Application of Quantified Risk Analysis in Landslide Risk Management Practice-Hong Kong Experience

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ABSTRACT: Landslide is a common form of natural hazard in Hong Kong that can cause significant loss-of-life and socio-economical consequences. The Geotechnical Engineering Office (GEO) of the Hong Kong SAR Government has implemented a comprehensive risk management regime to combat landslide problems and reduce landslide risk to the community over the last 30 years. Since the mid-1990s, the GEO has pioneered the novel development and application of Quantified Risk Analysis (QRA) for landslide risk management. This paper presents the role of QRA in Hong Kong's landslide risk management practice and gives a selection of case examples to illustrate the successful application of QRA in providing insights in tackling a range of practical slope safety problems.

1 INTRODUCTION

Landslide is a common form of natural hazard in Hong Kong that can cause significant loss-of-life and socio-economical consequences. Hong Kong is probably unique in the world in terms of its combination of high seasonal rainfall (24-hour intensity exceeding 250 mm and 1-hour intensity exceeding 50 mm are not uncommon), steep terrain in close proximity to dense urban development, a large stock of potentially substandard man-made slopes formed many years ago without geotechnical control, together with high public expectation of slope safety. Over 60% of the land area in Hong Kong is on sloping terrain, which can be susceptible to landslides during heavy rainfall. Several hundreds landslides are typically reported every year. Given the close proximity of dense urban hillside development, even a relatively small-scale landslide is liable to result in serious consequences.

The population in Hong Kong expanded rapidly after the Second World War due to a mass influx of immigrants from Mainland China. This surge in population created an acute shortage of housing. Extensive site formation works were carried out for building and infrastructure developments, which were mostly implemented with no regulatory geotechnical control by Government. The landslide risk was on an increasing trend with significant growth in population and unregulated hillside development. The scale of the problem is indicated by the fact that landslides have been responsible for the death of more than 470 people in Hong Kong since the late 1940s (Fig.1).

In the 1970s, Hong Kong experienced a number of disastrous landslides. In June 1972, a road embankment in a new housing development in the Kowloon foothills failed (Fig.2) and engulfed a temporary housing area resulting in 71 deaths. A few hours later, a temporary excavation in the Mid-levels district on Hong Kong Island collapsed, bringing down the natural hillside above it (Fig.3). The debris demolished a 13-storey building and killed 67 people. In August 1976, another road embankment in the same housing development of the 1972 landslide collapsed, killing 18 people.

In response to a series of fatal multiple-fatality landslides, the Geotechnical Control Office (renamed GEO in 1991) was established in 1977 as a central body to regulate slope safety and geotechnical engineering in Hong Kong. A comprehensive Slope Safety System incorporating the application of fundamental risk management concepts at policy administration level has been developed and implemented by the GEO to combat landslide problems in a holistic manner. The components of the Slope Safety System (Malone 1998) are shown in Table 1. The Key Results Areas of the Slope Safety System are presented by Chan (2003).

Absolute slope safety is neither affordable nor achievable given the adverse physical setting and climatic conditions. The mission of the GEO is to save lives. The goals are (a) to reduce landslide risk to a sufficiently low level that is considered tolerable by the community through the policy of priority and partnership, and (b) to address public attitude and tolerability of landslide

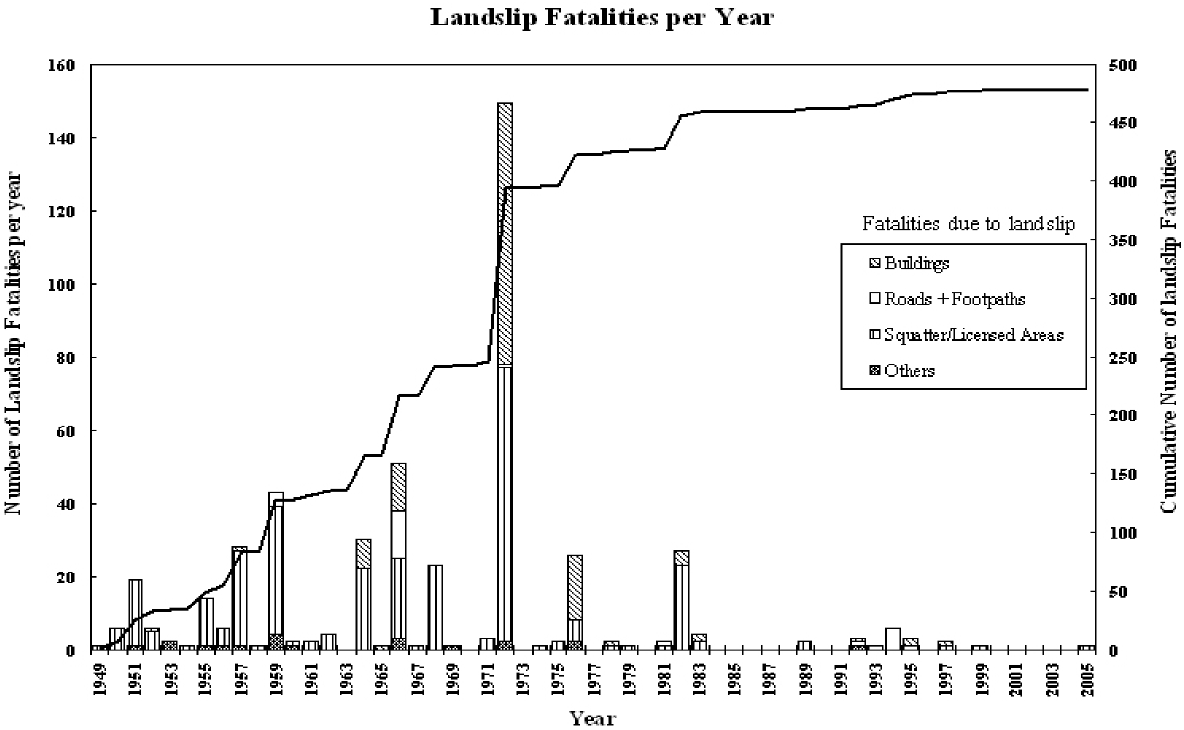


Fig.1 Landslip fatalities per year

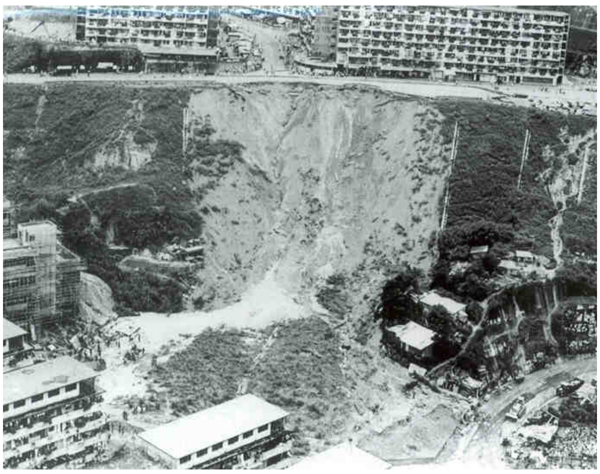


Fig.2 The 18 June 1972 landslide in the Kowloon foothills

Fig.3 The 18 June 1972 landslide in the Mid-levels district

risk to avoid unrealistic expectations. It adds value to the society through averting potential casualties and improving the built environment.

Given 30 years of sustained slope safety efforts, the overall landslide risk to the community has been reduced considerably, as reflected by a reducing landslide fatality trend. A postulated risk trend is shown schematically in Fig.4.

Since the mid-1990s, the GEO has pioneered the novel development and application of QRA for landslide risk management. It has played a key role in addressing pertinent questions relating to policy on public safety, such as (a) how safe is safe enough, (b) what is an appropriate level of effort and expenditure on safety, and (c) how can the effectiveness of effort and expenditure on safety be measured? QRA has also served as an important risk management tool in the formulation of slope safety policy in Hong Kong and in addressing technical issues. The successful development and application of QRA to landslide risk management relies on the enhanced knowledge of actual slope performance and mechanics of landslides, use of improved technology and development of suitably rigorous risk-based methodology, through concerted research and development work and continuous improvement.

This paper presents the role of QRA in Hong Kong's landslide risk management practice and gives a selection of case examples to illustrate the successful application of QRA in providing insights in tackling a range of practical slope safety problems.

2 IMPETUS FOR QUANTIFIED LANDSLISDE RISK MANAGEMENT

The International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) Technical Committee on Risk Assessment and Management (TC32) has suggested a Glossary of Terms for Risk Assessment (Fell et al 2005) for generic use.

Table 1 The Slope Safety System in Hong Kong (based on Malone 1998)

Slope Safety System Components	Primary Contribution by Each Component		
	To reduce landside risk		To address public attitudes and tolerability of landslides risk
	Reduce likelihood of landslide	Reduce consequence of landslide	
Policing			
• *Checking new slope works*	✓		
• *Slope maintenance audits*	✓		
• *Recommending safety clearance of vulnerable squatters and unauthorized structures threatened by hillslopes*		✓	
• *Exercising geotechnical control through input to land-use planning*		✓	
• *Safety-screening studies and recommending statutory repair orders for private slopes*	✓		
Works Projects			
• *Retrofitting substandard Government man-made slopes*	✓		
• *Natural terrain landslide mitigation and boulder stabilisation works*	✓		
Research and Setting Standards	✓	✓	✓
Education and Information			
• *Slope maintenance campaigns*	✓		✓
• *Risk awareness programmes and personal precautions campaigns*	✓	✓	✓
• *Information services*	✓	✓	✓
• *Landslip Warning and emergency services*		✓	✓

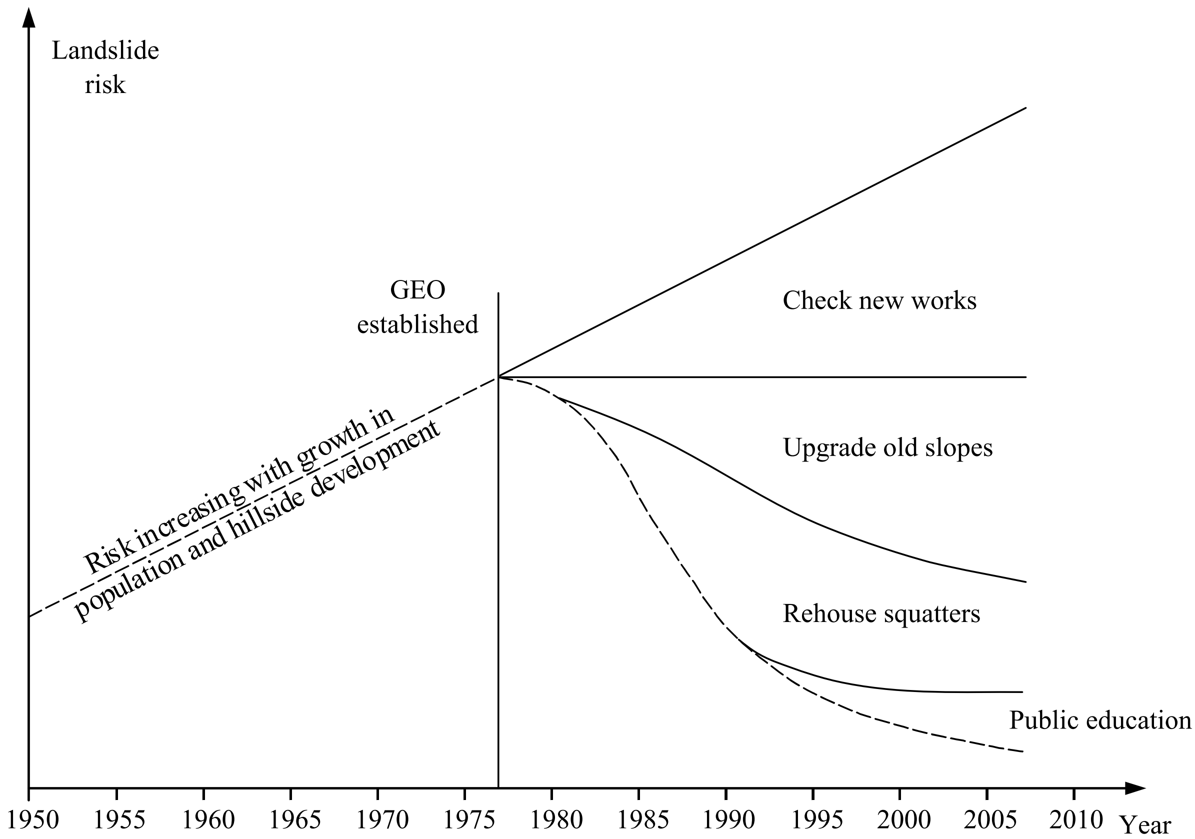


Fig.4 Postulated landslide risk trend (Malone 1998)

Landslide risk is a measure of the chance of occurrence of slope failure causing a certain amount of harm (e.g. fatalities and economic losses), and can be quantified as the product of the probability and consequence of failure.

Landslide risk analysis is the process of identifying the landslide hazard, examining the consequence of the landslide hazard and estimation of the risk. The assessment can be either qualitative or quantitative. QRA is carried out through a systematic examination of the factors contributing to the hazard and the severity of consequence, and establishing probabilities for the various factors. The following key questions are addressed systematically under a risk-based framework:

- What can cause harm? *[Hazard Identification]*
- How often? *[Hazard/frequency Assessment]*
- What can go wrong, how likely and how bad? *[Consequence Assessment]*
- What is the likelihood of damage? *[Risk Quantification]*
- What is the significance? *[Risk evaluation]*
- What should be done? [*Risk Mitigation*]

Landslide risk management comprises an estimation of the landslide risk, deciding whether or not the risk is tolerable, exercising appropriate control measures to reduce the risk where the risk level cannot be tolerated (Fig.5). In a more global context, landslide risk management also refers to the systematic application of management policies, procedures and practices to the tasks of identifying, analyzing, assessing, mitigating and monitoring landslide risk.

Slope engineering and landslide mitigation have always involved some form of risk assessment and risk management. Traditionally, this was often done with the use of engineering judgement. The idea of applying risk concepts to slope safety emerged in the 1960s and formal risk assessment methodologies and risk management principles emerged in the 1970s (Wu and Kraft 1970). It was confined to qualitative applications in the early years, but had been extended to quantified analysis since about the late-1980s.

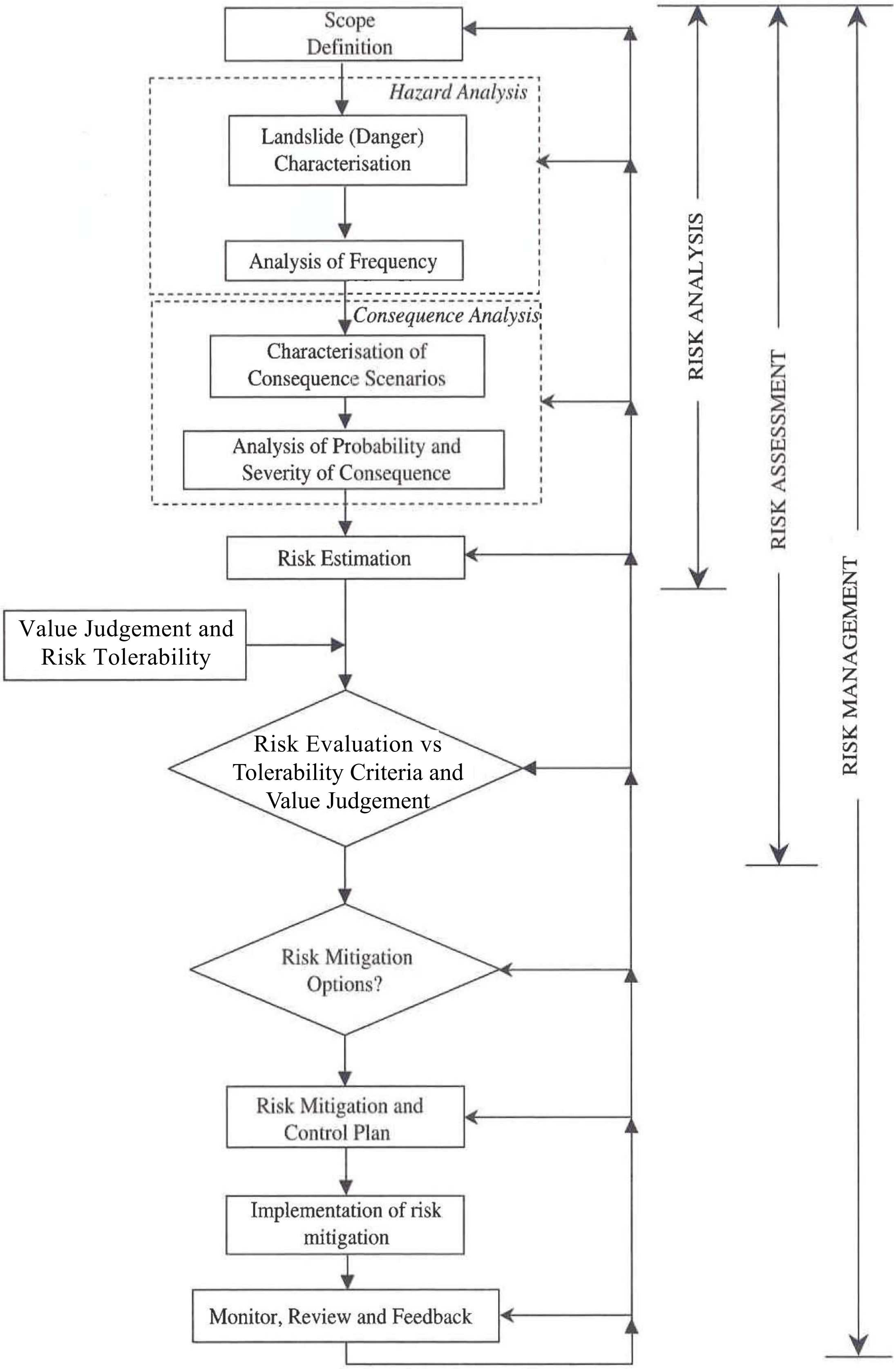


Fig.5 Flow chart for landslide risk management (based on Fell at el 2005)

In the early 1990s, formal risk management became well established in the hazardous industry as a process for handling risk to meet the expectations of the stakeholders concerned (Royal Society 1992). Since the mid-1990s, QRA has been formally applied in assessing and managing landslide risk, notably in Hong Kong (Wong et al 1997) and Australia (Australian Geomechanics Society 2000). The trend of increasing use of a quantitative approach in landslide risk management is evident and this is likely to continue (National Research Council 2004).

Whilst the value of quantified landslide risk management is recognised by the geotechnical profession and by many slope-related agencies and regulators, some are more advanced in its implementation than others. Hong Kong is a leading party in the application of quantified risk management, and in the development of a risk-based approach to supplement the conventional deterministic approach in slope assessment. This is attributed to the following considerations (Wong 2001):

- There are considerable uncertainties associated with the geological and groundwater conditions in the tropically weathered profiles and the rainfall characteristics in Hong Kong. This is illustrated by the fact that even slopes that have been engineered to the required geotechnical standards can have a fairly high failure rate.
- A risk-based approach can assist in the prioritisation of the retrofitting of the smaller-sized slopes with less serious consequences and the development of an optimal strategy to deal with such slopes.
- A risk-based approach can greatly facilitate the communication of landslide risk to the general public.

For managing landslide problems at specific sites, the following are some typical scenarios that require the use of a risk-based assessment, either supplementary to, or as a replacement of, the conventional deterministic approach (Wong 2005):

- where slope stability can be controlled via the provision of a safety margin against failure, but assessment of risk and the uncertainties involved is required to assist in determining the extent of the safety margin to be adopted;
- although slope stability can largely be controlled via the use of a design factor of safety, the residual chance of failure has to be considered, typically because of the severity of the failure consequences;
- where control of slope stability is not practical (or effective) and the landslide risk has to be managed by other means, e.g. mitigating the consequence of failure;
- where potential landslide hazards are known, but their risk needs to be evaluated to assist in determining the risk mitigation requirements and the preferred mitigation option; and
- where the exact nature of the potential landslide hazards and their possible consequences are not entirely known, and are to be assessed to assist in identifying the hazards and evaluating their risk.

2.1 Use of Probabilistic Analysis

Uncertainties in slope engineering are chronic, particularly for the highly heterogeneous tropically weathered profiles in Hong Kong. The literature on uncertainty is extensive. For practical purposes, Morgenstern (1995) suggested that the sources of uncertainty may be classified as follows:

- parameter uncertainty;
- model uncertainty; and
- human uncertainty.

Considerable advance has been made in the development of formal probabilistic slope stability analyses, including classical reliability methods and Monte Carlo simulation (e.g. El Ramly et al 2002), together with the modelling of spatial variation of groundmass properties (e.g. Nadim et al 2005). These provide a robust framework for assessing parameter uncertainty. In recent years, more sophisticated techniques, such as the random finite element method to deal with spatial correlation and local averaging effects, have also been developed.

Probabilistic analyses provide an assessment of the probability of failure, which can take account of spatial variability of the minor variables, statistical uncertainty due to limited data, etc. However, it is not straightforward to convert the calculated 'timeless' probabilistic of failure to the equivalent annual failure frequency, which is needed for formal risk assessment. Nadim (2002) put forward some suggestions on how this conversion may be done using statistical methods, such as Bayesian approach with Bernoulli sequence. The reliability of such approaches should be carefully considered.

Morgenstern (2000) noted that in real problems the model uncertainty could be a major source of uncertainty. In this event, the seemingly sophisticated probabilistic calculations would be meaningless because the major source of uncertainty has not been addressed.

Peter Lumb from the University of Hong Kong, a pioneer in geo-statistical analysis, advocated the use of probabilistic concepts in slope engineering in Hong Kong to account for uncertainties. The paper by Li and Lumb (1987) was, at the time, a state-of-the-art contribution in the use of probabilistic methods for slope design. The probabilistic approach has not been generally adopted in local slope design practice. Foremost amongst the reservations expressed by the practitioners was concern over the onerous task of measurement needed to compose the histograms of data and the idealised probability density functions (Malone 2005). Notwithstanding this, risk concepts have been embodied in the technical policy for slopes. For instance, the Geotechnical Manual for Slopes (GCO 1984) stipulates a higher factor of safety for slopes in high-consequence situations and permits a low factor of safety where the consequences of failure are not so serious. Another example is the priority ranking system introduced in 1978 to form a waiting list of old (i.e. formed before the establishment of the GEO in 1977) man-made slopes based on a risk-based scoring formula for stability study under the long-term slope retrofitting programme, viz. the Landslip Preventive Measures (LPM) Programme (Tang et al 2007a).

2.2 Technical Development Work

The formulation of QRA techniques and their application to slope engineering is a novel development (Tang et al 2007b). The following technical developments have paved the way for advancing the state-of-the-art in landslide risk assessment and management in Hong Kong.

2.2.1 Assessment of debris mobility for man-made slope failures

The assessment of landslide debris mobility is fundamental in the evaluation of the consequence of slope failure and quantification of landslide risk. Systematic collection of good quality field data on debris mobility commenced in the early 1990s in Hong Kong as reported by Wong and Ho (1996). This pragmatic approach involves the use of good quality landslide data together with appropriate classification of the failure and debris movement mechanisms (Fig.6) to assess the likely travel distance of landslide debris. The data in Hong Kong for man-made slopes indicate that the debris travel angle (Cruden and Varnes 1996) for typical small to medium-scale rain-induced landslides (viz. landslide volume of <2,000 m^3) generally ranges from 30^o to 40^o. The data also indicate that the travel angle tends to reduce with increase in landslide volume and is a function of the landslide mechanism. The travel angle concept is simple and appropriate in risk assessment in that it reflects directly the debris influence zone, and that it resembles the rate of energy loss during debris movement and incorporates the influence of the downslope gradient.

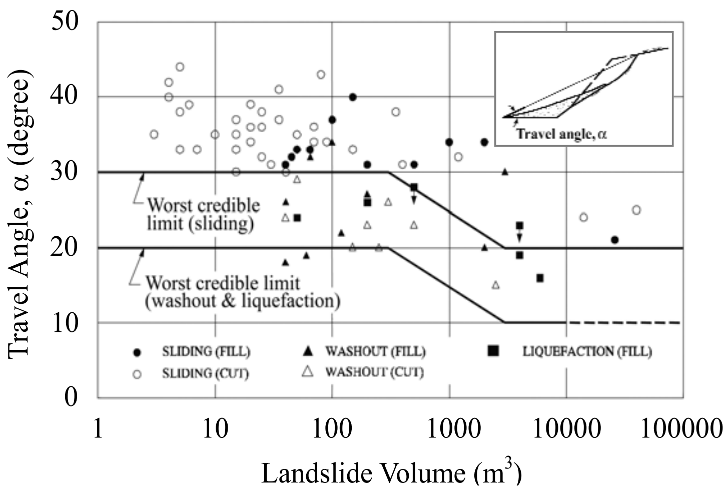


Fig.6 Data on debris mobility for landslides on man-made slopes (based on Wong and Ho 1996)

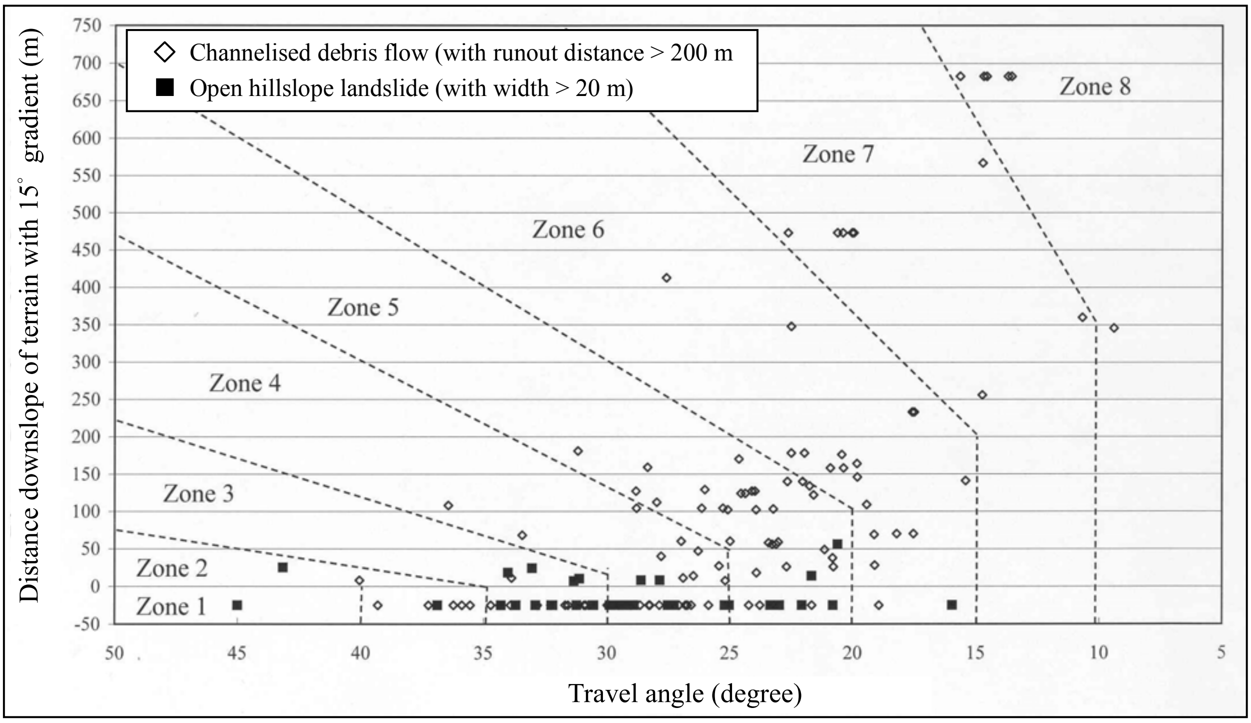


Fig.7 Data on debris mobility for natural terrain landslides and classification on proximity zones (Wong et al 2004a)

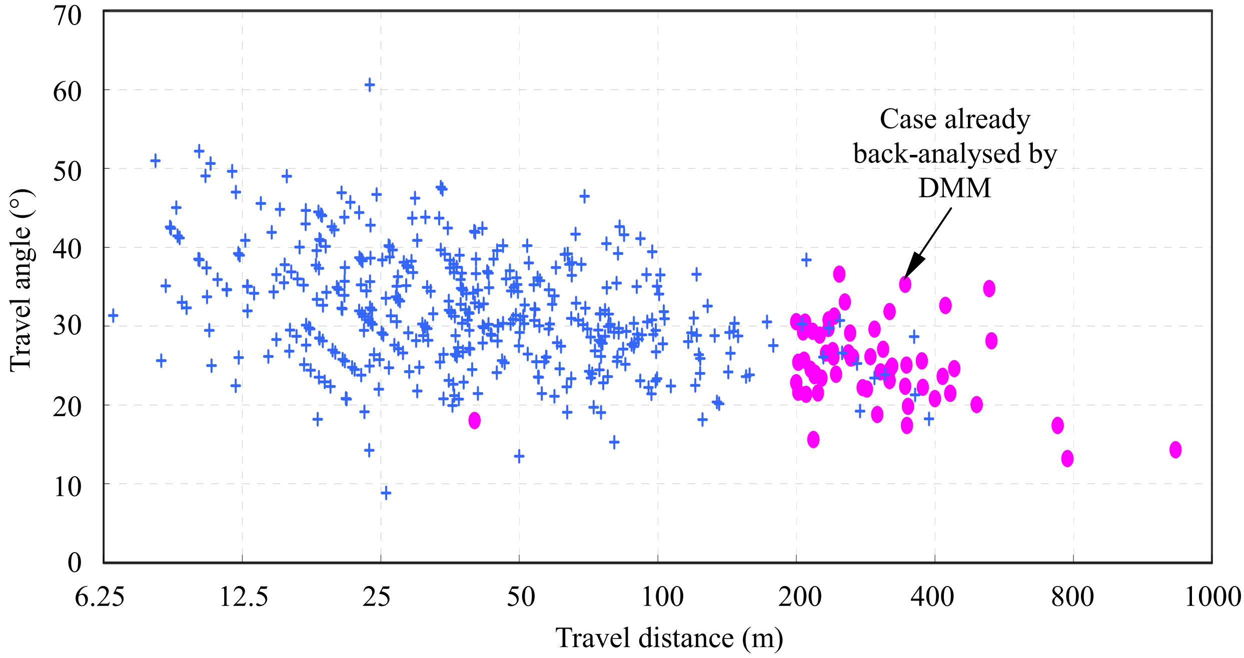
2.2.2 Assessment of debris mobility for natural terrain landslides

The use of travel angle (as adopted for man-made slopes) as an index to reflect debris mobility and proximity of affected facility has limitations in the case of natural terrain landslides. In the case of man-made slopes, the downslope gradient is usually fairly small and the length of the landslide trail is not significant and hence the travel angle concept provides a reasonable resolution for predicting the debris travel distance. Natural terrain landslides differ in that they usually involve a comparatively steep downslope profile. As such, the use of travel angle alone has poor resolution in assessing debris runout because of the relatively small difference between downslope gradient and travel angle.

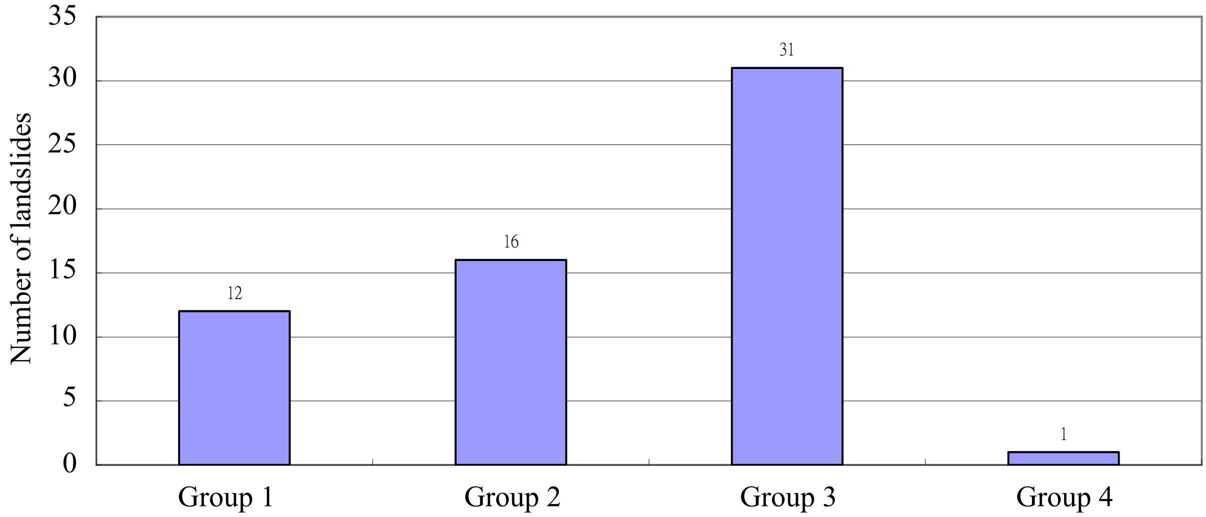
A more refined framework has been developed by the GEO for empirical assessment of mobility of natural terrain landslides (Fig.7). This involves the delineation of different mobility zones of debris runout in relation to the travel angle, as well as runout distance along terrain that has a gradient of less than 15^o steep, based on observations from detailed landslide studies in Hong Kong.

Various analytical approaches have also been put forward for assessing debris runout. A dynamic debris mobility computer algorithm (named Debris Mobility Model, DMM) has been developed by the GEO for numerical modelling of debris mobility. This Excel-based algorithm models the movement of landslide debris as a continuum using a finite difference solution of the governing dynamic equations in a Lagrangian framework, similar to that adopted in the DAN model developed by Hungr (1995) for debris runout analysis. As compared with DAN, enhancement has been made by the GEO to cater for consolidation of debris during motion and a more realistic channel geometry that may vary along the runout path, i.e. a channel profile is inputted instead of a pre-determined width of debris as in the DAN program (Kwan and Sun 2006).

Systematic back analysis of debris runout of 60 mobile historical natural terrain landslides in Hong Kong has been carried out using the DMM program. The ranges of the two key input parameters, viz. apparent friction angle (ϕ') and turbulence coefficient (ξ) assuming a Voellmy rheological model corresponding to the observed debris runout have been assessed (Fig.8). Further analyses are in progress to establish the probabilistic distribution of the degree of debris mobility for different hillside conditions.



(a) Runout data of historical debris flows



(b) DMM parameters back-analysed from the 60 cases

Group	**Apparent friction angle, ϕ' (°)**	**Turbulence coefficient, ξ (m/s^2)**
1	8	500
	11	500
2	15	1,000
	20	5,000
3	20	1,000
	25	1,000
4	30	5,000

Fig.8 Ranges of key input parameters

A GIS-based module, which is equipped with the capability to identify the 3-dimensional flow path based on the DMM algorithm using a digital elevation model, has also been developed under the direction of the GEO. This is intended for more advanced application on a GIS platform. In this module, information generated from the GIS (e.g. slope gradient, channel geometry, etc.) can be used to estimate the location, velocity and thickness of landslide debris at different times.

A new three-dimensional debris runout algorithm has also been developed by the GEO, as reported by Kwan et al (2007).

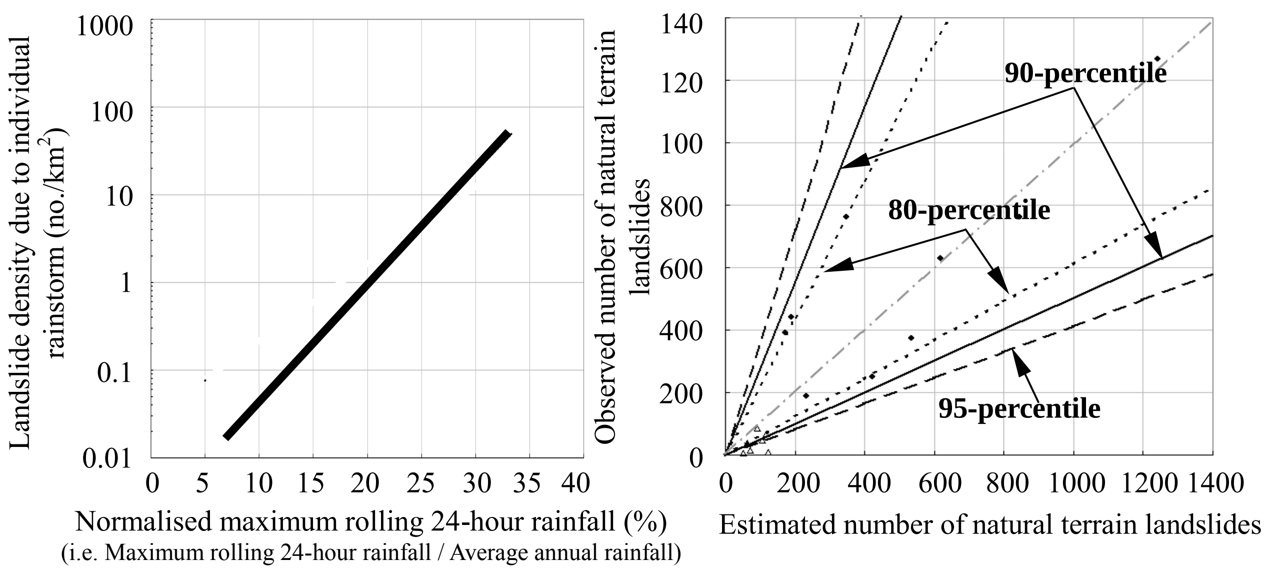
2.2.3 Quantification of landslide consequence

The need to evaluate the consequence of failure for risk quantification poses a new challenge to the geotechnical profession. Traditionally, the assessment of consequence is done either implicitly or qualitatively, largely based on subjective judgement. Wong et al (1997) have developed a generalized, quantitative landslide consequence model for use in QRA of man-made slopes. This generic model incorporates advances in the understanding and quantification of key factors that affect debris mobility and vulnerability of the population at risk under different scenarios. Due account is taken of the different mechanisms and scale of landslides, together with the nature and type of facilities, their proximity to the slope and the vulnerability. The model was calibrated against historical landslides in Hong Kong and gave reasonable estimates through application to QRA case studies. The model has also been refined for use with event tree analysis in site-specific QRA to derive an f-N curve to define the societal risk (Wong et al 1997).

With the improved capability of numerical modelling of debris runout that has been calibrated against field observations, it is now possible to carry out more refined assessment of the condition for collapse of different types of buildings for given impact scenarios (Ko and Kwan 2006).

2.2.4 Rainfall-landslide correlation for natural hillsides

The vast majority of the landslides in Hong Kong are triggered by rainfall. Hong Kong has a wide network of automatic raingauges at strategic locations across the territory, which has been established since 1984 and gradually expanded over a period of 20 years to the current level of service. There are at present a total of 110 raingauges that collate and transmit real-time rainfall data through either telephone lines or General Packet Radio Service, viz. a wireless transmission technology, to the head station at five-minute intervals round the clock. Generalised rainfall-landslide correlations, based primarily on records of past failures on man-made slopes, were derived by the GEO for use in the Landslip Warning system (Yu et al 2004).



(a) Correlation for individual rainstorm (b) Statistical variation

Fig.9 Rainfall-lansdslide correlation for individual rainstorm and its statistical variation.

Detailed GIS spatial analyses have been carried out using the rainfall data of 202 major rainstorms since 1985 and the historical landslide data from the NTLI to establish the rainfall-landslide correlations for natural hillside failures. This enabled the correlation of the natural terrain landslide density with the storm-based normalised maximum rolling 24-hour rainfall (i.e. % of mean annual rainfall at a given location), as well as the statistical variation of the correlation (Fig.9). The 90-percentile Figures are within about ± 1/3 order of magnitude from the best-fit correlated Figures. This order of accuracy is probably the best that can be achieved in a regional correlations (i.e. without differentiating terrain landslide susceptibility) and the use of a single attribute (i.e. maximum rolling 24 hours) to represent the severity of rainfall. Improved correlation was obtained with the combined consideration of the normalized maximum rolling 4-hour and 24-hour rainfalls (Wong et al 2004b).

2.2.5 Quantification of landslide frequency

For QRA applications, an assessment of the frequency of different types of landslides is required. A range of approaches may be adopted to assess the annual failure probability (IUGS 1997). Apart from the use of probabilistic approaches as discussed above, this can be assessed directly from failure data. It is noteworthy that use of archived failure data is the norm in QRAs for major industrial hazards. The GEO has compiled comprehensive information on past landslides on a GIS platform, as follows:

- Database on reported landslides - this contain records of inspections, by professional geotechnical engineers, of a total of about 8,000 landslides since systematic records began in 1984.
- Natural Terrain Landslide Inventory (NTLI) - This was compiled in 1997 based on interpretation of high-flight aerial photographs (8,000 feet or more) and the latest update covered the year 2003. The inventory comprises some 30,000 landslides, about 12,000 and 18,000 of which are considered recent and relict landslides respectively.
- Enhanced Natural Terrain Landslide Inventory (ENTLI) - This was compiled in 2007 based on interpretation of low-flight aerial photographs (<8,000 feet) and contains about 100,000 past hillside failures (comprising about 15,000 and 85,000 recent and relict landslides respectively). The increase in the number of landslides is largely due to an improved capability of the low-flight aerial photographs in identifying landslides. In addition, the landslide locations as determined with the use of

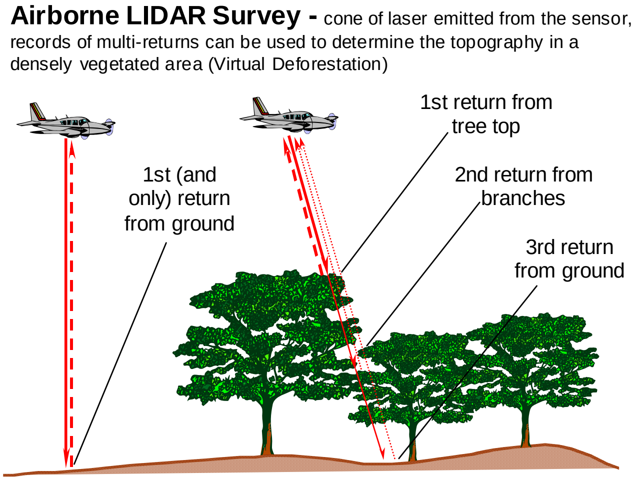


Fig.10 "Virtual deforestation" capability of airborne LIDAR survey.

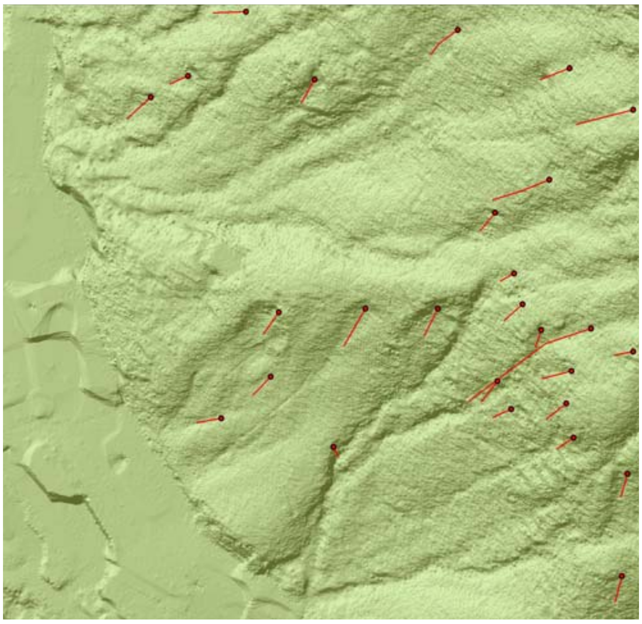
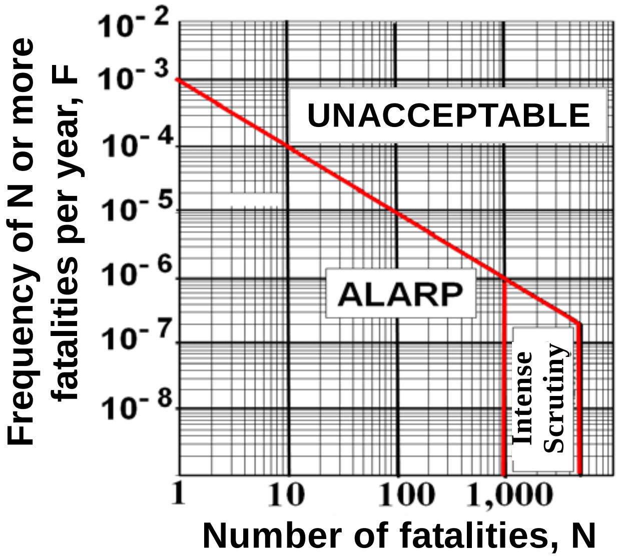


Fig.11 Landslide scars and geomorphological features on hillsides recognised by high-resolution digital elevation model from LIDAR, as compared with landslide records in ENTLI.

Individual Risk (IR)	New Developments	Existing Developments
Maximum Permissible IR*	10^{-5}	10^{-4}
Tolerable IR level*	$<10^{-5}$	$<10^{-4}$

* Apply to the most vulnerable person at risk (i.e. Personal Individual Risk)

(a) Individual risk tolerability criteria



Note: The above societal risk criteria are to be used in conjunction with a reference toe length of the natural hillside of 500 m. Appropriate scaling of the risk criteria is done where the actual toe length is greater than 500 m (ERM 1998).

(b) Societal risk tolerability criteria

Fig.12 Societal risk criteria adopted in Hong Kong for landslides and boulder falls from natural terrain.

GIS-based ortho-rectified images are more reliable.

Remote sensing technology, in particular multi-return airborne Light Detection and Ranging (LIDAR), has shown promising results in producing high resolution digital elevation models that can 'see through' vegetation (Wong 2007) (Fig.10). Landslide scars and geomorphological features on hillsides can be vividly recognised in the high-resolution digital elevation models derived from a recent pilot trial of airborne LIDAR in Hong Kong (Fig.11).

As Hong Kong is data-rich, landslide frequency assessment is commonly carried out by reference to the historical landslide data. For example, a frequency assessment using this approach was carried out as part of a global QRA of 37,000 old man-made slopes (Wong and Ho 1998). For the global QRA of natural terrain landslides in Hong Kong, an improved approach involving the application of GIS-based rainfall-landslide correlations in probabilistic terms (Ko 2003), which have been calibrated against historical natural terrain landslide data, were used to assess the landslide density. Different rainfall scenarios together with their probability of occurrence are considered to assess the likely landslide frequency. The above two global QRA's will be presented in the subsequent sections of this paper.

In making reference to the use of historical landslide data, the key is the proper classification of the mechanisms of failure and mechanisms of debris movement in the definition of the hazard model. This is tantamount to a better understanding of the landsliding process and the failure modes involved. In this regard, the systematic landslide investigation programme, which was implemented by the GEO in 1997, has played a key role in advancing the understanding of the types, causes and mechanisms of slope failures on man-made slopes and natural hillsides (Wong and Ho 2000a; Wong and Ho 2000b), as well as providing quality data for use in QRA.

The alternative of using a 'black-box' type approach and mixing together different historical information without proper data classification can significantly affect the accuracy of the assessment and may give misleading results. Over reliance on statistical analysis of past failure data with inadequate appreciation of the data constraints will not be appropriate.

2.2.6 Risk criteria

Risk criteria constitute an essential element in the framework of risk management for evaluating the tolerability of QRA results. However, there is little precedent in this area for landsliding problems. After reviewing the criteria used for major industrial hazards, dams and railways in several European countries, Australia and Canada, along with the local criteria for Potentially Hazardous Installations (PHI), dangerous goods transportation and railways, the GEO recommended tolerable risk criteria, on a trial basis, for natural terrain landslide and boulder fall hazards (ERM 1998). These interim risk criteria are defined in terms of both Individual Risk and Societal Risk, based on benchmarking with the existing PHI risk criteria in Hong Kong (Fig.12). The Individual Risk criteria apply to the annual probability of fatality for the most vulnerable person affected by the landslide hazard. The Societal Risk criteria apply to the total risk-to-life posed to the affected community by the landslide hazard, which is expressed as an F-N curve.

2.2.7 Management of natural terrain landslide risk

The strategy for dealing with natural terrain landslide hazards in Hong Kong has been to avoid, as far as possible, new developments in vulnerable areas. Where this is not practicable, the conventional approach in the past has been to design the natural hillside of concern to the factors of safety stipulated in the Geotechnical Manual for Slopes (GCO 1984). This approach is applicable if the design objective is to reduce the chance of natural terrain failures (e.g. in the study of natural terrain below a development site to ensure that natural terrain landslides that may adversely affect the site will not occur). However, in many other situations, this approach is fraught with difficulties because:

- as natural hillsides are often only marginally stable over a large area, stabilisation of the hillsides would be expensive and may not be justified. Also, widespread stabilisation works on natural hillsides could result in considerable impact on the environment.
- Averting failure may not be the most cost effective engineering solution. Provision of hazard mitigation measures (e.g. debris-resisting barriers) could be the preferred option in reducing the risk of natural terrain landslides.

Two alternative approaches were introduced by the GEO for the assessment and mitigation of natural terrain landslide hazards, namely QRA and Design Event Approach (Wong 2001).

Significant advances have been made in improving the knowledge of natural terrain landslides in Hong Kong in recent years through compilation of comprehensive landslide inventory, systematic landslide investigations (Wong and Ho 2000b), use of advanced digital technology (Wong 2007), development of rainfall-landslide correlations, age dating of landslide debris (Sewell and Campbell 2005), guidance on natural terrain hazard studies (Ng et al 2003) and mitigation measures (Franks and Woods 1997; Lo 2000; Sun and Lam 2006).

3 EXAMPLES OF QRA APPLICATIONS

Several key applications of both global and site-specific QRA are described to illustrate the development and role of QRA in landslide risk management in Hong Kong.

QRA has proved to be a useful risk management tool for the study of specific sites (e.g. to assess risk tolerability and determine the necessary risk mitigation measures), but the methodology can also be applied to a large group of slopes for quantifying and evaluating the overall risk. This is referred to as global QRA (Ho et al 2000). Typically, a global QRA serves to examine the overall scale of a problem, identify the relative contributions from different components and guide decisions on strategy formulation, programme management and resources allocation.

Global QRA differs from site-specific QRA in a number of aspects (Wong 2005):

- Unlike site-specific QRA, global QRA is not aimed at quantifying the risk on an individual site basis, nor does it evaluate site-specific risk management actions. However, site-specific QRA and global QRA are not entirely independent of one another. They often provide a benchmark for calibrating each other's results.
- As a large number of slopes are assessed in a global QRA, detailed investigations and geotechnical appraisals of each slope is normally not practical. This limits the type of data that may be used in a global QRA. Hence, simplified frequency and consequence models, which are less data demanding, are typically adopted in global QRA. However, use of simplified models and less detailed data does not necessarily degrade the reliability and useful functions of a global QRA. As global QRA is intended for quantifying and evaluating

the overall risk, the QRA results are less sensitive to model formulation, assumptions and input data as compared with site-specific QRA.

3.1 Global QRA

A number of global QRA have been carried out by the GEO, e.g. for all the registered man-made slopes (Wong et al 1997), natural terrain landslides (Wong et al 2004a), earthquake-induced landslides on man-made slopes (Wong and Ho 1998), slopes affecting squatters (FHK 2004), boulder fall hazards (MGS 1998), collapses and excessive displacements of deep excavations (OAP 2002), etc. Two examples are outlined in the following.

3.1.1 Old Man-made Slopes

All the sizeable (>3 m) man-made slopes and retaining walls have been registered in the New Catalogue of Slopes and incorporated in GEO's Slope Information System (SIS) (Mak et al 2001). The SIS, which can be assessed through the internet (http://hkss.cedd.gov.hk), contains pertinent information on about 57,000 man-made slope features and stores over 10 million slope data under about 30 information GIS layers. Of the 57,000 registered slopes, some 39,000 were formed prior to the establishment of the GEO in 1977 (denoted as old slopes), without geotechnical input and regulatory geotechnical control and hence may be substandard. These slopes are systematically included into the long-term slope retrofitting programme (viz. the LPM Programme) for detailed investigation and necessary upgrading in accordance with a risk-based priority ranking system.

Mechanism of failure	Cut slopes - Sliding Fill slopes - Sliding - Wash-out - Liquefaction
Scale of failure	- <20 m^3 - 20 - 50 m^3 - > 50 - 200 m^3 - > 200 - 1,000 m^3 - > 1,000 - 10,000 m^3 - >10,000 m^3

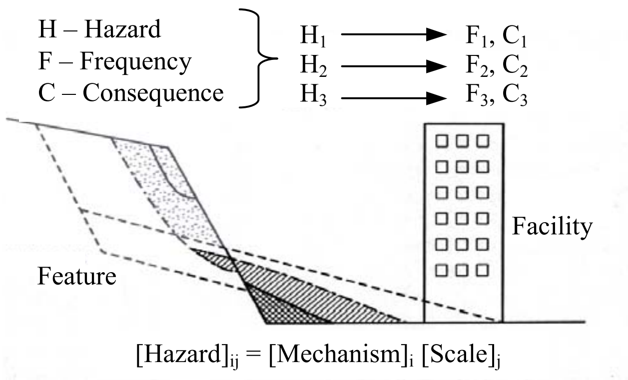


Fig.13 Hazard model for QRA of old man-made slopes (Wong et al 1997).

A global QRA was carried out for all the old man-made slopes in the Slope Catalogue in 1997, which totalled about 35,000 at that time. A formal QRA methodology was adopted to calculate the overall landslide risk of all the 35,000 slopes by integrating the hazard and consequence models.

The hazard model (Fig.13) considered the different key hazards based on experience from landslide investigations over the years. The different hazards are defined in terms of the slope type, failure mechanism and scale of failure. It entailed the calculation of the frequency of occurrence of each hazard type. This was done based on a detailed analysis of the records on reported landslides collected systematically in Hong Kong since 1984. The analysis included matching the landslides with the slopes, evaluating the baseline frequency for each hazard and distributing the baseline frequency to each slope via a frequency model.

The consequence model followed the generalised framework put forward by Wong et al (1997). For each type of hazard, account is taken of the scale of failure, nature of facility affected (Table 2), degree of protection afforded by the facilities to the users, proximity of facilities to the landslide source, and any aversion effects due to potential multiple fatalities (based on slope attributes and information on the facilities as obtained from the Slope Catalogue).

The overall landslide risk from the 35,000 slopes was calculated by integrating the hazard and consequence models and the respective calculated PLL Figures for difference slope types are shown in Table 3. The total PLL of the slopes (as at 1997) was estimated to be about 11 per year. By projection, it was estimated that the PLL of all the old man-made slopes was over 20 per year as at 1977 before the commencement of the LPM Programme.

The global QRA also provided useful information on the risk distribution and characteristics, which proved invaluable in the formulation of the risk management strategy for the current phase (2000-2010) of the LPM Programme. Some of the examples are given below:

- Application to priority ranking - The global distribution of the quantified risk from cut slopes, fill slopes and retaining walls is in the ratio of 6:1:1 (Table 4). In terms of average risk per slope feature, the corresponding ratios were about 3:1:1. Experience from the LPM Programme indicates that the average costs of stabilisation of a cut slope, fill slope and

Table 2 Classification of facility groups (based on Wong and Ho 1995)

Facility Group No.	Facilities	Potential loss of life
1 (a)	Occupied buildings, e.g. residential building, school, etc.	3
1 (b)	Road with very heavy vehicular or pedestrian traffic density Sheltered public waiting area, e.g. bus shelter	3
2 (a)	Moderately-used built-up areas, e.g. indoor car park, temple, etc.	2
2 (b)	Road with heavy vehicular or pedestrian traffic density	2
3	Densely-used open space Road with moderate vehicular or pedestrian traffic density	0.25
4	Lightly-used open space Road with low vehicular or pedestrian traffic density	0.03
5	Remote area Road with very low vehicular or pedestrian traffic density	0.001

Note:

(1) 'Potential loss of life' in this Table refers to the average number of fatalities in the event of a direct hit (i.e. 100% vulnerability) by a reference landslide of 10 m in width and 50 m^3 in volume, as derived from formal consequence assessment (Wong et al 1997).

Table 3 Results of global QRA of old man-made slopes in Hong Kong (Wong & Ho 1998).

Group no.	1 (a)	1 (b)	2 (a)	2 (b)	3	4	5	Building collapse	Total
Type of facility	Buildings	Roads	Buildings	Roads	Roads & open space	Roads & open space	Roads & open space		
(a) PLL for cut slopes (per year)									
Slope height									
< 10 m	1.53	0.43	0.51	1.07	0.86	0.215	$4.66 \mathrm{x} 10^{-3}$	0	4.62
10 – 20 m	0.61	0.23	0.20	0.58	0.46	0.111	$2.36 \mathrm{x} 10^{-3}$	0	2.20
> 20 m	0.26	0.20	8.60×10^{-2}	0.49	0.39	6.88×10^{-2}	$1.15 \mathrm{x} 10^{-3}$	0.171	1.67
Total	2.40	0.86	0.80	2.14	1.72	0.395	$8.17 \mathrm{x} 10^{-3}$	0.171	8.49
(b) PLL for fill slopes (per year)									
Slope height									
< 10 m	0.14	0.05	0.05	0.13	0.10	1.81×10^{-2}	3.03×10^{-4}		0.49
10 – 20 m	0.12	0.03	0.04	0.07	0.06	1.00×10^{-2}	1.71×10^{-4}		0.32
> 20 m	0.31	2.38×10^{-2}	1.03×10^{-1}	5.95×10^{-2}	4.76×10^{-2}	9.00×10^{-3}	1.61×10^{-4}		0.55
Total	0.57	0.10	0.19	0.26	0.21	$3.71 \mathrm{x} 10^{-2}$	6.35×10^{-4}		1.36
(c) PLL for retaining walls (per year)									
Wall height									
≤ 5 m	3.76×10^{-1}	2.21×10^{-2}	1.25×10^{-1}	5.53×10^{-2}	4.42×10^{-2}	7.31×10^{-3}	1.15×10^{-4}		0.63
> 5 m	4.44×10^{-1}	6.32×10^{-3}	1.48×10^{-1}	1.58×10^{-2}	1.26×10^{-2}	1.93×10^{-3}	2.74×10^{-5}		0.63
Total	8.20×10^{-1}	2.84×10^{-2}	2.73×10^{-1}	7.11×10^{-2}	5.69×10^{-2}	9.24×10^{-3}	1.42×10^{-4}		1.26

Table 4 Risk distribution according to type of slope (Wong and Ho 1998).

Slope type	Old man-made slope features		
	Cut slopes	Fill slopes	Retaining walls
Number	19,100	9,500	8,100
Global failure frequency (per year)	1 in 100	1 in 500	1 in 350
Proportion of total risk [Risk Ratio]	75% [6]	12% [1]	13% [1]
Average ratio of risk per feature	3.2	1	1.3

retaining wall are comparable. Hence, the ratio of risk per feature reflected the relative proportions of different slope types to be retrofitted under the LPM Programme, as an optimal strategy for effective reduction of the landslide risks associated with different slope types. This has formed the basis for decision-making on allocation of retrofitting resources to different slope types under the LPM Programme since the mid 1990s, which has been built into the scoring formulae for the risk-based priority ranking system.

- <u>Application to quantified risk reduction targets and risk communication</u> - The risk profile in Fig.14 shows the overall risk distribution amongst the slopes in different groups, based on the categorisation of the facilities at risk. About half of the overall risk came from approximately 10% of the slope population with the highest risk. This indicated that upgrading of a relatively small proportion of the old slopes posing the highest risk would result in major risk reduction. This risk reduction ratio (i.e. reduction of 50% risk by retrofitting the worst 10% of the slopes) reflects the outcome and the likely order of the effectiveness of the retrofitting programme, which can be achieved by implementing a suitable risk-based slope ranking system. The global forms the basis of the quantified risk reduction targets pledged by the Hong Kong SAR Government in 1998 (Works Bureau 1998). The LPM Programme was tasked to upgrade about 10% of the pre-1977 slopes by year 2000, and another 10% by 2010. The pledged risk reduction targets entailed: (a) by 2000, the overall landslide risk from the old man-made slopes would be reduced to 50% of the level in 1977; and (b) by 2010, the risk would be further reduced to 25% of the level in 1977. This is believed to be the first time that quantified landslide risk has been cited in a government policy goal. The pledge also makes it clear that residual risk will still exist after 30 years of sustained slope safety efforts given the significant scale of the problem to be tackled and the vulnerable physical and climatic settings.

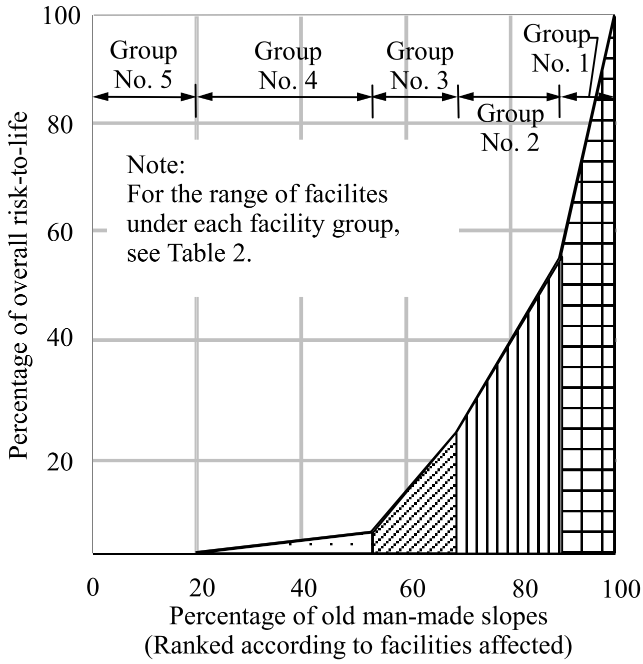


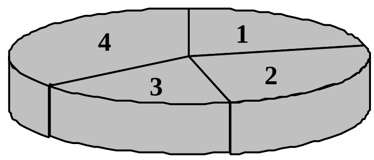
Fig.14 Risk profile of old man-made slopes in Hong Kong in 1997 (Wong and Ho 1998).

- <u>Application to cost-benefit evaluation</u> - Using the global QRA methodology, the overall theoretical annual fatalities can be predicted with some confidence to determine longer-term trends and project future performance, as well as to quantify the cost effectiveness of the risk mitigating actions. Cost-benefit calculations were performed to evaluate the investment made relative to the projected number of lives saved as a result of the efforts of the LPM

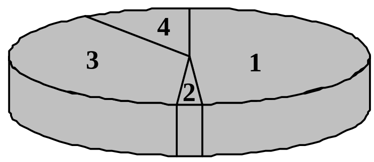
Programme. These showed that the 2000-2010 LPM Programme is operating at about HK$15 million per statistical life saved. This Fig.is within the limit of maximum justifiable expenditure as derived from the ALARP principle (ERM 1998). It is also near the lower end of the typical range of values used in risk management of potentially hazardous technological installations in current worldwide practice. There has been strong and unanimous public opinion that the GEO should implement the 2000 to 2010 LPM Programme. Hence, the findings of the global QRA provided a means of quantifying and benchmarking the expectation of the public in terms of landslide risk tolerability and ALARP deliberation.

The global QRA was updated in 2000 using the latest information in the Slope Catalogue to verify if the first pledged policy goal had been achieved. The methodology adopted in the update followed that of Wong and Ho (1998), and the findings were presented in Cheung and Shiu (2000). In this update, the overall landslide risk of all registered pre-1977 slopes in 2000 was quantified, which included the risk of the remaining old slopes that had not yet been upgraded by 2000, together with the residual risk of the old slopes that had been upgraded. The total PLL in 2000 of all old man-made slopes was found to be 10.3 per year. The PLL of all old pre-1977 man-made slopes as at 1977 was back-analyzed and was found to be 21.8 per year. Thus, the risk reduction from 1977 to 2000 as a result of the LPM Programme was 53%, i.e. the pledged risk reduction target was achieved.

The 2000-2010 LPM Programme is currently in progress. A global QRA was completed in 2004 by the GEO as an interim review of the progress made. The methodology adopted in the previous global QRA was adopted, with some enhancement made (e.g. the landslide frequency was expressed in terms of the number of landslides per year per unit slope area, instead of the number of landslides per year per slope). This refinement improved the reliability of applying the frequency model to slopes of different sizes. In addition, systematic landslide investigations carried out by the GEO on failure of engineered slopes (i.e. slopes formed or upgraded to the required geotechnical standards after 1977) provided improved data for estimating the landslide frequencies of different types of engineered slopes (Wong and Ho 2000a), which improved the assessment of the residual risk of engineered slopes. This QRA, which was documented by Lo and Cheung (2004), found that by 2010, the risk of all the old man-made slopes would be reduced to about 25% of the risk in 2000 based on a projection of the progress made. This indicated that the pledged risk reduction for the 2000 to 2010 LPM Programme was achievable and that the LPM Programme was making satisfactory progress towards meeting this target. The overall risk level of all of the 57,000 registered man-made slopes by 2010 (when the current phase of the LPM Programme completes), including the pre-1977 and post-1977 slopes (with distinction being made concerning whether robust measures were implemented in the works or not), was assessed in this global QRA. The overall risk was found to be about 5 PLL per year by 2010. The distribution of the



(a) Proportion by slope number (total 57,000 nos)



(b) Proportion by risk (total 5 PLL per year)

Legend:
1 = Un-engineered slopes affecting Groups No. 1 to 3 facilities
2 = Un-engineered slopes affecting Groups No. 4 & 5 facilities
3 = Engineered slopes formed/ treated by old technology
4 = Engineered slopes treated by robust technology

Note:
'Old technology' slopes refer to slopes formed/treated in the early years of setting up Hong Kong's Slope Safety System from late 1970s to late 1980s, which generally comprise unsupported cuts, based on the geotechnical knowledge and skills at the time. These slopes are less robust than those treated with structural support or reinforcement, such as soil nails.

Fig.15 Breakdown of risk of 57,000 registered man-made slopes by 2010 (based on Lo & Cheung 2004).

population and risks of the different classes of slope is shown in Fig.15.

3.1.2 Natural Hillsides

Hong Kong has about 650 km^2 of natural hillsides that have not been significantly modified by human activities. Natural hillsides are not registered in the Slope Catalogue but they pose a landslide risk to the community. Previously, the landslide risk in Hong Kong was predominantly associated with the large stock of un-engineered old man-made slopes affecting existing developments, which was addressed by the LPM Programme. Following sustained efforts since 1977, the landslide risk from old man-made slopes is reducing. This highlights the need to assess the risk of other types of landslide hazards, in particular natural terrain failures, in formulating the strategy for the post-2010 LPM Programme.

In 2004, the GEO completed a global QRA of the overall risk of natural terrain landslides in Hong Kong (Wong et al 2004a). The key components of the global QRA are described below:

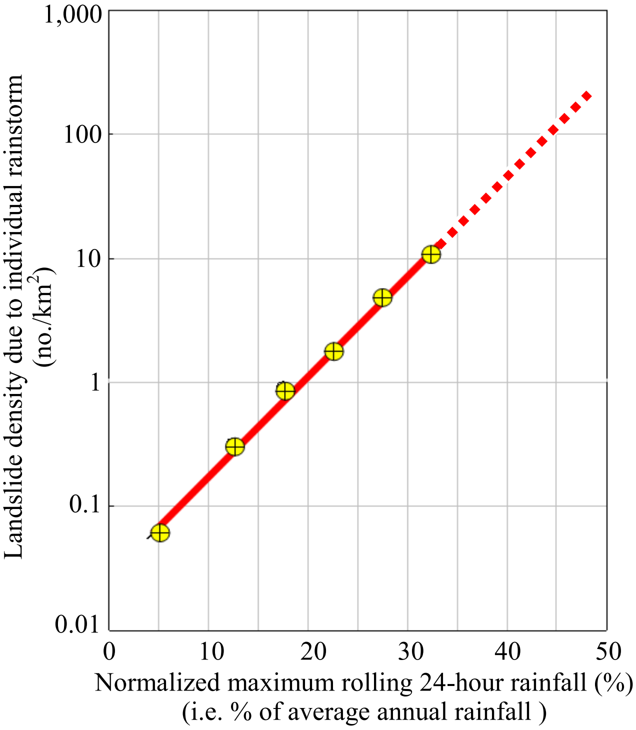


Fig.16 Rainfall-landslide correlation for natural hillsides (based on Ko 2003).

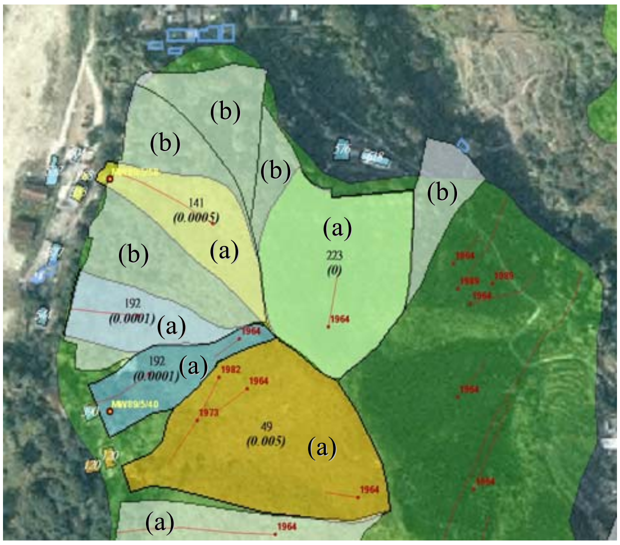


Fig.17 GIS inventory of (a) historical landslide catchments and (b) supplementary catchments.

- Compilation and analysis of data on past failures - over 30,000 natural terrain landslides were identified from interpretation of high-flight aerial photographs in the Natural Terrain Landslide Inventory (King 1999). The modes of failure were classified (e.g. channelised debris flow, open hillslope landslide, etc.) and empirical data were obtained on debris runout. A rainfall-landslide correlation was established by Ko (2003) and Wong et al (2004a) from spatial analysis of the historical landslide records and 5-minute rainfall data since 1985 (Fig.16). Territory-wide susceptibility analysis was carried out (Evans and King 1998) to establish the baseline landslide density for terrains with different characteristics.
- Identification of vulnerable catchments - While many of the natural hillsides adjoin developed areas, not all of them pose a significant risk. As part of the global QRA, a search of vulnerable catchments was carried out. This included identification of the following two types of catchments:
- Historical landslide catchments - these refer to catchments with known historical natural terrain landslides occurring close to existing important facilities, including buildings and important transport corridors (Fig.17). With the use of GIS spatial analysis supplemented by field validation, a total of 453 historical landslide catchments were identified. These 453

Table 5 Hazard classification for global QRA of natural hillsides.

Hazard combination	Classification	Definition
Mechanism of debris movement (as related to catchment characteristics)	C	Channelised debris flow
	T	Mixed debris flow/avalanche along topographic depression
	S	Open hillslope debris slide/avalanche
Scale of landslide (different magnitude-frequency relationships have been derived for different types of catchments, viz. C, T and S)	H1	20 m^3 to 200 m^3
	H2	>200 m^3 to 2,000 m^3
	H3	>2,000 m^3 to 20,000 m^3
	H4	>20,000 m^3

catchments had a total area of about 5 km^2, i.e. within about 1% of the natural terrain in Hong Kong.

- Supplementary catchments - these refer to catchments without any known historical natural terrain landslides occurring close to existing important facilities (Fig.17). It was estimated that many thousands of such catchments are present in Hong Kong, bordering the development boundaries. It was not practical to record and evaluate all these catchments in the global QRA. Hence, only samples of supplementary catchments were analysed in the QRA. A total of 1,018 supplementary catchments (about 23 km^2) in five selected regions were compiled. In addition, 43 supplementary catchments (about 1.5 km^2) in six areas where site-specific natural terrain landslide QRA had previously been carried out, were also examined for benchmarking purposes.

Table 6 Rainfall scenarios.

Rainfall scenario	Normalised maximum rolling 24-hour rainfall	Landslide density (no./km^2)	Annual frequency of occurrence[(2)]
A	≤10%	0.0593	0.8130
B	>10-20%	0.4387	0.4785
C	>20-30%	2.3354	0.0608
D	>30-35%	10.6811	0.0035

Notes:

(1) An 'extreme rainfall' scenario E, with normalised maximum rolling 24-hour rainfall >35% and a 500-year return period, was also considered through extrapolation of the calculated risk using rainfall-landslide correlation.

(2) Annual frequency of occurrence = 1 / (return period of the respective rainfall scenario)

- Hazard identification - The hazard model considered 12 types of hazards based on a combination of the scale of failure (four volume range classes) and mechanism of debris movement (three debris runout mechanisms) (Table 5).
- Frequency model - The frequency model adopted is based on rainfall-landslide density correlation and is statistically rigorous. The overall landslide frequency derived by the model is calibrated against the landslide records in the NTLI from 1985 to 2000. Although such alignment would ensure that the overall frequency model is consistent with the available historical landslide data, it is noteworthy that more severe rainfall events may not have been adequately represented given a relatively short observation period. Hence, apart from considering the four rainfall scenarios with normalized maximum rolling 24-hour rainfall ranging up to 35%, in the frequency model (Table 6), an 'extreme' rainfall scenario (i.e. maximum rolling 24-hour rainfall exceeding 35%), with an annual frequency of occurrence of 0.002 (return period of 500 years), was also considered. This latter scenario did not form part of the frequency model and its contribution to the risk was examined through extrapolation of the QRA results.

Table 7 Summary of results of global QRA of natural hillsides (based on NTLI data).

Component		Method of quantification	Risk (PLL per year)
Historical landslide catchments (453 nos.)	Rainfall Scenarios A to D (≤ 35% normalised rainfall)	Apply global QRA model to historical landslide catchments	1.4
	Rainfall Scenario E (> 35% normalised rainfall)	~30% increase in risk, from extrapolation of QRA results using rainfall-landslide correlations	0.4
Supplementary catchments		~ 200% increase, (see Fig.18)	3.2
Total			5.0

Notes:
(1) Other consequences, e.g. economic loss, disruption to community and public aversion to multiple fatalities, are not reflected in the calculated PLL.
(2) The number of historical landslide catchments are expected to increase at an average rate of about 10 per year. The risk level will further increase with more developments taking place near steep hillsides.

Bayesian updating has been adopted in the frequency model to ensure that due account is taken of the actual performance of the catchments in the NTLI observation period (dating back to pre-1950s), which is much longer than the observation period adopted in the rainfall-landslide correlation (1985 to 2000). Use of Bayesian updating helped to calibrate the estimated frequency of landslides in a catchment with that of the historical landslides in the catchment.

- Consequence model - The concept of travel angle, which is appropriate for man-made slopes, is not suitable for use as an indicator of debris mobility in assessing the consequence of natural terrain landslides, where the facilities at risk are often not close to the source of the landslide and the terrain between the facilities and the landslide source is steeply sloping. A tailored-made consequence model was developed by Wong et al (2004a), which also catered specifically for the possibility of building collapse due to landslides.
- Risk assessment - Integration of the frequency and consequence models gave the landslide risk of each catchment and for each of the affected facilities. The calculation involved a large volume of work involving spatial analysis and was performed on a GIS platform. To ensure the assessments are realistic, the global QRA were calibrated with results from sites where detailed site-specific QRA had been carried out.

The overall risk of natural terrain landslides, based on the state of development in Hong Kong as of 2004, was assessed to be about 5 PLL per year. As shown by the breakdown of the calculated risk (Table 7), the total PLL of the 453 historical landslide catchments was 1.8 per year. This included a contribution of 0.4 PLL per year (i.e. 22%) from the extreme rainfall scenario based on extrapolation. The results showed that the 453 historical landslide catchments constituted about one-third of the overall risk, i.e. the other two-thirds of the overall risk is associated with the supplementary catchments. The risk of the supplementary catchments was projected from analysis of the samples of supplementary catchments in the global QRA using the adopted risk model (Fig.18). This two-thirds of the overall risk was dispersed among a large number of supplementary catchments. Neither the exact locations of these supplementary catchments nor the risk distribution among them were known.

A series of sensitivity analyses were carried out to examine the reliability of the quantified risk results and their sensitivity to the assumptions made in the frequency, consequence and risk models. It was established that the overall risk might range from about 1 to 10 PLL per year, with 5 PLL per year being the best estimate. This range reflected the uncertainties in the assessment.

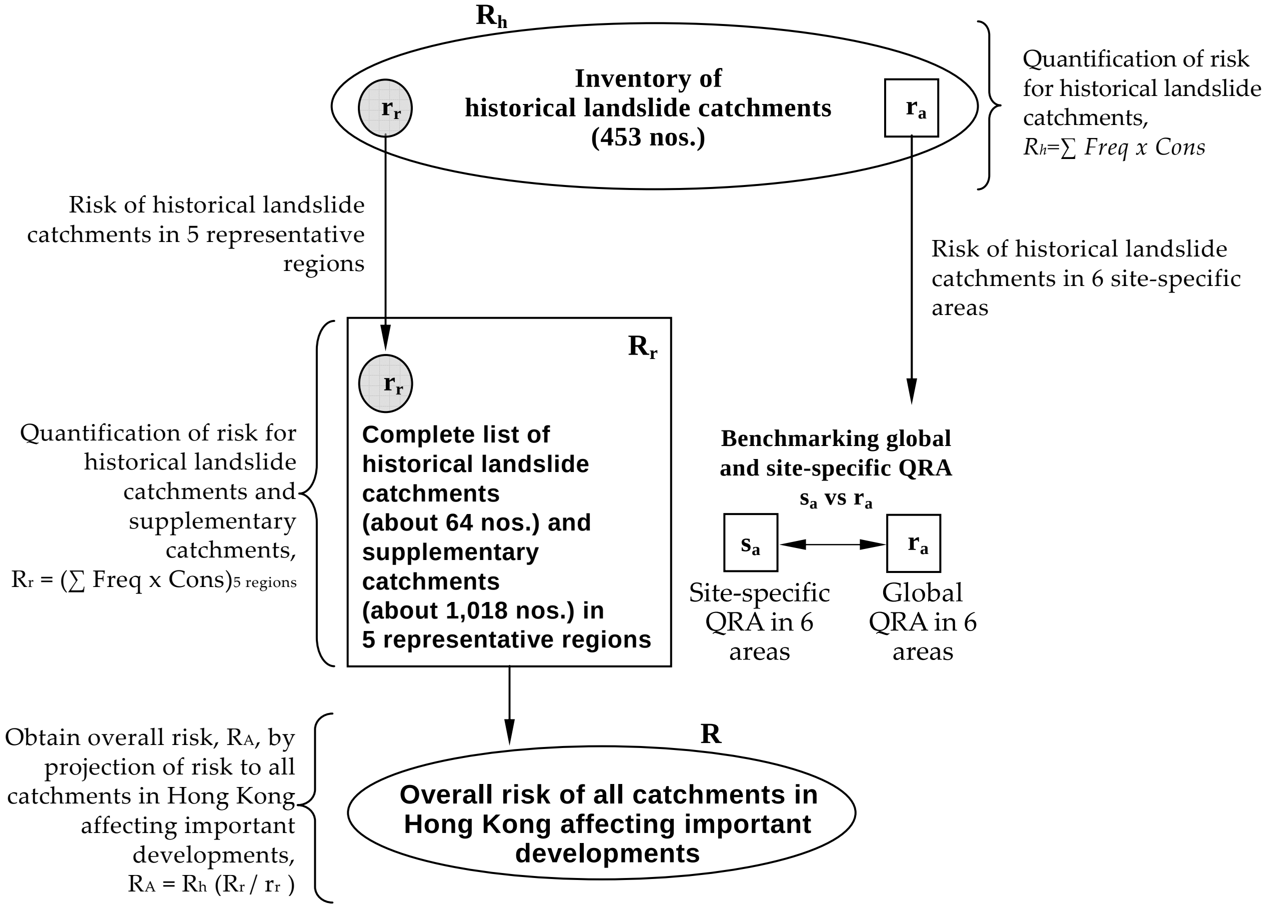


Fig.18 Global QRA model for natural terrain landslides in Hong Kong.

In early 2007, the global QRA for natural hillsides was updated based on the 100,000 historical landslides recorded in the ENTLI. A total of about 2,700 vulnerable catchments were identified.

The key area of improvement in the 2007 update of the global QRA concerns the frequency model. The previously adopted frequency model (Wong et al 2004a) was refined to account for the increase in the number of identified historical natural terrain landslides by (1) incorporating the degree of certainty of relict landslides as identified in the ENTLI to reflect better their actual status, and (2) making allowance for the improved information on the timing of the observation of relict landslides, better recognition of genuine landslides, and adjustment to the landslide magnitude-frequency relationships to reflect the ability of low-flight aerial photographs in identifying landslides that have occurred far back in time and with enhanced accuracy as compared to high-flight aerial photographs used in compiling the NTLI.

The findings from this QRA update indicate that the estimated total natural terrain landslide risk is comparable to that assessed in 2004, i.e. PLL of 5 per year. It is estimated that historical landslide catchments constitutes about half of the total risk from natural hillsides while the remaining half comes from supplementary catchments without known historical landslides.

The landslide risk profile in 2010 is shown in Table 8. An important observation is that the overall landslide risk of natural hillsides will be comparable to that of man-made slopes by 2010. Expanded efforts to mitigate the risk of natural hillsides systematically under the post-2010 LPM Programme, in accordance with the react-to-known-hazard principle, are called for. All in all, the findings from global QRA have provided a rational and consistent basis for formulating an appropriate risk management strategy.

Table 8 Landslide risk profile in year 2010.

	Type of slope	Approximate no.	Proportion of risk	Average annual PLL per slope
Natural hillside	Historical landslide catchments	2700 catchments	~ 25%	9.3×10^{-4}
	Supplementary catchments	Thousands	~ 25%	Not known
Unengineered man-made slopes	Affecting facilities of moderate risk and unplanned structures	12,400 slopes	~ 30%	2.4×10^{-4}
	Affecting facilities of low risk	14,300 slopes	Insignificant	$<7 \times 10^{-6}$
Engineered man-made slopes	by old technology	8,800 slopes	~ 20%	2.3×10^{-4}
	by robust technology	20,900 slopes	Insignificant	$<5 \times 10^{-6}$

Note:

(1) 'Old technology' slopes refer to slopes treated in the early years of setting up Hong Kong's Slope Safety System (typically from late 1970s to late 1980s) based on the geotechnical knowledge and skills at the time. These are less robust than those treated with structural support or reinforcement, such as soil nails.

3.2 Site-specific QRA

Site-specific QRA has mostly been applied to hillsides in Hong Kong, with very limited application to man-made slopes (Ho and Wong 2001). This is because QRA provides a more fitting assessment tool for natural hillsides than the factor of safety approach whereas the latter is an established and effective approach for man-made slopes. The lack of agreed risk criteria for landslide risk from man-made slopes is also a relevant consideration.

Natural hillsides in Hong Kong are susceptible to shallow, small- to-medium-sized landslides (Fig.19), which can develop into debris flows along drainage lines. Should the debris reach densely developed areas, serious consequences may occur even if the volume of the landslide is relatively small. The strategy adopted in Hong Kong for management of natural terrain landslide risk on a site-specific level entails the following two principles (Chan 2003):

- For existing developments, address natural terrain landslide risk following the 'react-to-known-hazard' principle, i.e. to carry out studies and mitigation actions where significant risk becomes evident.
- For new developments, contain the increase in overall risk through studying and undertaking any necessary mitigation actions for sites subject to natural terrain landslide hazards.

Use of QRA as a pragmatic technical tool to study natural terrain landslide risk and determine the required risk mitigation actions was formally introduced in Hong Kong in 2000. Since then, a number of site-specific QRA have been carried out. Typical examples include the Shatin Heights QRA (FMSWJV 2001; Pang et al 2007), the Pat Heung QRA (OAP 2003), the Ling Pei QRA (Wong et al 2004b), the North Lantau Expressway QRA (OAP 2005), the Po Shan QRA (FSWJV 2005) and the Fu Yung Shan Tsuen QRA (Wong and Ko 2006). These involved hillsides of different nature in terms of geological, geomorphological and hydrogeological conditions, as well as different types of facilities at risk. Although these followed in general similar principles with regard to the design of hazard and consequence

Fig.19 Landslide-prone natural terrain in Hong Kong.

models, the QRA methodologies adopted were subject to continuous improvement with a view to enhancing the accuracy of the results. As an illustration, four case examples are presented below.

3.2.1 Po Shan catchment

The hillside catchment above Po Shan Road and its adjacent hillsides in the Mid-levels area of Hong Kong have a long history of instability. A cross section through the catchment is shown in Fig.20. Horizontal drains were installed in the mid-1980s to lower the main groundwater table and improve the stability against potential deep-seated failures. The drains have served their intended purposes in drawing down the main groundwater table and no large-scale instability has occurred on the hillside since. However, in recent years the available monitoring data showed increased piezometric levels in local areas and that some of the horizontal drains have exhibited a decreasing trend of outflow. These are indicative of a deteriorating drain performance. In addition, signs of deterioration of the hillside condition and the failure scars were also evident from site inspections.

In view of the above, the GEO decided to replace the old horizontal drains with more robust landslide preventive works (viz. drainage adits) to prevent deep-seated failures. A site-specific QRA was also carried out to assess the risk of shallow failures (FSWJV 2005; Muir et al 2006).

The QRA aims to quantify the landslide risk arising from the Po Shan catchment to the high-rise residential buildings and the vehicular access road at the foothill. The key tasks comprised the following:

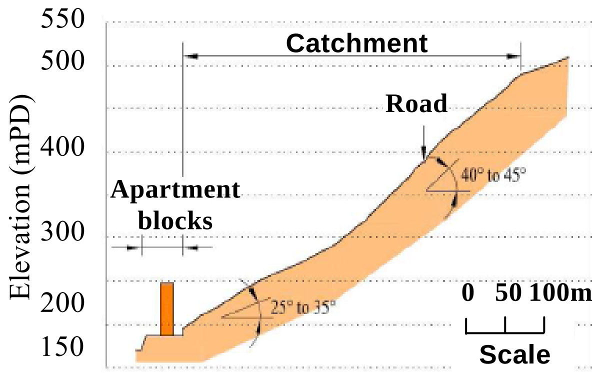


Fig.20 Cross section through catchment (Muir et al 2006).

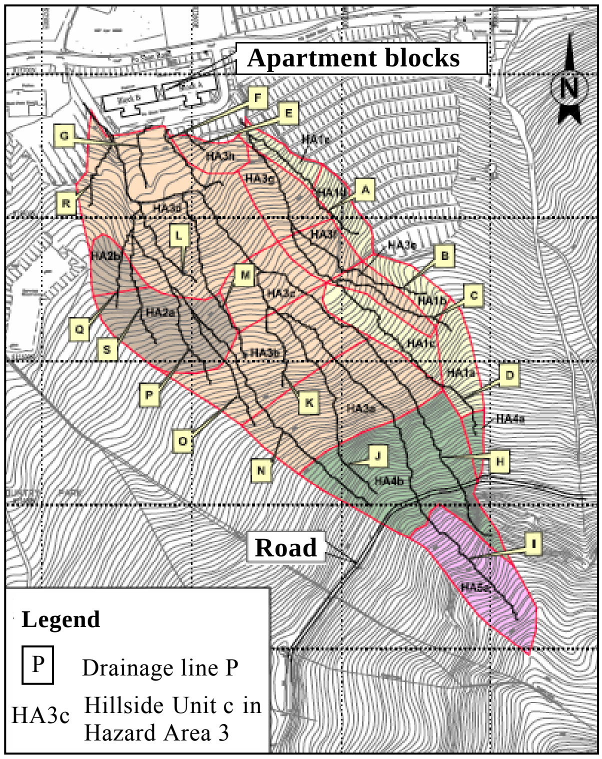


Fig.21 Hazard zones and hillside units (Muir et al 2006).

- Hazard Identification

  Based on a desk study review of the available data, an interpretation of aerial photographs, ground investigation data, together with geological and engineering geological mapping, four main groups of landslide hazards were identified: (1) open hillslope failures; (2) channelised debris flows; (3) rock slides and (4) deep-seated failures. These landslide hazards were classified into four failure scales (i.e. H1 - between 10 m^3 and 200 m^3; H2a - between 200 m^3 and 800 m^3; H2b - between 800 m^3 and 2,000 m^3; and H3 - between 2,000 m^3 and 8,000 m^3).
- Frequency Assessment

  The site was sub-divided into five hazard zones, within each of which the terrain was considered to have a similar potential to generate similar magnitude landslides with a similar frequency of occurrence (Fig.21). Each hazard zone was further sub-divided into smaller hillside units, which were of similar topography and with similar potential to generate landslides travelling along similar runout paths.

A baseline landslide frequency and a magnitude-frequency relationship were assessed for each of the hazard zones from historical landslide data, together with consideration of the available data from the whole of Hong Kong for the hazard zone with a single major relict scar covering more than 50% of the overall surface area of the catchment. The magnitude-frequency model for each of the hazard zones was spatially distributed to the individual hillside units on the basis of relative surface area and an assigned susceptibility factor, which accounts for the local topography, geology of the regolith and geomorphology.

The calculated frequencies of natural terrain landslides for the various hillside units were updated to take account of cases where there was more than one runout path (e.g. bifurcation of a drainage line). An event tree was constructed in such instances to assess the relative likelihood of scenarios following the initiation of a landslide.

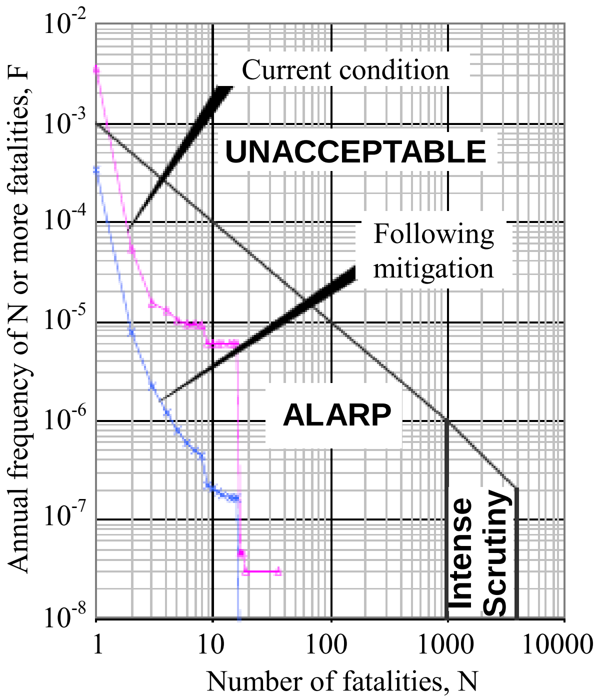


Fig.22 Calculated F-N curve (Muir et al 2006).

- <u>Consequence Assessment</u>

The consequence model adopted largely followed the generalised framework developed by Wong et al (1997), with the use of site-specific runout model and vulnerability factors for different types of facilities, such as car park, lobby and living units. The vulnerability factors were assessed on the basis of a number of important factors, such as landslide volume, debris mobility, location of facilities with respect to the hillside units with a range of debris runout distances, and the degree of protection accorded to individuals by the facilities. Landslide consequence was quantified by multiplying the expected number of people with the relevant vulnerability factor.

A digital elevation model was developed for the catchment using the published 1:1,000 scale digital topographic maps. This was supplemented by site-specific terrestrial survey, which was found to be imperative in achieving the necessary level of detail for the geometry of the drainage lines and hillside depressions, together with localised, sharp changes in topography, which could significantly debris flowpath and runout assessment.

Debris runout modelling was undertaken using the DMM computer program to assess the relative likelihood of debris with different runout distances.

- <u>Risk Calculation and Evaluation</u>

The landslide risk was calculated in terms of Personal Individual Risk (PIR) and societal risk. The results showed that PIR was generally in the order of 10^{-7} for the facilities located along and within Po Shan Road, while the PIR for carpark and driveway were of the order of 10^{-6}. The lobby of the residential building had the highest PIR of 2 x 10^{-4}, which was due to the high degree of exposure of the security guards stationed there. The societal risk for all affected facilities was found to be 3.9×10^{-3} PLL per year. The breakdown of the PLL showed that the landslide risk is unevenly distributed, with one of the five hazard zones contributing about 90% of the total PLL. With respect to volume of failure, about 60% of the PLL is attributed the H2a volume class (viz. 200 m^3 to 800 m^3), i.e. the hazard is derived mainly from fairly sizeable landslide events for this catchment. A notable share of the PLL (about 35%) is derived from the ground floor of the high-rise apartment block. The proportion of societal risk attributable to the scenario involving the total collapse of a portion of the apartment block due to landslides amounted to about 4% of the total PLL, i.e. not a significant proportion of the overall risk.

The calculated F-N curve is shown in Fig.22. Based on the interim risk criteria, both PIR and societal risk fell within the unacceptable zone and mitigation measures were considered necessary to reduce the landslide risk to within the ALARP region.

- Risk Mitigation Strategy

  Three mitigation strategies were considered: (1) construction of defensive measures, such as tensioned wire mesh or check dam or containment structure; (2) construction of stabilisation measures, such as soil nails, rock dowels or bolts and raking drains; (3) construction of a combination of defensive and stabilisation measures. Consideration was given to the capital costs, life-cycle costs, environmental considerations, aesthetic performance and maintenance requirements. The adopted solution comprised a combination of defensive and stabilisation measures, with stabilisation measures (soil nails, rock slope treatment works and bioengineering measures) within the hazard zone making a significant contribution to the overall risk and a flexible debris barrier within the lower reaches of the catchment to reduce the potential for debris reaching the vulnerable facilities downslope. The risk mitigation was found to be justifiable from a cost-benefit analysis. After risk mitigation, the PIR distribution and F-N curve would be well below the unacceptable zone.

3.2.2 North Lantau Expressway

The North Lantau Expressway is the sole vehicular access to the Hong Kong International Airport and the adjacent Tung Chung New Town in Lantau. It comprises a dual three-lane expressway that runs for about 20 km along the toe of the steep natural hillside of north Lantau. The hillside has numerous records of historical natural terrain failures, some of which have reached the present alignment of the expressway.

A qualitative hazard assessment was carried out (Ng and Wong 2002). The assessment included a review of the historical landslide records, appraisal of the geological and terrain conditions, consideration of historical landslide activities, proximity of the expressway to the hillsides and empirical debris runout data. On this basis, a 4 km long section of the expressway near the Tung Chung New Town (Fig.23) was considered to warrant further detailed study with the use of formal QRA technique. The findings of the QRA are documented in OAP (2005).

The QRA followed the procedures and techniques developed and adopted in previous QRA in Hong Kong. Three aspects of this QRA deserve attention:

- The natural hillsides to be assessed covered a large area and involved more variable geological conditions and landslide types. Hence, in this QRA, particular attention was given to the geological assessment of the terrain morphology and landslide process, which formed an integral part of hazard identification and frequency assessment. The information was synthesized into detailed morphology-based regolith maps and landslide process models.
- The expressway was located at some distance from the steep natural hillsides and was partly protected by buffer zones, which included open spaces, road reserves and drainage ditches and chambers. The QRA showed that both PIR and societal risk in terms of

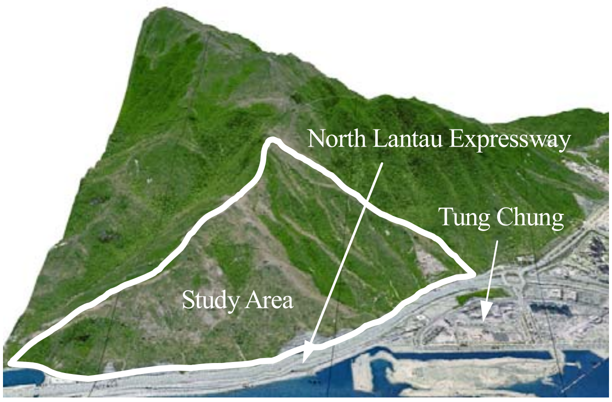
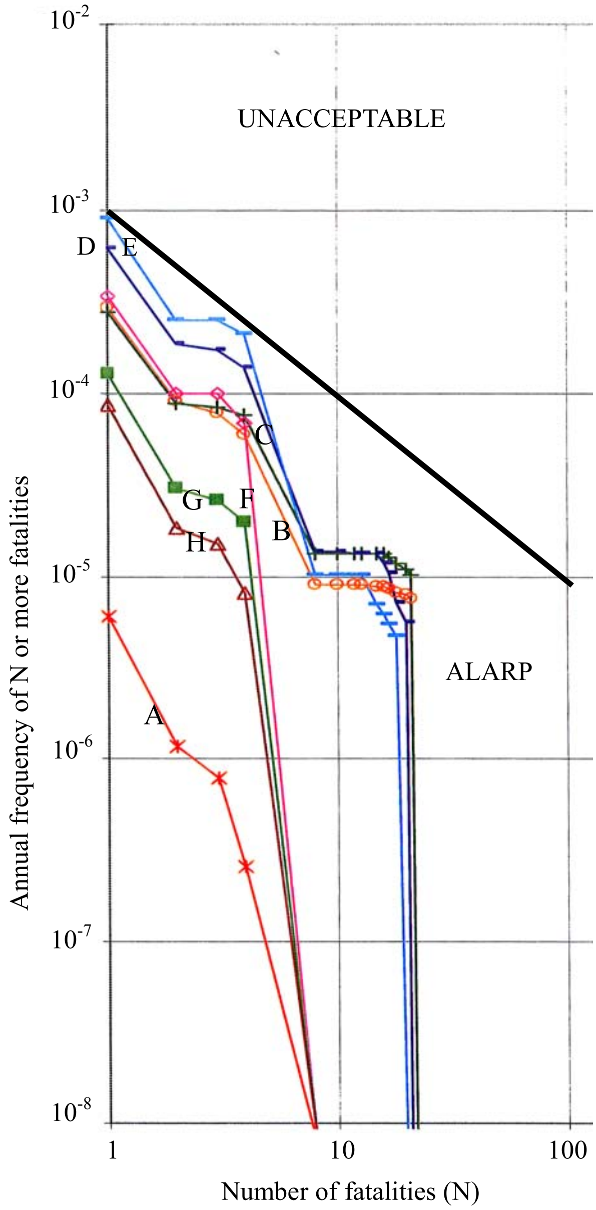


Fig.23 Natural hillside overlooking North Lantau Expressway.

risk-to-life were not in the unacceptable zone. The PIR for the most affected persons (i.e. bus drivers) was found to be 1.7 x 10^{-7} per year, which is well within the acceptable limit of 10^{-4} for an existing facility. For societal risk, the total calculated PLL is 6.8 x 10^{-3} per year, which came principally from channelised debris flows. The F-N curves for the eight sections (each of 500 m length) of the expressway were all within the ALARP region (Fig.24).

- While risk-to-life was found to be in the ALARP region, it was perceivable that the potential economic losses arising from landslides could be significant. This was confirmed by quantifying the risk in respect of different types of economic loss. The total potential economic loss was found to be about HK$450 million over 120 years.

The preferred risk mitigation scheme comprised provision of check dam basins at six vulnerable debris flow channels. The cost of the mitigation works was about HK$30 million. Based on the ALARP principle, the maximum justifiable expenditure for mitigating loss of life alone was found to be within HK$25 million, which was less than the cost of the preferred scheme. However, with account also taken of the significant potential economic losses, risk mitigation was considered justified. This case illustrates that for major infrastructures, potential economic losses due to landslides can be substantial and may have significant effects on the cost-benefit analysis.



Legend:

A - Chainage 0-500 m
B - Chainage 501-1000 m
C - Chainage 1001-1500 m
D - Chainage 1501-2000 m
E - Chainage 2001-2500 m
F - Chainage 2501-3000 m
G - Chainage 3001-3500 m
H - Chainage 3501-4000 m

Fig.24 Calculated F-N curves for North Lantau Expressway (OAP 2005).

3.2.3 Ling Pei

In 2004, a land-use concept plan was drafted by the Planning Department of the Hong Kong SAR Government to guide the future development of the Ling Pei area in Tung Chung. The planned development comprised the construction of 76 nos. 3-storey houses at the toe of the hillside that flanks the existing Ling Pei village (Fig.25). Wong et al (2004b) carried out a QRA to quantify the risk and evaluate risk tolerability. This case was a notable development in the application of landslide QRA in Hong Kong in respect of the following respects:

- This case study extended the application of formal landslide QRA to land-use and development planning at a specific site.

- As an attempt to standardise the QRA process and further improve the practice of QRA for natural terrain landslides, 16 key modules of work were identified (Table 9). The Ling Pei QRA served as a reference case that was aligned with the 16 key modules of work.

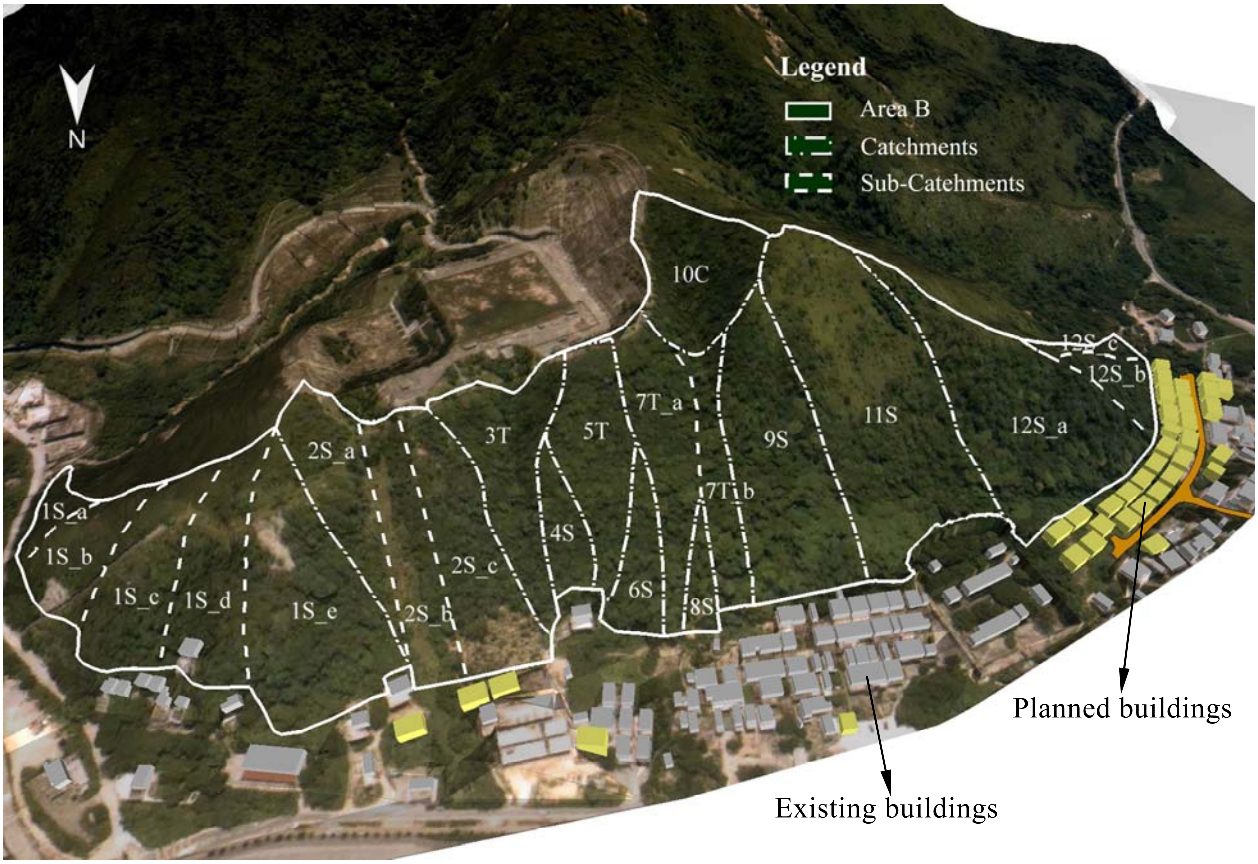


Fig.25 Catchments and Sub-catchments in Area B, Ling Pei (Wong et al 2004b).

Table 9 Key modules of work in natural terrain landslide QRA (based on Wong 2005).

Module of Work	Scope
(1) Determine study objectives and approach	– Identify the background and purposes of the study, and any special requirements – Determine the objectives and the level of details required – Select the approaches to be adopted
(2) Delineate study area	– Identify the extent of the site that may be at risk from landslide hazards – Set out the extent of the study area
(3) Validate historical landslides	– Collate information on historical landslides based on documentary records, aerial photograph interpretation, and findings from field mapping and geomorphological assessment – Validate the data and compile a dataset of landslides and related attributes
(4) Examine rainfall records and effects	– Collate information on the rainfall history – Examine any relevant rainfall-landslide pattern/correlation – Establish any need to adjust Figures on the historical landslide activity to account for rainfall effects
(5) Demarcate boundaries and types of catchments	– Delineate the boundaries of catchments – Sub-divide the catchments where necessary, e.g. based on topographic conditions and mechanism of debris movement – Match the catchments with the facilities at risk
(6) Identify facilities and population at	– Identify the types and locations of the facilities at risk – Establish degree of usage and temporal distribution of population at risk

risk, and their degree of proximity	– Examine degree of proximity with reference to GEO's screening criteria, empirical models, relevant historical runout data, etc.

Table 9 Key modules of work in natural terrain landslide QRA (based on Wong 2005) (Con't).

Module of Work	Scope
(7) Geological assessment	– Carry out field mapping to establish the engineering geological and geomorphological conditions – Examine landslide processes and mechanisms, regolith type and distribution, signs of distress, and other relevant terrain attributes – Classify terrain, and develop geological and landslide process models
(8) Formulate hazard and hazard models	– Identify potential landslide hazards and the relevant hazard scenarios that require risk quantification – Formulate hazard models for use in QRA and in assessment of Design Events
(9) Identify possible debris runout paths and influence zones	– Divide potential landslide sources into cells – Identify possible debris runout paths for each cell – Match the cells with the facilities at risk – Assess the degree of proximity and the degree of damage to the facilities at risk
(10) Carry out frequency assessment	– Formulate frequency model – Establish the frequencies of occurrence of different types of hazard – Assess the spatial distribution of the landslide frequency, together with the use of susceptibility analysis and Bayesian methodology as appropriate – Assess the frequency of occurrence of special hazard scenarios, e.g. building collapse and events with knock-on effects
(11) Carry out consequence assessment	– Formulate consequence model – Assess the consequence of occurrence of different types of hazards – Assess the consequence of occurrence of special hazard scenarios, e.g. building collapse and events with knock-on effects
(12) Analyze risk	– Calculate the risk by integrating frequency and consequence models – Evaluate the distribution of risk – Carry out sensitivity analysis and examine the reliability of the findings of the risk analysis
(13) Assess design events	– Assess the magnitudes of Design Events
(14) Evaluate risk management strategy	– Compare risk results with risk criteria – Formulate possible risk management options – Evaluate the pros and cons of different risk management options and identify the preferred risk management strategy – Interact with and obtain feedback from stakeholders
(15) Draw conclusion and recommendation	– Conclude the findings of the study – Recommend risk management strategy and follow-up actions
(16) Document findings	– Document the findings of the study – Update the relevant documentary and digital records

- As part of the work, further enhancements of site-specific QRA techniques were made. The enhancements helped to improve the rigor of the assessment and to overcome some known technical problems that have been encountered in previous QRA.

The procedures for the QRA and the key findings are summarized below, under the headings of the relevant modules of work:

- Study objectives, approach and area (Modules 1 & 2)
  The study served to assess the risk on the planned development and guide the development strategy. The hillside that flanked the planned buildings is denoted as Area B in Fig.26. As good practice in site-specific QRA of natural terrain landslides, a larger region was studied for a thorough examination of the landslide process and characteristics in the area (i.e. Areas A to D in Fig.26).

- Landslide history and rainfall effects (Modules 3 & 4)
  Historical landslide activities and characteristics in the area were evaluated from an interpretation of aerial photographs, field inspections and geomorphological mapping. A total of 91 recent natural terrain landslides (five of which are in Area B) and five large relict

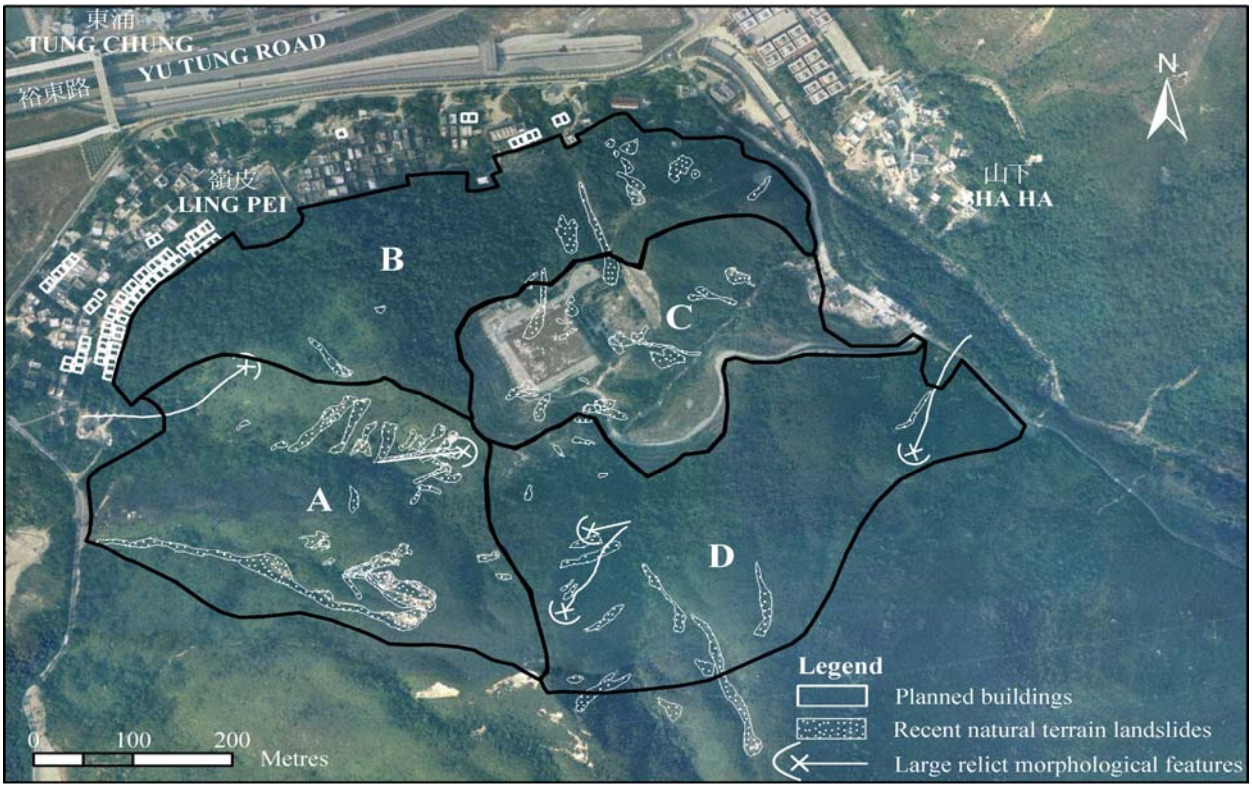


Fig.26 Historical landslides in Ling Pei (Wong et al 2004b).

  landslide-related morphological features (none of which is in Area B) were identified (Fig.26). The correlations of natural terrain landslide density with normalized rainfall intensity in Hong Kong established by Ko (2003) and Wong et al (2004a) were applied to the site. The landslide and rainfall histories at the site were found to be broadly consistent with the Hong Kong-wide trend, and that the available historical landslide data in Area B gave a reasonably conservative baseline value for use in frequency assessment.
- Catchment and facility identification (Modules 5 & 6)
  The topographic conditions of the hillside was assessed with the use of a 2-m grid digital elevation model, together with terrain evaluation based on field mapping and interpretation of aerial photographs. This resulted in demarcating the hillside in Area B into a total of 21 sub-catchments (Fig.25), with account taken of the topography and layout of the planned buildings. The sub-catchments were classified into three types according to the mechanisms of debris movement (Table 10).
- Geological assessment and hazard identification (Modules 7 & 8)
  The geological assessment comprised geological mapping, investigation and appraisal to establish the landslide processes at the site, examine the landslide mechanisms, classify the terrain, formulate geological models and diagnose possible hazards. The work provided a technical basis for formulating the terrain and hazard models. Two types of terrain were identified, namely Type A (with weathered rocks at a steep slope gradient located in the vicinity of heads of drainage lines or local topographic depressions where there is no

significant variation in slope gradient) and Type B (relatively more irregular slope profile with colluvium overlying weathered rocks).

The hazard model entailed classification of hazards according to the total volume of failure (4 volume range classes) and mechanism of debris movement (viz. open hillslope failure, channelised debris flow and mixed debris flow/avalanche at topographic depression).

Table 10 Hazard classification for the Ling Pei QRA.

Hazard	Classification	Definition
Mechanism of debris movement (as related to catchment characteristics)	C	Channelised debris flow
	T	Mixed debris flow/ avalanche along topographic depression
	S	Open hillslope debris slide /avalanche
Scale of landslide (different magnitude-frequency relationships have been derived for different types of catchments, viz. C, T and S)	H1a	20 m^3 to 60 m^3
	H1b	>60 m^3 to 200 m^3
	H2a	>200 m^3 to 600 m^3
	H2b	>600 m^3 to 2,000 m^3

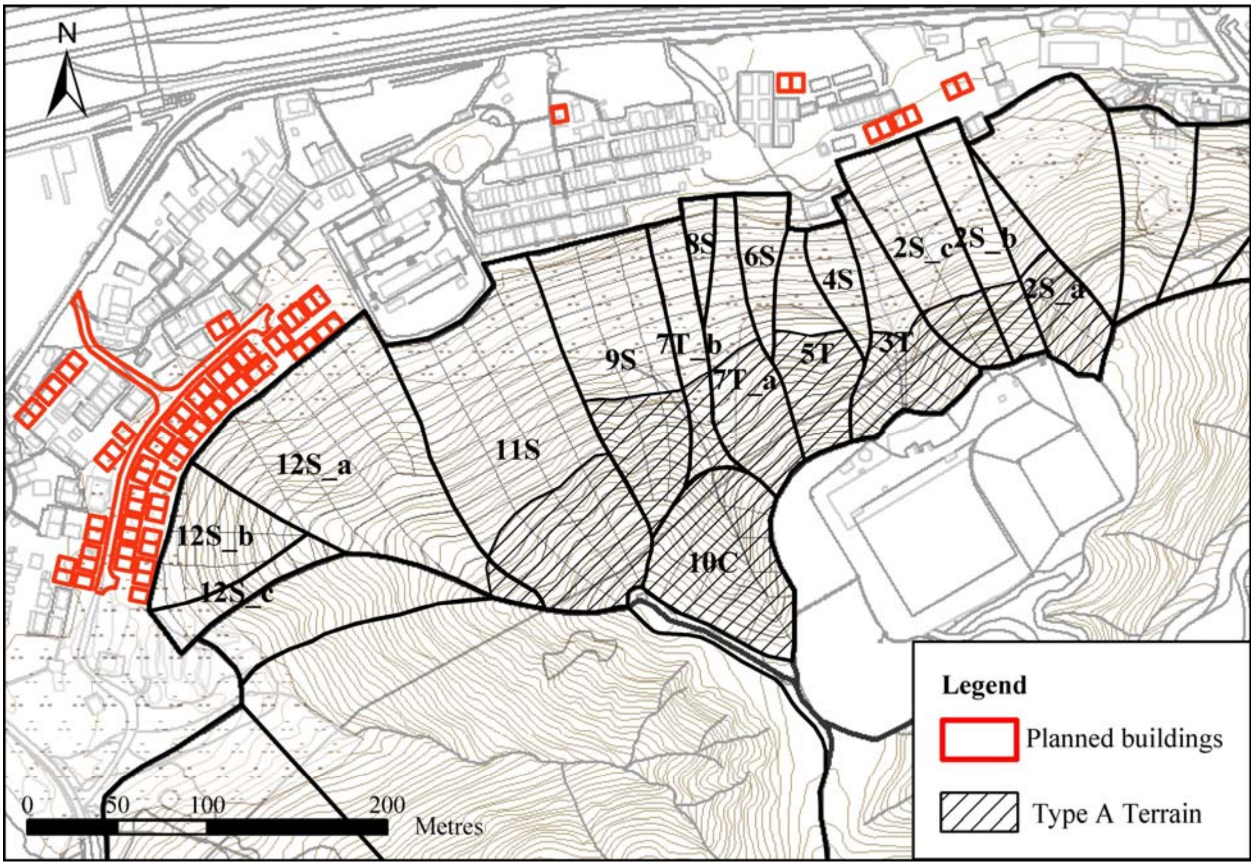


Fig.27 Hillside units (Wong et al 2004b).

- <u>Debris runout path and influence zone</u> (Module 9)
  There are two main aspects of evaluation of debris runout for use in consequence assessment. Firstly, the mobility of the landslide debris has to be assessed. In the Ling Pei site, this was done by statistical analysis of the historical debris runout data. The empirical runout model entails the definition of a worst credible runout distance for each hazard type and the

assumption of a double-triangular probability distribution of debris mobility, based on the use of a mean runout distance, which was taken to be half the worst credible runout distance. Secondly, the debris runout path has to be predicted. To do so, sub-catchments in Area B were further divided into small hillside units (Fig.27). Each hillside unit should have practically the same landslide susceptibility and debris runout path. Based on 3-D GIS

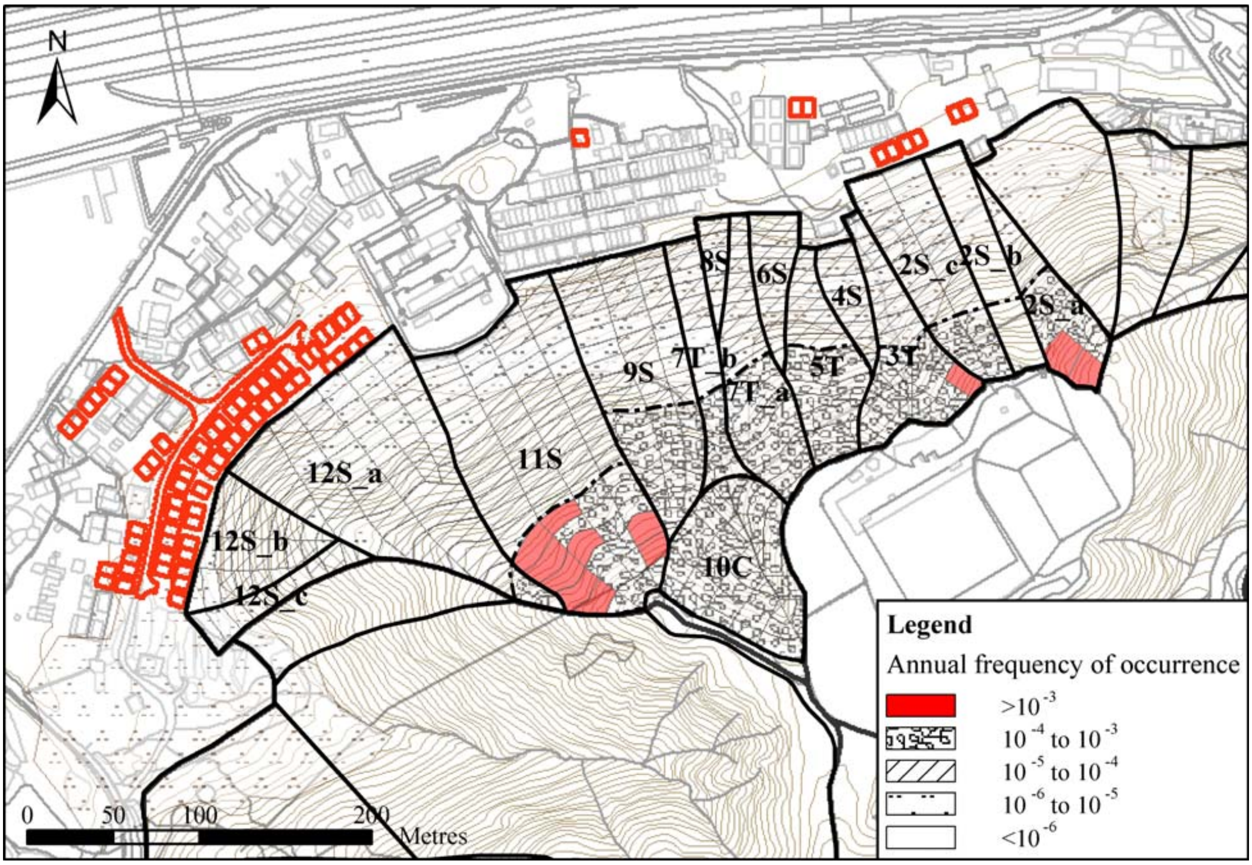
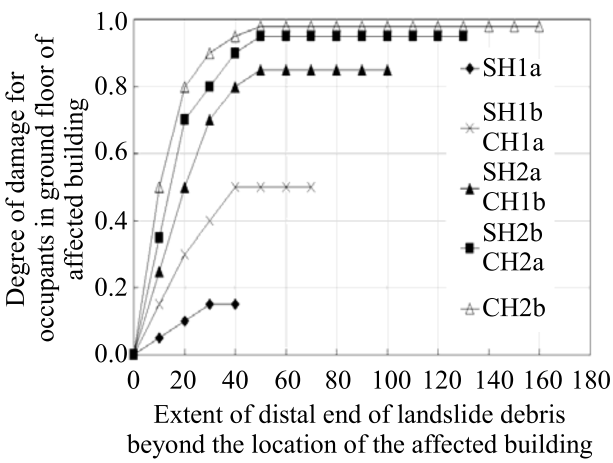


Fig.28 Calculated annual frequency of landslide hazard H1a (20 m^3 to 60 m^3) (Wong et al 2004b).

analysis and terrain evaluation, the possible debris runout paths originating from each hillside unit were determined. Each unit was then matched with the segments of the lower boundary of the catchments, and with the existing and planned houses. An event tree methodology was adopted in the matching to cater for the uncertainties in predicting the debris flow paths where a hillside unit may result in more than one possible debris flow path.

- Frequency assessment (Module 10)
  This followed standard magnitude-frequency correlation and spatial distribution of the baseline landslide densities to each hillside unit via a susceptibility analysis (Fig.28). In this QRA, different susceptibility models



Note: Different hazards, SH1a, CH2b, etc., are defined in Table 10.

Fig.29 Degree of damage for occupants in ground floor of affected buildings.

were adopted for two different terrain types, to cater for the fact that their landslide processes were different. Bayesian updating of the theoretical landslide density was carried out to account for the actual performance of the hillside in the past 50 years to derive the estimated landslide density for each hillside unit and hence the landslide frequency (= landslide density x plan area of hillside unit). For each hillside unit, the frequency of occurrence of a given hazard type was calculated by applying the magnitude-frequency relationship to the estimated

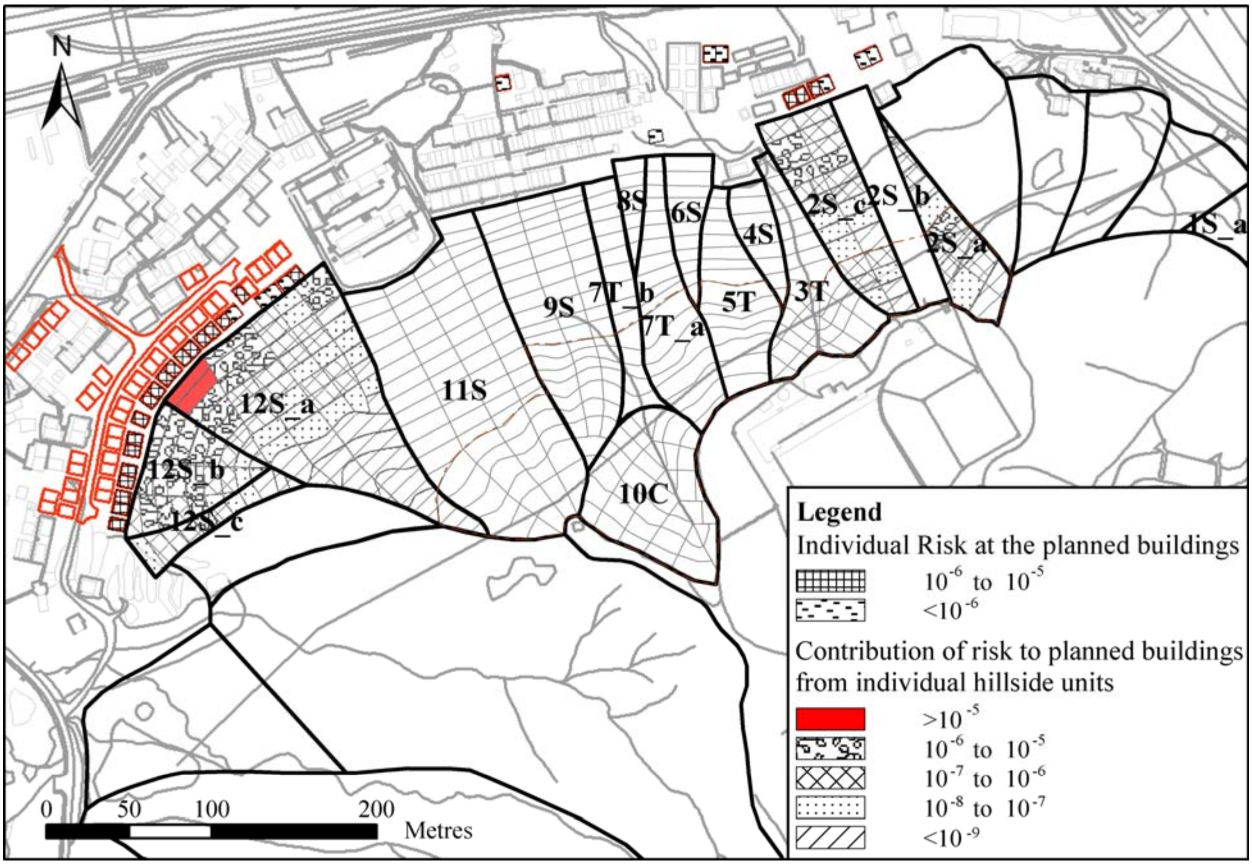


Fig.30 Individual Risk at planned buildings (Wong et al 2004b).

landslide frequency.

- <u>Consequence assessment</u> (Module 11)
  An enhanced consequence model, which incorporated consideration of the hazard type, runout mechanism, runout path, debris mobility and vulnerability factor, was developed for use in this QRA. The relevant vulnerability factors for the buildings were derived by integrating the probabilistic function of debris runout distance for the different hazard type and the degree of damage (as defined by a damage model), which is a function of the distance that the distal end of debris would travel beyond the location of the building (Fig.29).
- <u>Risk analysis and evaluation</u> (Modules 12 &13)
  The assessments and risk integration were carried out on a GIS platform. The calculated PIR of an individual in the planned buildings ranged from 3.3×10^{-7} to 8.9×10^{-6} per year (Fig.30), which was within the maximum permissible level of 10^{-5} per year for new developments (ERM 1998). The societal risk for the planned houses was 1.8×10^{-4} PLL per year. The corresponding F-N curve (Fig.31) was within the ALARP zone. Allowance was made for the possibility of concurrent occurrence of landslides in Area B in the F-N curve. In view of the uncertainty in assessing the probability of concurrent occurrence of landslides, the upper bounds of the two F-N curves were considered in the evaluation of risk tolerability.

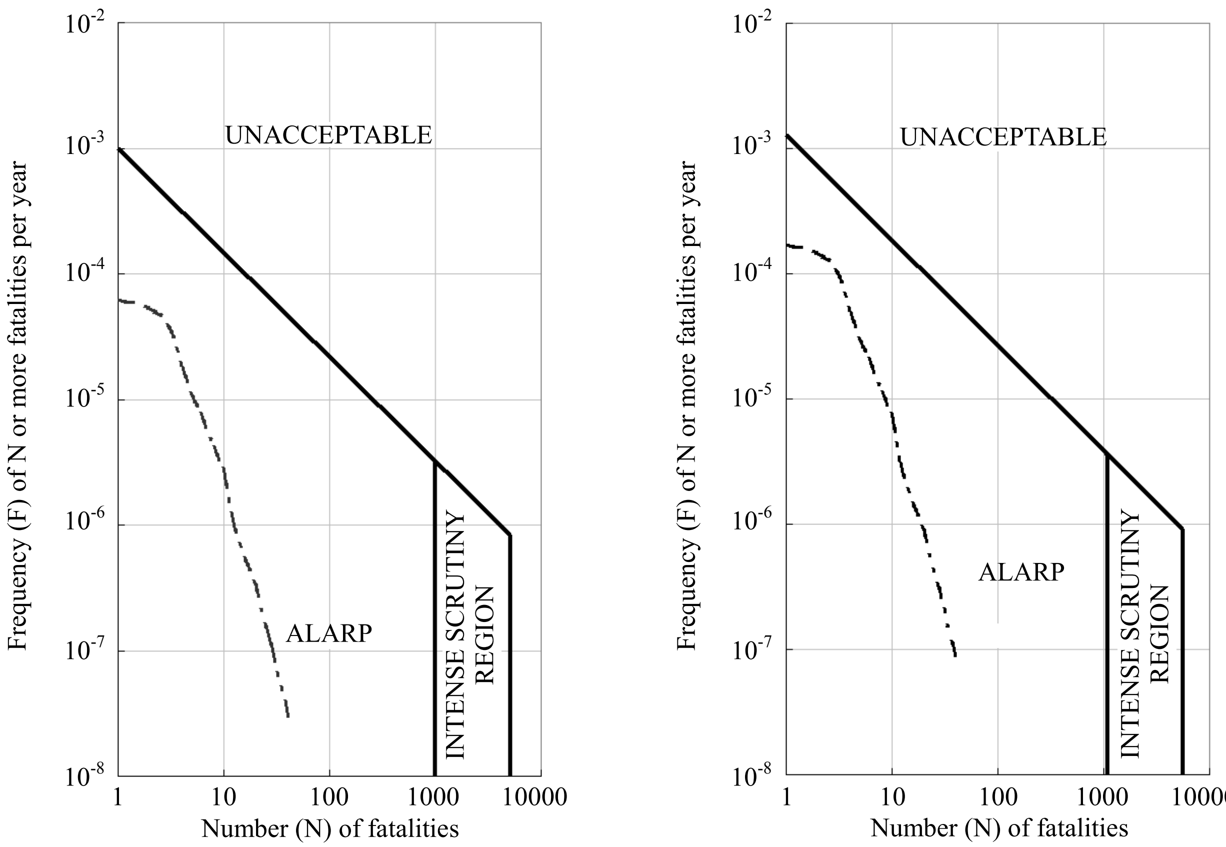
The PIR on the existing houses was also assessed and found to be within the maximum permissible level. The societal risk on the existing houses was 4.3 x 10^{-4} PLL per year. Hence, the planned development would result in more than 60% increase in societal risk. The F-N curve of the total societal risk for both the existing and planned houses was also within the ALARP zone (Fig.31).

- Risk management strategy (Module 14)
  The maximum justifiable expenditure calculated from the ALARP principle was found to be about HK$0.8 million. With this order of maximum expenditure, adopting extensive slope stabilisation measures (e.g. soil nailing) and provision of heavy-duty debris-retaining structures would not be practical. Two possible risk mitigation options were proposed (Fig.32), both of which were within the order of the maximum justifiable expenditure. The total cost of the planned houses was assessed to be about HK$250 million. Hence, provision of landslide mitigation measures would only amount to about 0.3% of the total cost.
- Risk communication and documentation (Modules 15 & 16)
  The QRA findings were presented to the stakeholders and the two possible risk mitigation options provide a guide for formulating the development strategy for the site.

Some sample calculations illustrating the key steps of the QRA are presented in Annex A.

3.2.4 Fu Yung Shan Tsuen

In August 2005, a major landslide (debris volume of about 400 m^3) occurred on a disturbed hillside within a squatter village, Fu Yung Shan Tsuen in Tsuen Wan (Fig.33), resulting in one fatality (MGS



(a) For planned buildings

(b) For both existing and planned buildings (Note: Risk criteria scaled up in proportion to the ratio of actual boundary toe length of 560 m to the reference length of 500 m)

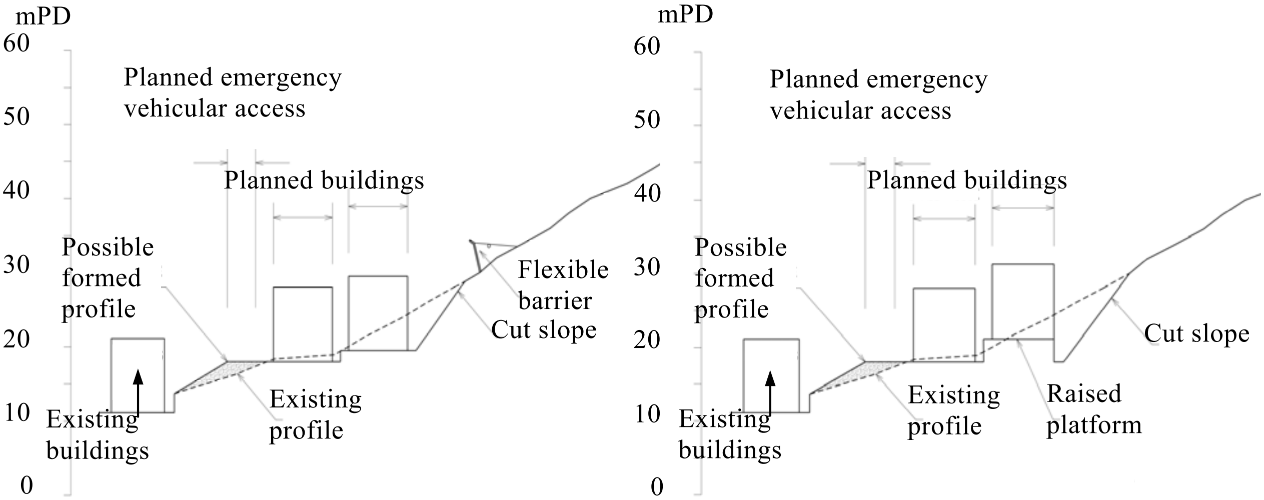
Fig.31 Calculated F-N curves for Ling Pei.

2006). Subsequently, the policy bureau requested the GEO to undertake a QRA of the landslide hazards posed to the squatter area.

The QRA followed in principle the procedures and techniques developed and adopted for man-made slopes and hillsides in previous QRA in Hong Kong. The main differences of this QRA with the previous QRA are as follows:

The landslide risk arises principally from the disturbed hillsides. The frequency models previously adopted are mainly concerned with landslide risk from natural hillsides. Hence, a The QRA followed in principle the procedures and techniques developed and adopted for man-made slopes and hillsides in previous QRA in Hong Kong. The main differences of this QRA with the previous QRA are as follows:

- The landslide risk arises principally from the disturbed hillsides. The frequency models previously adopted are mainly concerned with landslide risk from natural hillsides. Hence, a new frequency model for disturbed hillsides was developed with particular attention to the unfavourable terrain surface conditions (e.g. paved, bare or eroded land with vegetation, cultivation, cut and fill platforms, and refuse distribution), which was pertinent to the landsliding process.



(a) Provision of flexible barriers (b) Raised building platform

Fig.32 Risk mitigation options for Ling Pei.

- The QRA was a combined assessment of the risks from man-made slopes, natural hillsides and disturbed hillsides, as well as the risk of debris flows/debris floods potentially caused by overflow (caused by uphill landslides) from a catchwater channel located above the squatter area. Different frequency and consequence models were developed to account for the different types of slopes/ hillsides and their associated failure mechanisms, susceptibility to failure and debris runout characteristics.

Fig.33 Overview of Fu Yung Shan Tsuen.

The key tasks carried out are detailed by Wong and Ko (2006). The following areas of improvement were made to the QRA model:

- Site-specific frequency model was developed for assessing the risk from man-made slopes (with account taken of the slope type, geometry, condition, history of failure, adverse attributes such as inadequate drainage provision and concentration of surface water, etc.), and natural/disturbed hillsides (with account taken of topography, regolith, geomorphology, geological conditions, degree and type of human disturbance, history of failure, terrain surface condition, etc.). Adjustment to the magnitude-frequency relationships was incorporated in the frequency model to account for the variation in the sizes of the man-made slopes and the hillside catchments (i.e. small slopes or catchments will have low, if not negligible, chance of having large-scale failures).
- The consequence model for hillsides was enhanced in evaluation of debris mobility. The worst credible debris travel distances for different types of hazards were previously determined based on statistical analysis of the historical runout data (Wong et al 2004b). Enhancement was made in this case to allow the worst credible travel

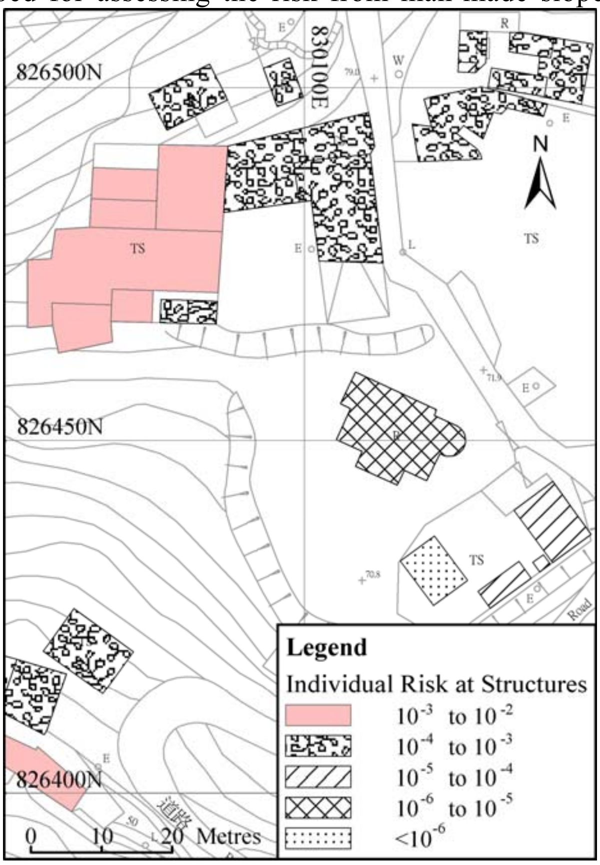


Fig.34 Calculated individual risk levels for a selected area in Fu Yung Shan Tsuen.

distances to be adjusted up or down as appropriate, in accordance with the angular elevation of the facility to the landslide source.

- 3-D numerical modelling was carried out to assess the lateral influence zones along the major drainage lines in the event of channelised debris flows or catchwater overflow and the degree of damage with increasing distance away from the drainage line.

Based on the QRA results (Fig.34), it was concluded that the clearance recommendations made previously by the GEO based on qualitative assessment and engineering judgement are consistent with the findings of the QRA, i.e. the vast majority of the existing structures identified for clearance are exposed to an unacceptably high landslide risk. Also, the clearance recommendations were not unduly conservative by reference to the risk tolerability criteria when benchmarked against the QRA results. Based on the QRA findings, some additional clearance recommendations were made to selected squatter structures.

Open hillslope failures were found to constitute about 68% of the hillside landslide risk, with the remaining associated with channelised debris flows. The relatively high proportion of hillside landslide risk due to open hillslope failures reflects the situation that the existing structures are scattered on steep terrain.

The societal risk and individual risk of the footpath network of the squatter area were found to be much lower than that at the squatter structures. This is consistent with the low pedestrian density and the low temporal probability of presence of an individual person on the footpath network during a rainstorm. The August 2005 landslide, which resulted in one fatality probably on the footpath, was an unfortunate incident in that the deceased was essentially in the ‘wrong’ place at the ‘wrong’ time.

4 DISCUSSION

QRA methodologies have evolved progressive through continued development and enhancement of the technique during QRA applications. A review of the professional practice and development trends of QRA is presented by Wong (2005).

The distinct advantages of QRA over qualitative assessment lie in its ability to quantify risk instead of analyzing risk in relative terms, and in the explicit consideration of risk tolerability and the ALARP principle to provide a rational basis for evaluating the appropriate risk mitigation strategy.

Although the quantified risk Figures should never be taken as precise numbers, it is vital that they should at least be sufficiently reliable and representative for use in risk evaluation and formulation of risk mitigation strategy. Risk quantification in itself does not gaurantee accuracy and reliability. The level of reliability of QRA results depends on the availability of good quality data, use of appropriate methodology, techniques and procedures, rigour of the assessment, realistic calibration of results and involvement of relevant experts to exercise sound engineering judgment.

Sufficient geotechnical, in particular engineering geological, input to hazard identification and classification is essential for risk quantification (Parry et al 2006). Integration of the good practice in geotechnical assessment with a suitable QRA framework is pertinent, as the assessment should be based on an adequate understanding of the landslide processes, potential failure modes and likely debris travel mechanisms. If the landsliding process and the nature of the potential hazards are not properly understood, there is little hope that the landslide risk can be reliably quantified.

Experience in Hong Kong indicates that the QRA results have generally been taken as sufficiently reliable estimates of the landslide risk to support risk management decisions for individual sites. This reflects a general recognition amongst the geotechnical profession that the risk levels assessed by rigourous QRA are consistent with the professional judgement of the scale of the problem, and that the risk mitigation actions found necessary by QRA are reasonable and practical to implement.

QRA is becoming an integral part of the local professional practice in slope engineering and landslide risk mitigation and input from risk analysts is generally not required. Landslide assessment and slope engineering is no longer confined to an investigation of slope stability. The consequence of landslide has to be considered and the landslide risk has to be assessed and evaluated in totality.

This risk-based perspective is fundamental to properly addressing and managing landslide problems. It has also helped to align the geotechnical profession with many other fields that explicitly practice risk management.

5 CONCLUSIONS

The slope safety work in Hong Kong has progressed to a stage whereby the landslide risk is examined and managed in totality. Quantitative risk management is being implemented in Hong Kong to direct its landslide risk management initiatives, which has paid dividends in improving public safety.

QRA has proved to be a versatile and effective tool for tackling a wide range of practical landslide problems. It provides a structured and transparent framework in putting uncertainties and engineering judgement into a system to aid decision-making. This promotes an enhanced awareness of the need to consider uncertainties and what can go wrong.

The worldwide trend of an increasing use of quantitative approach in landslide risk management is evident and this is likely to continue. The successful applications of QRA in Hong Kong has demonstrated the advantages of QRA and helped to refute some of the myths and misconceptions about QRA.

A diverse range of landslide problems has been brought under the agenda of QRA, which provides a structured and rational framework for formulating coherent landslide risk management strategy and a scientific basis for evaluating the risk mitigation options at individual sites, particularly those subject to natural terrain hazards. The challenge is for the geotechnical profession to master the range of QRA techniques and be able to select the right tool for the problem at hand.

More extensive application of QRA to individual sites subject to natural terrain landslide risk is envisaged. The explicit consideration of risk tolerability and the ALARP principle is more defensible and promotes optimisation and enhanced cost-effectiveness. However, it is imperative to ensure that the QRA framework is always based on a sound understanding of the natural terrain landslide process and failure mechanisms. Adequate geotechnical and engineering geological input is of the essence.

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Annex A

Sample Calculations for QRA of Natural Hillsides

A. INTRODUCTION

Sample calculations are presented for a hypothetical and simplified case to illustrate the key steps involved in a QRA.

B. SCOPE DEFINITION

For the hypothetical case below, the following are to be evaluated:

(a) Personal Individual Risk at the house;
(b) Societal Risk in terms of Potential Loss of Life (PLL) and F-N curve; and
(c) risk tolerability.

C. INFORMATION

C.1 Information for assessing landslide frequency

A 10 m square single-storey house is located at the toe of a 40 m high by 100 m wide planar hillside that has a gradient of 1 vertical : 2 horizontal (see Fig.A1).

Based on geological mapping and assessment of historical landslide records, it is established that the subject hillside has the following overall frequency of open hillslope landslides:

- Small scale landslides (volume within 50 m^3)
  = 1 no./year
- Large scale landslides (volume between 50 and 500 m^3)
  = 0.1 no./year (i.e. once every 10 year)

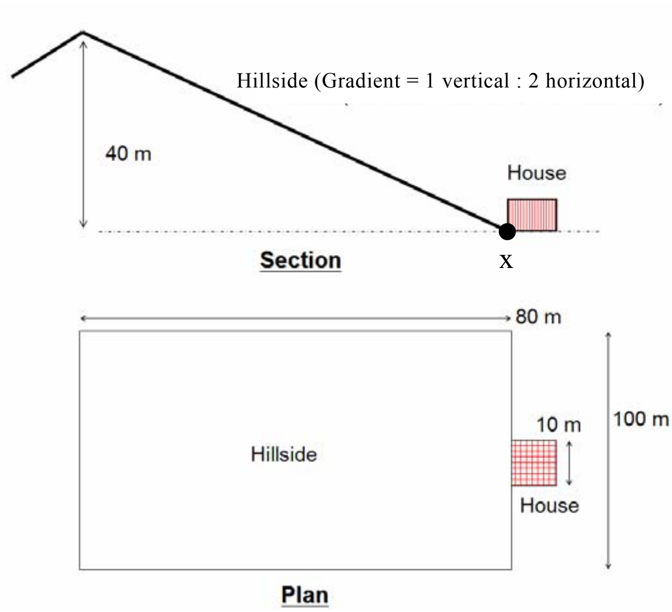


Fig.A1 Site setting.

C.2 Information for assessing consequence

Based on debris mobility analysis and empirical debris runout data, the probability distribution of debris runout distance (in plan) is taken to be as follows:

Horizontal runout distance (m)	Probability of debris runout	
	Small scale landslides	Large scale landslides
20	90%	40%
40	10%	60%

The affected house has a total of 4 occupants. The distribution of their temporal presence is as follows (for this simplified sample calculation, the probability of temporal presence of visitors in the house is not considered):

Time	8 am to 2 pm (6 hours/day)	2 pm to 8 pm (6 hours/day)	8 pm to 8 am (12 hours/day)
No. of people	1	3	4
Probability of temporal presence, P_p	0.25	0.25	0.5

Vulnerability factors are shown in Fig.A2.

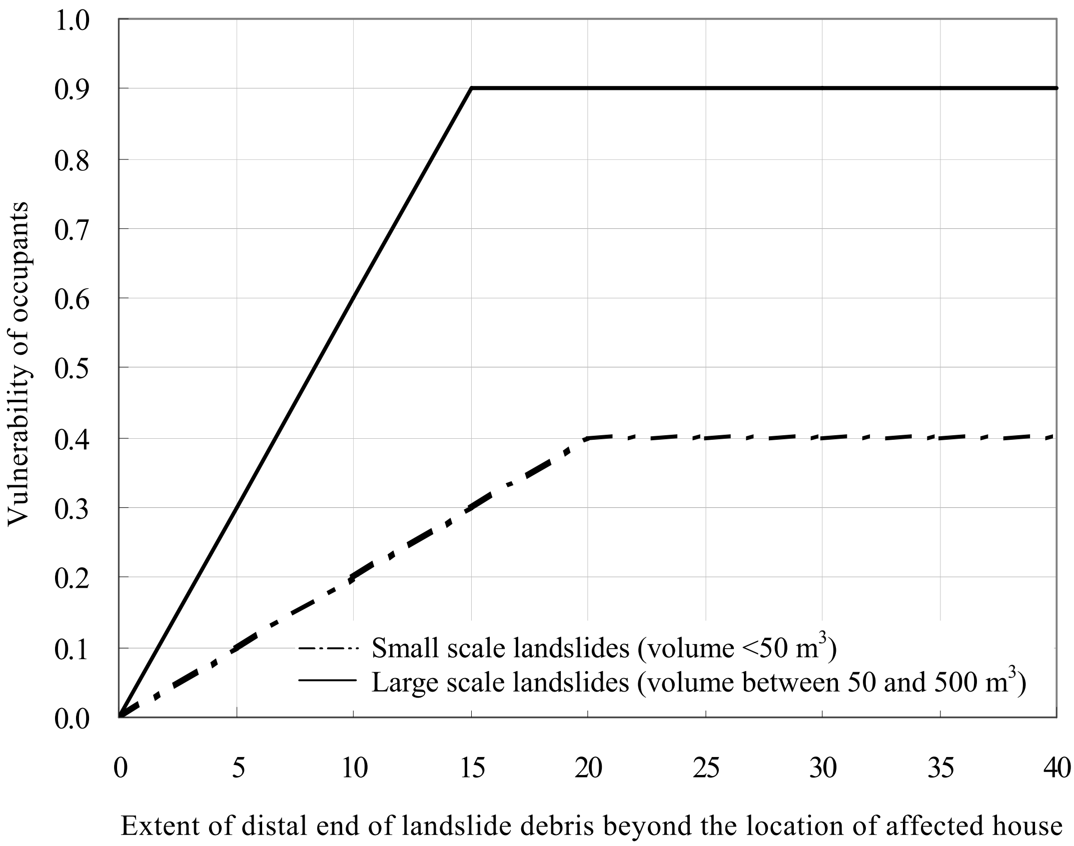


Fig.A2 Vulnerability factors for occupants in the house.

D. ANALYSIS OF FREQUENCY AND CONSEQUENCE

D.1 Hazard identification and frequency assessment

As only open hillslope failure is involved, it may be assumed for the present purposes that the house is at risk from a 10 m wide strip of the hillside which is directly flanking the house. The hazard model comprises 2 hazards, viz. open hillslope failure of <50 m^3 and open hillslope failure of 50 m^3 to 500 m^3 respectively. This strip of the hillside is divided into 5 zones, namely A to E, as shown in Fig.A3.

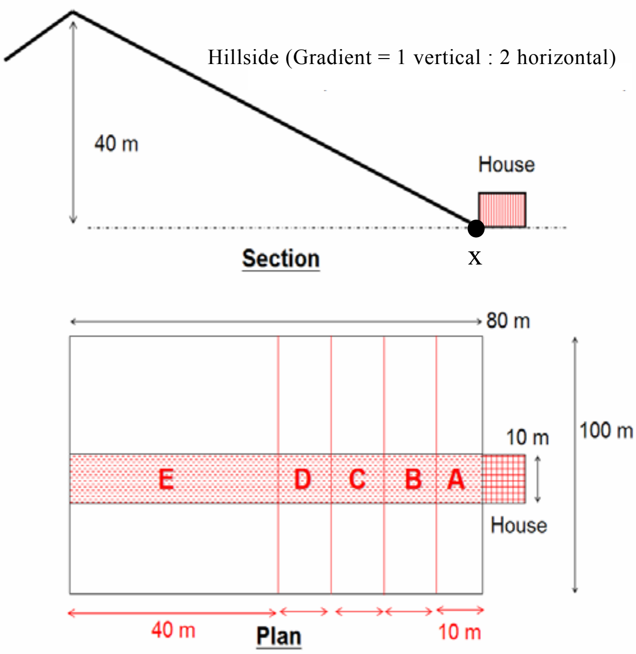


Fig.A3 Hazard identification.

As Zone E has a horizontal distance exceeding 40 m from the house, it is not posing any risk (see C.2 above).

The overall frequency of failure across the entire hillside needs to be spatially distributed to each of the different zones. Assuming that the hillside condition is uniform in all aspects in terms of its susceptibility to failure (e.g. gradient, geology, geomorphology, etc.), the overall failure frequency may be distributed in proportion to the relative areas and a detailed susceptibility analysis is not needed in this case.

The frequencies of landslide at each of the four zones (A to D) are calculated as follows:

- Frequency of small scale landslide
  = [(10 × 10) / (100 × 80)] × 1 (overall annual frequency of failures)
  = 1.25% × 1
  = <u>0.0125 no./year</u>

- Frequency of large scale landslide
  = [(10 × 10) / (100 × 80)] × 0.1 (overall annual frequency of failures)
  = 1.25% × 0.1
  = <u>0.00125 no./year</u>

Following the above frequency calculation for different scales of landslides (i.e. small and large scale failures), the full results are tabulated below:

Zone	Frequency of landslide, f (no./year)	
	Small scale	Large scale
A	0.0125	-
	-	0.00125
B	0.0125	-
	-	0.00125
C	0.0125	-
	-	0.00125
D	0.0125	-
	-	0.00125

D.2 Landslide consequence

(a) Debris mobility

The probability distribution of debris mobility for both small and large scale landslides is given in the table in C.2.

(b) Vulnerability of occupants at risk in the house

The vulnerability of occupants at risk in the house with respect to both small and large scale landslides is assessed from Fig.A2.

The vulnerability factors are dependent on how far the given landslide debris would travel past the house. A greater travel distance would mean that the impact of landslide debris on the house will be more severe causing more damage to the occupants at risk, hence a higher vulnerability factor is relevant in this event. The travel distance is measured from the centre of each hillside zone to the distal end of the landslide debris for a given landslide hazard.

(c) Expected number of occupants at risk, N_a

From the population information in C.2, the expected (average) number of occupants at risk in the house, N_a
= 1 x 25% + 3 x 25% + 4 x 50%
= <u>3</u>

(d) Consequence analysis

The consequence of landslides is determined based on the information from (a) to (c) above.

The consequence is calculated as follows:
Consequence = Probability of debris runout (P) × Vulnerability (V)

The relevant information is tabulated below:

Zone	Frequency of landslide, f (no./year)		Debris mobility		Mean distance of zone to house (m)	Runout distance beyond point x (Fig.A1) (m)	Vulnerability factor, V
	Small scale	Large scale	Runout distance (m)	Probability, P			
A	0.0125	-	20	0.9	5	15	0.3
			40	0.1		35	0.4
	-	0.00125	20	0.4		15	0.9
			40	0.6		35	0.9
B	0.0125	-	20	0.9	15	5	0.1
			40	0.1		25	0.4
	-	0.00125	20	0.4		5	0.3
			40	0.6		25	0.9
C	0.0125	-	20	0.9	25	-	-
			40	0.1		15	0.3
	-	0.00125	20	0.4		-	-
			40	0.6		15	0.9
D	0.0125	-	20	0.9	35	-	-
			40	0.1		5	0.1
	-	0.00125	20	0.4		-	-
			40	0.6		5	0.3

D.3 Risk summation

Risk analysis is carried out as follows:

Individual Risk = $\Sigma \{f\}_{ij} \{P\}_i \{V\}_i$

Societal Risk = $\Sigma N_a [\{f\}_{ij} \{P\}_i \{V\}_i]$

where N_a denotes expected number of occupants at risk
f denotes frequency of landslide
P denotes probability of reach of debris
V denotes vulnerability

The risk calculation is tabulated below:

Zone	Frequency of landslide, f (no./year)		Debris mobility		Mean distance of zone to house (m)	Runout distance beyond house (m)	Vulnerability factor, V	Individual Risk = (f)(P)(V)	Societal Risk = N_a[(f)(P)(V)]
	Small scale	Large scale	Runout distance (m)	Prob., P					
A	0.0125	-	20	0.9	5	15	0.3	0.003375	0.010125
			40	0.1		35	0.4	0.000500	0.001500
	-	0.00125	20	0.4		15	0.9	0.000450	0.001350
			40	0.6		35	0.9	0.000675	0.002025
B	0.0125	-	20	0.9	15	5	0.1	0.001125	0.003375
			40	0.1		25	0.4	0.000500	0.001500
	-	0.00125	20	0.4		5	0.3	0.000150	0.000450
			40	0.6		25	0.9	0.000675	0.002025
C	0.0125	-	20	0.9	25	-	-	0	0
			40	0.1		15	0.3	0.000375	0.001125
	-	0.00125	20	0.4		-	-	0	0
			40	0.6		15	0.9	0.000675	0.002025
D	0.0125	-	20	0.9	35	-	-	0	0
			40	0.1		5	0.1	0.000125	0.000375
	-	0.00125	20	0.4		-	-	0	0
			40	0.6		5	0.3	0.000225	0.000675
								Σ = 0.008850	Σ = 0.026550

(a) Personal Individual Risk

Assuming the person with the most exposure is present in the house all the time, the Personal Individual Risk
$= P_p \times \Sigma[(f)(P)(V)]$, where P_p is probability of temporal presence
$= 1.0 \times \Sigma[(f)(P)(V)]$
$= \underline{8.85 \times 10^{-3}\ /\text{year}}$

(b) Societal Risk in terms of PLL
$= N_a \times \Sigma[f(P)(V)]$
$= \underline{2.66 \times 10^{-2}\ \text{PLL/year}}$

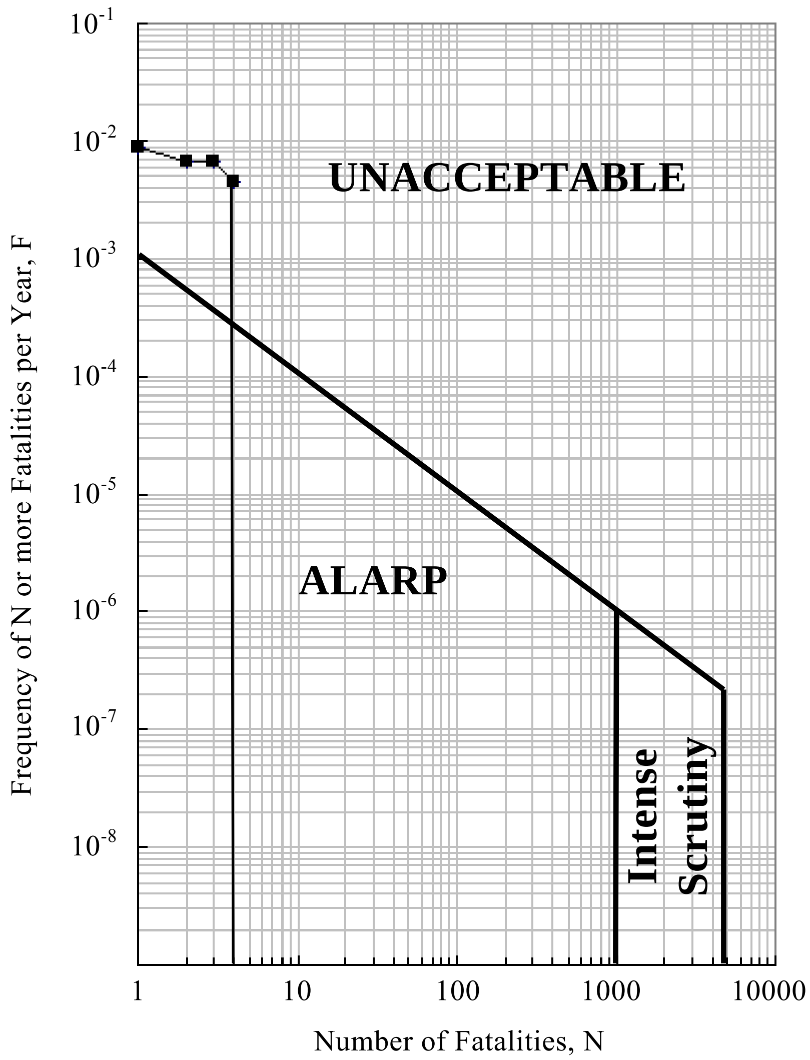
(c) Societal Risk in terms F-N curve

To derive the F-N curve, the distribution of the temporal presence of vulnerable persons is needed (see C.2). The calculations are tabulated below:

No. of fatalities, N	Probability of temporal presence, P_P	Frequency of occurrence of N fatalities, $P_N = P_P(\Sigma[(f)(P)(V)])$	Frequency of occurrence of N or more fatalities, F
4	0.5	0.0044250	0.0044250
3	0.25	0.0022125	0.0066375
2	0	0	0.0066375
1	0.25	0.0022125	0.0088500

The above is a breakdown of the Societal Risk for each fatality event according to its probability of occurrence accounting for all credible landslide hazards. The PLL is equal to the summation of the product of P_N and N (i.e. $\Sigma(P_N \times N)$) in the above table.

From the F-N pairs in the table, the F-N curve is plotted below:



E. RISK EVALUATION

E.1 Risk Distribution

The relative risks posed by the individual hillside zones can be calculated. For example, the risk posed by Zone A is calculated as follows:

Risk posed by Zone A
= $\Sigma(\text{PLL})_{\text{Zone A}}$
= 0.010125 + 0.001500 + 0.001350 + 0.002025 [see D.3 above]
= <u>0.01500</u>

The risk distribution for all hillside zones is tabulated below:

Zone	A	B	C	D	E	Sum
Risk posed to house (PLL/year)	0.01500	0.00735	0.00315	0.00105	0	0.02655
Risk proportion	56.50%	27.68%	11.86%	3.96%	0	100%

E.2 Risk Tolerability

The tolerability of the calculated risk is assessed based on the interim risk criteria adopted in Hong Kong.

The Personal Individual Risk = 8.85×10^{-3} /year, which is greater than the maximum permissible level of 1×10^{-4} for existing developments. It is therefore not acceptable.

The calculated F-N curve is in the UNACCEPTABLE zone, therefore the Societal Risk is not acceptable.

In conclusion, the calculated risks are not tolerable with respect to the risk criteria. Risk mitigation is required in order to manage the risk.

F. COST-BENEFIT CALCULATION

Adopting a value of statistical life of HK$24M to HK$33M and an aversion factor of unity, the maximum justifiable expenditure to mitigate the risk is as follows:
= (Societal Risk) × (Value of life) × (Aversion factor) × (Design life of mitigation measures in years)
= (2.66×10^{-2}) × (HK$24M to HK$33M) × 1 × 120
= HK$77M to HK$105M