

## Recent advancement in the application of Quantitative Risk Assessment in landslide risk management in Hong Kong

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**ABSTRACT:** Hong Kong has always been a densely populated place characterised by its hilly terrain with thick weathered soil profile and sub-tropical climate setting leading to seasonal heavy rainfall, which makes the place vulnerable to landslide risk. Since 1990s, the Geotechnical Engineering Office (GEO) has applied Quantitative Risk Assessment (QRA) in support of landslide risk management in Hong Kong. Major applications include priority ranking of man-made slopes and hillside catchments for priority action under the rolling Landslip Prevention and Mitigation Programme to manage the landslide risk systematically. The GEO also pioneered the development of site-specific QRA in support of landslide risk assessment for new development and existing development with an aim to evaluating the risk tolerability and to making risk-informed decisions on site-specific risk management actions.

Recently, the GEO has adopted site-specific QRAs to provide risk data for supplementing decision making in the early screening of new developments against potential landslides. The early screening criteria involve only broad consideration of terrain setting and facility type, without an explicit account of landslide hazards and population at risk. This occasionally results in over conservative, not cost-effective decisions regarding the requirement of landslide study and mitigation for facilities of relatively low population. As an attempt to enhance cost-effectiveness in the early screening process and thereby reduce the overall development cost, the QRAs aim to estimate the risk levels of different site conditions affecting different sparsely populated facilities. They also aim to identify means, based on explicit risk considerations, to improve the broad screening criteria. This paper presents the background, methodology and findings of the QRAs as well as the proposed supplementary technical guidelines for use in the early screening of new developments.

**KEYWORDS:** Landslides, risk, risk management, QRA, quantitative, natural terrain.

### 1 INTRODUCTION

Landslides have always been one of the common natural hazards in Hong Kong which brought about loss of life and economical loss due to the combined factors of the subtropical climate, dense population and urban development close to hilly terrain. Over the past decades, the GEO has made concerted effort by employing multi-pronged decision tools in implementing the Slope Safety System, successfully containing the overall landslide risk in Hong Kong to the “As Low As Reasonably Practicable” (ALARP) level that is commensurate to the international best practice.

Particularly in natural hillsides, under the current strategy for management of natural terrain hazards, a Natural Terrain Hazard Study (NTHS) is required to study the natural terrain hazards involved and identify any mitigation measures required for a site with proposed development fulfilling the Inclusion Guidelines and the Alert Criteria as stated in the 2<sup>nd</sup> Edition of GEO Report No. 138 (Ho & Roberts, 2016). In the Inclusion Guidelines, the facilities of the proposed development are first classified according to the grouping of facilities as tabulated in Table 1. The facilities in the grouping system are broadly ranked in the order of their consequence (i.e. Group 1 being the highest consequence and Group 5 being the lowest).

Table 1. Grouping of facilities.

Group No.	Facilities
1	(a) Buildings - any residential building, commercial office, store and shop, hotel, factory, school, power station, ambulance depot, market, hospital/polyclinic/ clinic, welfare centre (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

2	(a) Buildings - 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) (b) Others - road with heavy vehicular or pedestrian traffic density - major infrastructure facility (e.g. railway, tramway, flyover, subway, tunnel portal, service reservoir)
3	- densely-used open space and public waiting area (e.g. densely-used playground, open car park, densely-used sitting out area, horticultural garden) - quarry - road with moderate vehicular or pedestrian traffic density
4	- lightly-used open-air 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
5	- remote area (e.g. country park, undeveloped green belt, abandoned quarry) - road with very low vehicular or pedestrian traffic density

A site is regarded to satisfy the Inclusion Guidelines if (1) the proposed development involves Group 1, 2, or 3 facilities and (2) there is a hillside sloping at more than 15° within 100 m horizontally upslope of the site boundary.

Further screening of a site which satisfies the Inclusion Guidelines is conducted by applying two sets of technical criteria, viz. the In-principle Objection Criteria and the Alert Criteria. The In-principle Objection Criteria are targeted to address sites with severe natural terrain hazards and their details can be referred to Ho & Roberts (2016). For a site that does not satisfy the In-principle Objection Criteria, the Alert Criteria are used to identify whether a site may be affected by natural terrain hazards. NTHS is required for a site which satisfies the Alert Criteria as set out below:

- a) It is a new development site involving provision of Group 1 to 3 facilities (Table 1), or it is a redevelopment

that requires modification of the lease conditions and involves either a significant population at risk or a significant increase in population at risk.

- b) Where there is natural terrain outside the site, but within the same catchment, that is at an angular elevation of 20° or more from the site and where there is ground sloping at more than 15° within 50 m horizontally upslope of the site boundary, provided that there is a credible debris flow path to the site (Figure 1).

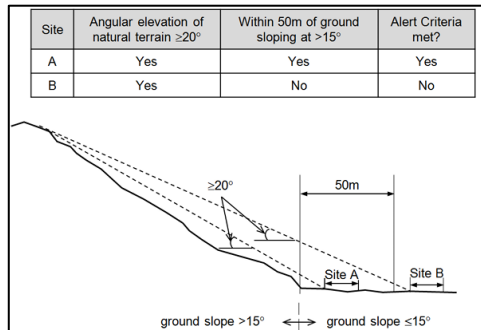


Figure 1. Application of Alert Criteria.

## 2 CURRENT APPROACHES IN NATURAL TERRAIN HAZARD STUDY

There are three NTHS approaches as suggested in Ho & Roberts (2016), namely Factor of Safety, QRA and Design Event Approach (DEA), for studying natural terrain hazards affecting a site involving provision of Group 1 to 3 facilities and meeting the Alert Criteria. Among the three approaches, the DEA is the most commonly adopted given its simplicity to apply. An NTHS adopting the DEA gives a probable design event affecting downslope facilities for design of mitigation measures. The mitigation measures derived as such are relatively massive in terms of their physical scale and resources required and cost millions of Hong Kong dollars. Thus, they are considered more cost-effective for protecting sites with large population at risk (e.g. multi-story buildings within Group 1 to 3 facilities).

Nevertheless, some scenarios listed in Facility Groups 1 to 3 may associate with relatively low consequence in terms of potential loss of life. For instance, sheltered facilities with apparently low usage are identified as Facility Group 1(b). Some examples provided for densely-used open space and public waiting area in Facility Group 3 may have sparse population at a given time as well. Without the explicit consideration of consequence and risk tolerability, conducting an NTHS using the DEA may result in mitigation measures that are disproportionate to the scale of consequence for these facilities.

## 3 THE QRA STUDY

Since 1990s, the GEO has applied QRA in support of landslide risk management in Hong Kong in a territory-wide scale. Examples include its application in priority ranking of man-made slopes and hillside catchments for priority action under the rolling Landslip Prevention and Mitigation Programme to systematically manage the landslide risk. The GEO has also pioneered the use of site-specific QRA to evaluate the risk tolerability of existing and new developments in the face of natural terrain hazards.

In this paper, the application of site-specific QRA is extended to differentiate the risk levels of different facility types comprising various sizes of population at risk within Groups 1 to 3 facilities. This risk-based approach enables the

devising of different study and mitigation requirements for these facilities of different scale of consequence in the current screening procedures. A pilot study was initiated to address the limitations of the broad risk considerations as adopted in the current screening procedures for conducting NTHS. It also aimed to develop potential supplementary technical guidelines on the application of screening procedures for achieving more cost-effective administrative decision-making based on more refined risk data. The study adopted QRA to evaluate the consequence of the hazards and assess the risk levels of these apparently low-usage sheltered facilities or densely-used open space and public waiting area. Individual QRAs were conducted for three selected sites. The general site settings and their proposed developments are shown in Figure 2 to Figure 4. Their basic information is summarised in Table 2.

Table 2. Basic information of the three sites.

	Total Catchment Area (m <sup>2</sup> )	Proposed Development
Site A	43,600	Metered car (15 nos.) and motorcycle (36 nos.) parking spaces
Site B	42,800	7 greenhouses and 1 security station
Site C	8,100	Public toilet

Site A (Figure 2) is overlooked by a south-east-facing natural terrain. Metered car and motorcycle parking spaces are proposed adjoining an existing road at the toe of the catchments. The elevation of the natural terrain rises from about +45 mPD at the toe to about +160 mPD at the north-western crest. The catchment is inclined at angles of about 30° to 45° in the upper reaches, flattening to between 20° and 30° in the lower portion. A drainage line is present at the lower portion of the catchment. Site B (Figure 3) is a proposed development site for agricultural structures overlooked by a single hillside catchment. It extends from an elevation of about +370 mPD to the proposed site at an elevation of about +260 mPD. Site C (Figure 4) comprises a largely planar natural hillside catchment with a public toilet proposed at the toe of the catchment. The elevation of the catchment rises from about +130 mPD at the toe to about +190 mPD at the crest.

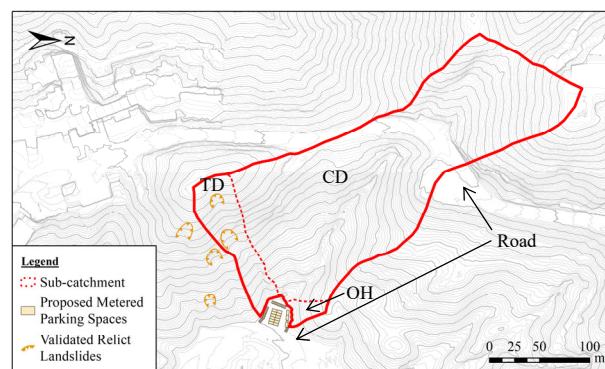


Figure 2. Hillside catchments and proposed facilities at Site A.

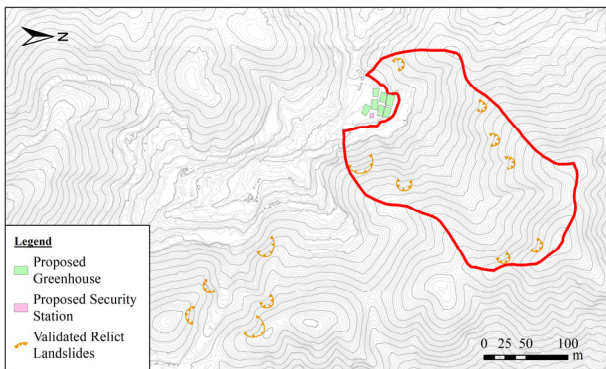


Figure 3. Hillside catchments and proposed facilities at Site B.

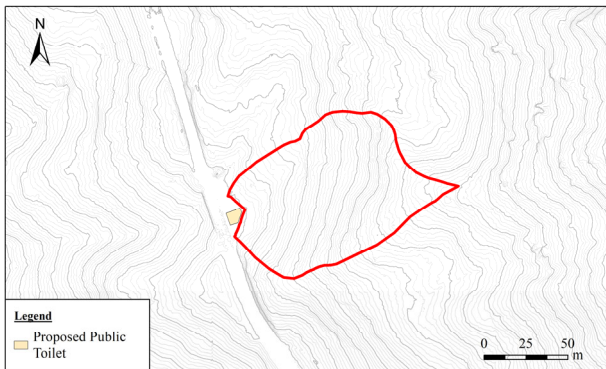


Figure 4. Hillside catchments and proposed facilities at Site C.

## 4 METHODOLOGY

The QRAs were carried out generally following the framework by Fell et al. (2005). The following 11 key modules of work were adopted in the study with reference to Wong et al. (2004) for site-specific QRA, with some further enhancements made.

1. Determination of the objectives and approach of the study;
2. Study area delineation; identification of facilities and population at risk, and their degree of proximity;
3. Demarcation of boundaries and types of catchments;
4. Validation of historical landslides;
5. Examination of rainfall records and effects;
6. Geological assessment and hazard identification;
7. Formulation of hazard models and assessment of design events;
8. Identification of debris runout paths and influence zones;
9. Frequency assessment;
10. Consequence assessment;
11. Risk analysis and evaluation.

In the following sections, the methodology of the QRA will be outlined using Site A as an illustration, considering the fact that it has the highest risk level amongst the three sites.

### 4.1 Landslide history and rainfall effects

Historical landslide activities and characteristics in the region were evaluated by examination of the landslide inventory compiled by the GEO as well as interpretation of aerial photographs. No recent landslides and 5 relict landslides were identified within and in the vicinity of the catchment concerned. The correlations of natural terrain landslide density with normalised rainfall intensity in Hong Kong established by Lo et al. (2022) were applied to the site. The site was found to be less susceptible than the average performance of the natural terrain in Hong Kong. Therefore, in the frequency assessment, the baseline landslide frequency was determined based on

historical landslides and reasonably adjusted up to account for the variability in rainfall effects.

### 4.2 Catchment identification

The topography of the hillside was assessed with the use of a 0.5m-grid Digital Elevation Model (DEM) together with terrain evaluation based on interpretation of aerial photographs. 3 sub-catchments were demarcated (Figure 2) and were classified into three types according to the debris movement mechanisms (Table 3).

Table 3. Catchment classification.

Catchment Type	Mechanism of debris movement
CD	Channelised debris flow
TD	Debris flow at topographic depression
OH	Open hillslope debris slide / avalanche

### 4.3 Geological assessment and hazard identification

A geological assessment was carried out for the site, including a review of all available desk study information, detailed interpretation of aerial photographs, etc. Different terrain units were then classified for the region based on geomorphological processes, relative landform age, etc. (Figure 5). The relative landslide susceptibility of these terrain units was taken into account in the frequency assessment. Based on the geological assessment, the possible hazard volumes were also determined (Table 4).

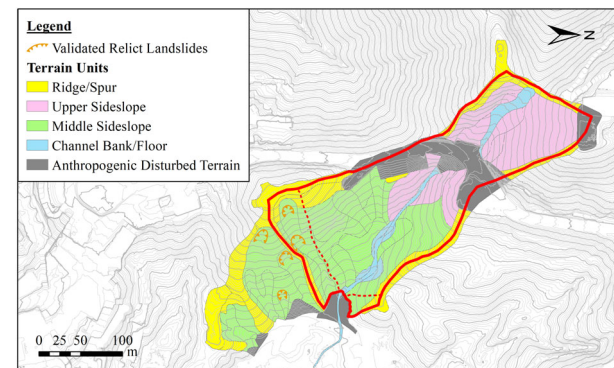


Figure 5. Terrain unit classification at Site A.

Table 4. Hazard volume classification.

Volume class	Landslide Volume
H1	30 m <sup>3</sup> notional (20 m <sup>3</sup> to 60 m <sup>3</sup> )
H2	100 m <sup>3</sup> notional (60 m <sup>3</sup> to 200 m <sup>3</sup> )
H3	300 m <sup>3</sup> notional (200 m <sup>3</sup> to 600 m <sup>3</sup> )
H4	1000 m <sup>3</sup> notional (600 m <sup>3</sup> to 2000 m <sup>3</sup> )

### 4.4 Debris runout path

The hillside was divided into smaller hillside units (Figure 6) with reference to factors including topographic conditions and terrain characteristics such that each of the hillside units possessed similar debris runout characteristics. Based on 3-D GIS analysis, possible debris runout paths from each hillside unit were determined. With the runout paths identified, the hillside units were matched with the boundary segments at the toe of the hillside, which were then further matched with the affected facilities.

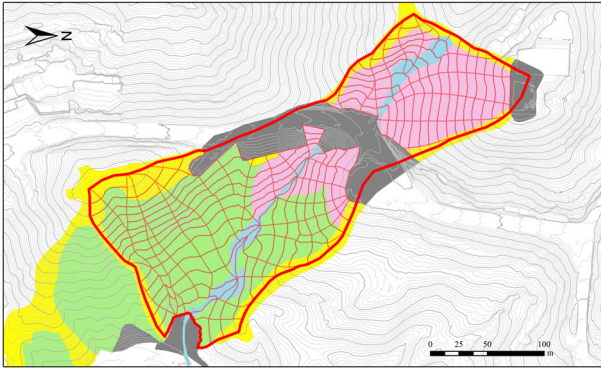


Figure 6. Hillside units at Site A.

#### 4.5 Frequency assessment

The baseline landslide density is determined with due reference to the territory-wide landslide density, the actual landslide density at the site and rainfall effects. Magnitude-frequency correlation and spatial distribution of the baseline landslide density were then applied with adjustment of gradient effect and relative susceptibility of different terrain units. Based on the estimated landslide densities ( $f_{v,k,m}$ ) with magnitude-frequency determination for different terrain units and slope gradient classes, the frequency of landslide of a hillside unit for a given landslide volume ( $F_{i,v}$ ) can be calculated as Equation (1). The calculated annual frequency of the landslide hazard volume class H3 is shown in Figure 7.

$$F_{i,v} = \sum_k \sum_m (f_{v,k,m} \times A_{i,k,m}) \quad (1)$$

where  $A$  = Area  
 $i$  = Hillside unit  
 $v$  = Volume classes of landslides  
 $k$  = Terrain unit  
 $m$  = Slope gradient class

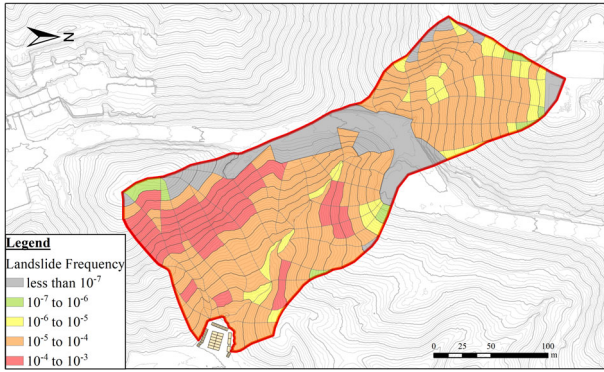


Figure 7. Calculated annual frequency of hazard H3 at Site A.

#### 4.6 Consequence assessment

In this study, the computer programme 2d-DMM (Version 2.0) (Law & Ko, 2015) was adopted for the assessment of debris mobility. Different sets of rheological parameters (Table 5) were adopted according to the hazard type.

Table 5. Rheological parameters (GEO, 2023a; GEO, 2023b; GEO, 2023c).

Hazard type	Rheological parameters	
	$\phi_a$ (°)	$\zeta$ (m/s <sup>2</sup> )
CD	11	500
TD	18	1000
OH	20 (for H1 – H3) / 25 (for H4)	-

#### 4.6.1 Probability of debris mobility

The probability of debris mobility in this study assumed a symmetric triangular distribution after Wong et al. (2004), which can be represented by the function as shown in Equation (2) below.

$$P_M(x) = \frac{2}{x_{\max}} \left(1 - \frac{|2x - x_{\max}|}{x_{\max}}\right) \text{ for } 0 \leq x \leq x_{\max} \quad (2)$$

where  $x_{\max}$  = Worst credible runout distance  
 $x$  = Possible runout distance

As an illustration for applying Equation (2), the probability distribution for worst credible runout distances of 40m, 80m and 160m is presented in Figure 8.

#### 4.6.2 Vulnerability factors

The vulnerability factor ( $VF$ ) model adopted in Wong & Ko (2008) is adopted in this study where the degree of damage to the occupied ground floor structures is considered with regard to the distance of debris travelling beyond the facility. The model for substantial structures (P) and flimsy or unprotected structures (U) is reproduced in Figure 9 and described by Equation (3).

$$VF = \begin{cases} \int_{x_f}^{x_{\max}} D(x - x_f) P_M(x) dx & \text{for } x_{\max} > x_f \\ 0 & \text{for } x_{\max} \leq x_f \end{cases} \quad (3)$$

where  $x_f$  = Distance from the hillside unit to the affected structure  
 $D(x - x_f)$  = Degree of damage to facilities

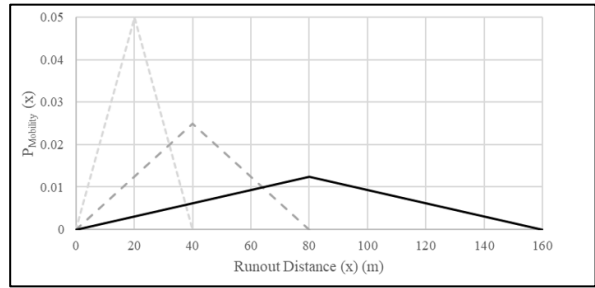


Figure 8. Probability distribution for different worst credible runout distances.

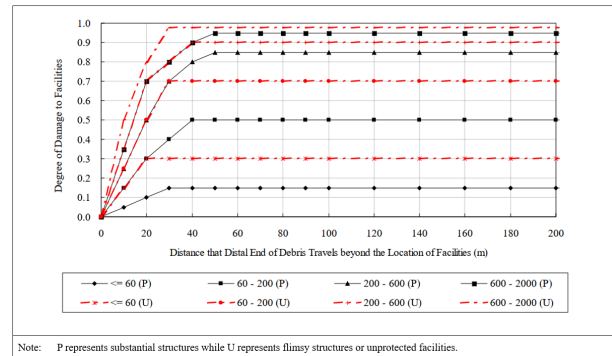


Figure 9. Degree of damage to facilities.

In this study, location factors ( $LF$ ) were also applied to account for the possibility that the facility may not be subject to the direct impact of the landslide debris passing through the boundary segment (Wong et al. 2004; Wong et al. 2006).

For OH hazard, the  $LF$  for a facility with width of  $b$  in front of a boundary segment with width of  $L$  is given by Equation (4). The reference width of the credible flow path,  $w$ , was adopted from Wong et al. (2004) for different hazard volume classes as shown in Table 6 to determine  $LF$ .

$$LF = \frac{w+b}{L} \leq 1 \quad (4)$$

Table 6. Width of credible flow path.

Volume class	Width of credible flow path, <i>w</i> (m)
H1	10
H2	10
H3	30
H4	30

For CD and TD hazard, considering the credible flow path is along a drainage line, it was assumed that the landslide debris would spread laterally at an angle of 45° at the drainage outlet. Therefore, a two-tier *LF* with respect to the possibility of direct hit is given by Wong et al. (2006) and extracted in Table 7.

Table 7. Location factors for facilities affected by CD and TD hazard.

Possibility of direct hit	Location Factor ( <i>LF</i> )
Very possible	1.0
Possible	0.5

#### 4.7 Risk estimation and evaluation

The risk of landslides from a hillside unit to a facility (i.e. the Frequency of Damage, *FoD*) was determined as the sum products of the frequency assessment and consequence assessment under different volume classes of landslide considered using Equation (5).

$$FoD_{i,n} = \sum_v F_{i,v} \times (VF \times LF)_{i,v,n} \quad (5)$$

where *n* = Numbering of affected facility

Individual Risk (IR), which denotes the calculated frequency of harm per year to a theoretical individual who is exposed to natural terrain landslide hazards for 100% of the time (ERM, 1998), was calculated by summing up the Frequency of Damage from all hillside units (Figure 10)

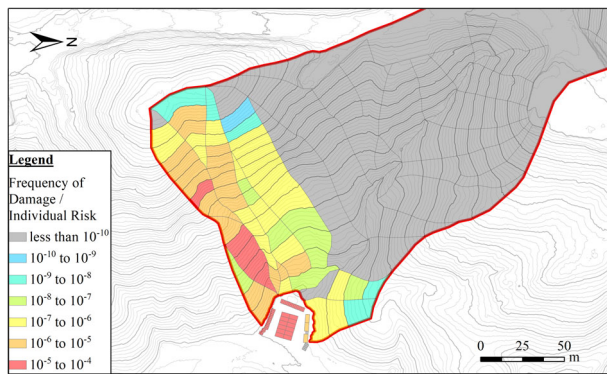


Figure 10. Frequency of Damage from hillside units and Individual Risk at affected facilities at Site A.

To postulate the population at risk and their temporal presence for the estimation of Societal Risk, site surveys were undertaken to consolidate the user behaviour at metered parking spaces under similar site settings for Site A. For Site B and Site C, information was obtained from the project proponent (e.g. manpower required for working in greenhouses) and site surveys were conducted respectively.

Personal Individual Risk (PIR) refers to the frequency of harm per year to an actual most vulnerable individual who is exposed to a hazard or hazards from a facility, taking into account temporal factors which expose the individual to the

hazard(s). The PIR of the three sites as given in Table 8 was found to be within the acceptable level ( $< 10^{-5}$ ) according to ERM (1998).

Table 8. Personal Individual Risk and Potential Loss of Life

	Personal Individual Risk (fatality/year)	Potential Loss of Life (fatality/year)
Site A	$3.38 \times 10^{-6}$	$4.02 \times 10^{-5}$
Site B	$7.46 \times 10^{-7}$	$3.74 \times 10^{-6}$
Site C	$8.44 \times 10^{-7}$	$1.19 \times 10^{-6}$

The societal risks in terms of potential loss of life (PLL) of the three sites are also given in Table 8. The corresponding F-N curves are shown in Figure 11. It can be seen that the derived F-N curves are well within the ALARP level, and no part of the F-N curves falls in the “Unacceptable” zone, as defined in ERM (1998).

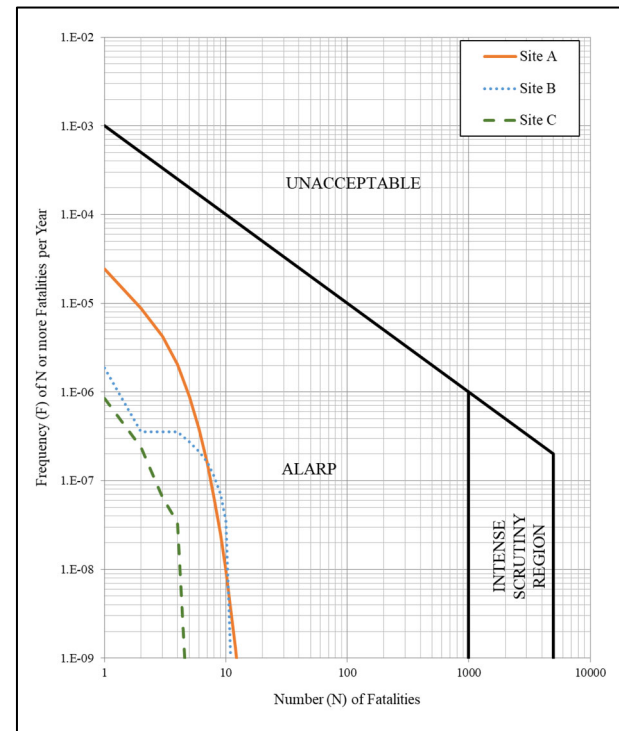


Figure 11. Calculated F-N curves.

Based on the ALARP principle, the Maximum Justifiable Expenditure (MJE) on the hazard mitigation works for the three sites were estimated to be in the range of HK\$0.007 to 0.230M, which are one to two orders less than the cost of typical mitigation measures designed under the DEA in Hong Kong, such as flexible and rigid barriers.

## 5 POTENTIAL ENHANCEMENT IN SITE SCREENING AND NTHS APPROACH

In the past, decision making based on facility grouping in Table 1 is considered effective as most developments involved large population at risk such as multi-story buildings, where the mitigation options were mainly derived based on DEA. With more development types being proposed, different site conditions affecting different sparsely populated facilities are not uncommon nowadays. Potential enhancement to current site screening and NTHS approach is therefore explored as follows:

- (a) From the QRA results, the limitation of the broad risk consideration in the grouping of facilities in Table 1 can be addressed properly when site specific data such as landslide hazards and population at risk are explicitly taken

into consideration under the QRA framework. With more “low-risk” sites being assessed using QRA approach, different hazard and population information collected can be used for benchmarking and formulating supplementary guidelines for facilities in Group 1 to 3 with apparently low usage. NTHS may not be required for these facilities, which would streamline the initial screening.

- (b) From the calculated MJE, the scale of mitigation measures required to mitigate the natural terrain hazards for these three sites is at least one order of magnitude less than what would be determined using DEA approach such as substantial barriers or large extent of soil nailing on the hillsides. Since MJE is correlated with quantifiable risk, more cost-effective mitigation options such as nature-based solutions or prescriptive small-scale fencing can be explored in future to mitigate the natural terrain risk arising from “low-risk” site setting.

## 6 CONCLUSIONS

Hong Kong has a vulnerable geographical setting to landslide risks. Given the dense population and vast economic growth, it is commonplace for high-rise buildings with large population at risk being proposed in close proximity of hillsides. The scale of mitigation measures derived from DEA was found to be proportional to the risk arising from these proposed developments. Relatively massive mitigation solutions such as barriers are considered necessary for these sites to safeguard the community.

When it comes to lower population at risk, however, mitigation measures derived from DEA may be disproportionate to the scale of problem. Therefore, a more risk-based NTHS approach is called for to enhance the cost-effectiveness in selecting mitigation solutions.

This paper presented the application of site-specific QRA to study the risk associated with sparsely populated facilities. The three sites considered involved the provision of some apparently low-usage sheltered facilities or densely-used open space. The risk of landslides of all three sites was found to fall within the ALARP level as given in ERM (1998). Based on the ALARP principle, the MJE on the hazard mitigation works for the three sites were estimated to be in the range of HK\$0.007 to 0.230M. Compared with the cost of typical mitigation measures determined from DEA, the MJE determined from QRA is at least one order of magnitude less.

The findings demonstrate there is room to enhance the current screening criteria and NTHS approach to achieve more cost-effective design based on risk tolerability. Potential further work including study on more sites with similar site settings and proposed developments may provide useful data for benchmarking their risk levels. With sufficient data demonstrating the risk level to be low enough, the need for NTHS for these facilities may no longer be required. Given the relatively low MJE, more cost-effective mitigation options such as nature-based solution or small scale prescriptive structures may be explored in mitigating the risk for these sites.

## 7 ACKNOWLEDGEMENTS

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