Assessment of Consequence of Landslides

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Abstract: Consequence assessment is an important but less developed component of quantitative landslide risk assessment. This paper examines the factors affecting landslide consequence, discusses usual methods for assessing consequence scenarios and reviews tools for quantifying the likelihood of occurrence of the scenarios. It reviews examples of the methods and describes the generalised consequence model developed in Hong Kong to assess landslide consequence. The paper then illustrates the application of the model for both global and site-specific risk assessment, including the construction of an example F-N curve.

1 INTRODUCTION

Consideration of landslide consequences is important in slope assessment and forms one of the fundamental components in the quantification of landslide risk. Traditionally, the main emphasis has often been placed on the evaluation of the likelihood of slope failure. The nature of damage that can be caused by landslides is complex and diffuse because of the many interacting factors that are involved and it may involve loss of life and injury or economic loss. A rational assessment of the consequences of a slope failure, including the consideration of potential travel distance of debris, spatial and temporal distribution of the vulnerable population, potential loss of life, etc. is rarely carried out, and landslide consequences are commonly gauged only on the basis of engineering judgement.

Many practical slope problems are best tackled by adopting a risk-based approach. These may include the selection of appropriate design standards (e.g. factors of safety or probability of failure), quantitative risk assessment (QRA), determination of priority ranking of substandard slopes for retrofitting, delineation of unsafe landslide zones, etc.

Advances have been made in addressing salient aspects of consequence assessments. For instance, simplified analytical approaches have been developed to predict the travel distance of landslide debris and computer algorithms have been developed to simulate boulder trajectories. However, in comparison with the fairly advanced methodology that has been developed and applied in the QRA field of the chemical and hazardous process industries, there seems to be, on the whole, a lack of a systematic and practicable framework for assessing the factors that affect the quantification of landslide consequences.

This paper provides an overview of the factors that need to be considered in a landslide consequence assessment, and the approaches that could be adopted in quantifying consequences. The different approaches are classified and examples are given to illustrate how they may be applied in practice.

A new consequence model for QRA of landslides is described in this paper. The derivation of the model is explained and its application is illustrated by means of a selection of examples.

It should be noted that for the purposes of this review, the discussion is primarily focused on consequence to life. Economic consequences are not addressed in detail; however, many of the basic principles outlined in this paper will also be relevant.

2 FACTORS THAT AFFECT LANDSLIDE CONSEQUENCE

Before a systematic framework can be developed, it is important to have an overview of the key factors that affect landslide consequence.

The factors that affect consequence assessment may be grouped together as described in the following.

2.1 *Classification of Landslide Hazards*

One of the prerequisites for a comprehensive QRA is the development of a suitable hazard model. The hazard model should aim to classify the different types of hazard, each of which will have its corresponding frequency of occurrence and consequence. For instance, landslides may be classified in accordance with the mechanisms of failure. In addition, for a given failure mechanism that may arise from a certain type of feature, the hazard may be further sub-classified according to the size of failure. In general, the degree of refinement adopted for the classification will affect the level of accuracy of the subsequent frequency and consequence assessments.

Techniques have been developed in the risk assessment field for hazard identification (Kletz, 1992). Standard methodologies, such as HAZOP (hazard and operability studies) and FMEA (failure modes and effects analysis), are used routinely in QRA studies in the chemical field.

2.2 *Travel Distance of Debris and Extent of Upslope Influence Zone*

Landslide consequence and risk assessment requires, inter alia, knowledge of the travel distance of the debris. A realistic estimate of the travel distance of debris relies on an adequate understanding of the generic factors that control travel. Relevant parameters to consider include the following:

(a) characteristics of the slope - the important slope characteristics include height and gradient as well as the nature of the slope-forming material.

(b) mechanisms of failure and modes of debris movement - certain failure mechanisms such as collapse of loose soil leading to static liquefaction (Sasitharan et al, 1993) and large scale rock fall may release mobile debris. Modes of debris movement (e.g. sliding, rolling, bouncing, viscous flow, etc.), disintegration of the failure debris during motion, 'wash-out' action of convergent flow of surface water, etc. obviously influence debris velocity and travel. In the case of natural terrain, complex phenomena, such as interface undrained loading, sliding surface liquefaction due to crushing of particles, comminution of grains resulting in an increase in fines content, may lead to mobile debris.

(c) characteristics of downhill path - the characteristics of the downhill path traversed by the debris can affect the mode of debris travel. Important parameters include the gradient of the downslope area, possibility of channelisation of debris, characteristics of ground surface on which the debris travels, e.g. susceptibility to depletion, response to rapid loading as a result of sudden debris impact (Hutchinson & Bhandari, 1971), type of vegetation, drainage condition of the downslope area, extent of catchment which collects surface water and discharges into the downslope area, potential for ponding, etc.

Apart from debris travel which affects facilities located downhill of the slope under consideration, it is also important to consider how far the failure will affect land beyond the slope crest if there are facilities (e.g. roads or buildings) above it. The extent of the upslope influence zone is critically dependent on the depth and mechanism of the landslide. Compared to the prediction of debris travel distance, it seems that comparatively little work has been done to quantify the extent of upslope influence zone.

2.3 *Type of Facilities Affected*

The type of facilities under consideration will affect the density of occupation and degree of usage. Thus, this directly affects the spatial and temporal distribution of population.

In addition, the type of facility will also influence whether significant secondary effects may occur, e.g. fire or explosion of dangerous goods given the impact of a landslide.

2.4 *Vulnerability of Facilities*

Vulnerability, in the present context, may be defined as the level of potential damage, or degree of loss, of a given element (expressed on a scale of 0 to 1) subjected to a landslide of a given intensity (Fell, 1994; Leone et al, 1996). Vulnerability assessment therefore involves the understanding of the interaction between a given landslide and the affected elements. In essence, vulnerability (v) can be considered as follows (Fell, 1994):

$$v = v_s \times v_t \times v_l \tag{1}$$

where v_s = probability of spatial impact of a landslide on an element

v_t = probability of temporal impact (e.g. that the element is occupied during impact)

v_l = probability of loss of life or proportion of the value of the element

In assessing vulnerability, account should be taken of the type, proximity and spatial distribution (e.g. whether within crest or toe area) of the affected facilities, population density, spatial and temporal distribution of population, degree of protection offered to persons by the nature of the facility, likely scale (i.e. volume) of failure, the degree of warning available to the affected people (e.g. signs of distress prior to detachment of material, velocity of landslide debris, etc.) and their response (e.g. evacuation, precautionary measures taken, such as avoiding the use of roads in a hilly terrain during heavy rainfall), possibility of secondary effects, etc.

Equally important, the vulnerability of a given facility is related to the types of slope hazard given their different scales of failure and mobility and velocity of debris.

3 ASSESSMENT OF TRAVEL DISTANCE AND VELOCITY OF DEBRIS

The travel distance and velocity of debris depend critically on the scale and mechanisms of failure as well as the mobility of debris movement. The accumulation zone determines the extent of the area affected and the velocity of debris affects the response of the affected population. For example, a 7-tier classification of slope movement based on the velocity of the landslide mass is given by Cruden & Varnes (1995); this ranges from "extremely slow" (<0.06 m/yr) to "extremely rapid" (>3 m/sec, which approximates to the speed of a running person). Together, these parameters (viz. extent of accumulation zone and velocity of debris) may be taken appropriately as an index of relative landslide damage potential. For structures located on top of an unstable mass, the degree of internal distortion can also be important but this can be difficult to quantify in practice (Hungr, 1981).

A variety of techniques have been developed to assess the travel distance and velocity of landslide debris and only a brief overview is given of the classification of the different methods in the following. Reference should be made to the original publications for a detailed explanation of the approaches and their scope of application and requirements on input data. It should be understood that the movement of debris is complex and more than one phenomenon may be operating at the same time, and different phenomena may prevail at different locations of a given landslide event. Many of the approaches are inevitably idealisations of the reality.

In general, there are three different classes of approaches:

(a) Analytical methods based on energy considerations - these include the different formulations based on lumped mass approaches, e.g. the 'sled' method by Sassa (1985), sliding-consolidation models by Hutchinson (1986) and De Matos (1988), the frictional and turbulent model by Voellmy (1955), consideration of rolling friction mechanism by Huang & Wang (1988), consideration of momentum transfer by Van Gassen & Cruden (1989) and 'leading edge' approaches, such as that described by Takahashi & Yoshida (1979) and Hungr & McClung (1987).

(b) Empirical methods - this approach is based on reference to actual landslide data with due regard to the mechanisms of failure and modes of debris movement. Examples of this approach are described by Wong & Ho (1996), Corominas (1996), Fang & Zhang (1988) and Fannin & Rollerson (1993).

(c) Numerical methods based on the motion of a continuum - examples of such approach include Jeyapalan et al (1983) for dam break problems, a bilinear viscous model for snow avalanches developed by Dent (1982), the use of a Lagrangian frictional model for dry sand flow by Savage & Hutter (1989), the use of a 2-dimensional Lagrangian finite difference solution technique to solve the dynamic equations based on different frictional models by Hungr (1995), consideration of change of mass along the flow path by Hungr & Evans (1997), allowance for collapse surface concept (Hungr et al, 1997), discrete element modelling techniques to simulate dry granular flow as described by Cleary (1994), use of distinct element methods by Huang (1996) and 3-dimensional models developed by Sassa (1988) and O'Brien et al (1993), etc.

Except for the empirical methods, many of the above analytical approaches can also be extended to provide an estimate of the velocity profile and acceleration of the landslide debris and, in the case of real time solution techniques (e.g. Hungr, 1995), the travel time of the debris. Observations of superelevation of debris around bends and run-up of debris against an obstacle also allow an estimate of the velocity to be made, e.g. Eisbacher (1979). This alternative approach provides an independent method to determine the velocity at certain points and may serve as a check of the predictions by analytical models. The velocity can also be evaluated using simplified flow models in the case of debris flows, e.g. Hungr et al (1984).

As for boulder falls, different computer codes have been developed to predict the trajectory and characteristics of the motion, e.g. Barrett et al (1989), Evans & Hungr (1993), Zhou et al (1996) and Leroi et al (1996). Most of the computer codes however do not model the potential for fragmentation of individual boulders during the course of descent which can have a major effect on the consequences.

Where a detailed assessment of debris/structure interaction is warranted to determine the extent of damage and hence the consequence, recourse may be made to analytical tools. In this case, knowledge on debris velocity and characteristics will be important. For instance, the extent of building damage or probability of building collapse due to boulder impact may be assessed by means of a boulder trajectory model combined with a dynamic impact model of the structure. However, the analyses are likely to be very complicated and careful consideration needs to be given to whether the simplifications made in the analyses are representative of the real situation and that the input parameters are appropriate.

4 METHODS OF PRESENTATION OF RISK ASSESSMENT RESULTS

Where landslide consequence is assessed as part of a QRA, it is instructive to distinguish between the use and application of risk assessment at different scales as this can have a bearing on the consideration of the appropriate approaches to be adopted for consequence assessments. For instance, the objective of a territory-wide (i.e. global) QRA would be different from that of a site-specific risk assessment.

Site-specific QRA serves to provide a systematic assessment of the hazards and level of risk in terms of fatality (or economic loss, as appropriate) at a given site. This facilitates the consideration of whether the risk levels are acceptable and the evaluation of different risk mitigation measures, usually on the basis of cost benefit analyses. Site-specific QRA may also provide a benchmark for calibrating the results of global risk assessment.

A global QRA, on the other hand, is aimed at defining the relative contribution to the total risk (e.g. number of fatalities per year), which can provide a reference for landslide risk management and consideration of resources allocation and policy-making. Detailed site-specific data are not normally required for a global QRA.

In general, the event tree technique is generally more suited for a site-specific QRA given its greater degree of refinement. On the other hand, the approach involving a consequence model may be applied to both global and site-specific assessments.

It is important to note that the method adopted for consequence assessment will, to a large extent, dictate the way in which the risk results may be presented. There are a number of ways to express the results of QRA and the choice of the appropriate risk indices should be compatible with the aim of the assessment.

In a formal QRA, the findings of a risk analysis can be presented in the following formats

(a) individual risk (which relates to the risk to a single person at a specific location), and

(b) societal risk (which relates to the risk to the population as a whole, independent of geographical location) - in the traditional risk assessment fields, the societal risk is expressed in terms of an F-N curve, i.e. a graphical representation of the cumulative frequency of N or more fatalities (viz. F) plotted against the number of fatalities (viz. N) on a log-log scale; alternatively, the results may be expressed in the form of a risk index known as potential loss of life (PLL), i.e. annual fatality rates or average number of fatalities per year calculated as follows:

$$PLL = \Sigma(f_i \times N_i) \quad (2)$$

where f_i is the frequency of landslide incident i (note that this is the corresponding frequency and not the cumulative frequency, F), and

N_i is the estimated number of fatalities for landslide incident i.

Thus, the PLL is given by the area under the curve of frequency of occurrence of N fatalities (f) plotted against N.

A global QRA study can only deal with societal risk. PLL appears to be a useful index to facilitate comparison of societal risks posed by different types of feature and consideration of cut-off level for upgrading works. However, it should be noted that PLL treat all fatalities as equally important, irrespective of whether they occur in high-fatality or low-fatality events. On the other hand, results presented in the form of F-N curves will allow assessment not only of the average number of fatalities but the full range of fatal scenarios, including single catastrophic events that are liable to kill many people in one event.

It is traditional to consider the cumulative frequency of N or more fatalities as this would facilitate comparison with established risk criteria. The slope of the risk acceptance criteria defined in F-N curve format reflects the degree of aversion to high-fatality events, i.e. a steeper line represents greater aversion to high-fatality incidents. The choice of the method of presentation of risk assessment results will dictate the details of the consequence assessment methodology that need to be adopted.

In practice, although F-N curves may be used in a global QRA, further assumptions would need to be made in the assessment and these may not necessarily be supported by the quality of the available data.

For site-specific QRAs, it is likely that both societal risk (either PLL or F-N curve) and individual risk will be relevant.

5 APPROACHES FOR CONSEQUENCE ASSESSMENT

Different tools may be adopted in different approaches for consequence assessment. The tools that may be employed include historical data, expert opinion and analytical methods.

Historical fatality data may be compiled in accordance with a simple classification of the type of facility affected, viz. buildings, squatters, roads/footpaths and others facilities, such as open spaces. For instance, the distribution of landslide fatalities in Hong Kong with respect to the type of facility affected can be examined as shown in Figure 1. Similar statistics can be compiled for injuries or damage to properties. The historical data may be analysed to establish, empirical values and relations, as is the case for the "inductive method" or the "back analysis" method suggested by Crozier (1995) and Leone et al (1996) respectively.

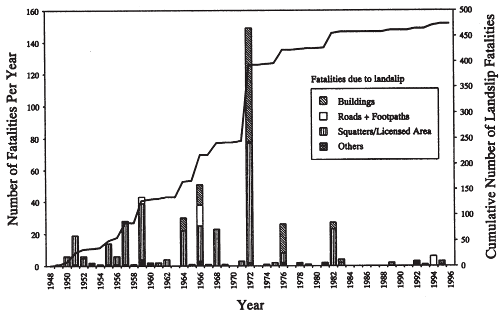


Figure 1. Annual landslip fatalities in Hong Kong

Another area where historical data may be used is the assessment of travel distance of debris. This empirical approach can reasonably be adopted where reliable information is available and the landslides are appropriately classified (Corominas, 1996). Wong &

Ho (1996) describe the work carried out using selected good quality landslide data in Hong Kong. This work involves the consideration of mechanisms and scale of failure which can be framed into a comprehensive hazard model for quantitative consequence assessments.

Expert opinion involves the use of judgement, based on general principles, theories and experience, to produce values and criteria for various scenarios. Crozier (1995) and Leoni et al (1996a) refer to this as "deductive method" and "expert system" respectively. The judgement may involve lumping together all the key factors into an overall estimate without explicit consideration of the individual factors by reference to a framework. Alternatively, expert judgement may be used in quantifying certain components or input parameters of a more elaborate approach. Expert judgement is usually subjective in that it involves the application of undisclosed judgement criteria. Some structured techniques have been developed to assist in making more consistent expert probabilistic judgement, e.g. Roberds (1990).

Analytical methods make use of mathematically-expressed concepts and theories to operate on input data. Analytical methods may be used for assessing boulder trajectories, modelling of debris movement and predicting the velocity of the sliding mass, as discussed previously. To allow for the uncertainties in the input data, simplified probabilistic methods, such as first-order (or higher order) second-moment methods or first-order reliability methods (FORM) as described by Low & Tang (1997) or simulation techniques, such as Monte Carlo analyses, may be used.

There are a number of generic approaches for quantification of consequence and these may be classified as:

(a) direct approach,
(b) event tree approach,
(c) consequence model, and
(d) influence diagram approach.

5.1 *Direct Approach*

The direct approach involves the direct assessment of consequence based on experience and expert judgement without reference to scenario components. The approach is usually adopted where the scenario components are too complicated to consider systematically and where past experience permits sensible judgement.

In principle, the direct approach may be more suited for qualitative assessment through a rating scheme, such as that the consequence may be categorised as being "very severe".

Finlay et al (1997) presented an example of a direct approach where vulnerability values (Table 1) are assigned directly by reference to historical data but without consideration of the components of the different scenarios. The "recommended value" represent best estimates from the data. In all cases the actual possible range is from 0 to 1.

5.2 *Event Tree Approach*

The event tree approach is a standard QRA technique in the chemical industry. In this approach, the consequence of a particular hazard realizing is assessed through tracing the progression of the various combinations of scenario components using logic tree technique and inductive reasoning to translate the different scenario components into a range of possible outcomes. The development of event trees aims to identify all the significant scenario components and the branching node probabilities need to be determined in order to quantify the frequency of the occurrence of the different possible outcomes. This is usually done by experts brain-storming the possible scenarios and collect probability and degree of damage functions accordingly. The input functions can be assessed by any of the tools described above but the level of details have to correspond to the effort needed in tracking the scenarios. Whitman (1984) describes an example for general dam stability and Vick & Bromwell (1989) present examples for the design of dykes in karst terrain.

An example of an event tree that has been developed in a QRA study of boulder fall hazard in Hong Kong is shown in Figure 2. In this particular event tree, account is taken of the influence of natural obstructions, man-made protective barriers, different types of facilities affected, including open areas, roads, squatters and buildings, possibility of perforation of boulder through windows or walls, potential for partial floor or building failure, etc. The frequency distributions of the volume and travel distance of boulders are combined with the event tree to assess the risk levels.

Figure 3 depicts another example of an event tree developed in a QRA study of a squatter area in Hong Kong threatened by landslide hazard from disused quarry slopes. In this particular application, consideration is given to the proximity of the affected facility, volume of failure and mobility of debris, temporal presence of population, the timing of the failure, whether warnings are likely to be heeded or not, efficiency of the response of the emergency services and secondary hazards, such as fire. The area affected is divided into blocks for consequence assessment and a total of 149 event trees were generated. The consequence assessment involves assigning the fatalities and injuries associated with the final outcome of each branch of the event tree.

Table 1. Summary of Hong Kong vulnerability ranges and recommended values for death from landslide debris in similar situations (Extracted from Finlay et al, 1997)

VULNERABILITY OF PERSON IN OPEN SPACE			
Case	Range in Data	Recommended Value	Comments
1 If struck by a rockfall	0.1-0.7	0.5[1]	May be injured but unlikely to cause death
2 If buried by debris	0.8-1.0	1.0	Death by asphyxia
3 If not buried	0.1-0.5	0.1	High chance of survival
Note [1] Better considered in more detail, i.e. the proximity of person to the part of the building affected by sliding.			

VULNERABILITY OF PERSON IN A VEHICLE			
Case	Range in Data	Recommended Value	Comments
1 If the vehicle is buried/ crushed	0.9-1.0	1.0	Death is almost certain
2 If the vehicle is damaged only	0-0.3	0.3	High chance of survival

VULNERABILITY OF PERSON IN A BUILDING			
Case	Range in Data	Recommended Value	Comments
1 If the building collapses	0.9-1.0	1.0	Death is almost certain
2 If the building is inundated with debris and the person buried	0.8-1.0	1.0	Death is highly likely
3 If the building is inundated with debris and the person not buried	0-0.5	0.2	High chance of survival
4 If the debris strikes the building only	0-0.1	0.05	Virtually no danger[1]
Note [1] Better considered in more detail, i.e. the proximity of person to the part of the building affected by sliding.			

5.3 *Consequence Model*

The consequence model involves the use of a rational framework based on the consideration of key factors affecting the consequence of failure, such as the travel distance of debris, type and proximity of facilities affected, spatial and temporal distribution of population at risk. The assessment is focused on scenarios and scenario components judged to be relevant to the particular hazard. The models can range from specific consequence models (that apply to one or two particular hazards) to collective consequence models that address a wide range of hazards. The models may be further classified into two broad categories:

(a) where there are no explicit provisions for adjustment of the assumptions made with respect to the key factors in devising the model, and
(b) where there are such provisions.

The assessment outlined by Bunce et al (1995) on the consequence of rockfall on road users is an example of this approach. The assessment focused on three scenarios, as follows:

(a) moving vehicle + falling rock,
(b) stationary vehicle + falling rock, and
(c) moving vehicle + fallen rock.

Bunce et al (op cit) applied the axiom that the vulnerability is a function of the probability of one or more vehicles being hit and the probability of loss of life of an occupant given a vehicle is hit by a rock. The latter probability is a function of the size of the rock, the number of occupants in the vehicle and the location and nature of the impact as well as the capability of the vehicle to protect the occupants from an impact and resulting hazards including flying glass or explosion. The probability of vehicles being hit (i.e. spatial and temporal impact) is assessed using the theory of binomial trials. The estimates for the probability of loss of life given an impact are based on expert judgement and they are 1 in 5, 1 in 8 and 1 in 10 for the probability of death for the above three hazard scenarios respectively.

The authors have also developed a model to assess the consequence of landslides in Hong Kong using this approach. This will be described in the later part of this paper.

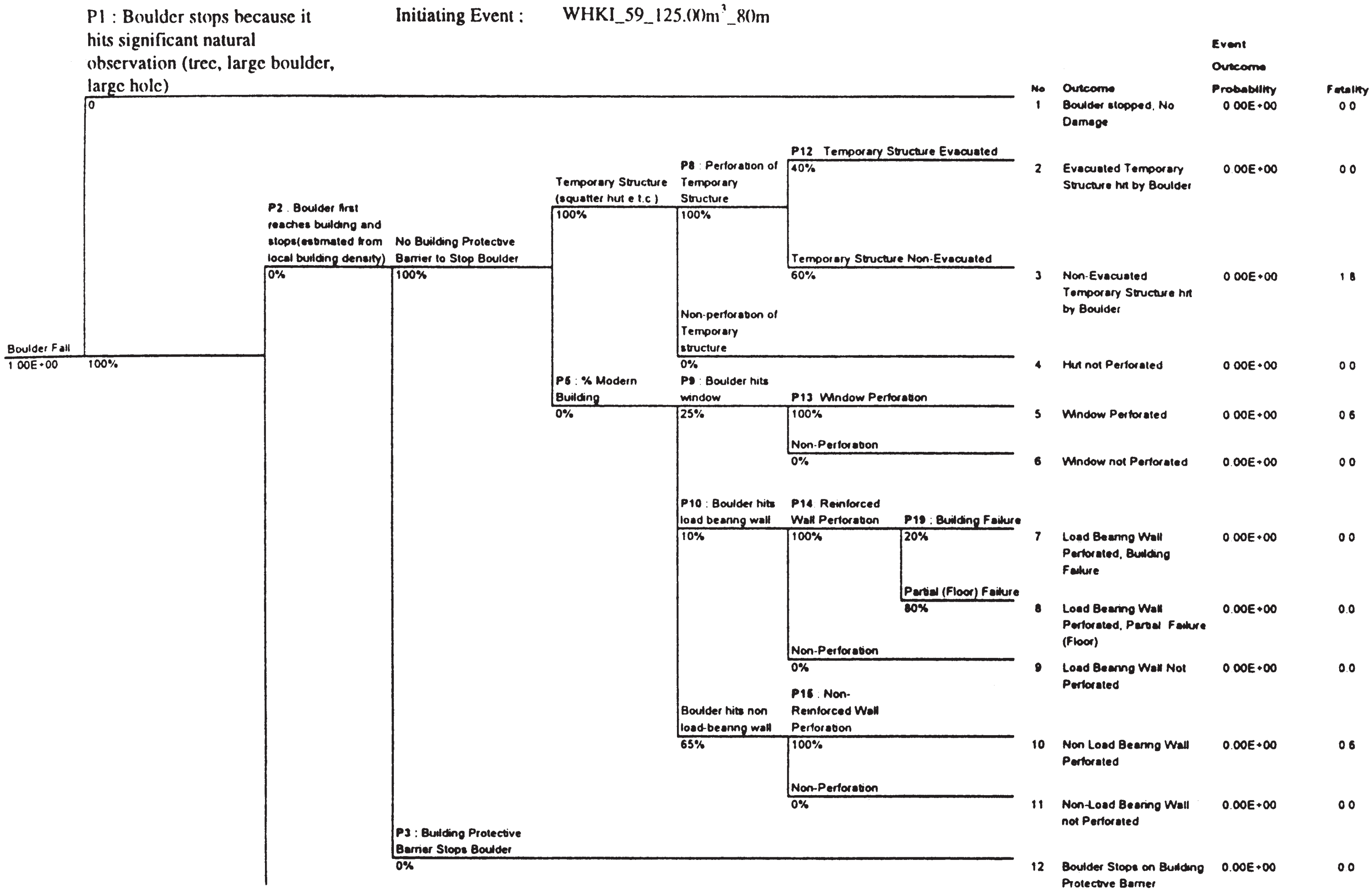


Figure 2. Example event tree for boulder fall (Extracted from QRA Report by ERM, 1996)

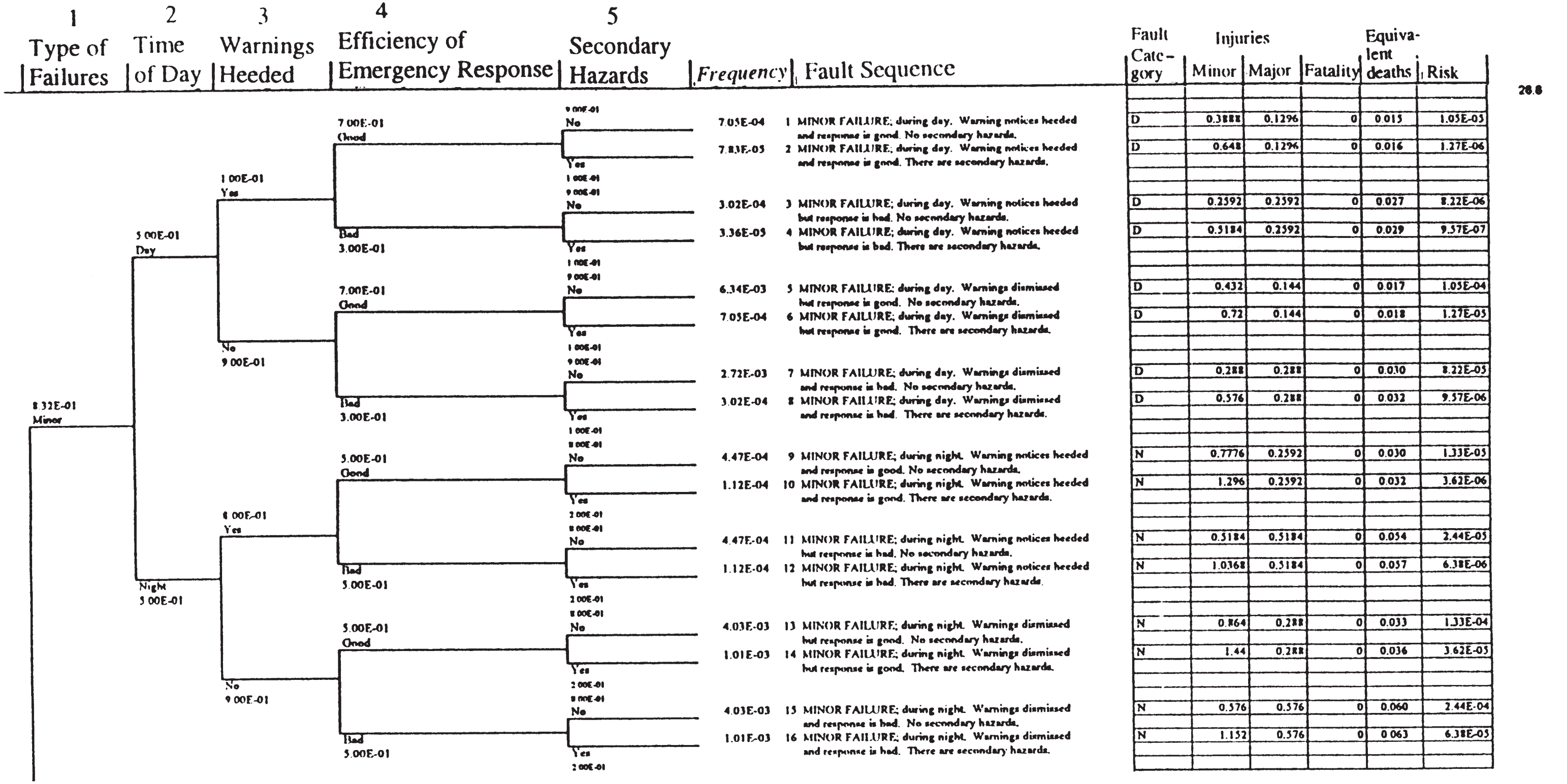


Figure 3. Example event tree for squatters affected by a slope (Extracted from QRA Report by Atkins Haswell, 1995)

A collective consequence model can be developed by collecting generically similar consequence models for a range of hazard nature or conditions and building them into a coherent structure with vulnerability functions or values for a combination of circumstances for application of other users with limited knowledge in consequence assessment. There is a tradeoff between details of each scenario, and the inclusion of the complete spectrum of scenarios and minimizing the need for judgement in respect of possible scenarios.

Leone et al (1996) described a collective consequence model that covers the full range of land-related hazards with damage and loss functions mainly obtained by back analyses and some expert opinion. In this system, three different vulnerable elements each with its corresponding specific damage function are distinguished, viz. structural damage function for material assets, corporal damage function for people and operational damage function for various activities and functions (i.e. economic loss). The framework considers different factors that affect vulnerability, including human, technical, economical, institutional, functional and construction factors. The mode and degree of damage is related to the intensity of the particular landsliding phenomenon and the resistance factor of the affected element. Broad failure modes (e.g. landslide, subsidence, mud flow, rock avalanche, collapse of rock, etc) and damage processes (e.g. horizontal and vertical displacements, lateral pressure, impact, air blow effects, etc) are defined and criteria are suggested for assessing the degree of damage. Correlation matrices that combine different elements and the type and intensity of damage are put forward and a vulnerability rating is proposed.

5.4 *Influence Diagram Approach*

In this approach, influence diagrams are constructed to show the interaction of factors (i.e. scenario components) leading to the outcome under consideration. They are drawn mainly based on concepts and knowledge of the relevant scenarios. The assessment of consequence is broadly similar to that of the event tree approach. Roberds & Ho (1997) describe a study using the approach. To maximise the flexibility and efficiency of the methodology, a modular approach is adopted to describe the scenario components so that the output of one module becomes the input for the next one in the line.

6 DISCUSSION OF APPROACHES FOR QUANTIFICATION OF CONSEQUENCE

The different approaches differ widely in their demand for input details and the experience of the personnel formulating the approach and the user. A comparison of the different approaches is given in Table 2.

The event tree approach probably demands the most detailed input in sharp contrast to that for the direct approach which may require little more than the information on slope geometry. Overall, the consequence model may be a good compromise in terms of data requirement, flexibility and resolution of the assessment.

The accuracy of a consequence assessment depends on the quality of input information, the experience of the user, as much as the approach itself. Of these, experience is probably more important than the others because judgement is indispensable in parts of the assessment process. The most elaborate approach in inexperienced hands may not yield meaningful results. However, everything being equal, the approach that considers more components of each event or scenario will be less sensitive to the accuracy of each judgement.

Regarding individual approaches, the *direct approach* may be of limited application if used in isolation, except in the case where only an approximate estimate is needed. The assessment is usually subjective and not explicit and different degree of rigour may be involved in terms of the extent to which interaction of scenario components has been considered. Substantiation and communication of the basis of the expert judgement can be difficult, particularly if quantitative assessment is made as opposed to qualitative assessment.

Finlay et al (1997) described an attempt to improve the assessment by making use of historical data. It contains the implicit judgement that factors such as the distribution of failure mechanisms, temporal distribution of population and nature of ground below slopes remain generally static. The recommended values of vulnerability do not seem to take into account the proximity of the affected facilities and the effect of failure mechanism and volume on the travel distance of landslide debris. Much experience and local knowledge is needed for their results to be used properly.

The *event tree* approach has been applied to landslide QRA. This approach is generally favoured by risk analysts as they are more accustomed to applying such techniques in formal QRA. It will be useful for very complex landslides or hazards of little prior knowledge, or very important facilities are at stake, generally for site-specific assessments.

The collective *consequence model* suggested by Leone et al (1996) is flexible and can cater for a wide range of situations. Not enough is known from the literature to appreciate the full details of the scheme and the adequacy of scenario components considered. For example, there may be scope for a more refined classification of the different types of landslide hazards, particularly those that can result in different debris mobility. The scale of the failure and the downslope gradient can also significantly affect the travel distance of debris. The range of damage

Table 2. Comparison of different approaches of consequence assessment

Approach		Direct	Consequence Model: No Adjustment by User	Consequence Model: Adjustment by User	Event Tree	Influence Diagram
Requirements in Formulating the Approach or Setting up the Model	Landslide Knowledge	$$$	$$$		$$$	$$$
	QRA Knowledge	$	$$		$$$	$$$
	Supporting Data	$$	$$$		$$	$$
Requirements in Using the Approach or Model	Landslide Knowledge	$$	$$	$$$	$$	$$
	QRA Knowledge	$	$	$	$	$
	Input Data	$	$	$$	$$$	$$ to $$$
Adaptability		✓	✓✓	✓✓✓	✓✓✓	✓ to ✓✓
Use in Global QRA	Suitability	✓	✓✓✓	✓✓	✓	✓
	Resolution of assessment	✓	✓✓	✓✓ to ✓✓✓	✓✓✓	✓ to ✓✓
Use in Site-specific QRA	Suitability	✓	✓✓	✓✓ to ✓✓✓	✓✓✓	✓✓
	Resolution of assessment	✓	✓✓	✓✓ to ✓✓✓	✓✓✓	✓✓

Legend: $$$ High ✓✓✓ High
$$ Moderate ✓✓ Moderate
$ Low ✓ Low
(in terms of data/knowledge requirement)(in terms of scope of application)

processes considered is extensive but some of the input data may be difficult to obtain directly from historical data (e.g. air blow effects and lateral pressure from debris). Also, the way in which debris runout of each landslide hazard is taken into account is not clear.

Bunce et al (1995) demonstrates the power of a simplified, specific consequence model in experienced hands. The specific consequence model presented is neat and rational although refinement is probably desirable by taking into account the size distribution of the rock fragments involved.

The *influence diagram approach* described by Roberds & Ho (1997) includes the use of analytical tools to explicitly incorporate probabilistic assessment of uncertainties in the key factors considered in the consequence assessment.

7 DEVELOPMENT OF A CONSEQUENCE MODEL

7.1 *Basic Framework*

A rational framework for landslide consequence assessment with respect to different facilities has been developed that takes the key factors into account. For the purposes of this paper, it will be referred to as the generalised consequence model.

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

$$\text{Expected no. of landslide fatalities for a given facility} = f\left\{\begin{array}{c}\text{Expected no. of fatalities for facility directly affected by the reference landslide}\end{array}\right\}\left\{\begin{array}{c}\text{Actual scale of failure}\end{array}\right\}\left\{\begin{array}{c}\text{Vulnerability factor}\end{array}\right\}$$

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

The first term relates to the type of facility that is directly affected by a reference landslide (taken to be a 10 m-wide failure of 50 m^3 in volume). The expected numbers of fatalities for the different facilities directly affected by the reference landslide are shown in Table 3.

The size of the actual failure serves to scale up, or down, the consequence with respect to that expected of the reference landslide. The scaling is based on the ratio of the width of the actual landslide to the width of the reference landslide, taking due account of the width of the affected facility (e.g. consideration of spatial impact). For instance, if a given landslide measures 40 m in width, the scaling factor will be 4 for a road in front of the landslide. On the other hand, for the same landslide, if the affected facility is a building that measures only 20 m, the appropriate scaling factor as far as consequence in respect of the building is concerned becomes 2 even though the landslide itself measures 40 m.

The vulnerability factor as defined above is in effect the probability of loss of life, i.e. v_1 in equation (1). Its value is influenced by a number of factors including:

(a) the nature, proximity and spatial distribution of the facilities,

(b) mobility of debris and likely extent of the upslope influence zone,

(c) scale of failure, and

(d) degree of protection offered to persons by the facility.

The generalised consequence model can also consider the vulnerability to building collapse in the event of impact by a large-scale landslide having regard to factors (a) to (c) above.

It should be noted that the above framework is for consequence assessment with respect to fatalities.

Table 3. Grouping of facilities and expected number of fatalities used for Hong Kong study

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

Notes: (1) To account for the different types of building structure with different detailing of window and other perforations etc., a multiple fatality factor ranging from 1 to 5 is considered appropriate for Group No. 1(a) facilities to account for the possibility that some incidents may result in a disproportionately larger number of fatalities than that envisaged. For global QRA, an average value of 3 is taken for the multiple fatality factor.

(2) For incidents that involve the collapse of a building, it is assumed that the expected number of fatalities is 100.

The framework can however be extended to consider injuries, economic losses and other social disruptions.

7.2 *Expected number of fatalities for the reference landslide*

The generalised consequence model involves assessing the expected number of fatalities for facilities directly affected by a reference landslide. The reference landslide has been taken to be a 10 m-wide failure of 50 m^3 in volume, which is a typical "major" failure for conditions pertaining in Hong Kong. Other suitable definitions of the standard landslide may be taken as appropriate for local conditions. It is important, however, that the assessment of the expected number of fatalities for the reference landslide is compatible with the specific definition of the reference landslide.

In assessing the expected number of fatalities for the reference landslide, the type of the facility, density of occupation and degree of usage and the vulnerability to death under direct impact are taken into consideration. The expected number of fatalities for different road types with specific traffic flow characteristics are assessed explicitly to classify roads using a 5-tier classification system. The way this has been done will be described in a later section.

Other types of facility are aligned with respect to the respective road classes in terms of the expected number of fatalities by means of expert judgement (Table 3). The main factors that influence the judgement are the nature of the facility (i.e. likely population density and degree of protection) and its likely degree of occupation at the time of a landslide (i.e. temporal presence).

7.3 *Travel Distance of Landslide Debris*

The assessment of the travel of debris from landslides of different mechanisms and scales in Hong Kong is discussed by Wong & Ho (1996). The landslides involved weathered volcanics and granite as well as colluvial deposits which originated from these materials. Based on a systematic study of reliable data obtained from field inspections and a critical review of other selected case histories with sufficiently reliable information, the following findings were reported:

(a) the travel of the landslide debris can be profoundly influenced by the mechanism of failure (viz. typical rain-induced 'sliding' failure, liquefaction of loose fill and wash-out by convergent surface water flow),

(b) the travel angle (defined as the inclination of the line joining the tip of the debris to the crest of the landslide scarp) for typical rain-induced landslides involving small to medium-scale failure (viz. landslide volume <2000 m^3), generally ranges from 30° to 40°,

(c) for landslides involving liquefaction of loose fill or wash-out action, the apparent angle of friction reduces to 15° to 30°,

(d) the apparent angle of friction reduces with increase in landslide volume, irrespective of the mode of failure, and

(e) the travel of landslide debris may be affected significantly by the gradient of the downslope topography; the use of apparent angle of friction will better account for such effects than L-H relationships (Figure 4).

More data have been compiled since the completion of the above pilot work and the available information is summarised in Figure 5.

For a given slope type, the failure (even for a specific mechanism and failure volume) can result in a range of debris runout distance because of differences in geomorphology, slope-forming materials, etc. Given the relationship between debris travel distance and failure volume for different failure mechanisms, the worst credible value for apparent angles of friction may be assessed. It should be noted that the smaller the apparent angle of friction, the more mobile is the debris.

For realistic vulnerability assessments, it is not sufficient to make reference only to the worst credible limit of debris runout. Instead, the distribution (or frequency of occurrence) of landslides having different travels needs to be taken into account. For practical purposes, the mobility of the debris is taken to be reflected by the travel angle, α, which is defined as the inclination of the line joining the far end of the debris to the crest of the slope. For shallow failures, α is practically the same as the apparent angle of friction. The use of travel angle as defined in this way simplifies the assessment procedure.

Given the information on the type and spatial location of the affected facility, the degree of protection offered to person and debris travel, the likely probability of death or vulnerability may be assessed systematically using a risk-based framework.

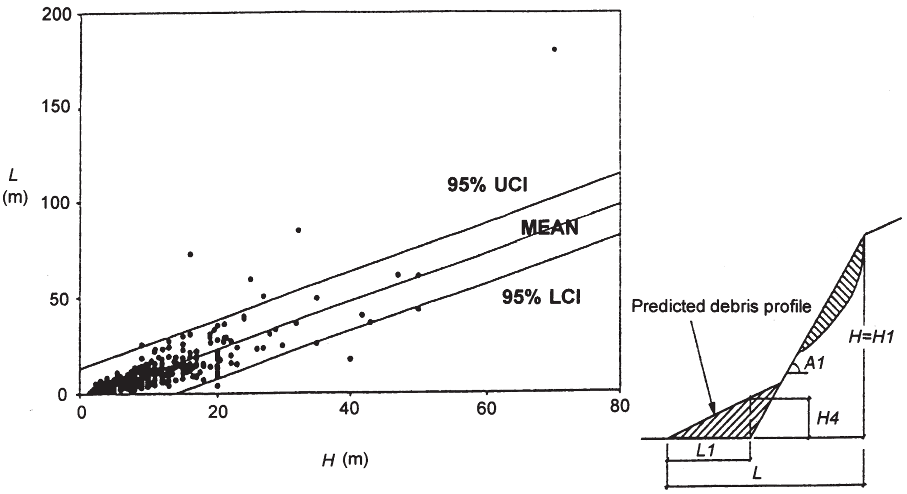
The extent of the retrogression is determined empirically from the database of more than 4000 landslides.

7.4 *Derivation of Vulnerability Factors*

Factors to be considered in assessing vulnerability is explained above. The derivation of the suggested vulnerability factors is best explained by means of an example.

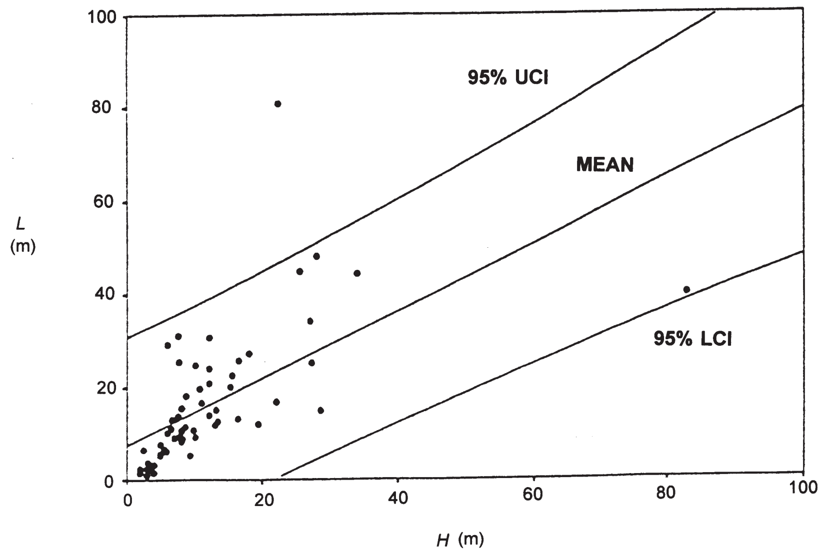
The following example illustrates the derivation of vulnerability factors for toe facilities threatened by potential landslides arising from 'sliding' failure of a cut slope with a landslide volume ranging from 500 m^3 to 2000 m^3.

For the above landslide hazard, the limit of debris travel is taken to correspond to an α value ranging between 25° and 40°. The assumed distribution, based on extrapolation of the presently available database, is as follows:



Problem definition for a cut slope runout distance prediction.

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



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

Figure 4. Empirical correlations for travel distance of debris (Extracted from Finlay et al, 1997)

(a) 5% of cases with $\alpha = 27.5°$ ($\pm2.5°$) ,
(b) 60% of cases with $\alpha = 32.5°$($\pm2.5°$), and
(c) 35% of cases with $\alpha = 37.5°$($\pm2.5°$)

Thus, based on the available database and previous experience, it is judged that in the majority of the cases, a landslide with the above characteristics in terms of scale and failure mechanism is most likely to result in debris deposition with α of between 30° and 35° and only in rare cases will the debris be expected to be so mobile as to have a runout distance corresponding to an α of between 25° and 30°

The shadow angle made by the facility with respect to slope crest (i.e. the angle of the line that joins the toe facility to slope crest) defines its proximity. The nature of the affected facility (e.g. building or road) will affect the degree of protection.

The spatial location of the facility also needs to be considered. For toe facilities, debris runout is relevant whereas for crest facilities, the influence zone is important. In the case of buildings located on the slope crest, the nature of the foundation (e.g. on piles or footings) is also taken into account because this will

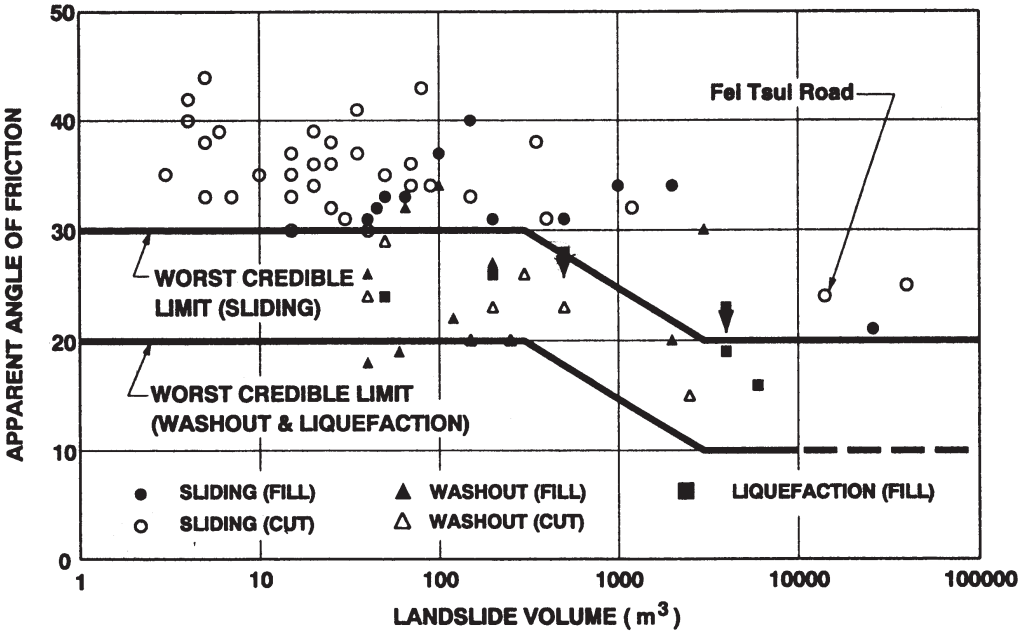


Figure 5. Data on debris mobility for different mechanisms and scales of landslides in Hong Kong

affect the degree of damage that can be caused and hence the vulnerability to loss of life.

Given a particular facility type and the probable depth of debris at the facility location, the appropriate vulnerability factors (i.e. probability of death) may be assessed systematically by expert judgement. This framework allows the important factors to be considered systematically and hence greatly facilitates more consistent judgement to be made of the vulnerability factors and how they relate to one other in a relative sense.

For example, in the case of an α of 25° the average probability of death for a road user located at a shadow angle of between 25° and 30° is judged to be 20% given that the affected facility is near the limit of debris runout. On the other hand, if the road user is located at a shadow angle of between 30° and 35° (i.e. closer to the slope), the corresponding probability is judged to be 60%. In making the above judgement, due regard is given to the likely depth of debris at the location of the facility. The likely depth of debris at a given location may be gauged relatively easily given the information on the location of the facility, scale of failure and the travel distance of the debris.

The corresponding vulnerability factors for people inside a building are taken as 5% and 20% respectively, having regard to the protection afforded by the structure whereupon some of the debris may enter the building via openings such as windows. It should be noted that the above assessment relates to average values. In practice, there may be a range of vulnerability factors depending on the details of the structure and the precise location of the people, e.g. different vulnerability factors may be applicable for people on different areas of the ground floor and for people on different floors. The framework may be refined but it should be noted that much more data will be required and more guesswork in one way or another will be unavoidable if an unnecessarily complicated framework is used.

The different vulnerability factors assessed for the above specific landslide hazard are summarised in Table 4. It should be noted that the vulnerability values given in this Table have duly taken into consideration the potential uncertainties associated with the runout distance of debris.

In the present example, for a person travelling on a certain road lane that is located at the slope toe with a shadow angle of between 35° and 40° the corresponding vulnerability factor is given by the following:

$$(0.95 \times 0.05) + (0.6 \times 0.6) + (0.2 \times 0.35) \approx 0.48$$

This means that should the above landslide occur, a given person at that location will have a 48% chance of dying, or that 48% of the population density present at that location is expected to perish.

The corresponding vulnerability of a person inside a building at the same location in front of the slope is given by the following:

$$(0.6 \times 0.05) + (0.2 \times 0.6) + (0.05 \times 0.35) \approx 0.17$$

The above illustrates the effect of the different degree of protection afforded to persons by different types of facility. In the above example, the vulnerability of a person within a building to loss of life given the above landslide is more than 50% less than a person on a road at the same location.

This example corresponds to one of the hazards for the slope. In practical cases, different tables need to be prepared for the crest and toe facilities for each of the landslide hazards considered in the present hazard model. The degree of refinement is related to the complexity of the hazard model adopted.

7.5 *Discussion*

Although the consequence framework as illustrated in this paper has been developed for Hong Kong conditions, the basic concepts are, in principle, applicable to different conditions in other countries and the framework can be extended as appropriate.

In evaluating the results of consequence assessments using the proposed framework, it is instructive to consider whether the assessment errs on the conservative side or not. The following simplifying assumptions made in the generalised consequence model in its present format are known to be conservative:

(a) The travel distance of landslide debris has been assessed assuming the failure involves the slope crest (this represents the worst case; in reality, some landslides are partial failures that involve the slope body below the crest with a smaller influence zone on toe facilities and little effect on crest facilities and the available data in Hong Kong suggests that some 70% of the failures involve the portion of the slope near its crest.

(b) The mobility angle of the debris is calculated with respect to the crest of the slope rather than the crest of the failure scarp (as in the case of apparent friction angle) - this is a conservative assumption, particularly for large-scale or deep failures, because the travel distance will have been over-estimated. However, it is an expedient assumption as the influence zone is more readily defined with respect to the slope crest without the need to predict the depth of failure. In Hong Kong, the vast majority of landslides involve shallow failures and the degree of conservatism implied by the above simplifying assumption is not excessive.

Although the somewhat conservative assumptions will result in a slight overestimate of the consequence and hence the risk, it is considered that the relative ratio and distribution of the total risk is unlikely to be greatly affected.

Table 4. Example calculation of vulnerability factors used for Hong Kong study

Likely Probability of Death for Different Ranges of Shadow Angle (β) of Affected Person with Respect to Slope Crest								Frequency of occurrence of landslides (of a given slope type) having different ranges of debris travel distances measured in terms of debris mobility angle, α
>60°	55°-60°	50°-55°	45°- 50°	40°- 45°	35°- 40°	30°- 35°	25°- 30°	
0.95 (0.95)	0.95 (0.95)	0.95 (0.95)	0.95 (0.95)	0.95 (0.95)	0.60 (0.95)	0.20 (0.60)	0.05 (0.20)	5% of cases with α = 27.5° (±2.5°)
0.95 (0.95)	0.95 (0.95)	0.95 (0.95)	0.95 (0.95)	0.60 (0.95)	0.20 (0.60)	0.05 (0.20)		60% of cases with α = 32.5° (±2.5°)
0.95 (0.95)	0.95 (0.95)	0.95 (0.95)	0.60 (0.95)	0.20 (0.60)	0.05 (0.20)			35% of cases with α = 37.5° (±2.5°)
0.95 (0.95)	0.95 (0.95)	0.95 (0.95)	0.83 (0.95)	0.48 (0.83)	0.17 (0.48*)	0.04 (0.15)	0.0025 (0.01)	Vulnerability Factor Calculated

Legend:

0.2	- likely probability of death for a person in a building given the impact of the landslide, at a given range of α and β.
(0.6)	- likely probability of death for a person on a road given the impact of the landslide, at a given range of α and β.

Note: The above tables are applicable for toe facilities of a cut slope with an estimated failure volume ranging from 500 m^3 to 2000 m^3 . The figures in the top table are based on judgement, having regard to the type of facility, its proximity to the feature and whether it is a toe or crest feature, its location in relation to the reach of the debris (hence accounting for the likely depth of debris at the affected facility) and the degree of protection afforded to persons by the facility.

8 LANDSLIDE CONSEQUENCE CLASSIFICATION SYSTEM FOR ROADS

Prior to the development of the generalised consequence model as described previously, the authors took part in formulating a landslide consequence classification system for roads based on quantified risk considerations. This classification system was further extended in the course of developing the generalised landslide consequence model as described above. A brief description of the salient aspects of the consequence classification system for roads is given below.

Before formulating the landslide consequence classification system for roads, reference was made to the available historical landslide data to see if a simple system can be derived. One of the main observations is that the limited data available are very sensitive to "near-misses" and other factors that affect the casualty figures, such as changes in traffic density over the years. In view of this, it was concluded that historical data cannot be relied upon and recourse needs to be made to a more analytical approach based on a risk framework.

The method for assessing the consequence of landslides affecting roads involves the consideration of the relative likelihood of fatalities with respect to a 5-tier facility grouping system. The expected number of fatalities given a reference landslide is assessed with due account taken of the temporal presence of population within the influence zone. The consideration of a reference landslide allows a realistic comparison of the different types of road with different degree of usage in terms of landslide consequence.

The expected number of fatalities (i.e. PLL) in the event of a reference landslide is given by the following equation:

$$N = \Sigma \frac{W * F * P * E * A}{v} \quad (3)$$

where W = width of landslide plus adjustment for effective stopping distance

F = frequency of passing passengers (taken to be the product of average daily traffic and average number of people inside a vehicle)

P = probability of death due to being caught in the reference landslide

E = extent of the landslide (i.e. number of lanes affected)

A = adjustment factor for actual proportion of normal road usage at the time of a landslide

v = speed of vehicles

In considering the influence zone of the reference landslide, the extent of the reference landslide is taken to affect up to three road lanes and that the effective width of the landslide is increased to allow for the sight distance and stopping distance of vehicles. Thus, the area of the influence zone is defined.

In assessing the temporal presence of population at the time of occurrence of the reference landslide, the frequency of the passing passengers being within the influence zone is considered having regard to:

(a) average traffic flow (in Hong Kong, information on the annual average daily traffic, AADT, is readily available; alternatively, traffic survey may be carried out to determine the frequency of road usage at different times),
(b) the split of different modes of transport (i.e. relative distribution of cars and buses),
(c) average number of people in a vehicle, and
(d) average speed of the vehicles.

An adjustment is also made for the likely proportion of traffic density relative to normal road usage at the time of a landslide. This accounts for the fact that the majority of landslides take place at times of severe rainfall during which time the overall degree of usage of the roads may be less than average.

Suitable assumptions also need to be made regarding the likely probability of death for people in a vehicle located on different road lanes. In doing so, reference is made to historical information. Suitable allowance has also been made for the additional risk arising from users of footpaths adjacent to roads.

The final format of the consequence classification system relates the type of road in terms of facility group number to the actual average traffic conditions, taking into account the degree of saturation relative to the design capacity of the road and the number of lanes of a road. Each of the facility group has a corresponding expected number of fatalities for the reference landslide, as calculated using equation (3).

9 APPLICATION OF GENERALISED CONSEQUENCE MODEL TO GLOBAL QRA

The generalised consequence model as described above has been applied to a pilot territory-wide QRA of man-made slope features (i.e. slopes and retaining walls) that were constructed prior to the implementation of geotechnical control by the Hong Kong Government. These slope features, which are potentially substandard, amount to a total of about 35,000. Some salient aspects of the approach taken and the key findings are described below in order to put the application of the generalised consequence model into context.

In the global QRA, the landslide hazard model adopted (Figure 6) has the following components:

(a) *Types of Feature* - namely, cut slope, fill slope and retaining wall (Figure 7).
(b) *Mechanisms of failure* - failure may take place via different mechanisms, each posing a differing degree of hazard. In fill slopes, for instance, the landslide records show that the dominant failure mechanisms are sliding, 'wash out' (viz. failure induced by the scouring action of running surface water) and liquefaction with the relative likelihood in the ratio of 45%: 45%:10%.

(c) *Size of failure* - for a given failure mechanism, the hazard may be classified according to the size of failure, taking into account the height of the slope. For example, in the case of fill slopes, the following classification has been adopted: <20 m^3, 20 m^3 - 50 m^3, 50 m^3 - 200 m^3, 200 m^3 - 1000 m^3 and > 1000 m^3. In addition, the possibility of knock-on effects, such as scenarios involving escalation of failure consequences (e.g. small sliding failure developing into a major 'wash out'), have also been considered.

Thus, a multitude of landslide hazards are considered (Figure 8). For instance, a fill slope that is disposed to liquefaction failure with a volume in the range 200 m^3 to 1000 m^3 will constitute a specific hazard, whilst a cut slope disposed to typical rain-induced sliding failure with a volume in the range of 50 m^3 to 200 m^3 is another hazard. Each hazard will have its corresponding frequency of occurrence and consequence. The likely maximum size of failure is related to the height of the slope feature. In other words, the hazards posed by some of the larger-scale failures are not credible for a relatively small slope and hence are not considered for such slopes.

Each hazard has its corresponding consequence, taking into account the characteristics of the affected facilities and their vulnerability. The different consequences for the range of hazards are combined with the corresponding frequencies of occurrence for individual slope features. The global QRA amounts to the summation of the risks of each of the 35000 slope features to give the total societal risk in terms of PLL. The information needed for the assessment essentially consists of the frequency of occurrence of the different hazards, number, nature and location of the affected facilities, together with the size and number of the different types of slope and their sizes (Figure 9). The basic framework is illustrated in Figure 10.

The failure frequencies of each of the hazard for each sizes of slope features have been assessed based on an interpretation of the historical landslide records. This approach is reasonable because there is a large body of information on over 5000 landslides in Hong Kong. The information on the characteristics of the facilities has been extrapolated from the presently available databases in respect of the Slope Catalogue.

The classification system adopted with respect to the different types of slope, range of slope heights and nature of facilities enables the relative distribution of the total risk to be studied. As an illustration of the kind of information that can be deduced from a global QRA, the main findings are summarised in Tables 5 to 7.

It may be seen that globally, the risk from cut slopes, fill slopes and retaining walls is in the ratio of 6:1:1 (Table 6). In terms of average risk per slope, the corresponding ratios are approximately 3:1:1. This can be a useful reference for the consideration of allocation of resources for slope upgrading works.

TYPE OF SLOPE FEATURE	• **CUT** • **FILL** • **RETAINING WALL**
MECHANISM OF FAILURE	• **SLIDING** • **WASH-OUT** • **LIQUEFACTION**
SCALE OF FAILURE	• **< 20 m^3** • **20 - 50 m^3** • **50 - 200 m^3** • **200 - 1000 m^3** • **1000 - 10000 m^3** • **> 10000 m^3**
FACILITY AFFECTED	• **GENERALISED CONSEQUENCE MODEL**

Figure 6. Hazard model (Pre-GCO Slopes)

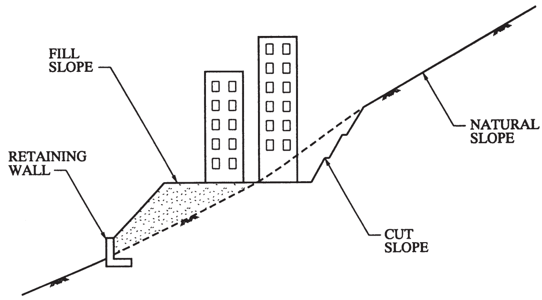


Figure 7. Types of slope for QRA model

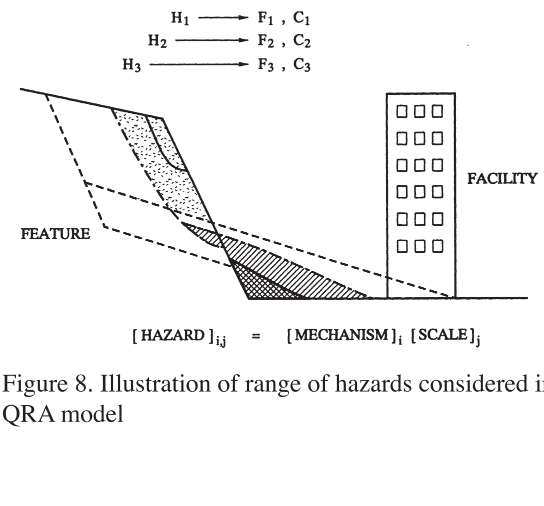


Figure 8. Illustration of range of hazards considered in QRA model

The distribution of the total risk with respect to the five facility categories is shown in Table 7. The average level of risk per feature for different facility groups are also depicted in Table 7. It can be seen that the average risk levels can differ by almost 4 orders of magnitude, depending on the type of facility. It should also be noted that within a particular group, the distribution of risk per feature can vary by almost two orders of magnitude, as shown in Table 7 for cut slopes of different heights that affect Group 1 facilities. The above information on risk proportions can be useful for making decisions on the necessary extent of the retrofitting work.

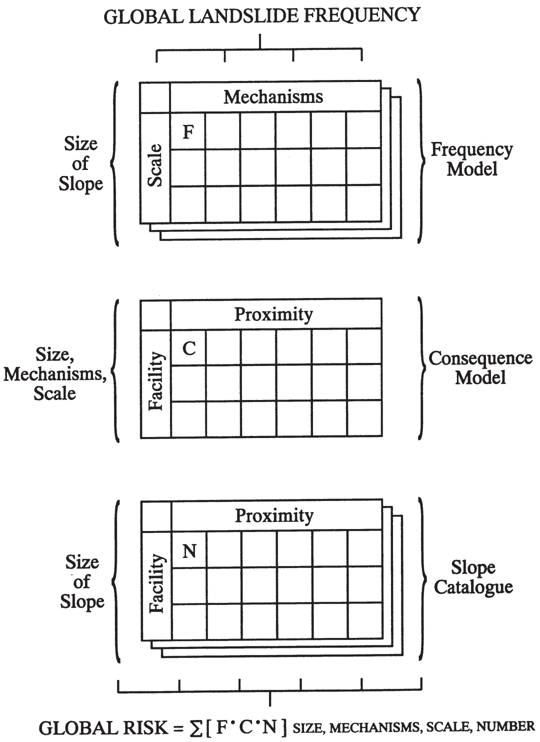


Figure 9. Risk summation using hazard model

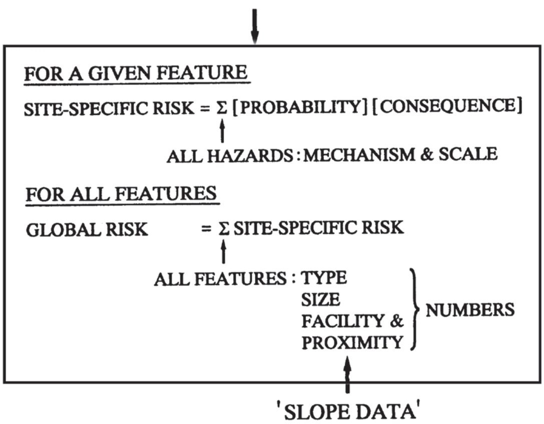


Figure 10. Framework for global and site-specific QRA of landslides

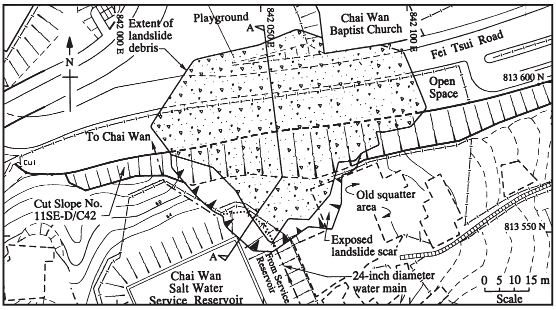


Figure 11. Plan of the Fei Tsui Road landslide, Hong Kong

10 APPLICATION OF GENERALISED CONSEQUENCE MODEL TO SITE-SPECIFIC QRA

The generalised consequence model may also be applied to site-specific QRA with sufficient accuracy. The model can provide a best estimate of the expected number of fatalities for a given type of slope feature and affected facility. As an example, the application of the model to the fatal landslide that occurred at Fei Tsui Road is described below.

The Fei Tsui Road landslide is described in the investigation report published by Geotechnical Engineering Office (1996). The landslide involved the failure of a 27-m high cut slope in the early hours of the morning of 13 August 1995 with an estimated failure volume of 14,000 m^3. The landslide debris buried a 12-m wide strip of open space in front of the slope toe, together with Fei Tsui Road (7.3 m wide) and the pedestrian pavement (3.3 m wide) along the northern side of the road (Figure 11). Some of the debris was deposited onto the playground across the road, and part of the debris piled up against the south-western comer of the Baptist Church to a maximum height of about 6 m. The maximum width of the failure measures 90 m.

A father and his son were walking along the pavement near the south-western corner of the church when the landslide occurred. The father was pushed by the debris into the church building, down a set of stairs and landed in the basement where kindergarten classes are held during daytime. He was only slight injured in the event but the son was trapped by the debris and unfortunately killed in the incident.

It is noteworthy that the landslide at Fei Tsui Road was unusual in terms of its scale of failure. It was the largest reported fast-moving cut slope failure in Hong Kong since systematic landslide records were kept in the early 1980's.

Table 5 - Results of territory-wide QRA of Pre-GCO man-made features in Hong Kong

Table 5(a)- PLL for cut slopes (per year)

Group No.		1	1	2	2	3	4	5	Building Collapse	
Type of Facility		Buildings	Roads	Buildings	Roads	Roads & Open Space	Roads & Open Space	Roads & Open Space	Buildings	Total
Slope Height	< 10m	1.53	0.43	0.51	1.07	0.86	0.215	4.66E-3	0	4.62
	10-20 m	0.61	0.23	0.20	0.58	0.46	0.111	2.36E-3	0	2.20
	> 20 m	0.26	0.197	0.086	0.49	0.393	6.88E-2	1.15E-3	0.171	1.67
	Total	2.40	0.86	0.80	2.14	1.72	0.395	8.17E-3	0.171	8.49

Table 5(b) - PLL for fill slopes (per year)

Group No.		1	1	2	2	3	4	5	
Type of Facility		Buildings	Roads	Buildings	Roads	Roads & Open Space	Roads & Open Space	Roads & Open Space	Total
Slope Height	< 10m	0.14	0.05	0.05	0.13	0.10	1.81E-2	3.03E-4	0.49
	10-20 m	0.12	0.03	0.04	0.07	0.06	1.00E-2	1.71E-4	0.32
	> 20 m	0.31	2.38E-2	1.03E-01	5.95E-2	4.76E-2	9.00E-3	1.61E-4	0.55
	Total	0.57	0.10	0.19	0.26	0.21	3.71E-2	6.35E-4	1.36

Table 5(c) - PLL for retaining walls (per year)

Group No.		1	1	2	2	3	4	5	
Type of Facility		Buildings	Roads	Buildings	Roads	Roads & Open Space	Roads & Open Space	Roads & Open Space	Total
Wall Height	≤ 5 m	3.76E-1	2.21E-2	1.25E-1	5.53E-2	4.42E-2	7.31E-3	1.15E-4	0.63
	> 5 m	4.44E-1	6.32E-3	1.48E-1	1.58E-2	1.26E-2	1.93E-3	2.74E-5	0.63
	Total	8.20E-1	2.84E-2	2.73E-1	7.11E-2	5.69E-2	9.24E-3	1.42E-4	1.26

Table 6. Distribution of total risk with respect to types of feature - Hong Kong study

FEATURE TYPE	Pre-GCO Slopes		
	Cut Slopes	Fill Slopes	Retaining
Number of Features	19100	9500	8100
Global Failure Frequency (per year)	1 in 100	1 in 500	1 in 350
Proportion of Total Risk [RATIO]	75% [6]	12% [1]	13% [1]
Average Risk Per Feature (Fatality per year) [RATIO]	1.2 x 10^{-4} [3.2]	3.8 x 10^{-5} [1]	4.8 x 10^{-5} [1.3]

Note: The average risk per feature has been calculated by normalising the total calculated PLL to 3 persons per year as established from historical records.

10.1 *Consequence Assessment in Terms of Potential Loss of Life*

The generalised consequence model defined using the PLL format may be applied to the case history at Fei Tsui Road to illustrate the kind of information and insight that may be obtained from a systematic consequence assessment based on QRA methodology. The application of the consequence model to the critical failure section is shown in Figure 12.

Table 7. Global risk (fatality per year) based on facility affected - Hong Kong study

Facility Group No.	Total Number of Slope Features	Distribution of Total Risk [RATIO]	Average Risk Per Feature [RATIO]
1 (Buildings - densely used Roads - very high traffic density)	3900	44.5% [445]	3.5×10^{-4} [875]
2 (Buildings - lightly used Roads - high traffic density)	7400	33.5% [335]	1.35×10^{-4} [340]
3 (Roads - moderate traffic density Open Space - densely used)	6000	17.9% [179]	9.0×10^{-5} [225]
4 (Roads - low traffic density Open Space - lightly used)	11900	4% [40]	1.0×10^{-5} [25]
5 (Roads - very low traffic density Remote areas, such as country parks)	7500	0.1% [1]	4.0×10^{-7} [1]

<u>Distribution of risk for different slope heights - cut slopes affecting facility group no. 1 - Hong Kong study</u>

Facility Group No.	Slope Height (m)	Total No.	Risk Per Feature [RATIO]
1 (Buildings - densely used Roads - very high traffic density)	> 20 10-20 < 10	25 90 2100	6.8×10^{-3} [17000] 2.6×10^{-3} [6500] 2.6×10^{-4} [650]

Footnote: The average risk per feature has been calculated by normalising the total calculated PLL to 3 persons per year as established from historical records.

For large-scale failures, the mechanism of debris movement may involve significant breaking up of the debris and the main source of energy dissipation may be in the form of rolling and collision of the individual particles as opposed to frictional sliding of an intact mass (i.e. the 'sled' model). The result of the possible change in debris movement mechanism may be an increase in mobility relative to the case of frictional sliding of a smaller debris mass. In the present instance, the worst credible limit of travel is taken to correspond to a travel angle of 20° as measured from

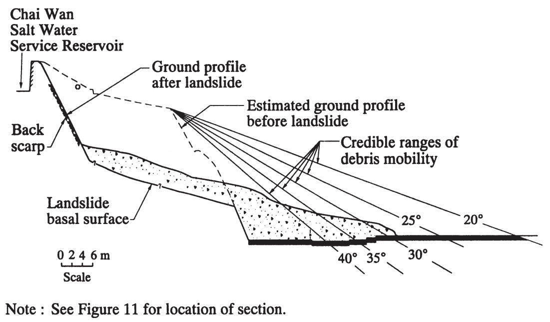


Figure 12. Section A-A through the Fei Tsui Road landslide, Hong Kong

the crest of the cut slope.

The facilities affected by this landslide belong to different facility groups (Table 3). Fei Tsui Road is a Group 3 facility, having regard to its traffic density and number of lanes, with an estimated reference PLL of 0.25 persons given a reference landslide (i.e. 50 m^3 in volume). The open space immediately in front of the slope toe is a Group 5 facility; the church building is a Group 1 facility whereas the playground is a Group 4 facility. The assessed vulnerability factors for Fei Tsui Road, the open space, church building and playground using the framework described above are 0.85, 0.95, 0.17 and 0.15. The assessed vulnerability factors are shown in Figure 13.

The results of the assessment using the generalised consequence model are summarised in Table 8. It may be seen that the total PLL amounts to about 4 compared to the actual figure of one fatality. In terms of relative contributions, the baptist church, in theory, contributes 62% of the total risk, with a calculated PLL of over 2. Thus, this landslide incident represents a 'near-miss' case in that if the landslide did occur during day time instead of 1.15 a.m. with a lot more traffic on the road and possibly children in

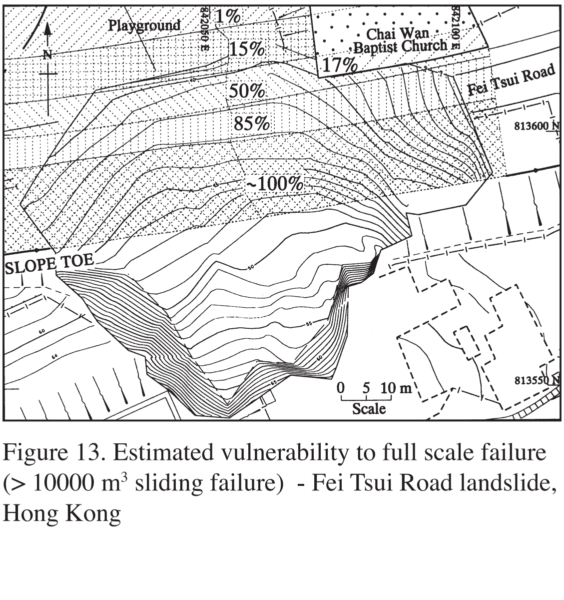


Figure 13. Estimated vulnerability to full scale failure (> 10000 m^3 sliding failure) - Fei Tsui Road landslide, Hong Kong

the kindergarten, the fatality figures could conceivably be much higher than the actual figure of one. This emphasizes the difficulty in interpreting, and the danger in extrapolating, historical data in the absence of a rational framework. The actual fatality figure on its own does not permit much progress to be made in the understanding of possible landslide consequences in a risk-based framework.

It is also instructive to consider the predicted consequence if a similar landslide in terms of volume and characteristics affected a different type of road. For instance, if the road affected were a Group 2 facility, the predicted PLL amounts to 7.6 as opposed to 1.9. If the road affected were a Group 1 facility, the predicted PLL becomes 23.

10.2 *Consequence Assessment Expressed in Terms of F-N Curve*

As noted previously, the risk results can also be expressed in terms of an F-N curve. To illustrate how this may be done, the calculations have been repeated using F-N curves to establish the risk associated with the landslide that occurred in 1995.

In the present case, four separate facilities are affected, namely open space, road, building and playground. The previously assessed PLL for the road is 1.91. This average loss of fatality may also be expressed in terms of an F-N curve which considers the probability of occurrence of different numbers of fatalities under different credible scenarios.

As an example, the construction of the F-N curve for Fei Tsui Road is illustrated. First of all, the population density needs to be determined. For the purpose of the assessment and in accordance with standard QRA methodology, a discrete number of likely scenarios involving different population density being within the influence zone of the landslide are considered. In the present instance, the credible range of population density consists of 0, 1, 5, 10, 30, 100 and 200. The extreme scenario of the given landslide causing up to 200 fatalities is considered credible for the case where both lanes of the Fei Tsui Road are jammed tight with vehicles with full passenger capacity (e.g. up to 40 cars are jammed in front of the landslide area due to, say, a road accident). The frequency of occurrence of each credible scenario involving different numbers of vehicles and the corresponding number of passengers, together with users of the pavement within the landslide area need to be assessed. This may be facilitated by reference to the available traffic data (and if necessary, surveys may be carried out) and experience.

The assessed frequencies for the different scenarios involving different degree of population density within the landslide area are summarised in Table 9. It should be noted this information relates the frequency of occurrence of different numbers of persons within the facility. In other words, this represents the spatial and temporal vulnerabilities.

As a check of whether the frequency-fatality curve is equivalent to the assessed reference PLL of 1.91 for Fei Tsui Road, the area under the curve using the data given in Table 9 may be calculated as follows:

PLL = (0.002% x 170 + 0.028% x 85 + 0.33% x 25.5 + 8.75% x 8.5 + 22.25% x 4.25 + 18.75% x 0.85 + 49.89% x 0)
= 1.96

This is close to the previously assessed PLL (viz. 1.91) and hence the frequency-fatality curve is compatible with the above PLL. One of the advantages

Table 8. Results of consequence assessment for Fei Tsui Road landslide, Hong Kong

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

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

Table 9. Frequency-fatality relationship for Fei Tsui Road given the 1995 landslide, Hong Kong

	No. of People Present within the Landslide Area (Equivalent Number of fatalities)						
	200 (170)	100 (85)	30 (25.5)	10 (8.5)	5 (4.25)	1 (0.85)	0 (0)
no cars	-	-	-	-	-	-	49.89%
1 car	-	-	-	-	6.25%	18.75%	-
2 cars	-	-	-	5%	15%	-	-
3 cars or more, or a bus involved	-	-	0.25%	3.75%	1 %	-	-
20 cars	-	0.02%	0.08%	-	-	-	-
40 cars	0.002%	0.008%	-	-		-	-
	Σ= 0.002%	Σ= 0.028 %	Σ= 0.33%	Σ= 8.75 %	Σ= 22.25 %	Σ= 18.75%	Σ= 49.89%

Notes (1) The numbers in the table represent the assessed frequencies of occurrence of the respective number of people present within the landslide area for the given number of vehicles involved.
(2) The above assessment has taken into account the likelihood of traffic density present within the landslide area, with suitable allowance for the temporal presence of people on the pedestrian pavement.
(3) The equivalent number of fatalities is obtained by multiplying the population density with the vulnerability factor.

of having the risk results presented in the form of an F-N curve is that it provides additional information on the full range of credible fatal scenarios and the corresponding likelihood of occurrence.

The equivalent number of fatalities is obtained by multiplying the number of people present within the influence zone with the vulnerability factor which has been assessed using the generalised consequence model as 0.85 for Fei Tsui Road (Table 8).

A similar approach may be taken in expressing the consequence curve in terms of frequency-fatality curve for the other facilities. For instance, in the case of the church building which has a kindergarten in the basement, due consideration needs to be given to the size and duration of the classes, number of school days in a year, etc. in assessing spatial and temporal presence. The scenario of building collapse given the landslide was also considered but this was found to have an insignificant contribution to the overall risk in this particular case.

In principle, event trees may be constructed to assist in the assessment of the different credible scenarios in a systematic manner in assessing the corresponding frequencies. However, the use of the event tree approach will require more input data. For the purposes of illustrating how the results may be presented as an F-N, a direct assessment approach has been taken.

It should be understood that the above results represent the assessed consequence given the occurrence of the landslide. To establish the risk of the landslide, the frequency of occurrence of this particular landslide must also be taken into account. Analysis of the intensities of the rainstorm that triggered the failure shows that the 31-day rainfall was the most extreme, with a corresponding return period of about 100 years. Thus, this may be used in constructing the F-N curves.

To plot standard F-N curves, the different fatal scenarios need to be tabulated for the range of facilities affected and the cumulative frequencies can be determined by adding together the corresponding frequencies for scenarios that produce a given number of fatalities or more. The results are shown in Table 10. For example, the cumulative frequency for 170 or more fatalities is calculated as 0.016% per year (= 0.014% + 0.002%) given the occurrence of the given landslide (i.e. probability of occurrence equals one).

The relative contributions to the total PLL from the different scenarios are also shown in Table 9.

Alternatively, if the probability of occurrence of this landslide is taken into consideration, the cumulative frequency for 170 or more fatalities will be 1.6×10^{-6} per year (= 0.016 %/100, where 100 is the return period of the severe rainstorm that triggered the failure).

Using the results given in Table 10, the corresponding F-N curve may be constructed for this site as shown in Figure 14. This can then be compared with appropriate risk criteria to evaluate whether the risks are tolerable.

11 SUMMARY AND DISCUSSION

Most of the work undertaken in geotechnical QRA studies tend to place the emphasis on assessing the probability of failure, and comparatively little work seems to have gone into the assessment of consequence of failure. In the majority of QRA studies reported in the literature, the consequence assessment

Table 10. Results of site-specific risk assessment for Fei Tsui Road landslide

		Frequency of different fatalities given the 1995 landslide, f (%)							
Potential Loss of Life (PLL)	Equivalent No. of Fatality	Church (collapse)	Church (no collapse)	Road	Playground	Open Space	Number of Fatalities, N	Cumulative frequency of different fatalities given the 1995 landslide (%)	Cumulative frequency of different fatalities, F
0.028	200	0.014	-	-		-	200	0.014	1.4E-6
0.0034	170	-	-	0.002	-	-	170	0.016	1.6E-6
0.042	100	0.042	-	-	-	-	100	0.058	5.8E-6
0.0238	85	-	-	0.028	-	-	85	0.086	8.6E-6
0.028	50	0.056	-	-	-	-	50	0.142	1.42E-5
0.0336	30	0.112	-	-	-	-	30	0.254	2.54E-5
0.08415	25.5	-	-	0.33	-	-	25	0.584	5.8E-5
0.14875	17	-	0.875	-	-	-	17	1.459	1.459E-4
0.0056	10	0.056	-	-	-	-	10	1.515	1.515E-4
1.33875	8.5	-	7	8.75	-	-	8	17.265	1.7265E-3
0.847875	5.1	-	16.625	-	-	-	5	33.89	3.389E-3
0.002375	4.75	-	-	-	-	0.05			
0.945625	4.25	-	-	22.25	-	-	4	56.19	5.619E-3
0.357	1.7	-	21	-	-	-			
0.000375	1.5	-	-	-	0.025	-	1	77.215	7.7215E-3
0.004275	0.95	-	-	-	-	0.45			
0.204	0.85	-	5.25	18.75	-	-			
0.0091875	0.75	-	-	-	1.225				
0.002975	0.17	-	1.75	-	-	-			
0.013125	0.15	-	-	-	8.75	-			
Σ = 4.123									

Notes (1) $(PLL)_i$ is given by the product of the equivalent number of fatality and the corresponding frequency, f.
(2) The F-N curve shown in Figure 14 is obtained by plotting the values given in the columns for "F" and "N" above.
(3) The equivalent number of fatality is given by the product of the population density and the respective vulnerability factor for the facility under consideration.

is usually done via subjective judgement in the absence of a systematic framework. It is considered that the state-of-the-art with respect to landslide consequence assessment is such that there is considerable scope for further improvement.

In this paper, the different approaches to vulnerability calculations are classified and illustrated by means of examples. It is considered that the use of an empirical approach based on historical data is of limited practical use principally because of the shortcomings associated with the effects of "near-misses".

This paper describes the development of a simple and rational analytical framework based on QRA methodology for consequence assessment in landslide QRA. The model is well suited for a global landslide QRA and, in most instances, sufficiently accurate for a site-specific QRA. Although the model is still in its development phase, its robustness and practicality have been illustrated through its successful application to two examples of landslide QRA. Useful insight may be obtained from the results which would otherwise not be possible in the absence of a risk-based framework.

The consequence assessment has been carried out in terms of potential loss of life (PLL) in accordance with standard QRA methodologies to illustrate how the generalised consequence model may be applied in practice. It has also be extended to include an F-N curve for use in more detailed site specific assessment.

Some of the assumptions made in the generalised consequence model are inevitably based on expert judgement. The need for these is not necessarily

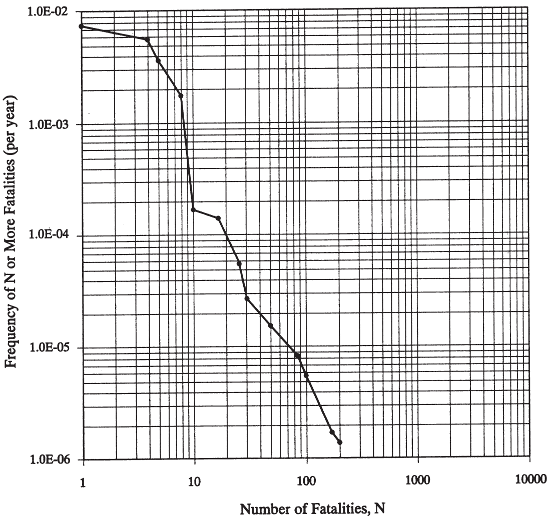


Figure 14. F-N curve for Fei Tsui Road landslide

a setback to the generalised consequence model. Experience gained during the development of the model shows that the availability of a rational framework greatly facilitates the exercising of judgement and better ensures internal consistency of the judgement made for different scenarios. This was clearly borne out when the subjective overall judgement made initially was compared with the final assessment made under the framework of the model. There are indications that the subjective overall judgement may be unable to take into account all the factors for the different scenarios systematically and consistently.

The assessment of certain input values by means of expert judgement is naturally open to debate; however, the availability of a rational framework provides a basis for further refinement and facilities more effective communication and discussion of individuals' judgement. In effect, the scope for debate may be narrowed as not necessarily all the assumptions made are in dispute whereas if only the overall judgement is in dispute, there is usually little scope for compromise, and effective communication of the basis of the judgement can be difficult.

It should be noted that the subjective judgement made in the generalised consequence model is not entirely arbitrary in that it has been benchmarked against a number of notable landslide incidents in Hong Kong with detailed information. Such benchmarking exercise confirms the applicability of the model for the selected cases and serves to provide a basis for making more consistent judgement for the other scenarios.

Overall, it is considered that the accuracy of consequence assessment using the proposed model is comparatively better than the assessment of the frequency of failure, particularly for large-scale landslides. The uncertainty associated with assessing the number of fatalities is likely to be less than assessing the probability of failure, particularly for mobile landslides. In particular, the uncertainties in the assessment of the probability of debris flows or rock avalanches from the natural terrain are further exacerbated by the lack of a fundamental understanding of the mechanistic processes that control the triggering of failure and the modes of debris movement during the downslope motion.

The hazard model adopted in the consequence assessment and some of the basic assumptions made in the framework are relevant to the conditions and setting in Hong Kong. However, many of the principles can be generalised and the hazard model and assessment framework may be refined or extended to suit the local conditions of other countries. The hazard model should, in principle, encompass the range of landslide phenomena, and a broad understanding of the different failure mechanisms and the corresponding debris runout is needed. A suitable reference landslides needs to be defined to establish the base PLL using a similar risk-based approach as outlined in this paper and appropriate scaling factors for the size of failure and effects of proximity and protection of the different facilities should be determined using a similar framework.

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