of failure (probability of failure 0.1, 0.01, 0.001 was assumed for a design factor of safety 1.0, 1.2 and 1.4 respectively)
- derived the acceptable risk level for different types of landslide hazards from the potential loss of life corresponding to the interim risk criteria for natural terrain landslides and boulder falls
- apportioned this acceptable risk value to different mode and scale of failure
- assumed the expected loss of life for each mode and scale of failure
- determined the probability of failure for each mode and scale of failure corresponding to the apportioned acceptable risk level
- derived the required design factor of safety based on the correlation between design factor of safety and probability of failure

Input Data:
- probability of failure for different types and scale of failure
- the consequence (i.e. the expected loss of life) for each type and scale of failure

Results: Derived design factors of safety for different slopes. Values ranged from 1.4 to 2.0.

Duration: First submission was made in March 1998 and report was finalised in September 1998.
Commentary:  
• The risk-based slope design model was sound in principle. However, inadequate support had been provided to the key assumptions involved, e.g. the probability and consequence of failure for each mode and scale of failure, the correlation between the probability of failure and design factor of safety, the apportionment of the ‘acceptable’ risk level, etc.
• The ‘acceptable’ risk level for man-made slopes was derived from risk criteria for natural terrain of 500 m in length.

Reference:  
Castle Peak Road (CPR) Improvement between Area 2 and Ka Loon Tsuen, Tsuen Wan
Geotechnical Risk Assessment Report

Objective: To carry out risk assessment to identify and evaluate the potential geotechnical hazards and associated risk to commuters travelling along the CPR, to adjacent properties and to personnel involved in the construction works.

Background: The improvement of an 8-km section of CPR between Area 2 and Ka Loon Tsuen, Tsuen Wan involved the upgrading of the existing road alignment and the widening of the existing carriageway to dual 2-lane standard which would result in extensive slope works. A risk assessment was conducted to ensure that the temporary and permanent works could be safely implemented under the prevailing site constraints and conditions.

Decision Required from the QRA: To examine if the prevailing risk is acceptable. If not, recommend appropriate mitigation measures to reduce the potential geotechnical risks to tolerable levels.

Approach:

- four types of landslide hazards were considered: failures due to fill slopes, cut slopes, retaining walls and natural slopes
- frequency estimation based on desk study
- consequence assessment adapted from that proposed by Wong et al (1997)
- risk evaluated in terms of potential loss of life and F-N curve

Input Data:

- landslide frequency from historical data of landslides
- traffic/people/facilities temporal and spatial distribution data
- slope geometry data from desk study and walk-over survey

Results: The QRA study indicates that the calculated risks are larger than the broadly acceptable levels of risk (as defined in the interim risk guidelines for landslides and boulder falls from natural terrain) before improvement of CPR and during construction, and concluded that mitigation measures were necessary.

Duration: First submission was made in December 1997 and the report was finalised in August 1999.

Commentary:

- QRA is used only for the assessment of the risk of slope failure before and during the construction of CPR improvement. The reduction in risk by the proposed improvement works has not been quantified.
- The frequency estimation of different types of landslide hazards was very crude.
• No distinction was made between pre-GCO and post-GCO slopes in the landslide frequency assessment.

• Cost-benefit analyses of various mitigation measures should have been carried out to facilitate the selection of optimum measures for the CPR improvement works.

Quantitative Risk Assessment - Feature No. 11SW-C/F188
Aberdeen Catchwater

Objective: Carry out a quantitative risk assessment of the failure of a loose fill body.

Background: A 50-year old fill body did not meet the current geotechnical standard and upgrading options involving soil nailing, recompaction or removal were considered. However, these remedial options were not favoured because of site constraints (e.g. difficult access and removal of mature trees) and difficulties defining the limit of works since the underlying colluvium could possibly be as unstable as the fill body itself. It was suggested that defensive works against possible overflow of water from the catchwater above could perhaps be the best remedy.

Decision required from the QRA: To assess the prevailing landslide risk and that after the implementation of the defensive works to help decide if the upgrading works are necessary.

Approach:
- estimated the landslide frequency and failure volume from aerial photograph interpretation and site reconnaissance assuming the failure frequency of the fill body to be similar to that of the natural terrain in the vicinity
- the mobility of the debris was modelled using angles of reach compiled from data on man-made slopes, the debris trail was assumed to be along a natural drainage line downslope of the fill body
- the consequence model was adapted from that developed by Wong et al (1997)
- the effectiveness of the defensive works was assumed by judicious adjustment of the failure frequency
- the estimated individual risk was compared to the risk criteria established for natural terrain

Input Data:
- landslide frequency and failure volume data from API and site reconnaissance
- the casualty figures for different facilities were derived from the facility grouping in NPCS

Results:
- The results of the study indicated that the individual risk both before and after the implementation of the proposed defensive works due to failure of the fill body was in excess of $10^{-5}$ (the acceptable limit for natural terrain landslides).
- It was also concluded that the proposed defensive works alone would not be sufficient to reduce the landslide risk to an acceptable level. The implementation of the proposed upgrading works is necessary.
Duration: First submission was made in May 1998 and the report was finalised in June 1999.

Commentary:
- The annual failure frequency of the fill body was approximated by that of the adjacent natural terrain.
- The manner in which the effectiveness of defensive works was assumed by arbitrarily reducing the failure frequency is open to debate.
- The individual risk was judged to be unacceptable assuming that the risk criteria for man-made slopes are identical to those for natural terrain.
- No sensitivity analysis was carried out.

Usefulness: This study showed that QRA could be used as a supplementary tool in aiding of decision making.

Geotechnical Assessment for Natural Slope Adjoining
Tsing Yan Temporary Housing Area, Tsing Yi

Objective: Carry out a geotechnical assessment which comprises a quantitative risk assessment of the natural terrain landslide hazards affecting a proposed housing development to evaluate the current landslide risk level and slope stability analysis.

Background: A housing development was proposed to be located at the foot of a natural terrain with landslide activities. The natural terrain has a plan catchment areas of 1.35 ha and a toe length of about 130 m, and an average gradient of 15° to 25°. As mitigation works to the natural terrain were perceived to be prohibitively expensive, a QRA was carried out to determine the acceptability of the risk posed by the prevailing natural terrain landslide hazards and to identify cost-effective mitigation measures to reduce the landslide risk.

Decision Required from the QRA: Evaluate the acceptability of the prevailing landslide risk levels and put forward appropriate cost-effective mitigation measures.

Approach:
- estimated previous landslide activities from desk study, API and site reconnaissance
- classified the landslides according to types and sizes and assessed the probability of the debris reaching the development
- divided the slope toe length abutting the development into a number of line segments and apportioned the landslide frequency to those line segments according to a landslide hazard rating scheme, taking account of the slope gradient, topography and accumulation of colluvium
- used a vulnerability factor to account for protection, e.g. presence of buildings and barriers, offered to the individual
- used a fatality factor a account for proximity of the individual to the toe of slope
- determined the individual risk and societal risk

Input Data:
- the frequency, scale and age of different types of landslides
- the population distribution within the development
- judgement to assign the vulnerability factors and fatality factors and to apportion of the landslide frequency at the toe of slope

Resources:
- Landslide frequency data from desk study, API and site reconnaissance took 2 months to complete (approx. 3 man-months).
- 5 drillholes, 2 strippings and 6 trial pits were carried out to obtain information for the development of the geological model and the hazard rating system (took 1 month to complete).
- Population survey of adjacent housing development took 1 month to complete (approx. 2 man-months).
• Risk analysis took two weeks to complete (approx. 2 man-months).

Results: The QRA indicates that the prevailing individual risk is generally below \(10^{-5}\) except at the periphery of the development. The societal risk is within the ALARP region. It is proposed to build a reinforced concrete barrier at the toe of the slope to reduce the risk further. The barrier was designed against a debris volume of \(556 \text{ m}^3\) to \(1770 \text{ m}^3\) and an impact velocity of \(15 \text{ m/s}\).


Commentary: • The QRA is fairly comprehensive, there was significant judgement input to the assessment.
• The societal risk was estimated to be within the ALARP region and a barrier was recommended to be constructed at the toe of the slope to mitigate the boulder falls and landslide hazards.
• No sensitivity analysis was carry out.

Usefulness: • The process of carrying out the QRA has helped to show that some kinds of mitigation measures are needed to reduce the landslide risk further.
• The QRA framework developed has indicated that such a mitigation measure could bring about a significant reduction in the landslides risk, through a reduction in vulnerability factor from 1.0 (without barrier) to 0.1 (with barrier).

Preliminary Quantitative Risk Assessment for Soil Slope at Lok Sang Tong, Luk Wu, Lantau

Objective: Carry out a quantitative risk assessment of the failure of a cut slope adjacent to monastery.

Background: A 10-m high cut slope adjacent to a monastery failed and left it vacated since then. Different remedial options were put forward. A risk-based framework was considered to assist in selecting the most cost-effective mitigation measures.

Decision required from the QRA: To help decide which remedial option is most cost-effective.

Approach:
- estimated the landslide frequency and failure volume from aerial photograph interpretation and site reconnaissance
- the mobility of the debris was modelled using angles of reach compiled from data on man-made slopes
- divided the debris runout path into regions each with different vulnerability
- the estimated individual risk was compared to the risk criteria established for PHI

Input Data:
- landslide frequency and failure volume data from API and site reconnaissance
- the vulnerability figures and population estimate were derived from judgement

Results:
- The prevailing individual risk was in the ALARP region and risk should be further reduced.
- The cost data for some remedial options (e.g. flattening the slope, installation of soil nails, relocation of the building) were given. A rough comparison was made assuming that these options would bring about similar degree of risk reduction.

Duration: Submission was made in July 1996.

Commentary:
- The methodology was crude and critical assumptions e.g. the casualty figures and reasons for discounting the effect of very large landslide, have not been given.
- The analysis was not repeatable because calculations of the frequencies of failure of different types of landslides have not been provided.
- The computation of F-N curve did not account for the spatial distribution and temporal presence of the population.
- No proper calculations have been made to assess the adequacy of reduction in risk and cost-benefit of the different mitigation options. No recommendation was made regarding the option to be adopted.
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