Quantitative Risk Assessment of a Natural Terrain Catchment at Sha Tin, Hong Kong

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ABSTRACT: This paper presents a case study on the use of formal quantitative risk assessment (QRA) technique to evaluate the landslide risk of a natural terrain catchment at Sha Tin in Hong Kong. The study was initiated following the occurrence of six landslides in the study area in 1997. This paper describes the methodology adopted in the study, including the landslide hazard and consequence models in the QRA and a cost benefit analysis of the various mitigation options. The semi-quantitative risk assessment technique of Failure Mode and Effect Analyses (FMEA), which was used to assess part of the site, is also presented.

1 INTRODUCTION

The natural terrain below Shatin Pass Road in Sha Tin, Hong Kong is bounded by residential buildings at the crest and toe of the hillside. In 1997, a total of six landslides occurred on the hillside, three of which developed into debris flows and affected the residential developments at the toe of the hillside. Following the 1997 landslides, the site was selected for a risk assessment based on the established 'react-to-known-hazard' policy to establish the necessary follow-up actions in the management of natural terrain landslide hazards. The landslides were investigated and a Natural Terrain Hazard Study (NTHS) of the site using the QRA approach was undertaken (FMSWJV, 2004).

2 THE SITE

The study area is a southeast-facing hillside with an area of about 3.2 hectares. Varying from 60 m to 70 m high with inclinations between 24° and 42°, the hillside comprises alternating spurs and gullies (Figure 1). Many slopes and platforms were formed in association with the residential development along the crest of the hillside, which began in the mid-1950s, resulting in the deposition of fill material below the ridge crest. Severe gully erosion was apparent in 1963 on some larger fill slopes suggesting that the fill slopes were relatively loose and unprotected at the time. In more recent years prior to 1997, the hillside was covered generally with bushes, vines and small trees. In some areas, the hillside has been terraced, apparently associated with cultivation activities in the past. Large areas of shotcrete surface have been applied along most of the drainage lines as urgent slope repair works following the 1997 landslides.

2.1 Geology and Hydrology

Fill of about 2.4 to 3 m thick was found mostly in the upper part of the hillside, which consisted of a heterogeneous mixture of loose to medium dense silt, sand, gravel and boulder-size rocks or construction debris. Colluvium was found over much of the hillside with thicknesses generally varying from about 0.5 m at spurs to about 2.8 m within the valleys and at the slope toes.

Residual soil was found in scattered locations and mostly less than 2 m thick. Underlying the fill, colluvium and residual soil layers was the completely to highly decomposed coarse-grained granite.

The hillside is drained by eight ephemeral drainage lines, which are generally smooth and broad and mostly covered by large areas of shotcrete after the 1997 landslides. Drainage outlets discharged stormwater directly onto the hillside from the platforms of five residential apartment blocks at the crest of the hillside. Foul water was also observed to be seeping below some apartment blocks onto the hillside.

2.2 Historical Landslides

The hillside has a history of shallow instability. Within the study area, 27 landslides were identified to have occurred on the hillside from the GEO's landside incident records and by aerial photographic interpretation. The identified landslides are generally scattered across the hillside. Most of the landslides were less than 150 m^3 in volume, but one landslide in 1981 involved a debris volume of 250 m^3, and three landslides in 1997 involved volumes between 150 m^3 and 200 m^3.

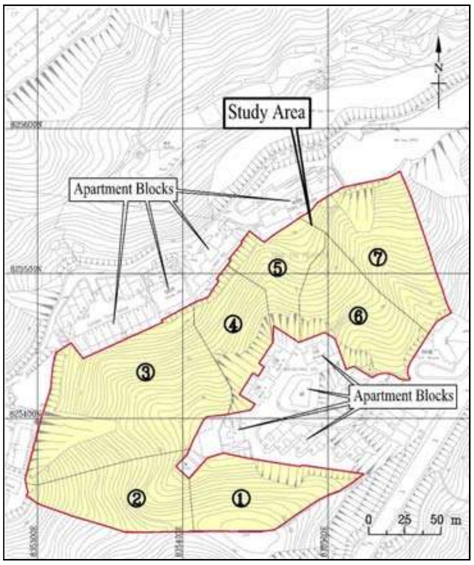

Figure 1 Layout of Study Area

3 QRA FRAMEWORK

Quantitative risk assessment for site-specific applications involves the quantification of the risk levels for risk tolerability evaluation and consideration of risk management actions. The QRA adopted in this study essentially consisted of four key tasks: (1) hazard identification, (2) failure frequency assessment, (3) failure consequence assessment, and (4) landslide risk estimation and evaluation.

(1) Hazard identification-Hazard is a condition with the potential to cause undesirable consequences. The descriptions of landslide hazard generally include the scale and runout of the potential landslides, together with the probability of their occurrence within a given period of time. Hazard identification included a desk study of all the available data, comprising interpretation of historical aerial photographs and study of the 1997 landslides. Only shallow landslides on the hillsides (viz. up to about 3 m deep) were considered to be significant for this study. The landslide hazards were classified according to the failure mechanisms and volume of failure.

(2) Failure frequency assessment-Frequency is a measure of the likelihood of an event in a given time, expressed as the number of occurrence. Frequency assessment in this study involved

the determination of the baseline overall landslide frequency for the study area from an interpretation of the historical landslide data, which is then spatially distributed across the site according to terrain susceptibility (i.e. via a susceptibility analysis), with due regard to the potential failure mechanisms and scale of failure.

(3) Failure consequence assessment-Consequence is the outcome associated with landslide occurrence, typically expressed in terms of loss of life, damage to property, disruption to the community, economic losses, etc. In this study, a site-specific consequence model for potential landslide fatalities was adopted. This model entailed the consideration of landslide mobility and vulnerability factors (i.e. the probability of death of an individual in a given facility when the facility is affected by a landslide hazard) for persons within different types of elements at risk (i.e. facilities in the area affected by landslide hazards) at different 'proximity zones' from the potential landslide source areas. The landslide consequence assessment was quantified by the product of the expected number of people present and the relevant vulnerability factor (i.e. the expected number of fatality at a given facility when subjected to landslide hazard).

(4) Risk estimation and evaluation-Landslide risk is a measure of the chance of landslide occurrence causing harm (e.g. fatalities, economic losses, etc.), and can be quantified as the product of the probability and consequence of slope failure. In this study, landslide risk was calculated as the summation of the product of landslide frequency and landslide consequence in terms of loss of life, for all credible hazard scenarios, i.e.

$$\text{Landslide Risk} = [\text{Landslide Frequency} \times \text{Landslide Consequence}] \qquad (1)$$

The risk figures are expressed in terms of Personal Individual Risk (PIR) and Societal Risk in terms of F-N curve, i.e. a curve depicting cumulative frequency of N or more fatalities per year. PIR is a measure of the risk of fatality per year to a particular individual at a given location, who is exposed to landslide hazards, with due account taken of (1) the temporal probability of presence, (2) the chance of escape and (3) the vulnerability. F-N curve is a measure of the overall risk to the community within the area affected by landslide hazards and is expressed in a log-log plot that relates the cumulative frequency of having N or more fatalities per year (F) to the number of fatalities (N). Reference to PIR and F-N curve allows the evaluation of the assessed risk levels with respect to established risk tolerability criteria.

4 LANDSLIDE RISK TOLERABILITY CRITERIA

As part of the technical development work undertaken by the GEO in formulating suitable QRA methodology for applications to landslide risk management, a set of interim risk guidelines (ERM 1998), which were benchmarked against those adopted for Potentially Hazardous Installations in Hong Kong, was developed in the late 1990's for natural terrain landslide hazards. The risk guidelines entail the suggested tolerable risk criteria for natural terrain landslides and boulder falls with respect to both PIR and Societal Risk. PIR and Societal Risk estimated in site-specific QRA are to be evaluated against the risk criteria to assist in assessing the necessary risk management actions based on risk tolerability and risk-cost-benefit considerations in accordance with the As Low As Reasonably Practicable (ALARP) principle.

The PIR criteria apply to the annual probability of fatality for the most vulnerable person affected by the landslide hazards. The corresponding maximum allowable limit is 1×10^{-5} in the case of new developments, and 1×10^{-4} for existing developments. The Societal Risk, as expressed in the form of an F-N curve (Figure 2), apply to the overall risk-to-life posed to the affected community by the landslide hazards for an area with a maximum toe-length of 500 m. If the toe-length is greater than 500 m, the acceptance criteria would need to be scaled up linearly. The Societal Risk can also be expressed in terms of Potential Loss of Life (PLL) per year. Mitigation measures are to prevent unacceptable risk and to reduce the risk following the ALARP principle. The cost of each of the possible mitigation measures is compared with the risk reduction achieved. This involves a comparison of the cost of implementing the measures against the reduction in landslide risk. The maximum justifiable expenditure (ERM, 1998) can be calculated as follows:

$$\text{Maximum Justifiable Expenditure} = \text{Total PLL} \times \text{Value of a Statistical Life} \times \text{Aversion Factor} \quad (2)$$

As recommended in the interim risk guidelines (ERM, 1998), the value of a statistical life ranges from HK$24M to about HK$33M. The aversion factor is to take account of the society's aversion to multiple fatality incidents. The interim risk guidelines suggest that aversion factor of greater than one should be applied for 'high risk' situations. To take account of the design life of the risk mitigation measures, the maximum justifiable one-off expenditure can be calculated as follows:

Maximum Justifiable One-off Expenditure =
Maximum Justifiable Expenditure × Design Life of Risk Mitigation Measures (3)

The priority, or cost-effectiveness, of the different mitigation measures may be assessed based on their Implied Cost of Averting a Fatality (ICAF), which is defined as follows:

$$\text{ICAF} = \frac{\text{Cost to Implement Risk Mitigation Measure}}{(\text{PLL Reduction}) \times (\text{Design Life of Mitigation Measure})} \quad (4)$$

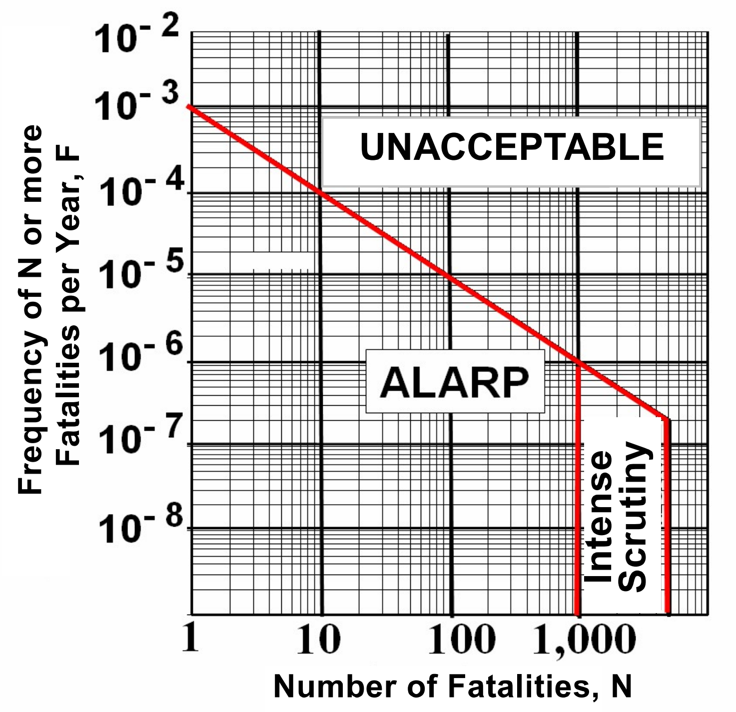

Figure 2 Societal Risk Criteria Adopted by the Government of the Hong Kong SAR for Natural Terrain Landslide Hazards

5 LANDSLIDE HAZARD IDENTIFICATION AND FREQUENCY ASSESSMENT

Initially, five potential landslide hazards (viz. shallow landslides, massive landslides, surface erosion, retaining wall failures and boulder falls) were considered but eventually only shallow landslides were assessed as being of significance for the study area, based on a detailed evaluation of the available landslide records, detailed study of the 1997 landslides, findings of a site-specific ground investigation (which involved primarily trial pitting) and geological mapping and appraisal. The stratigraphy comprises fill, colluvium, residual soil and weathered granite (see Section 2.1). Based on a review of the characteristics of the past instabilities on this hillside and the landslide data in Hong Kong as a whole, shallow landslides were classified into two failure mechanisms, namely open hillslope landslide and channelised debris flow, and in terms of three failure scales, viz. small (<50 m^3), medium (50 m^3 to <200 m^3) and large (200 m^3 to 1 000 m^3).

The study area was divided into 7 sub-catchments and a total of 62 hillside segments, based on consideration of the topographic conditions (Figure 1). The overall historical landslide frequency (i.e. average annual landslide frequency) was assessed from interpretation of historical aerial photographs taken between 1963 and 1997 for different landslide volume classes. The landslide frequencies for different failure volume classes were adjusted with due regard to the different degrees of recognition from interpretation of aerial photographs, in particular for smaller-scale landslides.

As part of the emergency slope repair works following the 1997 landslides, large areas of shotcrete were applied to different parts of the hillside, resulting in a major change to the hillside condition. In assessing the landslide hazards, the condition of the hillside after the repair of the 1997 landslides was referred to as the 'present-day' condition, which provided the basis for assessing the landslide risk in this study as of 2001.

All substandard man-made slopes at the crest of the hillsides were scheduled to be upgraded under the Landslip Preventive Measures (LPM) Programme of the GEO. The unsatisfactory state of uncontrolled discharge from the residential apartment blocks at the crest of the hillside would also be dealt with in the near future. As such, the condition of the site after the implementation of these measures was referred to as the 'impending' condition.

In the susceptibility analysis, Monte-Carlo simulation technique was used to determine the analytical probability of failure of the individual hillside segments by repeatedly calculating the slope stability 10,000 times, using the @Risk computer program. Different sets of assigned terrain and geotechnical parameters were adopted according to the 'present-day' and 'impending' conditions of the hillside segment. The adopted baseline landslide frequency was obtained by averaging the analytical landslide frequency from Monte-Carlo simulation and the observed historical landslide frequency (with suitable adjustment for recognition factors as noted above) based on the Bayesian approach. (a method to combine judgmental information with observational data).

The analytical landslide probability values also provided a basis for assessing the spatial distribution of the overall landslide frequency to the 62 different hillside segments as follows:

$$F_i = \frac{F \times (A_i \times P_{fi})}{\sum (A_i \times P_{fi})} \tag{5}$$

where
F_i = landslide frequency distributed to segment i
F = baseline frequency for a particular landslide hazard (e.g. large channellised debris flow)
A_i = area of hillside segment i
P_{fi} = failure probability of segment i from Monte-Carlo simulation

6 LANDSLIDE CONSEQUENCE ASSESSMENT

Field reconnaissance was carried out to collate information on the usage of facilities, population density and characteristics of temporal presence of population within the different facilities. A site-specific consequence model was formulated based on the generalised model for man-made slope failures (Wong et al, 1997). The model entails the use of site-specific data on landslide debris mobility, an empirical landslide runout model and best-estimated vulnerability factors for different types of facilities at different distances from the landslide source area.

In the site-specific consequence model, the maximum runout distance of landslide debris was assessed based on consideration of the topography of the site, the type of landslide hazard and failure scale, taking due account of the historical landslide data (Figure 3). The area within the maximum reach of landslide debris (i.e. between the landslide source area and the distal end of landslide debris) was divided into 6 proximity zones, each with the same horizontal distance (see

Figure 4). To account for the likelihood of variation in landslide debris runout, the probability of debris reaching each of the proximity zones was assigned based on the assumption of a triangular-shaped frequency distribution function (see Table 1).

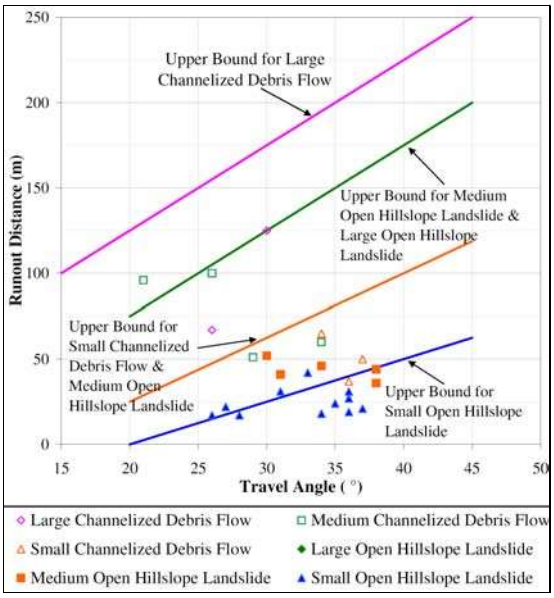

Figure 3 Landslide Debris Runout Model

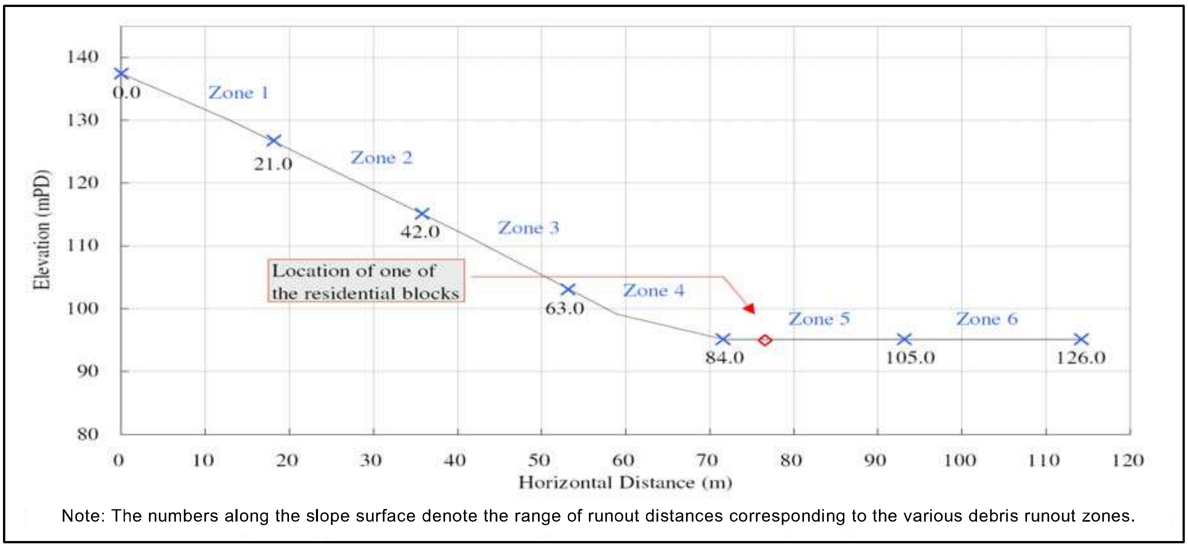

Figure 4 Debris Runout Zones of Segment 5e

The vulnerability of an individual person to fatality was assessed based on Hong Kong-wide historical landslide records together with expert judgement. Vulnerability factors were first derived for an unprotected individual (i.e. in open space) subjected to a large landslide (see Section 4), considering the proximity of the individual and the mobility of landslide debris (Table 1). A set of scaling factors was developed for assessing the vulnerability factors for the individuals with protection where appropriate (e.g. building) and for smaller-scale landslides (Table 2).

Based on the data collected from the field population survey, the expected number of vulnerable people in a given facility directly impacted by a landslide were determined for different scales of landslides, accounting for the types of facilities within the study area, population density and the degree of usage (i.e. temporal presence of people), see Table 3.

The landslide consequence was expressed in terms of the expected number of fatalities at a given facility when subjected to a given landslide hazard (e.g. landslide type and scale). The landslide consequence was calculated as the product of the vulnerability factor and the expected number of vulnerable people in a given facility directly impacted by a landslide, i.e.

Landslide Consequence = [Vulnerability Factor × Expected Number of People affected] (6)

Table 1. Vulnerability of an Individual in an Unprotected Facility Subjected to a Large Landslide

Debris Reaching Zone No.	Facility Located in Zone No. 6	5	4	3	2	1	Probability of Debris Reaching Various Zones
1	0	0	0	0	0	0.50	5.5%
2	0	0	0	0	0.40	0.90	16.7%
3	0	0	0	0.25	0.80	0.95	27.8%
4	0	0	0.20	0.65	0.90	0.95	27.8%
5	0	0.15	0.50	0.80	0.95	0.95	16.7%
6	0.15	0.50	0.80	0.95	0.95	0.95	5.5%

Table 2. Scaling Factor for Adjusting Vulnerability Factors

Scale of Landslide	Protected Facility	Unprotected Facility
Small (<50 m^3)	0.4	0.6
Medium (50 m^3 to <200 m^3)	0.7	0.8
Large (200 m^3 to 1 000 m^3)	0.9	1.0

Table 3. Expected Number of Vulnerable People in a Facility

Scale of Landslide	Type of Facilities: Residential Building	Guard House	Car Park	Open Space
Small (<50 m^3)	1.5	0.25	0.05	0.015
Medium (50 m^3 to <200 m^3)	3	0.5	0.1	0.03
Large (200 m^3 to 1 000 m^3)	6	1	0.2	0.06

7 LANDSLIDE RISK ESTIMATION AND EVALUATION

Landslide risk was calculated based on the landslide frequency and landslide consequence assessments. The PIR was obtained by the summation of the product of landslide frequency and the vulnerability of an average person for all credible landslide hazard scenarios. The QRA results indicated that the most critical ‘present-day’ PIR was 6.3×10^{-4} per year for an individual on the first floor of one of the residential blocks at the toe of the hillside. Under the ‘impending’ condition, the PIR at this location would be reduced to 5.05×10^{-4} per year. Both maximum PIR values are considered to be unacceptably high based on the interim risk guidelines (ERM, 1998).

The Societal Risk results indicated that the F-N curve of the ‘present-day’ Societal Risk was within the ALARP region, except for the fatality range of ten or less, which was within the unacceptable zone (Figure 5). As the hillside in the present case is less than 500 m long, scaling up of the risk tolerability criteria was not required. The assessed results indicated that the ‘present-day’ Societal Risk was 5.67×10^{-3} PLL per year, and the ‘impending’ Societal Risk was 4.44×10^{-3} PLL per year.

8 SENSITIVITY ANALYSIS

In this case study, the predicted future landslide frequencies were determined using the Bayesian approach, taking due account of the analytical as well as the observed past failure frequencies. Within some slope segments (e.g. sub-catchments 3, 5 and 7, see Figure 1), it was noted that the observed past failure frequencies were higher than the predicted failure frequencies. Parametric studies have been carried out to assess the sensitivity of landslide frequencies to the calculated risk. The landslide risk values were re-calculated firstly based solely on the observed past failure frequencies, and secondly based solely on the analytical failure frequencies. It was found that the overall calculated landslide risk value would increase by 28% if the observed past failure frequencies were used, while it would reduce by 22% if the analytical failure frequencies were used. This variation was well within one order of magnitude in the calculated risk and is considered to be comparable to other conventional QRA's.

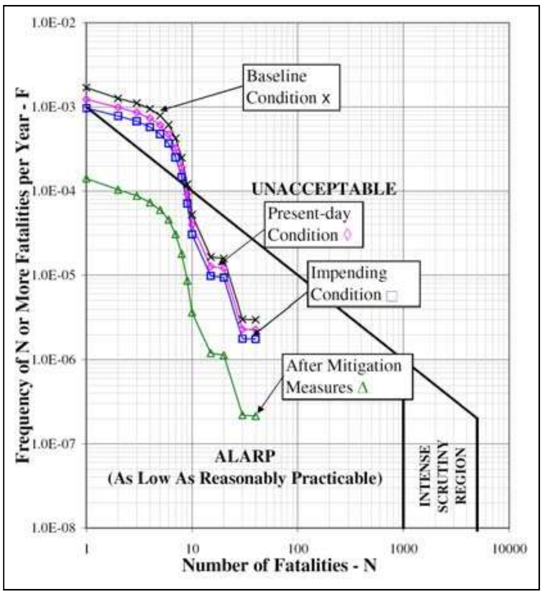

Figure 5 Societal Risk of Different Conditions in F-N Curves

Sensitivity analyses have also been carried out to assess the sensitivity of the landslide debris runout distance to the risk calculations. It was found that the landslide risk figure would reduce by 30% (i.e. within the same order of magnitude) if a normal probability distribution function were adopted for the debris runout distance, instead of a triangular-shaped probability function as used in the analyses. This suggests that the risk calculation was not particularly sensitive to the probability distribution assumed for the runout distance of landslide debris.

9 RISK MITIGATION STRATEGY

As both the calculated PIR and the Societal Risk were found to be unacceptable, and given that the existing developments were affected by recent major landslides, risk mitigation measures are considered warranted. The mitigation strategy was formulated with emphasis on those facilities that were subjected to a high level of landslide risk. Three critical sub-catchments (Nos. 3, 5 and 7), which together contributed some 99.5% of the total PLL, were identified. Landslide preventive/mitigation measures, including provision of soil nails, construction of barrier walls and erection of a series of check dams along the drainage lines, were considered.

The mitigation strategy was developed from a qualitative assessment of the design hazard scenarios followed by a cost-benefit analysis based on the ALARP principle. The design event assessment for the preventive/mitigation measures was established from the Worst Credible Event (WCE) as described by Ng et al (2003), with a notional return period of 1,000 years. Based on cumulative landslide frequency-debris volume method as described by Lo (2000), the design debris volumes for a WCE were estimated to be 600 m^3, 500 m^3 and 500 m^3 respectively for the above three hillside sub-catchments.

A cost-benefit analysis was carried out to assess the cost-effectiveness of the various mitigation options. The calculated maximum justifiable expenditure was HK$5.3M to HK$7.3M, assuming an aversion factor of 1.0 and a design life of 50 years. The priority of the different risk mitigation options was ranked using the Implied Costs of Averting a Fatality

The cost-benefit analyses suggested that a combination of barrier walls and check dams with soil nail tie-back was the most cost-effective scheme. The estimated cost of these measures was about HK$6.5M, which was comparable to the maximum justifiable expenditure over the design life of the mitigation measures.

Following the implementation of the recommended risk mitigation measures, the maximum PIR would be reduced from 5.05×10^{-4} to 6.48×10^{-5} and the Societal Risk reduced from 4.44×10^{-3} PLL to 5.81×10^{-4} PLL per year. As shown in Figure 5, the F-N curve after implementation of the mitigation measures would drop by about one order of magnitude and fall entirely within the ALARP region.

10 SEMI-QUANTITATIVE RISK ANALYSIS

Site-specific risk analysis may comprises qualitative, semi-quantitative or quantitative assessment for the management of landslide risk at a given site. Quantitative risk assessment, as demonstrated above, is characterised by formal and rigorous quantification of the risk levels for risk tolerability evaluation and formulation of risk mitigation strategy. Failure Mode and Effects Analysis (FMEA) is an example of semi-quantitative risk assessment, which can assist hazard identification and screening, serve as a precursor to more detailed risk assessment, or as a stand-alone preliminary risk assessment methodology.

The assessment of natural terrain landslide risks would require the analysis of the possible failure modes, together with their likelihood of occurrence and consequences. The FMEA methodology directs attention towards understanding the behaviour of the physical components of a system, the potential modes of failure and the consequences of failure. FMEA can be undertaken with the use of a tailor-made FMEA table, which is designed for the analysis of failure modes and their effects, by examining the likelihood of failure and the corresponding consequences.

Wong & Ko (2005) provided an example of applying the FMEA technique to the assessment of natural terrain landslide risk for a portion of the subject hillside within the study area. The adopted FMEA classification scheme is given in Table 4 and the FMEA formulation for a selected portion of the hillside is shown in Table 5.

The apparent disadvantage of the FMEA technique is that the FMEA table can become very long (i.e. with many rows) when it is applied to a large site. Formulating a suitable FMEA table that addresses the particular circumstances of a site is of fundamental importance to the efficient and effective application of the FMEA methodology.

This example also illustrates the possible use of a risk matrix in evaluating the risk category and providing a basis for risk estimation and hazard identification. The risk matrix combines different classes of the frequency and consequence of landslides, which are aligned with some notional probabilities of failure and descriptions of the severity of landslide consequence respectively. In this example, the qualitative descriptors given in the AGS guide (AGS, 2000) were adopted. However, due cognizance should be given to the degree of rigour that should be exercised, before one can reliably gauge the likely numerical values of the susceptibility/hazard/risk levels assessed. In this study, given the benefit of having a QRA carried out, the frequency and consequence classes were determined based a judgmental assessment with reference to the quantitative assessment in the QRA. In practice, without quantitative input, it would be difficult to choose suitable descriptors for qualitative or semi-quantitative assessment, because one cannot be reasonably certain about the numerical values of the susceptibility/hazard/risk levels that correspond to the scenarios.

Finally, the corresponding risk levels were determined in a semi-quantitative manner via a risk matrix. Established methods, such as FMEA and risk matrix analysis, can be used in semi-quantitative or qualitative landslide risk assessment to assist in hazard identification, risk screening and risk evaluation. It may also be undertaken as a stand-alone qualitative or semi-quantitative risk assessment procedure, or as a precursor to more detailed risk assessment, such as

QRA. However, this kind of semi-quantitative or qualitative assessment would not provide explicit cost-benefit analysis for risk mitigation measures. The appropriate alignment of the relative descriptors with a range of numerical values is typically fraught with considerable difficulty, particularly for the person doing the field mapping. As for all types of landslide risk assessment, it is also important to note that the availability of quality data and technical understanding of the landslide hazards at the site are prerequisites for the successful application of this approach.

Table 4. FMEA Classification Scheme

Risk Category		Risk to Life					Economic Loss				
		Loss of Life Consequence Category					Economic Loss & Disruption to Community Consequence Category				
		1	2	3	4	5	I	II	III	IV	V
Hazard Likelihood Category	A	H	H	H	H	R	H	H	M	L	R
	B	H	H	H	L	R	H	M	L	V	R
	C	H	M	L	V	R	M	L	V	R	R
	D	M	L	V	R	R	L	V	R	R	R
	E	L	V	R	R	R	V	R	R	R	R
	E-	V	R	R	R	R	R	R	R	R	R

Note: PLL is the average number of fatalities per year. Risk Category is defined as follows:

(a) Risk Category

Class	Descriptions (PLL for risk to life)	Further Study
H	High - of major concern (notional PLL > 1×10^{-3})	This failure mode should be examined with priority attention, to assess/verify the scale of the problem
M	Moderate - of considerable concern (notional PLL from 1×10^{-3} to 1×10^{-4})	This failure mode should be examined, to assess/verify the scale of the problem
L	Low - of some concern (notional PLL from 1×10^{-4} to 1×10^{-5})	It is advisable to examine this failure mode, to assess/ verify the scale of the problem
V	Very Low - practically not a concern (notional PLL less than 1×10^{-5})	Further study not warranted except in special circumstances
R	Residual risk - no indication of risk problem	Further study not warranted

(b) Likelihood Category

Class	Failure Likelihood Category	Class	Effect Likelihood Category (likelihood of occurrence of the stated effects given the failure mode)	Adjustment to Failure Likelihood Category
A	Very high (notionally 1 in 10 years)	x	Probable (notionally 0.5 or higher)	No change
B	High (notionally 1 in 10 to 100 years)	y	Quite possible (notionally 0.1 to 0.5)	Downgrade by half a category
C	Moderate (notionally 1 in 100 to 1,000 years)	z	Possible (notionally < 0.1)	Downgrade by one category
D	Low (notionally 1 in 1 000 to 10 000 years)			
E	Very Low (notionally much less than 1 in 10 000 years)			

(c) Consequence Category

Class	Consequence Category in Terms of Loss of Life
1	Very high chance of loss of life (PLL notionally > 1); multiple fatalities may occur
2	High change of loss of life (PLL notionally 0.1 to 1); low chance of multiple fatalities
3	Moderate chance of loss of life (PLL notionally 0.01 to 0.1)
4	Low chance of loss of life (PLL notionally < 0.01)
5	Very low chance of loss of life (PLL much less than 0.01)

Class	Consequence Category in Terms of Economic Loss & Disruption to Community
I	Very high (severe structural damage to multi-story buildings; prolonged evacuation of multi-story building or a large number of houses; prolonged breakdown of transportation network)
II	High (severe structural damage to a few flats or individual houses; prolonged evacuation of a few flats or individual houses; prolonged closure of major road or important access; temporary breakdown of transportation network)
III	Moderate (some damage to properties; temporary evacuation of a few flats or individual houses; temporary closure of major road or important access)
IV	Low (less serious than above)
V	Very low (much less serious than above)

Table 5. FMEA for Selected Hillside Segments in Sub-catchment No. 7

Component	Failure Mode	Effects on Building Named K.K. Terrace	Likelihood Category			Loss of Life		Economic Loss & Disruption to Community		Risk Category (Proceed to Detailed Assessment?)
			Failure	Effect	Hazard	Consequence Category	Risk Category	Consequence Category	Risk Category	
Segments 7b, 7e, 7f, 7i & 7j	Shallow landslide resulting in small- to medium-scale debris flow without significant entrainment	Debris runs into and affects 1/F of K.K. Terrace	B	X	B	2	H	III	L	High (Yes)
		Debris hits and affects the entrance to K.K. Terrace		Y	B to C	3	H to L	IV	R	Moderate (Yes)
	Shallow landslide resulting in medium- to large-scale debris flow with significant entrainment	Debris runs into and affects 1/F of K.K. Terrace	D	X	D	2	L	III	R	Low (Yes)
		Debris hits and affects the entrance to K.K. Terrace		Y	D to E	3	V to R	IV	R	Very Low (No)
		Debris hits K.K. Terrace and results in building collapse or major structural damage	D	Z	E	1	L	II	R	Low (Yes)

	Shallow landslide resulting in small-scale debris flow with limited mobility	Temporary evacuation of 1/F of K.K. Terrace	B	Y	B to C	5	R	IV	V to R	Very Low (No)

11 DISCUSSION AND CONCLUSIONS

The use of formal risk quantification technique in geotechnical applications allows the logical and rational quantification of the risk level, comparison with risk tolerability criteria and evaluation of risk management actions based on risk tolerability and cost-benefit considerations. Over the past decade, the GEO has pioneered the development and application of QRA for a wide range of geotechnical and landslide problems. The methodology and technique continue to evolve and this case study represents one of the early milestones in the development of site-specific QRA for natural terrain landslide hazards in Hong Kong.

In this case study, the probability of failure of the hillside was assessed based on both historical landslide records and probabilistic slope stability analyses using Monte-Carlo simulation. The consequence of failure was assessed based on consideration of mobility of landslide debris, site-specific population data, proximity of the vulnerable population to the potential landslides and the degree of protection provided by the buildings. A cost-benefit analysis was carried out to assess the cost-effectiveness of the various risk mitigation options. The most optimum solution was derived using the Implied Costs Averting a Fatality. Sensitivity analyses have been carried out to examine the significance of various uncertainties.

This paper also presented an example of the application of Failure Mode and Effect Analysis (FMEA) technique.

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