Landslide Risk Assessment for Individual Facilities

H. N. Wong
Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong

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Abstract: Geotechnical practice has progressed to the stage that slope engineering is no longer confined to investigation of slope stability. Instead, landslide risk has to be examined and managed in totality. This brings a broad spectrum of landslide-related problems to the agenda of risk assessment. This paper addresses landslide risk assessment that is undertaken at a large scale, in which the facilities at risk are individually recognized and assessed. Selected application cases are presented to illustrate the approaches adopted, their capability and constraints, and the development trends in risk assessment practice. There is a choice between using a qualitative or quantitative approach. There are also significant differences between applying the assessment to a few individual sites and to a large number of slopes. The challenge is for the geotechnical profession to master the diverse range of landslide risk assessment processes, to use the right tools for the right problems, and to become more effective in risk communication with stakeholders.

1 INTRODUCTION

Many practical slope problems are best tackled by a risk-based approach. The key principle is to examine both the likelihood and adverse consequence of slope failure, and thereby address risk in totality. This concept is implicit in our slope design and engineering practice. It has also been explicitly applied in different places, particularly where formal risk assessment is adopted in managing landslide problems.

Different aspects of landslide risk assessment and relevant technological developments are addressed in State of the Art Paper (SOA) 1 to SOA 6. Application of risk assessment is covered in SOA 7 and SOA 8. SOA 7 focuses on landslide hazard and risk zoning, with particular attention given to applications at a smaller scale for urban planning and development.

This paper (SOA 8) deals with landslide risk assessment at a larger scale and its application to risk management. It reviews the methodologies used to assess landslide risk for individual facilities, examines good practice and diagnoses the development trends, with particular attention being given to application and case histories. Selected qualitative risk-based slope rating schemes adopted in various countries are described to illustrate the practice and approaches. Selected examples of qualitative and quantitative risk assessment (QRA) applications are presented to show the range of applications and evolution of techniques.

2 RISK ASSESSMENT FOR INDIVIDUAL FACILITIES

In this paper, 'landslide risk assessment for individual facilities' refers to the assessment that is undertaken at a resolution and scale sufficient for the elements at risk (i.e. the facilities where adverse consequences may occur) to be individually recognized and their landslide risk evaluated, either by qualitative or quantitative means. This is the most common type of landslide risk assessment that is carried out for location-specific risk management purposes. It differs from risk assessment as applied to general landslide hazard and risk zoning (SOA 7) in the following aspects:

(a) It is often carried out at a larger scale, typically 1:2,000 or more detailed, such that both the slopes that pose the risk and the elements at risk can be clearly identified and examined. Landslide hazard and risk zoning is usually carried out at a smaller scale.

(b) The element at risk is known, be it an existing or a planned facility. Hence, not only the likelihood of a landslide but also its consequence can be explicitly evaluated. Landslide hazard and risk zoning would not necessarily involve a comparable level of consequence assessment and may in some cases be carried out without examining in detail the specific facilities at risk.

(c) It is often carried out to support or guide risk management decisions affecting specific sites, such as the priority and need for risk mitigation. Its reliability and resolution have to be commensurate with the intended application. The assessment would normally require the use of more detailed data and specific risk analysis techniques.

Depending on the intended application, landslide risk assessment for individual facilities can be carried out in different ways and to different levels of detail. The assessment may be classified according to the analytical approach adopted, i.e. whether it is primarily based on qualitative, semi-quantitative or quantitative methodology. Alternatively, classification may be

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made in relation to the purpose of the assessment. This typically includes risk rating, screening, prioritization, evaluation of overall risk, formulation of risk management strategy, site-specific risk management action, etc. There is no hard-and-fast rule for classification. It is obvious that the analytical approach must be related to the purpose of the assessment. As a broad categorization to facilitate review and assessment of the current state of practice, a pragmatic classification as summarized in Table 1 is adopted in this paper.

Table 1. Different types of landslide risk assessment for individual facilities

Extent of application	Approach	
	Qualitative	Quantitative
A large number of slopes	Qualitative risk rating	Global quantitative risk assessment (QRA)
Individual slopes	Site-specific qualitative risk assessment	Site-specific quantitative risk assessment (QRA)

* This includes semi-quantitative risk assessment.

** This refers to quantification and evaluation of risk using formal quantified risk assessment methodology

3 QUALITATIVE RISK RATING

Qualitative risk rating is the most common form of application of qualitative landslide risk analysis to a large number of slopes. This is commonly carried out by devising a rating scheme to evaluate the relative likelihood of landslide (i.e. hazard rating) and the relative severity of the consequence of failure (i.e. consequence rating), based on qualitative analysis of the slope attributes and data on the individual facilities affected. The qualitative analysis may be performed by different methods, such as the use of a scoring system, flow charts, qualitative descriptors, a risk matrix, or a combination of these methods. The rating scheme is then applied to a large number of slopes. Provided that the required slope attributes and facility data are collected, the risks of the slopes can be rated and their relative risk compared. Depending on the complexity of the qualitative risk analysis method adopted, the scheme may be targeted on one or many types of slope (e.g. rock cut slopes and fill embankments), and for one specific type of facility (e.g. roads) or different types of facility.

Qualitative risk rating has been formulated and applied in many different places, some dating back to the late 1970s. It is typically adopted by agencies that are responsible for managing the risk for a large number of existing slopes. The risk rating provided a relatively simple but consistent means to achieve the following objectives:

– to evaluate and rank their relative risk (i.e. 'risk ranking');
– to prioritize the slopes for follow-up study, repair or maintenance (i.e. 'prioritization for action'); and
– to assist in the preliminary assessment of the scope and cost of follow-up action (i.e. 'preliminary estimate')

Selected risk rating schemes are described in Sections 3.1 to 3.8 below to illustrate the practice and approaches adopted in different places. A comparison of the key features of the schemes is summarized in Table 2.

In some cases, the rating process involves a preliminary screening to first identify the more problematic slopes within a large number of slopes, as candidates for risk rating. This is referred to as 'preliminary screening' in Table 2. Some rating systems have also been adopted as a tool and to provide reference data for use in QRA. This is denoted as a 'QRA tool' in Table 2. As explained in Item (g) of Section 3.9.4 below, a rating system may also be characterized depending on whether it is principally an 'expert judgment scheme', or an 'expert formulation scheme', or a 'mixed scheme'.

3.1 *Cut Slope Ranking System, Hong Kong*

The dense urban development since the Second World War in Hong Kong has resulted in the formation of a large number of cut slopes, fill slopes and retaining walls. Until about the mid 1970s, cut slopes were generally built empirically to an angle of 10 vertical to 6 horizontal. Fill slopes formed prior to the mid 1970s were generally not compacted to an acceptable standard. These un-engineered man-made slopes were susceptible to landslides. Some resulted in very significant loss of life.

In 1977, upon setting up the Geotechnical Control Office (GCO, which was renamed Geotechnical Engineering Office, GEO, in 1991), the Hong Kong Government embarked on a long-term programme for retro-fitting substandard slopes. A pre-requisite for implementation of this programme was the registration and risk ranking of the existing sizeable man-made slopes in the urban area. This prioritized the slopes, so that the most risky slopes could be stabilized first.

The registration of man-made slopes completed by the GCO at the time identified a total of about 8,500 cut slopes and retaining walls. These were catalogued in a slope inventory (referred to as the 1977/78 Slope Catalogue), which contained the key slope attributes and data on affected facilities. In 1979, the GCO and Binnie & Partners jointly formulated the Cut Slope Ranking System, which was a qualitative risk rating scheme. The system was used by the GCO to calculate a 'Total Score' for each of the 8,500 cut slopes and retaining walls registered in the inventory. Based on

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Table 2. Comparison of different qualitative slope rating systems

Case No. / Place (Section in SOA8)	Primary application	Type of slope for rating		Rating method
		Slope	Facility	
1 / Hong Kong (Section 3.1)	– Risk ranking – Prioritization for action	Un-engineered cut slopes and retaining walls	All types	– Scoring system, with hazard and consequence ratings – Expert formulation scheme
2 / Hong Kong (Section 3.2)	– Risk ranking – Prioritization for action	Un-engineered fill slopes	All types	– Scoring system, with consequence rating before hazard rating – Expert formulation scheme
3 to 6 / Hong Kong (Section 3.3)	– Risk ranking – Prioritization for action – QRA tool	Un-engineered cut slopes, fill slopes and retaining walls	All types	– Scoring system, with hazard and consequence ratings – Expert formulation scheme
7 & 8 / USA (Section 3.4)	– Preliminary screening – Risk ranking – Prioritization for action – Preliminary estimate	Rock cut slopes	Roads	– Scoring system, with emphasis in hazard rating – Mixed scheme
9 / Canada (Section 3.5)	– Risk ranking – Prioritization for action	Rock cut slopes	Railway	– Hazard rating system – Mixed scheme
10 / Australia (Section 3.6)	– Risk ranking – Prioritization for action	Man-made slopes but primarily rock cut slopes	Primarily Roads	– Risk matrix system, with hazard and consequence ratings – Expert judgment scheme
11 / Malaysia (Section 3.7)	– Risk ranking – Prioritization for action	All types including natural slopes	Primarily Roads	– Scoring system, with hazard and consequence ratings – Expert formulation scheme
12 / Australia (Section 3.8)	– Risk ranking – Land-use planning	Clay slopes	Different types of land-use	– Scoring system, with simple hazard and consequence ratings – Expert formulation scheme
13 / Japan (Section 3.8)	– Risk ranking – Prioritization for action	Rock slopes, deep-seated landslides and debris flows	Roads	– Scoring system, with emphasis in hazard rating – Expert formulation scheme
14 / New Zealand (Section 3.8)	– Risk ranking – Prioritization for action	Cut and fill slopes	Roads	– Scoring system; primarily hazard rating – Mixed scheme
15 / UK (Section 3.8)	– Risk ranking – Prioritization for action	Rock slopes	Roads	– Scoring system; primarily hazard rating – Mixed scheme

the Total Score, which reflected the relative landslide risk, the cut slopes and retaining walls were ranked for follow-up studies to assess whether they met the required safety standard and whether retro-fitting was necessary.

The system was described in Koirala & Watkins (1988). The ranking system was based on an assessment of the potential for failure and the consequence of failure, with numeric weightings assigned to the relevant slope and facility data

(Table 3). The weightings were used to calculate an 'Instability Score' and 'Consequence Score' for each slope. The relative risk-to-life of the slope is represented by a Total Score, which is the sum of its Instability Score and Consequence Score.

A plot of the Instability Score vs Consequence Score of the ranked slopes is shown in Figure 1. It is notable that the Consequence Score has a wider spread than the Instability Score. This was consistent with the fact that the consequence of landslide among the slopes varied to a greater extent than the likelihood of landslide that could be differentiated by the scoring methodology used to assess instability.

Experience in using the system indicated that the system performed very satisfactorily in differentiating the 10% to 20% of the slopes with the greatest risk concern, which were subsequently selected by the GCO for investigation and retro-fitting. The calculated Total Score of many of these slopes was dominated by their Consequence Score.

3.2 *Fill Slope Ranking System, Hong Kong*

The Fill Slope Ranking System was formulated in parallel with the development of the Cut Slope Ranking System. The fill slopes constructed before 1977 in Hong Kong were mostly substandard in that the fill material was commonly placed by end-tipping with little, if any, compaction effort applied. Static liquefaction failure, in the form of a fast-moving, mobile flow slide, was known to be the key landslide problem from the fill slopes, as was evident from the 1972 and 1976 Sau Mau Ping landslides, which together resulted in 90 fatalities. It is implicit in the Fill Slope Ranking System that the ranking is based primarily on the relative risk of liquefaction failure.

The system was described in Koirala & Watkins (1988). The Fill Slope Ranking System was applied by the GCO to about 2,000 fill slopes registered in the 1977/78 Slope Catalogue to establish their relative risk ranking and priority for follow-up treatment.

3.3 *New Priority Classification System, Hong Kong*

The GEO has been operating a government-funded Landslip Preventive Measures (LPM) Programme to systematically study old man-made slopes and carry out stabilization works on sub-standard slopes that are under Government's responsibility. The Cut Slope Ranking System and Fill Slope Ranking System formulated in the late 1970s were applied by the GCO in ranking the priority of the man-made slopes registered in the 1977/78 Slope Catalogue, for treatment under the LPM Programme. The two ranking systems served their intended purposes effectively. By the mid 1990s, about 1,000 top-ranking slopes were selected for detailed studies. Over 630 government-owned slopes that were found to be substandard and of serious consequences in the event of failure were upgraded under the LPM Programme. Engineering

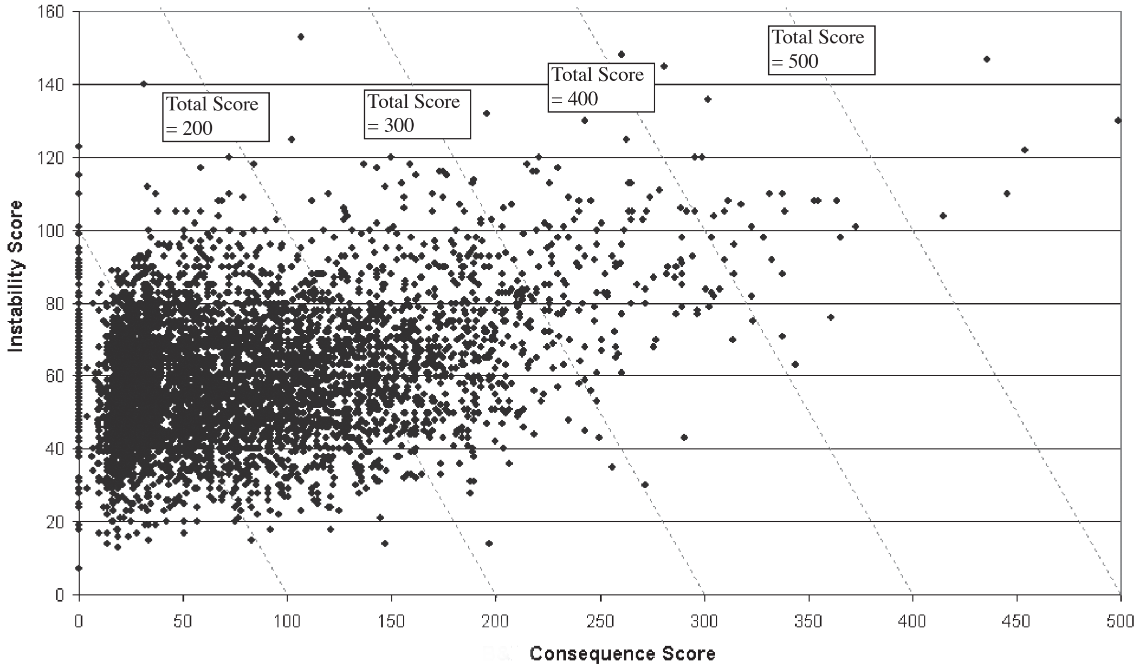

Figure 1. Instability Score vs Consequence Score of slopes ranked by the Cut Slopes Ranking System, Hong Kong (Wong & Ho 1995)

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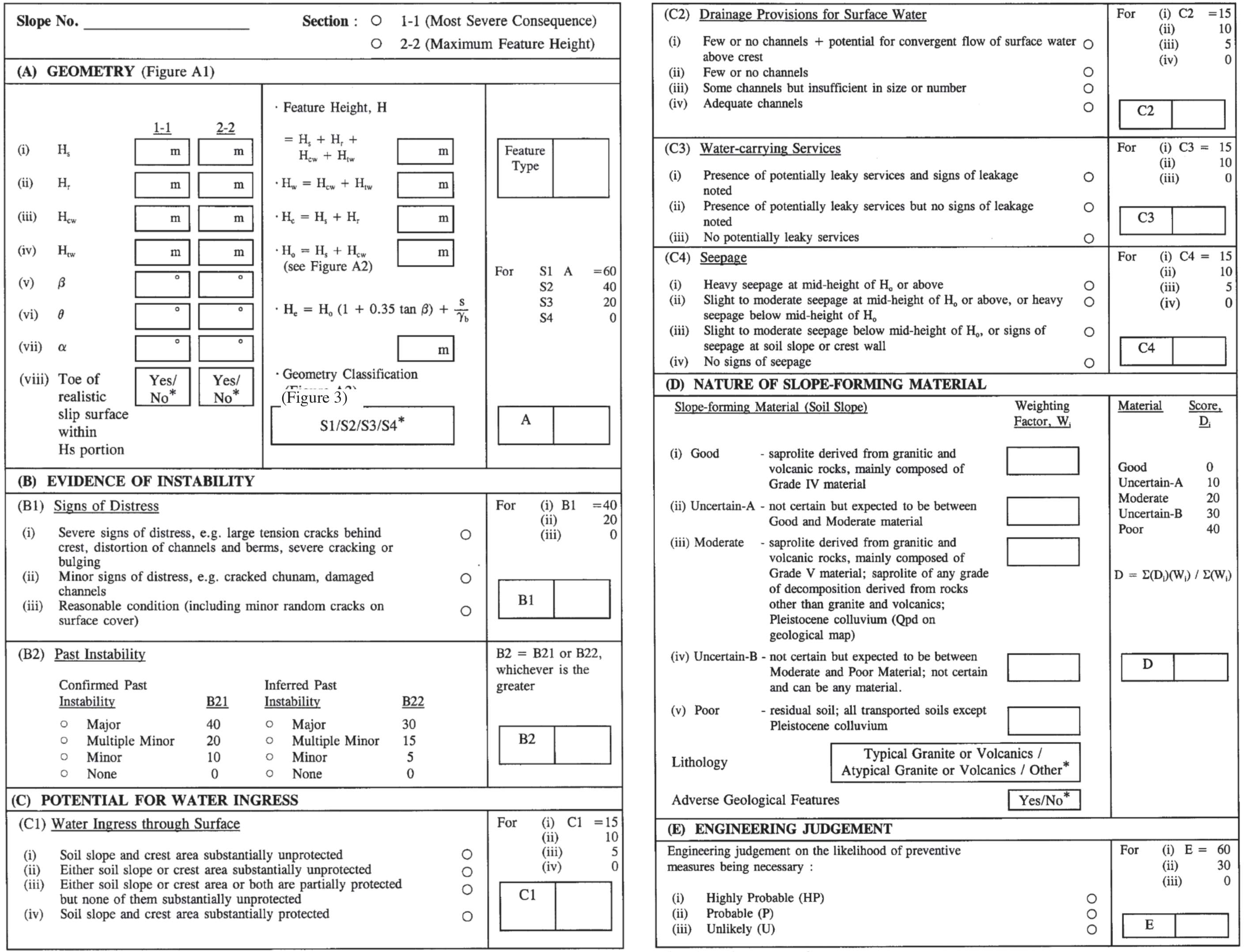
Table 3. Numeric weightings and scoring formulae of Cut Slope Ranking System, Hong Kong (Koirala & Watkins 1988)

Component	Score	Max. score	Component	Score	Max. score
e) Height, H (metre)	Soil slopes, H x 1 Rock slopes, H x 0.5 Mixed slopes, H x 1	Un-limited	o) Ponding potential at crest	Ponding area at crest = 5	5
f) Slope angle	Rock: 90° = 10 ≥ 80° = 8 ≥ 70° = 5 ≥ 60° = 2 < 60° = 0 Others: ≥ 60° = 20 ≥ 55° = 15 ≥ 50° = 10 ≥ 45° = 5 35° = 3 < 35° = 0	20	p) Channels	None, incomplete = 10 Complete – major cracks = 10 Complete = 0	10
			q) Water carrying services	Services within "H" of crest - Yes = 5 - No = 0	5
g) Angle of slope above, or presence of roads above	Slope ≥ 45° =15 Slope ≥ 35°, or Major road =10 Slope ≥ 20°, or Minor road = 5 Slope < 20° = 0	15	r) Seepage	Amount Position / Heavy / Slight Mid-height & above / 15 / 5 Near toe / 10 / 2	15
i) Associated wall	Height of associated wall (metre) x 2	Un-limited	t) Distance to building, road or playground from toe of slope (metre)	Buildings = actual distance Roadways = distance + 2 metres Playground=greater of actual distance or ½H	Un-limited
j) Slope condition	Loose blocks =10 Signs of distress =10 Poor = 5 Good = 0	10	u) Distance to buildings, roads or playgrounds from toe of slope (metre)	As for (t)	
k) Condition of associated wall	Poor =10 Fair = 5 Good = 0	10	v) Extensive slope at toe or slope	Extensive slope at top 0.5 Extensive slope below 20	25
l) Adverse jointing	Adverse joints noted = 5	5	w) Multiplier for type of property at risk at top	Hospitals, schools, residential 2 Factories, playgrounds 1.5 Major roads 1.0 Minor roads 0.5 Open space 0	2
m) Geology	Colluvium/shattered rock, thin soil mantle =15 Thick Volcanic soil =10 Thick Granitic soil = 5 Sound rock (massive) = 0	15	x) Multiplier for type of property at risk at top	As above	2
n) Water access - impermeable surface on and above slope	None =15 50% (partial) = 8 Complete – poor = 5 Complete – good = 0	15	y) Multiplier for risk factor	For densely populated area or where buildings may collapse 1.25 Otherwise 1.0	1.25
Instability Score = $\sum(e,f,g,i,j,k,l,m,n,o,p,q,r)$					
Consequence Score = $y\ \{20w\left(\frac{1.5\,(e+i)-t}{1.5\,(e+i)}\right)+(40\,x)\left(\frac{(e+i)-u}{(e+i)}\right)+(vx)+2\,(e+i)\}$					
Total Score = Instability Score + Consequence Score					



Slope No. ____________________ **Section :** ○ 1-1 (Most Severe Consequence) ○ 2-2 (Maximum Feature Height)

(A) GEOMETRY (Figure A1)

		1-1	2-2
(i)	H_s	m	m
(ii)	H_r	m	m
(iii)	H_{cw}	m	m
(iv)	H_{tw}	m	m
(v)	β	°	°
(vi)	θ	°	°
(vii)	α	°	°
(viii)	Toe of realistic slip surface within Hs portion	Yes/No*	Yes/No*

· Feature Height, H $= H_s + H_r + H_{cw} + H_{tw}$ m

· $H_w = H_{cw} + H_{tw}$ m

· $H_c = H_s + H_r$ m

· $H_o = H_s + H_{cw}$ m (see Figure A2)

· $H_e = H_o (1 + 0.35 \tan \beta) + \frac{s}{\gamma_b}$ m

· Geometry Classification (Figure 3) S1/S2/S3/S4*

Feature Type

For S1 A =60
S2 40
S3 20
S4 0

A

(B) EVIDENCE OF INSTABILITY

(B1) Signs of Distress

(i) Severe signs of distress, e.g. large tension cracks behind crest, distortion of channels and berms, severe cracking or bulging ○
(ii) Minor signs of distress, e.g. cracked chunam, damaged channels ○
(iii) Reasonable condition (including minor random cracks on surface cover) ○

For (i) B1 =40
(ii) 20
(iii) 0

B1

(B2) Past Instability

Confirmed Past Instability	B21	Inferred Past Instability	B22
○ Major	40	○ Major	30
○ Multiple Minor	20	○ Multiple Minor	15
○ Minor	10	○ Minor	5
○ None	0	○ None	0

B2 = B21 or B22, whichever is the greater

B2

(C) POTENTIAL FOR WATER INGRESS

(C1) Water Ingress through Surface

(i) Soil slope and crest area substantially unprotected ○
(ii) Either soil slope or crest area substantially unprotected ○
(iii) Either soil slope or crest area or both are partially protected but none of them substantially unprotected ○
(iv) Soil slope and crest area substantially protected ○

For (i) C1 =15
(ii) 10
(iii) 5
(iv) 0

C1

(C2) Drainage Provisions for Surface Water

(i) Few or no channels + potential for convergent flow of surface water above crest ○
(ii) Few or no channels ○
(iii) Some channels but insufficient in size or number ○
(iv) Adequate channels ○

For (i) C2 =15
(ii) 10
(iii) 5
(iv) 0

C2

(C3) Water-carrying Services

(i) Presence of potentially leaky services and signs of leakage noted ○
(ii) Presence of potentially leaky services but no signs of leakage noted ○
(iii) No potentially leaky services ○

For (i) C3 = 15
(ii) 10
(iii) 0

C3

(C4) Seepage

(i) Heavy seepage at mid-height of H_o or above ○
(ii) Slight to moderate seepage at mid-height of H_o or above, or heavy seepage below mid-height of H_o ○
(iii) Slight to moderate seepage below mid-height of H_o, or signs of seepage at soil slope or crest wall ○
(iv) No signs of seepage ○

For (i) C4 = 15
(ii) 10
(iii) 5
(iv) 0

C4

(D) NATURE OF SLOPE-FORMING MATERIAL

Slope-forming Material (Soil Slope)		Weighting Factor, W_i
(i) Good	- saprolite derived from granitic and volcanic rocks, mainly composed of Grade IV material	
(ii) Uncertain-A	- not certain but expected to be between Good and Moderate material	
(iii) Moderate	- saprolite derived from granitic and volcanic rocks, mainly composed of Grade V material; saprolite of any grade of decomposition derived from rocks other than granite and volcanics; Pleistocene colluvium (Qpd on geological map)	
(iv) Uncertain-B	- not certain but expected to be between Moderate and Poor Material; not certain and can be any material.	
(v) Poor	- residual soil; all transported soils except Pleistocene colluvium	

Lithology: Typical Granite or Volcanics / Atypical Granite or Volcanics / Other*

Adverse Geological Features: Yes/No*

Material	Score, D_i
Good	0
Uncertain-A	10
Moderate	20
Uncertain-B	30
Poor	40

$D = \Sigma(D_i)(W_i) / \Sigma(W_i)$

D

(E) ENGINEERING JUDGEMENT

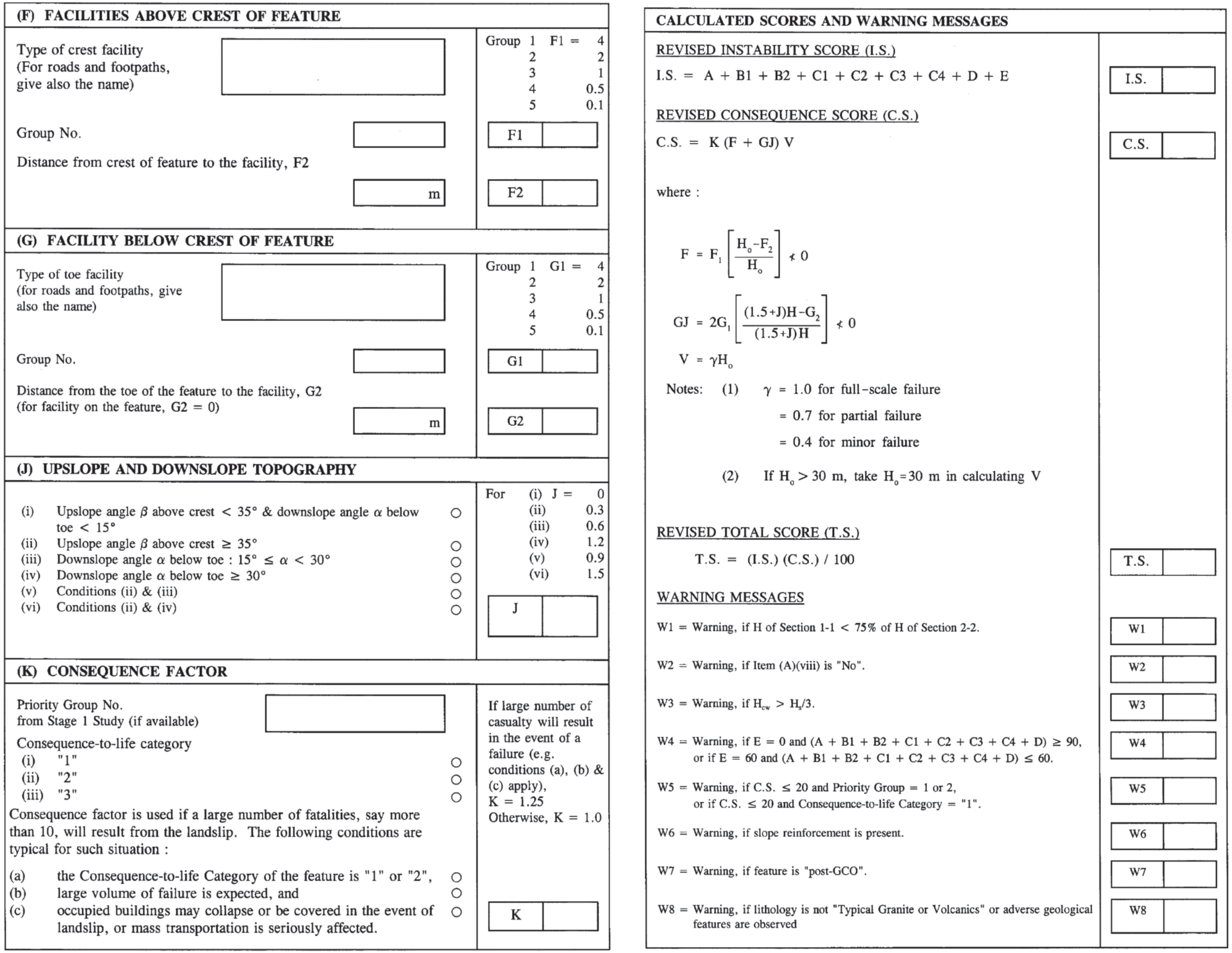
Engineering judgement on the likelihood of preventive measures being necessary :

(i) Highly Probable (HP) ○
(ii) Probable (P) ○
(iii) Unlikely (U) ○

For (i) E = 60
(ii) 30
(iii) 0

E

Figure 2. Scoring scheme of Soil Cut Slope Priority Classification System, Hong Kong (Wong & Ho 1995)



(F) FACILITIES ABOVE CREST OF FEATURE

Type of crest facility (For roads and footpaths, give also the name) ☐

Group No. ☐

Distance from crest of feature to the facility, F2 ☐ m

Group	F1 =
1	4
2	2
3	1
4	0.5
5	0.1

F1 ☐

F2 ☐

(G) FACILITY BELOW CREST OF FEATURE

Type of toe facility (for roads and footpaths, give also the name) ☐

Group No. ☐

Distance from the toe of the feature to the facility, G2 (for facility on the feature, G2 = 0) ☐ m

Group	G1 =
1	4
2	2
3	1
4	0.5
5	0.1

G1 ☐

G2 ☐

(J) UPSLOPE AND DOWNSLOPE TOPOGRAPHY

(i) Upslope angle β above crest $< 35°$ & downslope angle α below toe $< 15°$ ○
(ii) Upslope angle β above crest $\geq 35°$ ○
(iii) Downslope angle α below toe : $15° \leq \alpha < 30°$ ○
(iv) Downslope angle α below toe $\geq 30°$ ○
(v) Conditions (ii) & (iii) ○
(vi) Conditions (ii) & (iv) ○

For	J =
(i)	0
(ii)	0.3
(iii)	0.6
(iv)	1.2
(v)	0.9
(vi)	1.5

J ☐

(K) CONSEQUENCE FACTOR

Priority Group No. from Stage 1 Study (if available) ☐

Consequence-to-life category
(i) "1" ○
(ii) "2" ○
(iii) "3" ○

Consequence factor is used if a large number of fatalities, say more than 10, will result from the landslip. The following conditions are typical for such situation :

(a) the Consequence-to-life Category of the feature is "1" or "2", ○
(b) large volume of failure is expected, and ○
(c) occupied buildings may collapse or be covered in the event of landslip, or mass transportation is seriously affected. ○

If large number of casualty will result in the event of a failure (e.g. conditions (a), (b) & (c) apply), K = 1.25
Otherwise, K = 1.0

K ☐

CALCULATED SCORES AND WARNING MESSAGES

REVISED INSTABILITY SCORE (I.S.)

I.S. = A + B1 + B2 + C1 + C2 + C3 + C4 + D + E

I.S. ☐

REVISED CONSEQUENCE SCORE (C.S.)

C.S. = K (F + GJ) V

C.S. ☐

where :

$$F = F_1 \left[\frac{H_o - F_2}{H_o} \right] \nless 0$$

$$GJ = 2G_1 \left[\frac{(1.5+J)H - G_2}{(1.5+J)H} \right] \nless 0$$

$$V = \gamma H_o$$

Notes: (1) γ = 1.0 for full-scale failure
= 0.7 for partial failure
= 0.4 for minor failure

(2) If $H_o > 30$ m, take $H_o = 30$ m in calculating V

REVISED TOTAL SCORE (T.S.)

T.S. = (I.S.) (C.S.) / 100

T.S. ☐

WARNING MESSAGES

W1 = Warning, if H of Section 1-1 < 75% of H of Section 2-2. W1 ☐

W2 = Warning, if Item (A)(viii) is "No". W2 ☐

W3 = Warning, if $H_{cw} > H_s/3$. W3 ☐

W4 = Warning, if E = 0 and (A + B1 + B2 + C1 + C2 + C3 + C4 + D) ≥ 90, or if E = 60 and (A + B1 + B2 + C1 + C2 + C3 + C4 + D) ≤ 60. W4 ☐

W5 = Warning, if C.S. ≤ 20 and Priority Group = 1 or 2, or if C.S. ≤ 20 and Consequence-to-life Category = "1". W5 ☐

W6 = Warning, if slope reinforcement is present. W6 ☐

W7 = Warning, if feature is "post-GCO". W7 ☐

W8 = Warning, if lithology is not "Typical Granite or Volcanics" or adverse geological features are observed W8 ☐

Figure 2. (continued) Scoring scheme of Soil Cut Slope Priority Classification System, Hong Kong (Wong & Ho 1995)

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inspections were also carried out on about 4,000 slopes in the Catalogue.

As many high ranking slopes were selected for action under the LPM Programme by the mid 1990s, it was evident that a new rating system was required to further improve the effectiveness of prioritizing the remaining slopes. A number of factors contributed to this need:

(a) The old ranking systems were targeted at, and calibrated for, identification of the worst slopes. As a result, many high and sub-standard slopes close to occupied buildings were selected for action under the LPM Programme. By the mid 1990s, landslides affecting roads and other facilities were becoming increasingly important for effective landslide risk reduction. However, the old ranking systems were not tailor-made for differentiating the relative risk of these lower ranking slopes.

(b) Lack of suitable slope data for use in rating was a major constraint faced by the old ranking systems. It was known that a large number of slopes, in particular slopes outside the main urban areas, had not yet been registered in the 1977/78 Slope Catalogue. Hence, in the early 1990s, the GEO commenced compilation of a new Catalogue of Slopes to register all sizeable man-made slopes in Hong Kong. The work included systematic interpretation of the historical aerial photographs and field inspections (Lam et al. 1998). This provided an opportunity to collect new data for use in risk rating. The Catalogue of Slopes now comprises some 57,000 man-made slopes, and about 39,000 of these were formed before 1977.

(c) Improved knowledge of landslides and related technical issues provided a basis for improving the slope rating methodology.

The New Priority Classification System (NPCS) was developed in 1995 and 1996, to replace the old ranking systems as the qualitative risk rating scheme for ranking pre-1977 man-made slopes registered in the new Catalogue of Slopes for treatment under the LPM Programme. There are four main types of man-made slope feature in Hong Kong, viz. soil cut slopes, rock cut slopes, fill slopes and retaining walls. Since the landslide risk of different types of slope feature is affected by different factors, four separate rating schemes have been developed. They combine to form the NPCS.

In each scheme, a Total Score is calculated for each slope, which reflects its relative landslide risk. The Total Score is given by multiplication of the Instability Score and Consequence Score of the slope.

3.3.1 Soil Cut Slope Priority Classification System

The detailed formulation and calibration of the Soil Cut Slope Priority Classification System are described in Wong & Ho (1995). The scoring scheme is summarized in Figure 2.

A large amount of calibration work was carried out to assist in formulating the numeric weightings and the scoring formulae and to validate the ranking results. For example, the slope geometry classification has been calibrated with the outcome of the detailed stability assessment of 69 slopes under a 10-year groundwater condition (Figure 3). The worst zone, denoted as 'S1', has about 80% of cases with a calculated factor of safety less than 1.1. Monte Carlo simulation was carried out to validate the boundaries of the geometry zone and to calibrate the landslide probabilistic distributions, using typical ranges of soil parameters and groundwater conditions in Hong Kong. There is also an empirical correlation between the Instability Score and the calculated factor of safety for the 69 sites (Figure 4). An Instability Score of less than 80 corresponds with a factor of safety of more than about 1.2, whereas an Instability Score of more than 120 corresponds to a factor of safety of less than 1.1. There is a 'grey' zone in between these Instability Scores where the factor of safety can be within a large range. Findings from technical development work on assessment of debris mobility and QRA have been

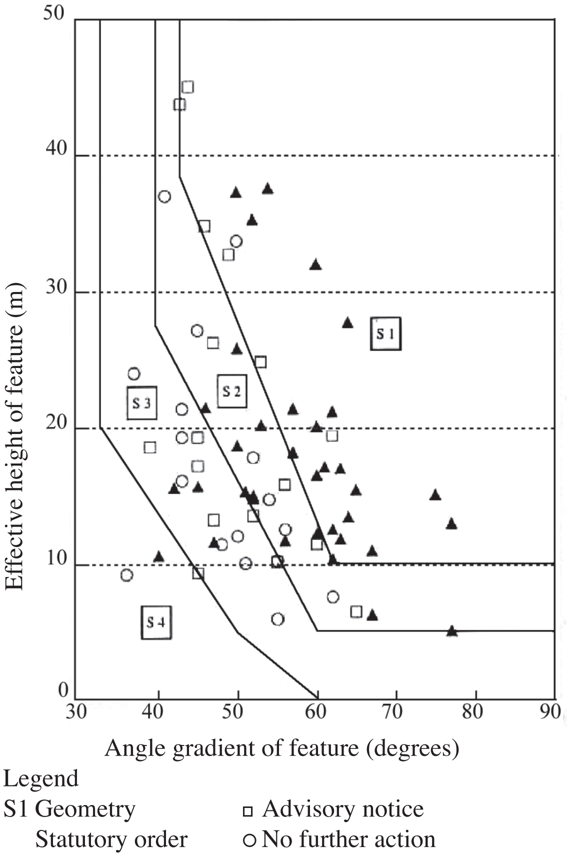

Figure 3. Cut slope geometry classification (Wong & Ho 1995)

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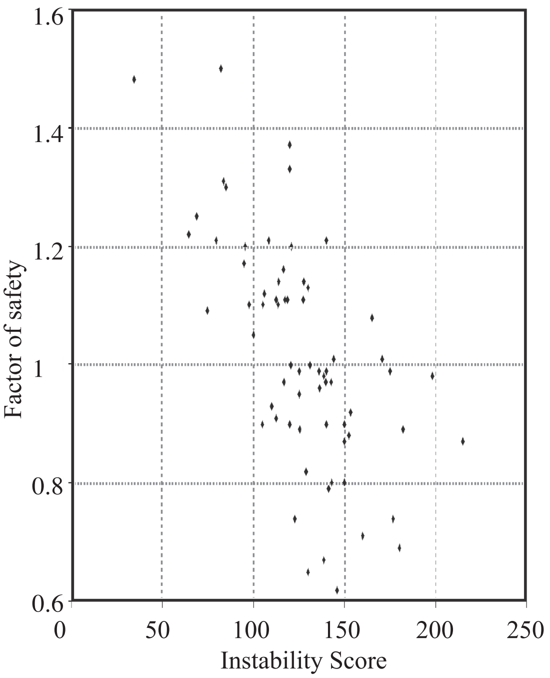

Figure 4. Correlation between Instability Score and calculated factor of safety of soil cut slopes (Wong & Ho 1995)

incorporated into the formulation of the Consequence Score. Table 4 shows the grouping of different types of facilities adopted in the NPCS and the corresponding potential loss of life (PLL) in the event of a direct hit by a reference landslide, which is derived by QRA on alignment of the facility grouping using PLL (Wong et al. 1997).

3.3.2 Formulation of Rock Cut Slopes Priority Classification System

The detailed formulation and calibration of the Rock Cut Slope Priority Classification System are described in Golder Associates (1996) and summarized in Wong (1998). The system for rock cut slopes is similar, in terms of its rationale and structure, to that for soil cut slopes. However, the parameters and their combinations as adopted in the rating were tailor-made to address the nature of rock slope failures in Hong Kong. Summarized in Table 5 are the key groups of factors considered in the scoring scheme and the range of individual scores that may be assigned.

Four different mechanisms of rock slope failures were examined in the rating: (a) raveling – small scale (<5 m^3) detachment of individual overhanging rock blocks or isolated loose blocks from the slope face; (b) toppling; (c) planar failure; and (d) wedge failure. Their risks were rated separately by multiplying the Instability Score with the Consequence Score of each mechanism of failure. These were then summed up to give the combined Total Score.

Table 4. Group of facilities adopted in NPCS (based on Wong & Ho 1995)

Group	Facilities	Potential loss of life
1(a)	Buildings - any residential building, commercial office, store and shop, hotel, factory, school, power station, ambulance depot, market, hospital/polyclinic/clinic, welfare centre	3
1(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 - 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
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 (if future use not certain)	1
3	- 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	- 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	- 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 windows 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.
(2) 'Potential loss of life' in this Table refers to the average number of fatalities in the event of a direct hit (i.e. 100% vulnerability) by a referenced landslide that is 10 m wide and 50 m^3 in volume, as derived from formal consequence assessment (Wong et al. 1997).

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Table 5. Key groups of factors for rock cut slope priority classification system, Hong Kong (Golder Associates 1996)

Type of score	Key groups of factors	Range of scores
Instability Score	Slope geometry	10 – 80
	Mode of slope failure	0.5 – 5
	Evidence of distress or past instability	0 – 70
	Potential for water ingress	0 – 30
	Rock mass condition	0 – 110
	Engineering judgment	0 – 30
Consequence Score	Type and proximity of crest facility	0 – 450
	Type and proximity of toe facility	
	Upslope and downslope topography	
	Likely scale of failure	
	Consequence factor/ vulnerability	

3.3.3 Fill Slopes Priority Classification System

Details of the system and the relevant calibration work are described in Wong (1996) and summarized in Wong (1998). Unlike the old Fill Slope Ranking System, which focused on rating the risk of static liquefaction failure, the Fill Slope Priority Classification System rates the total risk arising from three mechanisms of fill slope failure commonly observed in Hong Kong. These included: (1) sliding and minor washout; (2) liquefaction; and (3) major washout.

For each fill slope, a separate Instability Score and Consequence Score were calculated for each of the failure mechanisms. The scoring scheme is shown in Table 6.

The QRA-based consequence model described in Wong et al (1997) was adopted in calculating the Consequence Score, which gave a direct indication of the potential loss of life in the event of failure. As in the case with the other schemes of the NPCS, the Fill Slope Priority Classification has been benchmarked with case histories to calibrate the scoring methodology and to examine whether the risk rating is reasonable. In addition, trial application of the system was undertaken on sixteen cases, including notable fill slope failures and typical fill slopes in Hong Kong (Wong & Ho 2000). Some of the results of the trial application are extracted and shown in Table 7. The results showed that the relative instability ratings for different mechanisms of failure and the potential number of fatalities (i.e. Consequence Score) were reasonable.

3.3.4 Retaining Wall Priority Classification System

The detailed formulation and calibration of the Retaining Wall Priority Classification System are described in Wong (1998). The key groups of factors considered in the scoring scheme and the range of individual scores that may be assigned are summarized in Table 8.

The available landslide data and knowledge of the performance of old retaining walls in Hong Kong have been examined in devising the system. Guidelines on assessment of wall conditions, consolidated from local experience, were prepared to facilitate the use of the system. Typical forms of masonry wall construction were examined and illustrative examples were provided to assist in diagnosing the form of wall construction in field inspections (Chan 1996).

3.3.5 Combined Priority Ranking

The four priority classification systems each provided a list of slopes of the respective type, ranked according to their relative landslide risk as reflected by Total Score (TS). The four ranking lists were merged, to allow different types of slope feature to be rated in a single list to establish their priority for treatment under the LPM Programme. The combined system is collectively referred to as the NPCS, and the combined relative risk was denoted by a calculated Risk Score (RS).

The RS was assessed based on the following methodology:

(a) A global QRA was performed to assess the overall distribution of landslide risk among different types of slope feature registered in the Catalogue of Slopes (see Section 6.3). The QRA found that the proportion of total risk of the pre-1977 soil and rock cut slopes, fill slopes and retaining wall are 75%, 12% and 13%, respectively. This formed the basis for a risk-based merging of four separate ranking lists.

(b) The risk proportion was distributed to each individual slope to derive the RS, based on the calculation TS and the proportion of total risk of the specific slope type. For soil cut slopes, rock cut slope and retaining walls, RS is given by:

$$\text{RS} = (\text{TS of Individual Slope} / \sum \text{TS of all slopes of the same type}) \text{ x Proportion of total risk for the slope type x } 10^5 \qquad (1)$$

For fill slopes, e^{TS} is used in place of TS, which reflects the nature of the scoring methodology adopted in the ranking system. The resulting scoring formulae of RS for different slope types are given in Table 9.

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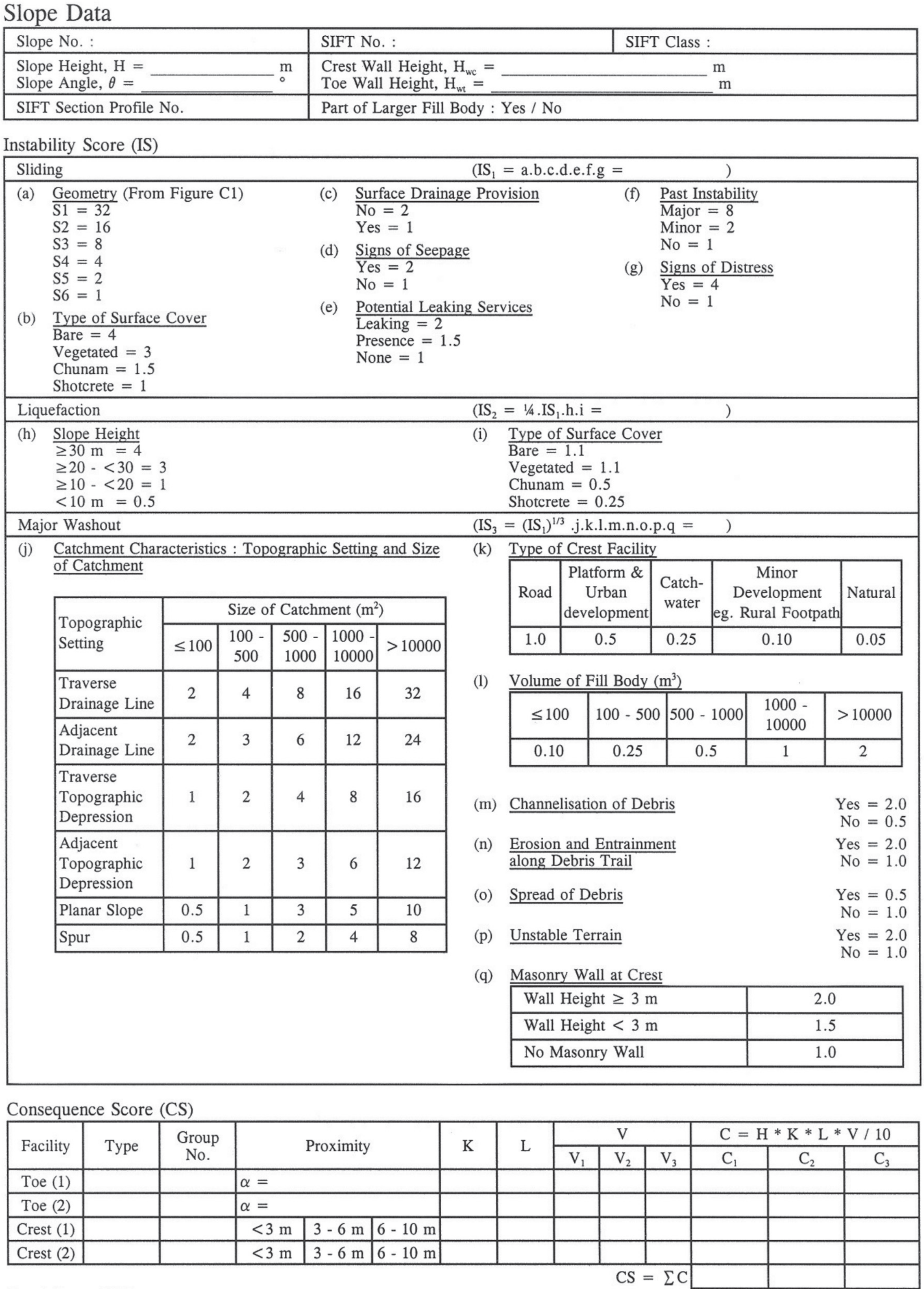
Table 6. Scoring scheme of Fill Slope Priority Classification System, Hong Kong (Wong 1996)



Slope Data

Slope No. :	SIFT No. :	SIFT Class :
Slope Height, H = ______ m Slope Angle, θ = ______ °	Crest Wall Height, H_{wc} = ______ m Toe Wall Height, H_{wt} = ______ m	
SIFT Section Profile No.	Part of Larger Fill Body : Yes / No	

Instability Score (IS)

Sliding (IS_1 = a.b.c.d.e.f.g =)

(a) Geometry (From Figure C1)
S1 = 32
S2 = 16
S3 = 8
S4 = 4
S5 = 2
S6 = 1

(b) Type of Surface Cover
Bare = 4
Vegetated = 3
Chunam = 1.5
Shotcrete = 1

(c) Surface Drainage Provision
No = 2
Yes = 1

(d) Signs of Seepage
Yes = 2
No = 1

(e) Potential Leaking Services
Leaking = 2
Presence = 1.5
None = 1

(f) Past Instability
Major = 8
Minor = 2
No = 1

(g) Signs of Distress
Yes = 4
No = 1

Liquefaction (IS_2 = ¼.IS_1.h.i =)

(h) Slope Height
≥30 m = 4
≥20 - <30 = 3
≥10 - <20 = 1
<10 m = 0.5

(i) Type of Surface Cover
Bare = 1.1
Vegetated = 1.1
Chunam = 0.5
Shotcrete = 0.25

Major Washout (IS_3 = $(IS_1)^{1/3}$ .j.k.l.m.n.o.p.q =)

(j) Catchment Characteristics : Topographic Setting and Size of Catchment

Topographic Setting	Size of Catchment (m^2)				
	≤100	100 - 500	500 - 1000	1000 - 10000	>10000
Traverse Drainage Line	2	4	8	16	32
Adjacent Drainage Line	2	3	6	12	24
Traverse Topographic Depression	1	2	4	8	16
Adjacent Topographic Depression	1	2	3	6	12
Planar Slope	0.5	1	3	5	10
Spur	0.5	1	2	4	8

(k) Type of Crest Facility

Road	Platform & Urban development	Catch-water	Minor Development eg. Rural Footpath	Natural
1.0	0.5	0.25	0.10	0.05

(l) Volume of Fill Body (m^3)

≤100	100 - 500	500 - 1000	1000 - 10000	>10000
0.10	0.25	0.5	1	2

(m) Channelisation of Debris
Yes = 2.0
No = 0.5

(n) Erosion and Entrainment along Debris Trail
Yes = 2.0
No = 1.0

(o) Spread of Debris
Yes = 0.5
No = 1.0

(p) Unstable Terrain
Yes = 2.0
No = 1.0

(q) Masonry Wall at Crest

Wall Height ≥ 3 m	2.0
Wall Height < 3 m	1.5
No Masonry Wall	1.0

Consequence Score (CS)

Facility	Type	Group No.	Proximity			K	L	V			C = H * K * L * V / 10		
								V_1	V_2	V_3	C_1	C_2	C_3
Toe (1)			α =										
Toe (2)			α =										
Crest (1)			<3 m	3 - 6 m	6 - 10 m								
Crest (2)			<3 m	3 - 6 m	6 - 10 m								
										CS = ∑C			

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The distribution of RS for different slope types as in 1999 is shown in Figure 5.

The NPCS has been adopted by the GEO since the late 1990s in prioritization pre-1977 man-made slopes for action under the LPM Programme. The Government of the HKSAR has pledged that in the 10-year period from 2000 to 2010, detailed studies would be carried out on 5,500 pre-1977 man-made slopes. Among these slopes, 2,500 government slopes would be upgraded to current safety standards. The total capital investment in this 10-year programme is about US$ 1 billion.

The NPCS has also been used as a risk rating tool in connection with slope-related technical development work, including rainfall-landslide correlation and QRA. The NPCS is also serving some other landslide risk management purposes in Hong Kong. For example, it has been estimated that the 'cut-off' value of RS for selection of government-owned slopes into the 10-year LPM Programme is 8, i.e. slopes with an RS of less than 8 would not become eligible for action under the LPM Programme before 2010. Hence, regular slope maintenance has to play an important role in maintaining the continued stability of these lower ranking slopes.

The calculated RS provides a useful risk-based rating for use by the relevant Government departments in planning their slope maintenance works. The definition of a cut-off value by reference to the calculated RS for each slope has facilitated the planning of landslide risk management action and assessment of resource requirements. This illustrates the benefits offered by qualitative risk rating in landslide risk management. However, it should be

Table 7. Results extracted from trial application of Fill Slope Priority Classification System, Hong Kong (Wong & Ho 2000)

Cases (year of failure)	Sliding		Liquefaction		Wash-out		Total score	Description of failure
	IS1	CS1	IS2	CS2	IS3	CS3		
Sau Mau Ping - A (1976)	2304	0.85	2534	10.27	106	3.19	4.45	4,000 m^3 liquefaction failure; 18 fatalities. IS includes consideration of 1972 failure.
Sau Mau Ping - B (1972)	576	1.16	634	18.08	133	6.60	4.11	6,000 m^3 liquefaction failure; 71 fatalities (high fatalities due to flimsy structures completely damaged by landslide debris).
Kennedy Road - A (1992)	3072	1.71	845	3.91	5	3.49	3.93	500 m^3 liquefaction failure; 1 fatality. Slope exhibited signs of distress before failure.
Kennedy Road - B (1989)	96	1.63	36	3.90	1	4.18	2.48	500 m^3 sliding failure; no fatality: a near-miss event.
Baguio Villas (1992)	192	0.32	53	1.32	277	0.60	2.47	3,000 m^3 wash-out failure; 2 fatalities (a child and an engineer on inspection duty).
Waterloo Road (1989)	96	0.43	26	0.67	11	0.43	1.80	50 m^3 liquefaction failure; blockage of 3 lanes of road but no fatality.
Broadcast Drive (1988)	72	0.05	10	0.16	4	0.05	0.73	120 m^3 wash-out failure due to burst of water main; insignificant consequence.
Kung Lok Rd. Park (1988)	24	0.01	3	0.02	46	0.01	-0.02	200 m^3 wash-out failure; insignificant consequence

Notes:
(1) IS = Instability Score, which reflects the likelihood of the respective mechanism of failure
(2) CS = Consequence Score, which is the potential loss of life (PLL) for the respective mechanism of failure
(3) Total Score = $\log (\sum IS * CS)$

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Table 8. Key groups of factors for Retaining Wall Priority Classification System, Hong Kong (Wong 1998)

Type of score	Key groups of factors	Range of scores
Instability Score	Wall slenderness ratio and nature of retained material	0 - 100
	Past instability	0 - 30
	Type of wall	0 - 30
	Potential for water ingress	0 - 60
	Wall condition	0 - 110
	Gradient of terrain below wall	0 - 60
Consequence Score	Type and proximity of crest facility	0 - 600
	Type and proximity of toe facility	
	Upslope and downslope topography	

Table 9. Risk Score adopted in combined ranking using the New Priority Classification System, Hong Kong

Slope type	Risk score (RS)
Soil cut slopes	0.19 x TS
Rock cut slopes	0.20 x TS
Retaining walls	0.038 x TS
Fill slopes	$0.64 \times e^{TS}$

noted that the NPCS is primarily developed for priority ranking and its resolution in differentiating the relative risk of the slopes is constrained by the available slope data.

3.4 *Rockfall Hazard Rating System, USA*

3.4.1 Development and application in Oregon

Pierson et al (1990) described the Rock Fall Hazard Rating System (RHRS) developed by the Oregon Department of Transport (ODOT) for qualitative rating of the risk of rock falls from existing rock cut slopes alongside transportation routes. Oregon has many miles of highways passing through steep terrain with road-side rock cut slopes, which are prone to failure. In the mid 1980s, ODOT noted the need to develop a procedure, together with the use of a risk rating system, to assist in identifying problematic slopes and prioritizing repair works. Prototype development and trials were carried out from 1985 to 1998. Finalization of the RHRS began in 1989. As at 1990, the RHRS was tested at about 3,000 rock fall sections, and of these, 1,340 were included in Oregon's RHRS database. A 'rock fall section' referred to any uninterrupted slope alongside a highway where the level and occurrence mode of rock fall were deemed to be the same.

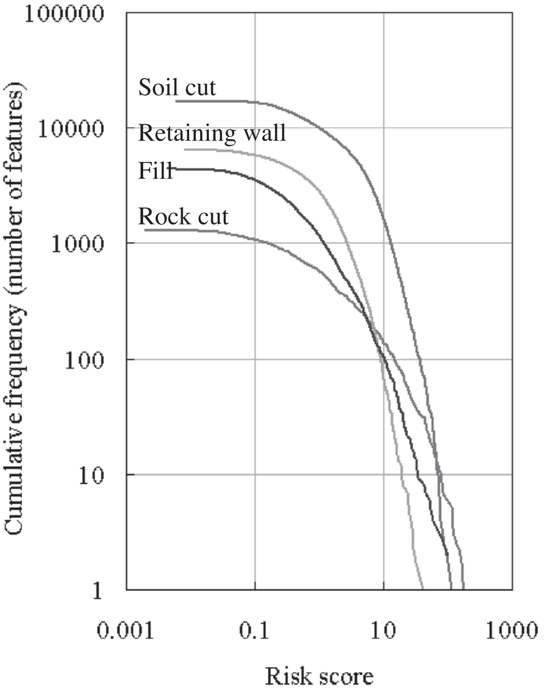

Figure 5. Distribution of Risk Score of different slope types in Hong Kong

Procedures and guidelines for implementation of the system were given in Pierson et al (1990). The RHRS formed part of a process that helped agencies to rationally manage the landslide risk from rock slopes affecting a highway system. The process involved slope survey, risk rating and preparation for follow-up action, such as cost estimation and preliminary design.

The risk rating comprised two parts, viz. a preliminary rating and a detailed rating. The preliminary rating was a subjective evaluation of the 'estimated potential for rock on roadway' and the historical rock fall activity, to broadly classify the risk into three classes: A (high); B (moderate); and C (low). The 'estimated potential for rock on roadway' was judged by the rater, based on observations on the slope conditions. 'Historical rock fall activity' was assessed based on information provided by the maintenance personnel. Among the approximately 3,000 rock fall sections surveyed in Oregon, 501 were given Class A, and 839 received Class B preliminary ratings. The preliminary rating helped to focus use of resources on the more problematic slopes.

The detailed rating system includes 12 attributes to be evaluated and scored (Table 10). The sum of the scores gives the relative risk rating. Some attributes can be directly measured and scored, e.g. slope height and road width. However, some attributes, e.g.

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Table 10. Rockfall Hazard Rating System, ODOT, USA (Pierson et al. 1990)

Category			Rating criteria and score			
			Points 3	Points 9	Points 27	Points 81
Slope height			25 ft	50 ft	75 ft	100 ft
Ditch effectiveness			Good catchment	Moderate catchment	Limited catchment	No catchment
Average vehicle risk			25% of the time	50% of the time	75% of the time	100% of the time
Percent of decision site distance			Adequate site distance, 100% of low design value	Moderate site distance, 80% of low design value	Limited site distance, 60% of low design value	Very limited site distance, 40% of low design value
Roadway width including paved shoulders			44 ft	46 ft	28 ft	20 ft
Geologic character	Case 1	Structural condition	Discontinuous joints, favorable orientation	Discontinuous joints, random orientation	Discontinuous joints, adverse orientation	Continuous joints, adverse orientation
		Rock friction	Rough, irregular	Undulating	Planar	Clay infilling, or slickensided
	Case 2	Structural condition	Few differential erosion features	Occasional erosion features	Many erosion features	Major erosion features
		Difference in erosion rates	Small difference	Moderate difference	Large difference	Extreme difference
Block size			1 ft	2 ft	3 ft	4 ft
Quantity of rockfall/event			3 cubic yards	6 cubic yards	9 cubic yards	12 cubic yards
Climate and presence of water on slope			Low to moderate precipitation; no freezing periods; no water on slope	Moderate precipitation or short freezing periods or intermittent water on slope	High precipitation or long freezing periods or continual water on slope	High precipitation and long freezing periods or continual water on slope and long freezing periods
Rockfall history			Few falls	Occasional falls	Many falls	Constant falls

ditch effectiveness and geologic character, require an evaluation by expert judgment. Since the system was devised for use on rock slopes alongside roads, where the consequence setting is fairly uniform, its consequence evaluation was relatively simple.

A preliminary assessment of the rock fall mitigation measures and cost were also made as part of the rating process for the high-ranking sites.

3.4.2 Development and application in Colorado

In parallel with the development of the RHRS in Oregon, the Colorado Department of Transport was also devising a system to identify and rank, by milepost, those segments of state highways that had chronic rock fall problems (Stover 1992).

Road segments with rock fall problems were recognized by the occurrence of vehicle accidents caused by rock fall, or identified by highway maintenance personnel as rock-fall prone areas. Road segments that had a high accident data and frequency ranking by maintenance personnel formed the primary targets for more detailed evaluation. Segments with a high frequency ranking but low accident data were secondary targets. This process of identification of rock fall-prone segments served a similar purpose to that of ODOT's preliminary rating system.

ODOT's RHRS was selected as a risk-rating tool for ranking the identified rock fall-prone segments. Some modifications were made to adapt ODOT's system for use in Colorado (Table 11). New parameters that were considered relevant, including accident data, slope inclination and segment length, were added. However, sight distance, roadway width, average traffic risk and ditch effectiveness were excluded. Their exclusion was noted by Stover (1992) as due to the consideration that their effects were factored in by the accident data and that some of the parameters were difficult to acquire.

3.5 *Rock Slope Hazard Rating, Canada*

Qualitative risk rating systems have been used in Canada for many years in managing the risk of rock falls on transportation routes. Bruce et al (1997) reported that, prior to the Just incident in 1982 (Cory & Sopinka 1989), the British Columbia Ministry of Transportation and Highways (MOTH)

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Table 11. Colorado Rockfall Hazard Rating System (Stover 1992)

Factor			Rank			
			Points 3	Points 9	Points 27	Points 81
Slope profile	Slope height		25 to 50 ft	50 to 75 ft	75 to 100 ft	100 ft
	Segment length		0 to 250 ft	250 to 500 ft	500 to 750 ft	750 ft
	Slope inclination		15° to 25°	25° to 35°	35° to 50°	50°
	Slope continuity		Possible launching features	Some minor launching features	Many launching features	Major rock launching features
Geologic character	Average block or clast size		6 to 12 in	1 to 2 ft	2 to 5 ft	5 ft
	Quantity of rockfall event		1 cu ft to 1 cu yd	1 to 3 cu yds	3 to 10 cu yds	10 cu yds
	Case 1	Structural condition	Discontinuous fractures, favorable orientation	Discontinuous fractures, random orientation	Discontinuous fractures, adverse orientation	Continuous fractures, adverse orientation
		Rock friction	Rough, irregular	Undulating smooth	Planar	Clay, gouge infilling, or slickensided
	Case 2	Structural condition	Few differential erosion features	Occasional erosion features	Many erosion features	Major erosion features
		Difference in erosion rates	Small difference	Moderate difference	Large difference	Extreme difference
Climate and presence of water on slope			Low to moderate precipitation; no freezing periods; no water on slope	Moderate precipitation or short freezing periods or intermittent water on slope	High precipitation or long freezing periods or continual water on slope	High precipitation and long freezing periods or continual water on slope and long freezing periods
Rockfall history			Few falls	Occasional falls	Many falls	Constant falls
Number of accidents reported in mile			0 to 5	5 to 10	10 to 15	15 and over

specified locations for rock scaling where resources were available. Subsequently, MOTH developed a comparative method to rank areas by hazard, based on which the limited resources were deployed to reduce the risks posed by the areas with the greatest ranked hazard. Since 1993, the RHRS was adopted by MOTH as the risk rating scheme, which reduced the subjective aspects of the rating.

More recently, a new rock slope hazard rating system was formulated (Hungr et al. 2003), which provided a method of characterizing the relative risk posed by the slopes to Canadian Pacific Railway (CPR) track. This was intended to help to prioritize allocation of mitigation resources for over 1,500 rock slopes alongside over more than 2,100 km of railway track.

The rating system comprised two parts of assessment, viz. ‘random rock fall’ and ‘structurally controlled failure’.

‘Random rock fall’ referred to small-scale (volume less than 10 m^3) detachment of individual rock blocks from a rock slope. It was rated by a rock mass classification system, with adjustments to cater for effects of any slope stabilization measures that had been provided, recent instability and overburden materials. The rock mass classification system was adapted from the Rock Mass Quality Index (Q) formulated by Barton et al (1974), and the modified rock mass index was empirically correlated with historical rock fall frequency data. ‘Structurally controlled failure’ refers to large-scale failure of the rock slope that is controlled by well-defined discontinuities. The degree of hazard for this mode of failure was intended to be assessed by a deterministic approach, based on mapping of dominant discontinuities and supported by simple analysis if necessary. Given the nature of the assessment, subjective rating was made on the relative likelihood of the most likely failure magnitude.

Overall, the system is principally a hazard rating scheme that is independent of the consequence evaluation.

3.6 *Slope Risk Analysis System, Australia*

The Roads and Traffic Authority (RTA) of New South Wales (NSW), Australia, in conjunction with external consultants, has developed a scheme for rating the landslide risk of cut and fill slopes and retaining structures, adjacent to main roads in NSW. The scheme is intended to be used in rating the relative risk of the slopes and thereby setting priorities for further work, such as investigation, monitoring and remediation.

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Stewart et al (2002) described the background of the formulation of this RTA Slope Risk Analysis scheme. The development of a systematic slope risk rating procedure by the RTA first started in the early 1990s. The early procedures were based on weighted scoring of slope attributes and a subjective assessment of consequences, which were grouped via a risk matrix to give the landslide risk level. According to Stewart el al (2002), the procedures were used in a very limited way prior to 1997, but in late 1997 and early 1998, a revised version (No. 2) was used statewide in NSW to rate about 2,500 slopes. However, review of the results indicated that its reproducibility was poor and that the risk levels derived were not sufficiently accurate for the use in priority setting. Version 3.0 was developed, and tested in late 2000 with about 700 slopes by a panel of consultants. The test identified further revisions to the rating scheme (Baynes et al. 2002). Together with some other changes arising from additional development work, these were incorporated into Version 3.1 of the procedures, which is the scheme described in this Section.

The details of the formulation of the RTA Slope Risk Analysis scheme are given in RTA (2002). Details are summarized in Figure 6. The relative risk of a slope was rated in terms of an Assessed Risk Level, which was given by combining the Likelihood Rating and Consequence Rating. The system was aligned with a QRA framework. The rating was principally assigned by expert judgment combined via qualitative rules and risk matrices, without any quantified risk analyses. The slope unit is generally defined by its physical boundary, but a large slope may be sub-divided based on differences in geological or landform conditions.

This system is a notable development in respect of qualitative slope risk-rating methodology, in view of its attempt to align with the QRA framework and its extensive use of expert judgment in the rating process. The findings of a study on the reproducibility and accuracy of the different versions of the RTA system are given in Baynes et al (2002). They noted the subjective nature of the rating process and the need for the rating to be carried out by trained personnel to improve the accuracy and precision of the results.

3.7 *Slope Management and Risk Tracking System, Malaysia*

Landslides from slopes alongside roads have resulted in loss of life in Malaysia, as well as major economic consequences due to closures of the road network. A study was carried out on the slopes along the 300 km long Tamparuli-Sandakan Road in Sabah in the early 2000s (TSR 2004). The study comprised collection of data on the slopes along the TSR and formulation of a qualitative slope risk rating scheme to assist in prioritizing remedial and maintenance works on the slopes.

The slope risk rating and management system that has been developed is known as the Slope Management and Risk Tracking System (SMART). Before commencement of the project, little information on the slopes along the TSR was available. The vast majority of the slope data that was used in the risk rating was collected in the project by airborne Light Detection and Ranging (LIDAR) survey and field mapping. Information on a total of 4,740 slopes features was recorded.

SMART rates the risk of slopes through the use of a scoring scheme, which is akin to that adopted by the GEO. The risk rating is represented by a Total Score, which is given by the product of the Instability Score and Consequence Score.

The Instability Score reflects the likelihood of slope failure. The details of its formulation are given in Figure 7. It is calculated by a weighted average of two probabilities of failure, DS and MC. DS is the discriminant probability score, based on a discriminant function obtained from a step-wise discriminant analysis that a slope feature would fall into the failed slope groups. MC is the Monte Carlo probability score, based on findings from Monte Carlo analysis on the probability that the theoretical factor of safety of the slope would fall below 1.0 under a 1 in 100 year rainstorm condition. In applying the scoring scheme to the TSR project, a 90% weighting factor was applied to DS and only 10% was assigned to MC. These reflect the perceived relative reliability of the probability scores obtained from the two approaches.

The Consequence Score was modified from the NPCS of GEO, with the inclusion of a specific term for the road facility because SMART is intended for application to rating landslide risk on roads. The calculated score has been normalized by 480 (maximum value), and hence falls within the range of 0 to 1.

3.8 *Other Rating Systems*

The systems were selected for a more in-depth description in the above sections in consideration of their more extensive scope of actual or planned application. These are by no means exhaustive. Other systems exist, and each has its own characteristics that serve particular purposes or address specific problems. Selected examples have been incorporated into Table 2. These include:

(a) Risk Rating

The Assessed Risk Level (ARL) is established based on the following risk matrix:

Likelihood	Consequence Class				
	C5	C4	C3	C2	C1
L1	ARL3	ARL2	ARL1	ARL1	ARL1
L2	ARL4	ARL3	ARL2	ARL1	ARL1
L3	ARL5	ARL4	ARL3	ARL2	ARL1
L4	ARL5	ARL5	ARL4	ARL3	ARL2
L5	ARL5	ARL5	ARL5	ARL4	ARL3
L6	ARL5	ARL5	ARL5	ARL5	ARL4

Notes:

(1) The Likelihood Rating L1 to L6 shown in Figure 6 (b).

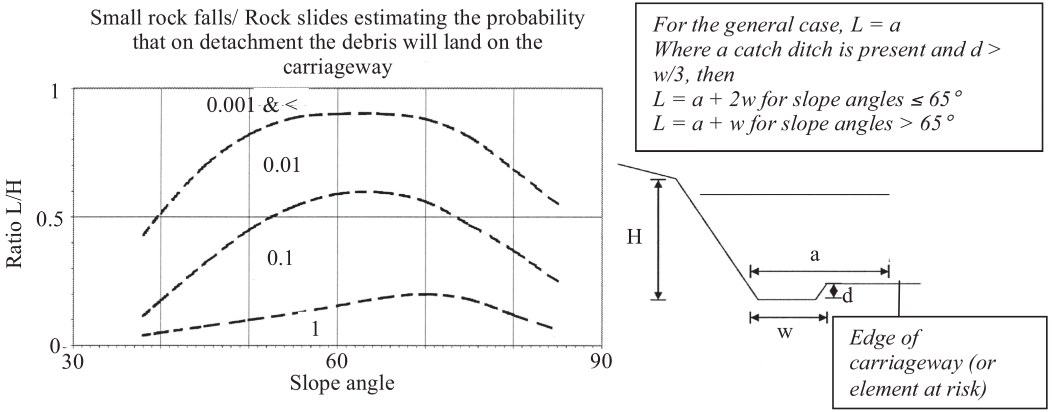
(2) The Consequence Rating C1 to C5 shown in Figure 6 (c).

(b) Likelihood Rating

– Likelihood Rating is categorized as follows:

Class	Descriptions
L1	The event may, or is expected to, occur within a short period under average circumstances, or the mechanism is active at present (depending on circumstances the "short" period could be from days to no more than two to three years). Indicative Annual Probability around 0.9.
L2	The event may, or is expected to, occur within a moderate period (from a few years to no more than about 30 years) or within the inspection period under slightly adverse circumstances. Indicative Annual Probability around 10^{-1}.
L3	The event could be expected to occur at some time over about a 100 year period in the normal course of events but would only occur within the next inspection period under adverse circumstances. Indicative Annual Probability around 10^{-2}.
L4	The event would not be expected to occur within about a 100 year period under normal conditions and is unlikely to occur within the next inspection period except under very adverse circumstances. Indicative Annual Probability around 10^{-3}.
L5	The event would not be expected to occur within about a 100 year period and is unlikely to occur within the next inspection period even under very adverse circumstances. Indicative Annual Probability around 10^{-4}.
L6	The event is unlikely to occur even under extreme circumstances. Indicative Annual Probability < around 10^{-5}.

– The likelihood Rating reflects the probability of a landslide occurring and reaching the element at risk. For failures from road-side rock cut slopes, the probability of small rock fall/slide reaching the road may be assessed from the following chart:



Small rock falls/ Rock slides estimating the probability that on detachment the debris will land on the carriageway

For the general case, L = a
Where a catch ditch is present and d > w/3, then
L = a + 2w for slope angles ≤ 65°
L = a + w for slope angles > 65°

Figure 6. Formulation of RTA Slope Risk Analysis Scheme (extracted from RTA 2002)

(c) Consequence Rating

- Consequence Rating for loss of life is categorized as follows:

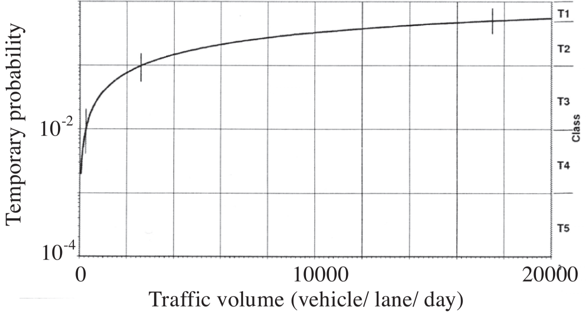
Vulnerability	Temporal Probability of an Individual Being Present at the Time of Failure				
	T5	T4	T3	T2	T1
V1	C4	C3	C2	C1	C1
V2	C4	C3	C2	C1	C1
V3	C5	C4	C3	C2	C2
V4	C5	C5	C4	C3	C3
V5	C5	C5	C5	C4	C4

Notes:

(1) Temporal probability is classified as follows:

Class	Descriptions
T1	Person usually expected to be present as part of the normal pattern of usage (eg residential buildings, some commercial buildings). Road users in the heaviest of urban traffic conditions. ($p > 0.5$).
T2	Person often expected to be present as part of the normal pattern of usage (eg many commercial buildings). Road users on major urban arterial roads and the most heavily trafficked rural roads. (p 0.1 – 0.5).
T3	Person may sometimes be present as part of the normal pattern of usage. Road users on many urban arterial roads and most major rural arterial roads. (p 0.01 – 0.1).
T4	Person unlikely to be present even where there is a pattern of usage. Road users on suburban roads and minor rural arterial roads. (p 0.001 – 0.01).
T5	Person is very unlikely to be present. Road users on the most lightly trafficked roads, road shoulders etc. ($p < 0.001$).

(2) For landslides affecting roads, the following chart may be used in assessing the temporal probability:



(3) Vulnerability is classified as follows:

Class	Descriptions
V1	Person in the open unable to evade rockfall or other debris (movement very/extremely rapid), or buried, or engulfed in a building collapse. Vehicle impacting a block > 1 m high or lost into a deep, narrow void at highway speeds. ($p > 0.5$).
V2	Partial building collapse. Person in open may be able to evade debris. Vehicle impacting a 0.5 – 1 m high block at highway speeds or a block > 1 m high at urban speeds or lost into a shallow void. (p 0.1 – 0.5).
V3	Building penetrated, no collapse. Emergency evacuation possible. Most people in open able to evade debris. Vehicle impacting a 0.5 – 1 m high block at urban speeds, or a block > 1 m high at low speeds. Vehicle impacting loose or wet mixed soil/rock debris (or crossing a stepped surface with c 0.1 – 0.2 m steps caused by a developing embankment failure) at highway speeds. (p 0.01 – 0.1).
V4	Building struck, damaged but not penetrated. Vehicle impacting a block around 0.2 m high at highway speeds or a 0.5 – 1 m high block at low speeds. Vehicle impacting loose or wet mixed soil/rock debris (or crossing a stepped surface with c 0.1 – 0.2 m steps caused by a developing embankment failure) at urban speeds. Vehicle interacting with a shallow void/depression where guardfence may prevent a vehicle from leaving the road. (p 0.001 – 0.01).
V5	Building struck, only minor damage etc. Vehicle impacting a block around 0.2 m high at urban speeds or a smaller block at highway speeds. Vehicle impacting loose or wet mixed soil/rock debris at low speeds. Vehicle traversing an irregular surface formed by soil or small (< 100 mm min dimension) rock, or by a developing embankment failure, at highway speeds. ($p < 0.001$).

- Consequence Rating for damage to property and consequential effects is categorized as follows:

Class	Descriptions
C1	Total closure of a Sub-Network Rank 5 or 6 (SN5-6) road for an extended period Major infrastructure or property damage (other than road) Very high disruption cost (other than road users) Very high repair cost (Total direct and indirect costs > \$10M)
C2	Total closure of one carriageway of an SN5- 6 road or total closure of an SN3–4 road for an extended period Substantial infrastructure or property damage Large disruption costs High repair cost (Total direct and indirect costs > \$2M < \$10M)
C3	Partial or total closure of an SN3-4 road for a short period, longer period if reasonable alternatives are available Moderate infrastructure or property damage Moderate disruption costs Moderate repair cost (Total direct and indirect costs > \$0.5M < \$2M)
C4	Partial or total closure of an SN2 road for a short period Minor infrastructure or property damage Minor disruption costs Low repair cost (Total direct and indirect costs > \$0.1M < \$0.5M)
C5	Partial or total closure of an SN1 road for a short period Negligible infrastructure or property damage Little or no disruption costs Very low – no repair cost (Total direct and indirect costs < \$0.1M)

Figure 6 (continued). Formulation of RTA Slope Risk Analysis Scheme (extracted from RTA 2002)

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Instability Score (IS) = α DS + β MC
where,
α and β are weighting factors, with $\alpha + \beta = 1$

DS = Discriminant Score which is the probability of a slope feature belonging to the failed slope group, ranging from 0 to 1 and based on the following parameters:

Cuts and natural slopes	Fill embankment
(11 significant variables)	(7 significant variables)
– Vegetation cover condition – Height – Presence of corestone boulders – Measure of ground saturation – Slope angle – Cutting topography relationship – Slope shape – Exposed percentage (rock) – Rock condition profile – Plan profile – Surface Drainage rating	– Main cover type – Vegetation cover condition – Slope angle – Geology – Plan profile – Presence of structures – Upslope / downslope geometry

MC = Monte-Carlo probability score which is the probability of the Factor of Safety < 1 for the 1 in 100-year return period 24-hour rain storm, ranging from 0 to 1.

Figure 7. Formulation of Instability Score, SMART (extracted from TSR 2004)

(a) Rating of Relative Landslide Risk of Clay Slopes, Tasmania, Australia – Stevenson (1977) described a simple method of evaluating the relative landslide risk of clay slopes. This was one of the earliest reported qualitative, risk-based rating schemes. However, compared with current practice, the scheme is coarse and may at best be taken as a general zoning system. The method was applied to selected areas in Tasmania.

(b) Stability Evaluation Method, Road Bureau of the Ministry of Construction, Japan - A scoring scheme developed and adopted in Japan for qualitative rating of the relative risk of landslides on roads in Japan was described in Ministry of Construction (1990), and summarized in Escartio et al (1997).

(c) Slope Condition and Risk Rating, New Zealand - The scheme was intended for rating cut and fill slopes alongside highways, railway and canals, to highlight areas of landslide concern and allow priorities to be set for further investigation and treatment. Sinclair (1991) reported that the method was applied to data obtained for the design of improvement works of a 50 km section of the Kuala Lumpur to Seremban Expressway in Malaysia.

(d) Rock Slope Hazard Index System, Scotland – This scheme was developed in 1996 for use as a first stage assessment of the relative risk of rock slopes affecting roads and determination of the required follow-up actions. Development of the system was supported by the Scottish Office Industrial Department, and the system was tested on 179 rock slopes alongside a 50 km section of Trunk Road in the Scottish Western Highlands (McMillan & Matheson 1997).

(e) Terrain Susceptibility and Risk Zoning – There are a range of methodologies developed for assessing the relative susceptibility and risk of landslides originating from undeveloped hillsides. Qualitative and semi-quantitative risk assessment techniques, together with statistical analyses and expert judgment, are commonly adopted. A detailed review of the methodologies and practice was given in SOA 7. The relevant systems and applications are not further examined in this paper. Most of the applications are couched at a smaller scale, and do not clearly differentiate the individual facilities. Wong (2003) summarizes the practice in compilation and use of susceptibility and risk maps in Hong Kong.

3.9 *Observations on State of Good Practice*

A total of fifteen different slope rating schemes are reviewed above. While most of the schemes have certain features in common, the schemes developed in various places differ because of particular circumstances of their formulation and different key issues that they address. There is no hard-and-fast rule as to which particular rating methodology is the best scheme. The best scheme is that which best meets the landslide risk management needs under the particular circumstances. However, some observations can be made on the state of good practice in formulation and application of qualitative slope rating systems, as summarized below.

3.9.1 Objective of rating system

A rating system is designed for specific purposes. The intended objectives of the system and the circumstances of its application should be clearly defined, in order to guide the formulation of the system. This would also help to ensure that the system would be correctly applied. GEO's experience illustrates that even if the intended purposes remain the same, different systems may be required at different times because of changing circumstances in which the systems are applied.

It is evident from the cases reviewed that slope rating systems are typically adopted to provide a relative risk ranking of existing, potentially hazardous

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slopes. The systems are commonly required by agencies that are responsible for managing the risk of a large stock of slopes, to set out the priority and direct resources for follow-up studies and treatment works. A wealth of experience of successful use of qualitative slope rating in this area is available. There are indications that such applications are receiving increasing attention by many agencies in different countries.

3.9.2 Risk management process

A rating scheme provides a means of relative risk ranking. Although it is a useful tool that plays an important role in the risk management process, it is not the totality of the process. Effective landslide risk management calls not only for the formulation of a slope rating scheme, but also the establishment of a suitable risk management process to which the rating scheme applies. Such a process typically involves systematic collection of landslide and maintenance records, compilation of a comprehensive slope inventory, formulation of a slope rating scheme, collation of data for use in slope rating, establishment of procedures for initiation of follow-up actions, maintenance and dissemination of information, etc. The slope rating scheme would best serve its intended purposes when it is applied in the context of a risk management process. Such applications would in turn provide useful feedback on how the rating scheme should be further improved to achieve better performance.

3.9.3 Slope inventory

Compilation of a slope inventory and collation of the relevant slope data are prerequisites for relative slope rating. This work is an important investment for landslide risk management, and it often constitutes the most resource-demanding component of the task. For example, the compilation of the new Catalogue of Slopes in Hong Kong, which comprises about 57,000 man-made slope features, cost about US$ 15 million to produce. In comparison, the NPCS was principally formulated in-house by the GEO and the staff cost was less than US$ 0.1 million, i.e. less than 1% of the cost of compiling the slope inventory. It is therefore essential that in devising a rating scheme, due consideration is given to the practicality of obtaining the required input data. A detailed and sophisticated system may not be the most suitable scheme to adopt if inadequate resources are available to support the data collection.

Where there are major resource constraints, it may be necessary to implement the rating in phases, i.e. the more problematic slopes are first identified with the use of a preliminary rating that is less resource-demanding, and then a more detailed rating is applied to the identified slopes for risk ranking and prioritization. Due consideration should be given to proper demarcation of slope units, which has significant implications for the cost and rating resolution. For example, if a coarse demarcation is adopted, such as one based on the average slope conditions per mile or km along a road, the work would be less costly. However, if individual slopes are registered and rated separately, a much better resolution would be achieved although the cost would also escalate.

To avoid double handling in data collation, it has been good practice adopted by some agencies to develop the rating scheme in advance of compiling the full slope inventory. This is done to ensure that slope parameters required for use in the rating are identified in time, such that the data can be collected when the slope inventory is compiled. In practice, the rating system would inevitably require field trials and calibration, which would often lead to refinements in the rating scheme and changes in either the types or forms of the required slope parameters. Hence, the compilation of the slope inventory and formulation of the rating system have to be carried out in an interactive manner, preferably under the coordination of a dedicated team.

Different methods can be used to assist in identifying the slopes and collating slope data. Advances in digital technology, such as in the use of GIS, remote-sensing, digital photogrammetry and global positioning techniques, have led to improved capability, enhanced efficiency and reduced human error (Wong et al. 2004a). It is also common practice now to operate the slope inventory on a GIS platform that incorporates spatial functionality for retrieval, analysis and web-based dissemination of the data.

3.9.4 Slope rating methodology

Although there is no unique methodology for relative slope rating, some good principles that are embodied within many of the more successful systems are notable:

(a) Risk-rating, which accounts for both the relative likelihood and consequence of landslide, is preferred to simply rating the hazard (or the consequence). For slopes affecting a linear facility, e.g. a road or railway track, the type of facility and characteristics of the population at risk are often relatively uniform. Hence, system developed for linear facilities would tend to place more emphasis on hazard rating. However, due account should also be taken of the key factors that affect the likely consequence of a landslide, e.g. proximity of the facility to the slope, any presence of protective ditches or buffer zones and the scale of failure, if the systems are designed for risk rating. For systems that are applied to slopes affecting different types of facility, the consequence rating would warrant considerable attention because it has a very significant contribution to make in assessing

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the relative risk.

(b) A rating scheme is always subject to constraints associated with data availability, and it should be formulated with due consideration taken of these constraints. The effects are two-fold. Firstly, if the data are not readily available and cannot be made available, the rating scheme cannot incorporate the use of the data irrespective of their relevance to assessing the relative risk. Secondly, even if data on a slope attribute are available and used in the rating scheme, the relative weighting assigned to the slope attribute in the scheme depends not only on the relevance of the attribute to assessing the relative risk, but also on the quality and resolution of the data available. For example, in some schemes where signs of water seepage were included in the rating, a relatively low weighting score was given to this parameter irrespective of the knowledge that groundwater has a significant effect on slope instability. This is appropriate given the relatively poor quality and resolution of the data available for this attribute, e.g. observations being made in different weather conditions and hence not being entirely reliable and consistent. In other cases, subjective judgment is required to be made on, say, the likelihood of landslide. It is fairly common for the rating scheme to involve categorizing the likelihood into different classes that are aligned with notional ranges of probability. These notional ranges of probability typically differ by orders of magnitude. However, the weightings to be assigned to the different classes should not represent a likelihood of failure that differs by such orders of magnitude, if the subjective judgment made by the raters could not support a resolution that could truly differentiate the likelihood of landslide by these orders of magnitude. Otherwise, the significance of this subjective judgment would be mis-represented in the rating scheme, and the overall reliability of the scheme adversely affected.

(c) Separate rating schemes may have to be devised for different types of slope. Many of the existing rating schemes deal with rock slopes alongside transportation routes. In such cases, use of a single rating scheme that is tailor-made for application in a particular place would usually be adequate for use in rating rock slopes of different size and geological condition. In other cases, a system may be required for rating different types of slope, such as cut slopes and fill slopes. It is often necessary to formulate different rating schemes, each tailor-made for a specific type of slope, because the factors that govern the likelihood and consequence of landslides on different types of slope may differ very significantly. A key technical challenge to overcome in these cases is the merging of different schemes into a single rating system. Alignment with the findings of QRA and probabilistic analyses has been adopted as the solution.

(d) Parameters that are often adopted in hazard rating include: slope height; slope gradient; history of instability; signs of distress; type of slope forming material; presence of geological weaknesses or adverse discontinuities; unfavorable groundwater conditions; unfavorable surface water conditions including the type of slope cover; and the effectiveness of any existing slope stabilization measures. To ensure consistency in rating the likelihood of landslide, it is essential that the hazard rating is applied to slopes of a similar class, e.g. un-engineered soil cut slopes should not be mixed in the rating with engineered slopes. It is notable that in a more sophisticated rating system, different mechanisms of failure may be rated separately using different hazard rating methods.

(e) Parameters that are often adopted in consequence rating include: type and proximity of crest facility; type and proximity of crest facility; slope size or volume of landslide; mobility of landslide debris; and effectiveness of any existing provisions for protecting the facility from landslide effects. Consequence rating for slopes affecting a linear facility, e.g. transportation routes, usually involves the use of simpler methods. For slopes that affect a diverse range of facilities under different site settings, a detailed consequence rating may call for the use of a more complicated methodology, and may involve the use of QRA consequence assessment techniques. Loss of life is typically considered in consequence rating. However, the more sophisticated rating systems may include consideration of economic loss and aversion effects associated with multiple fatalities.

(f) Use of a scoring formula appears to be more popular than use of a qualitative risk matrix. They vary in presentation, and have pros and cons. However, in terms of capability as a relative risk rating tool, there is practically little difference between them. The more updated rating systems tend to use qualitative risk descriptors, which are aligned with some standardized categorization (e.g. AGS 2000) or notional ranges of probability figures. This helps to provide a reference point for subjective assessment and communication, and gives the rating schemes a semi-quantitative connotation. However, the probability figures are often loosely defined and the standardized descriptors are not intended to be precise. They would not necessarily improve the reliability of the quality rating, which is to a large extent governed by the rating methodology, quality of the input parameters and reliability of the subjective judgment made.

(g) Two different approaches in formulating the rating methodology are notable: (i) 'expert judgment schemes', which require considerable judgment to be exercised in rating the slopes (e.g. RTA Slope Risk Analysis, Section 3.6 above); and (ii) 'expert

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formulation schemes', which require the use of relatively simple, factual data (e.g. NPCS, Section 3.3 above). An expert judgment scheme refers to that which requires considerable subjective judgment to be made by the raters in acquiring the input data or in rating the hazard or consequence, e.g. making a subjective rating of 'the likelihood of landslide' or of 'the likelihood that the detached material would reach the downslope facility'. Formulation of an expert judgment scheme may not require much supporting correlation and analytical work to define the effects of different slope data on the likelihood and consequence of landslide. However, its application requires input from experts in exercising subjective judgment. The schemes may be less difficult to formulate, but the demand on data collection is high and their application can be sensitive to reproducibility and consistency issues. An expert formulation scheme adopts relatively simple and factual data as input parameters, and does not require the raters to exercise much subjective judgment in collecting the data and applying the scheme. This is made possible because the relative significance of the various input data and their appropriate weightings have already been assessed, correlated and incorporated into an expert system when the rating scheme is formulated. The work typically involves correlation with historical landslide data, statistical analysis and numerical modeling. These effectively replace the subjective judgment that would otherwise have to be made by the individual raters in applying an expert judgment scheme. An expert formulation scheme is usually more repeatable and less operator-dependent. However, formulating such a scheme is practical only when suitable data and techniques for establishing the correlations are available. The reliability of an expert formulation scheme is governed by that of the correlations established. In some cases, a mixed scheme, i.e. a hybrid of the two approaches, is adopted in a single rating system.

3.9.5 Testing and calibration

All rating systems require trial uses for testing and calibrating their performance. The key aspects to be evaluated include:

- Repeatability of data collection, i.e. whether the judgment made by different raters or data collected by different personnel are reasonably consistent.
- Reproducibility of the system, i.e. whether the system can give relatively consistent results for slopes of comparable conditions.
- Performance of the system, i.e. whether the rating given by the system is reliable as compared with the available statistics, actual slope behavior and other indicators (e.g. professional judgment), and whether the system can adequately fulfill its intended purposes.
- Ease of use of the system, i.e. any scope to streamline the system and data collection, without adversely affecting the performance of the system

Systems that are being more extensively applied have all been subject to improvements and refinements after repeated testing and calibration. The testing and calibration work also facilitates the documentation of guidelines on collection of data and use of the systems.

3.9.6 Maintenance of system

A rating system would easily become outdated if not properly maintained. There are two key aspects of maintenance. Firstly, the data that are adopted as input parameters should be updated to reflect the latest slope conditions. This may have significant resource implications, which should be duly factored in when designing the risk management process. For example, quality procedures are in place in Hong Kong for checking the key components of the input parameters of each rated slope before it is selected for action under the LPM Programme, and for regularly updating the slope data based on findings from an inspection by a qualified geotechnical professional at least once every five years on each registered slope (GEO 1998a). Secondly, the rating methodology would require enhancement from time to time when new experience in using the system becomes available, or when there are new requirements to be met.

3.9.7 Public perception of qualitative rating system

The public perception of landslides and their risk management is affected by many social, economical and political factors, which vary in place and time. There is little published information available on the public perception of use of qualitative risk rating methodology, and this is an area deserving further study and experience sharing. Hong Kong has almost 30 years of experience in using risk ranking methods for prioritizing un-engineered man-made slopes for detailed studies and retro-fitting under the LPM Programme, which involves considerable public works expenditure. Experience shows that application of qualitative risk rating is fairly well received by the public as a rational and pragmatic approach for prioritizing where resources should be used for landslide risk reduction. Challenges, either on the technical or administrative aspects, are rarely received from the public on the rating systems. When a low-ranking slope fails and results in notable consequences, the case would inevitably attract public concern. However, it seems that the public would tend to be more tolerant towards imperfections in the rating methodology due to technical limitations, rather than human errors in collecting the slope data and in exercising professional judgment. In this respect, use of an expert formulation scheme would probably be less prone to criticism than use of an expert judgment

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scheme. At least, this is the case as far as the raters are concerned.

3.9.8 Limitations of rating system

Proper awareness of the capability, as well as the limitations, of a qualitative rating system is fundamental in applying the system successfully. The various systems that have been developed have differing degrees of complexity, with differing resolutions and reliabilities. Overall, it should be recognized that these systems are, by nature, relative risk rating tools that operate with the use of relatively simple, readily acquired, qualitative parameters and subjective judgment. They may give a useful indication of the relative risk, but cannot provide a sufficiently reliable, absolute risk figure. Even if they have been aligned with some quantitative or semi-quantitative figures, the alignment typically involves subjective judgment and contains significant uncertainties. The rating should only be applied in the circumstances for which it is intended. A rating scheme that has been successfully applied in one place may be entirely inappropriate for use elsewhere, if the nature of slope problems and the risk management objectives are different.

Due care should also be exercised when a system is used for purposes other than relative risk rating, such as risk-screening or risk-based decision making on individual slopes. This is often beyond the capability and reliability of a qualitative rating system, unless it has been specifically calibrated for such applications. Site-specific landslide risk assessment and decision-making would normally call for the use of more detailed data and enhanced risk assessment techniques, such as site-specific qualitative risk assessment and formal QRA as described in the following Sections.

4 SITE-SPECIFIC QUALITATIVE RISK ASSESSMENT

4.1 *Overview*

Site-specific qualitative risk assessment embraces a broad range of qualitative and semi-quantitative processes applied to analyzing and managing the landslide risk at individual sites. The work is carried out with a resolution and reliability that are deemed to be adequate for use in making site-specific risk management decisions, without formally quantifying the risk.

The conventional approach for dealing with landslide problems at individual sites is to provide for a safety margin in slope design based on deterministic stability assessment. This Factor of Safety approach is aimed at reducing the chance of failure. It neither evaluates risk directly, nor manages risk in a holistic manner. For managing landslide problems at specific sites, the following are some typical circumstances that require the use of a risk-based assessment, either supplementary to, or as a replacement of, the conventional factor of safety approach:

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

These issues are beyond the scope of conventional slope stability assessment, and can only be tackled from a risk perspective. This often applies to small slopes, natural hillsides and large distressed sites, where detailed characterization of the ground and pore water conditions is not practical, and where prevention of slope failure can be difficult. Depending on the needs of the particular case, the risk assessment process may or may not involve formal quantification of the risk. Qualitative risk analysis had been the principal approach of risk assessment before QRA methodology emerged. Over the years, it has supported sound risk management decisions to be made in many circumstances, without explicitly quantifying the risk.

A variety of qualitative and semi-qualitative risk assessment methods are available, e.g. a summary is given in Lee & Jones (2004). Many examples of site-specific application of qualitative risk assessment have previously been reported in the literature (e.g. Hutchinson 1992, Morgenstern 1995, Vick 2002, Morgenstern 2000). Three cases are described in the following Sections to illustrate its unique role and diverse range of applications in landslide risk management.

4.2 *Design Event Assessment for Natural Terrain Landslides*

The strategy for dealing with natural terrain landslide risk in Hong Kong has been to avoid, as far as possible, new developments in vulnerable areas (Wong 2003). Where this is not practicable, the conventional approach in the past has been to design the natural hillside to the factors of safety stipulated in GCO (1984). However, in many circumstances, this

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approach is fraught with inherent difficulties and its use in natural terrain is not practical in that:

(a) As natural hillside is often only marginally stable over a large area, stabilization of the hillside would be expensive and may not be justified. Also, widespread stabilization works on natural hillside are difficult to carry out and could result in considerable impact on the environment.

(b) Preventing failure is not necessarily the most cost-effective engineering solution. Provision of hazard mitigation measures (e.g. debris-resisting barriers) may be the preferred option in reducing the risk of natural terrain landslides.

Two alternative approaches, viz. the QRA approach and the Design Event approach, have been introduced for use in assessment and mitigation of natural terrain landslide risk in Hong Kong (Wong 2001, Ng et al. 2002). The QRA approach would require a detailed assessment of the probability and consequence of natural terrain landslides, together with consideration of the tolerability of the assessed risk level (ERM 1998). Although it may be considered as the most rigorous and comprehensive assessment (see Section 5), it often requires expert input and may be fairly involved and costly.

The Design Event Approach is a qualitative risk assessment and design framework, which is applicable when designers opt for mitigation of natural terrain landslide risk without carrying out a formal QRA. Under this approach, the mitigation measures (e.g. debris-resisting barriers) required to protect a development from natural terrain landslides are determined by reference to an assessment of the design landslide event that may occur on the hillside affecting the development. Uncertainties are generally considered in an implicit and lumped manner through the assessment of the design event (e.g. a landslide of a certain size with a given degree of mobility).

The framework for the Design Event approach takes account of the failure consequence and the susceptibility of the hillside to landsliding in a semi-quantitative manner. Under the framework, the susceptibility of the hillside to failure is categorized into 4 classes (Table 12), based on its historical landslide activity and assessment of geomorphological features and other relevant information. The consequence of failure is categorized into 5 classes based on the types of facilities affected and their proximity to the hillside (Table 13). The design requirements for mitigation measures are given in Table 12. Further studies will not be required if the consequence of failure and the landslide susceptibility of the hillside are insignificant. Otherwise, further studies should be carried out to establish the need for any mitigation measures to deal with the relevant design events. Depending on the consequence and susceptibility classifications of the site, the required design event may be either a 'conservative' event or

Table 12. Design requirements for Design Event Approach

Susceptibility Class	Consequence Class				
	I	II	III	IV	V
A	WCE	WCE	WCE	CE	N
B	WCE	WCE	CE	CE	N
C	WCE	CE	CE	N	N
D	N	N	N	N	N

Notes:
(1) See Table 13 for definition of Consequence Class.
(2) Susceptibility Class as defined in Wong (2000), where:
A = Extremely susceptible; notional annual probability ≥ 0.1
B = Highly susceptible; notional annual probability 0.1 to 0.01
C = Moderately susceptible; notional annual probability 0.01 to 0.001
D = Low susceptibility; notional annual probability < 0.001
(3) WCE = Adopt a 'worst credible' event as the design event. A 'worst credible' event is a very conservative estimate such that the occurrence of a more severe event is sufficiently unlikely. Its notional return period is in the order of 1,000 years.
CE = Adopt a 'conservative' event as the design event. A 'conservative' event is a reasonably safe estimate of the hazard that may affect the site, with a notional return period in the order of 100 years.
N = Further study is not required

Table 13. Consequence Class (Wong 2002)

Proximity	Facility Group No.			
	1 & 2	3	4	5
Very Close (e.g. if angular elevation from the site is ≥ 30°)	I	II	III	IV
Moderately Close (e.g. if angular elevation from the site is ≥ 25°)	II	III	IV	V
Far (e.g. if angular elevation from the site is < 25°)	III	IV	V	V

Notes:
(1) Facility groups are described in Table 4.
(2) For channelized debris flow, if the worst credible event affecting the site is judged to have a volume exceeding 2,000 m^3, the angular elevation given in the above examples should be reduced by 5°.
(3) The above are for general guidance only. Other factors, such as credible debris path, topographical conditions and site-specific historical data, should also be taken into account in assessing the 'proximity' of the natural terrain to the site.

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a 'worst credible' event (Table 12). For the purposes of calibration, the design requirements for the Design Event Approach have been applied to 17 cases where developed areas have been affected by natural terrain landslides or where the landslide hazards have previously been studied.

Applying the Design Event calls for use of geotechnical professional skills to identify the nature of the landslide hazards, assess their severity, establish the required design event requirements (i.e. notional return periods) following the design framework, and determine the magnitude of the landslide for risk mitigation (i.e. the design event). This qualitative method of risk assessment is relatively easy to apply. It does not demand formal and rigorous quantification of risk, and is favored by many geotechnical practitioners in Hong Kong.

However, there is always a trade-off between simplicity and versatility. This qualitative risk assessment methodology does not explicitly consider the practicality and cost-effectiveness of risk mitigation. Such consideration is inherent in the QRA approach if the risk level is found to be within the 'As Low As Reasonably Practicable (ALARP)' region.

Observation: The Design Event approach is an illustration of integration of risk assessment and conventional geotechnical practice, to offer a tailor-made methodology for qualitative landslide risk assessment for individual sites.

4.3 *Risk Analysis for Landslides below Wah Yan College*

In the morning of 8 May 1992, a 500 m^3 landslide occurred on a loose fill slope bordering the building platform of Wah Yan College, Hong Kong. The liquefied fill material ran onto Kennedy Road (Figure 8). The landslide did not result in any serious consequences at Wah Yan College, but the driver of a car on Kennedy Road was buried and killed by the liquefied debris. The incident highlighted the landslide concern in the area because in 1989, another landslide of similar size had also occurred on an adjoining fill slope bordering Wah Yan College. Fortunately, the debris of this landslide did not liquefy and was deposited on the pedestrian pavement without running onto Kennedy Road (Figure 9). In 1989, the slope that failed was largely covered by chunam (a 75 mm think cement-soil slope cover), which prevented the loose fill from reaching a high degree of saturation, thereby making it less susceptible to liquefaction. An imminent risk management issue to address after the 1992 landslide was whether there were other potentially unstable loose fill slopes bordering Wah Yan College, and if so, what were their liquefaction potential and risk implications.

A qualitative risk assessment was carried out. The development history of the site was reviewed by a detailed interpretation of the old aerial photographs, and the locations and extent of the loose fill bodies bordering Wah Yan College were identified. Apart from the slopes that failed in 1989 and 1992, another sizeable fill slope was present to the north of Wah Yan College overlooking Queen's Road East and the Ruttonjee Clinic (Figure 9). Detailed ground investigation confirmed that the fill was loose and had comparable susceptibility to liquefaction failure as the 1992 landslide site. The findings provided the technical basis for carrying out stabilization works on the slope. However, as the works would take some time to arrange, further assessment was made, in particular on the consequences of failure.

Figure 8. Liquefied debris of the 1992 Kennedy Road landslide

The consequence assessment involved modeling the mobility of landslide debris. The operating apparent angles of friction along the failure surface and along the debris path in the event of a liquefaction failure were back-analyzed from the 1992 landslide. Based on the results, the area that might be affected by the landslide debris was classified into a primary impact zone and a secondary impact zone (Figure 9). The primary zone was taken to be of high risk, where serious damage would result, as in the case of the 1992 fatal landslide. The secondary zone represented a lower risk region, where serious damage might also occur in case of a larger volume of failure, or more mobile debris than the 1992 landslide. The risk at the Ruttonjee Clinic was also assessed. It was found that the road together with the 1.5 m high retaining wall in front of the clinic would protect the clinic from direct impact from most of the debris.

The risk assessment offered invaluable information on the likely scale of the problem, which was adopted in emergency planning and implementation of precautionary measures. The case may be taken as an example of Consequent Risk Analysis, which was advocated by Morgenstern (2000) as a qualitative risk assessment process to assure geotechnical performance and control risk.

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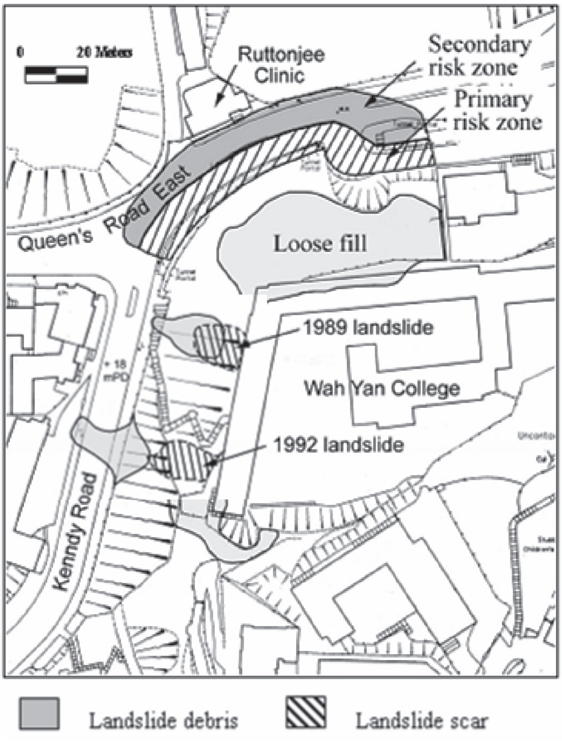

Figure 9. Qualitative risk assessment, Wah Yan College, Hong Kong

Observation: Landslide study, geotechnical investigation, engineering appraisal and consequence analysis can be combined in a qualitative risk assessment to resolve landslide risk management issues that would otherwise be difficult to handle by conventional means.

4.4 *Failure Modes and Effects Analysis for Shatin Heights*

Over the years, a suite of technical methods have been developed and adopted in qualitative risk assessment. Examples include Failure Modes and Effects Analysis (FMEA), Hazard and Operability Study (HAZOP) and Potential Problem Analysis (PPA). Among these methods, FMEA was fairly commonly adopted in geotechnical risk assessment, e.g. geo-environmental risk management in mining projects (Dushnisky 1996) and dam risk management (Hughes et al. 2000, Stewart 2000). FMEA directs attention towards understanding the behavior of the physical components of a system, the possible modes of their failure, and the influence their failure would have on each other and on the system as a whole. It is usually used in two ways, as noted by (Vick 2002):

(1) to assist in hazard identification and risk screening, typically as a precursor to more detailed risk assessment; and
(2) to serve as a stand-alone preliminary risk assessment procedure.

Table 14 shows an example of applying FMEA to assessing the risk of natural terrain landslides in Shatin Heights, Hong Kong. The FMEA table was devised to address the specific circumstances of the site. The classification schemes that accompanied the FMEA are explained in Figure 10.

The natural hillside at Shatin Heights is bounded by residential buildings at the crest and toe of the hillside (Figure 11). In 1997, a total of six landslides occurred on the hillside, and three of these developed into debris flows that ran into the buildings at the toe of the hillside. After the failures, the landslides were studied (GEO 1998b) and a Natural Terrain Hazard Study was carried out on the site (FMSW 2001). These provided data, which were incorporated into the FMEA for working out the semi-quantitative hazard and consequence categories in the FMEA table. The case showed the following:

(a) The FMEA has facilitated hazard identification and provided a preliminary assessment of the risk. In this case, out of the 15 possible hazard scenarios, 5 were identified by FMEA as of risk concern and requiring further risk assessment. The likely order of risk of each of the five hazards was also estimated. Although these are not formal QRA figures, they give a preliminary indication of the possible level and severity of the risk.
(b) Availability of data and technical understanding of the landslide hazards at the site is a prerequisite for successfully using FMEA in site-specific qualitative risk assessment. Otherwise, the reliability of the assessment and its suitability for supporting site-specific risk management application are in question. In such cases, the FMEA assessment would practically be reduced to at best a relative risk rating process.
(c) The FMEA table can become very long (i.e. with many rows) when applied to a large site. Formulating a suitable FMEA table that addresses the particular circumstances of the site is important to the efficient and effective use of FMEA.
(d) The case also illustrates the use of a risk-matrix (Figure 10) in evaluating the risk category and thereby providing a basis for risk estimation and hazard identification. The risk matrix combines different classes of the frequency and consequence of landslide, which are aligned with some notional probabilities of failure and descriptions of the severity of landslide consequence respectively. An interesting example of application of risk-matrix to assessing the landslide risk on a proposed house on the western slope of the Warringah Peninsula, Northern Sydney is described in Walker (2002). In this example, the qualitative descriptors given in AGS (2000) were adopted. For each type of landslide that might affect the house, the frequency and consequence classes are determined from judgmental assessment and the corresponding risk

Table 14. FMEA on Shatin Heights Catchment No. 7

Component	Failure Mode (Notes (1))	Effects on 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	
Catchments 7a, 7d & 7h	Shallow landslide resulting in small-scaled open-slope debris slide/ avalanche (SH1)	Debris run into and affect 1/F of K.K. Terrace	C to D	z	D to E	2	L to V	III	N	Low (Yes)
	Deep landslide resulting in medium- to large-scaled fast moving debris slide/avalanche (SH2 to SH3)	Debris run into and affect 1/F of K.K. Terrace	E	x	E	2	V	III	N	Very Low (No)
		Debris hit K.K. Terrance and result in building collapse or major structural damage		z	E-	1	V	II	N	Very Low (No)
	Deep landslide resulting in medium- to large-scaled debris with limited mobility (SH2 to SH3)	Prolonged evacuation of K.K. Terrace	E	y	E-	5	N	II to III	N	Residual (No)
Catchments 7b, 7e, 7f, 7i & 7j	Shallow landslide resulting in small- to medium-scaled debris flow without significant entrainment (TH1 to TH2)	Debris run into and affect 1/F of K.K. Terrace	B	x	B	2	H	III	L	High (Yes)
		Debris hit and affect the entrance to K.K. Terrace		y	B to C	3	M to L	IV	N	Moderate (Yes)
	Shallow landslide resulting in medium- to large-scaled debris flow with significant entrainment (TH2 to TH3)	Debris run into and affect 1/F of K.K. Terrace	D	x	D	2	L	III	N	Low (Yes)
		Debris hit and affect the entrance to K.K. Terrace		y	D to E	3	V to N	IV	N	Very Low (No)
		Debris hit K.K. Terrance and result in building collapse or major structural damage		z	E	1	L	II	N	Low (Yes)
	Shallow landslide resulting in small-scaled debris with limited mobility(TH1)	Temporary evacuation of 1/F of K.K. Terrace	B	y	B to C	5	N	IV	V to N	Very Low (No)
Catchments 7c, 7g & 7k	Shallow landslide resulting in small-scaled open-slope debris slide/ avalanche (SH1)	Debris hit and affect the entrance to K.K. Terrace	C to D	z	D to E	3 to 4	V to N	IV	V	Very Low (No)
	Deep landslide resulting in medium-to-large scaled fast moving debris (SH2 to SH3)	Debris hit and affect the G/F of K.K. Terrace, including the entrance, G/F lobby, car park and drive way	E	x	E	2	V	III	N	Very Low (No)
		Debris hit K.K. Terrance and result in building collapse or major structural damage		z	E-	1	V	II	N	Very Low (No)
	Deep landslide resulting in medium- to large-scaled debris with limited mobility (SH2 to SH3)	Temporary evacuation of K.K. Terrace and the sole vehicular access to K.K. Terrace and Woodcrest	E	x	E	5	N	III	N	Residual (No)
		Prolonged closure of the sole vehicular access to K.K. Terrace and Woodcrest		z	E-	5	N	II	N	Residual (No)

Notes:

(1) See Table 21 for definition of 'SH1' to 'SH4' and 'TH1' to 'TH4'.

(2) See Figure 10 for likelihood, consequence and risk categorization. See Figure 18 for site plan.

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	M	L	R	R
	B	H	H	H	L	R	M	L	V	R	R
	C	H	M	L	V	R	L	V	R	R	R
	D	M	L	R	R	R	V	R	R	R	R
	E	L	V	R	R	R	R	R	R	R	R
	E-	V	R	R	R	R	R	R	R	R	R

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

Class	Descriptions (PLL for risk to life)	Further study
H	High – of major concern (notional PLL > 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 form 10^{-3} to 10^{-4})	This failure mode should be examined, to assess/verify the scale of the problem
L	Low – of some concern (notional PLL form 10^{-4} to 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 10^{-5})	Further study not warranted except in special circumstances
R	Residual risk – no indication of risk problem	Further study not warranted

(a) Risk Category

Class	Failure Likelihood Category
A	Very high (notionally 1 in 10 years)
B	High (notionally 1 in 10 to 100 years)
C	Moderate (notionally 1 in 100 to 1,000 years)
D	Low (notionally 1 in 1,000 to 10,000 years)
E	Very low (notionally much less than 1 in 10,000 years)

Class	Effect Likelihood Category (likelihood of occurrence of the stated effects given the failure mode)	Adjustment on Failure Likelihood Category
x	Probable (notionally 0.5 or higher)	No change
y	Quite possible (notionally 0.1 to 0.5)	Downgrade by half a category
z	Possible (notionally < 0.1)	Downgrade by one category

(b) Likelihood Category

Class	Loss of Life Consequence Category
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	Economic Loss & Disruption to Community Consequence Category
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 within a few flats or individual houses; prolonged evacuation of within 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 within 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)

(c) Consequence Category

Figure 10. FMEA categorization scheme

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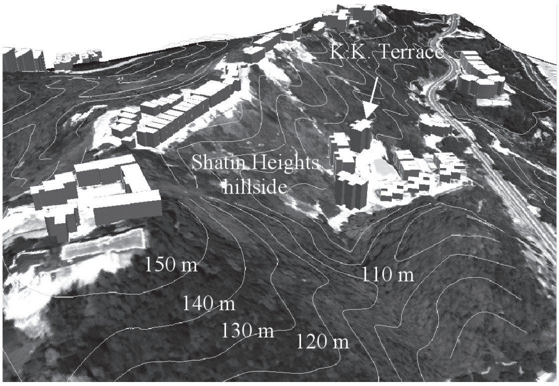

Figure 11. Shatin Heights, Hong Kong

level established in a semi-quantitative manner via a risk-matrix.

Observation: Established methods, such as FMEA and risk-matrix analysis, can be used in qualitative landslide risk assessment, to assist in hazard identification, risk screening and evaluation. It may be carried out as a stand-alone qualitative or semi-quantitative risk assessment procedure, or as a precursor to more detailed risk assessment, and in particular QRA.

5 SITE-SPECIFIC QUANTITATIVE RISK ASSESSMENT (QRA)

5.1 *Overview*

QRA is characterized by quantification of risk, for risk tolerability evaluation and risk management applications. Undertaking landslide QRA at individual sites requires the use of formal risk quantification techniques. It differs from qualitative landslide risk assessment as applied to site-specific level in two key aspects:

(a) the landslide risk, typically in terms of risk-to-life, is explicitly quantified; and

(b) the quantified risk figures are formally compared with the corresponding risk criteria for evaluation of risk management action, based on risk tolerability and risk-cost-benefit considerations.

Geotechnical practice embraces the assessment and management of risk, but the approach taken to handling risk has evolved with time. Qualitative deliberation prevailed in the 1970s and 1980s. Geotechnical application of QRA emerged in the 1990s, particularly in the mining industry, dam management and slope safety (e.g. Fell & Hartford 1997, Wong et al. 1997, Ho et al. 2000). Over the past few years, formal QRA has found a broader and more in-depth application to landslide risk assessment. The methodology and techniques continue to evolve.

There is now a wide spectrum of cases in which QRA was applied at varying degrees of complexity and detail, and conceivably with differing levels of rigor. Selected examples of site-specific QRA applications are summarized in the following Sections. While the examples are selected from the more detailed end of the spectrum of QRA cases to illustrate the state of good practice, they also demonstrate the evolution of QRA techniques in recent years.

5.2 *QRA of Notable Landslides*

Landslide back-analyses are conventionally undertaken primarily for examining the mechanisms and causes of slope failure. QRA offers another dimension to landslide back-analysis – to assess the landslide risk in retrospect. This provides a basis for a landslide to be evaluated in the light of its theoretic risk, damage potential and consequence scenarios. It also facilitates the interpretation of ‘near-miss’ events and examination of potential landslide loss figures and risk tolerability. The following are some known examples:

(a) The 1995 Fei Tsui Road landslide, Hong Kong: This landslide, which occurred in mid-night and resulted in one fatality, was a ‘near-miss’ incident. QRA by Wong et al (1997) showed that the landslide had a Potential Loss of Life (PLL) of about 4. The F-N curve (Figure 12) indicated the slope could result in multiple fatalities, e.g. the chance of 10 fatalities or more occurring was 0.015% per year. The back-analysis was also extended to predicting the consequences if the same landslide were to occur alongside a more heavily-used road. The QRA facilitates examination of possible hazard scenarios and risk projections, and provides information for consideration in risk management, including emergency planning.

(b) The 1982 Argillite Cut rock fall, Canada: The rock fall resulted in one fatality and one another person injured. QRA by Bunce et al (1997) found that the annual PLL was 8 x 10^{-2}, and annual probabilities of death of a one time user and a daily commuter on the highway were 6 x 10^{-8} and 3 x 10^{-5} respectively. Bunce et al (1997) and Morgenstern (1997) noted that the case set a legal precedent when compensation was awarded because it effectively identified the level of risk at which the judicial system considered the public should be protected, although no QRA results were offered in evidence. This QRA back-analysis, which was carried out after the court case, helped to quantify the likely level of risk posed by the Argillite Cut to road users, and thereby facilitated the interpretation of risk tolerability.

(c) The 1999 Shek Kip Mei landslide, Hong Kong: The landslide caused significant slope movement and resulted in permanent evacuation of about 700 residents from a housing estate. Based on the QRA results by El-Ramly et al (2003), Wong (2005) assessed that the probability of multiple fatalities (> 40 deaths) was about 10^{-2} to 10^{-3} after significant

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slope movement had occurred. Although there are uncertainties due to the simplified assumptions adopted, the results give a quantified estimate of the likely order of risk perceived at the time when evacuation was recommended on the basis of engineering judgment.

(d) The 1997 Thredbo landslide, NSW, Australia: A fill embankment below the Alpine Way collapsed and the mobile debris destroyed two buildings, which resulted in 18 fatalities. QRA by Mostyn & Sullivan (2002), which was based on consideration of the historical fill embankment failure data in the Alpine Way, debris mobility and consequence analysis, found that the individual risks at the two buildings before the landslide (2.2 x 10^{-3} and 5.3 x 10^{-3} per year) exceeded the unacceptable limit (10^{-6} per year) suggested by the NSW Department of Planning for tourist resorts. The societal risk was also found to be high, and was within the unacceptable zone according to the societal risk criteria reviewed by Fell & Hartford (1997). The QRA findings were presented to the Coroner Inquest, and the Coroner took the view that the community would regard the individual risk as 'totally unacceptable' (Hand 2000).

5.3 *Lei Yue Mun Squatter Area QRA*

QRA has been used in Hong Kong for about a decade in formally assessing landslide risk for evaluating site-specific risk management strategy. The QRA of the Lei Yue Mun squatter area (Hardingham et al. 1998) was an early application. The QRA methodology adopted at the time was relatively simplistic. However, all the essential components of a formal QRA, e.g. quantification of individual and societal risks and evaluation in comparison with risk criteria, were in place.

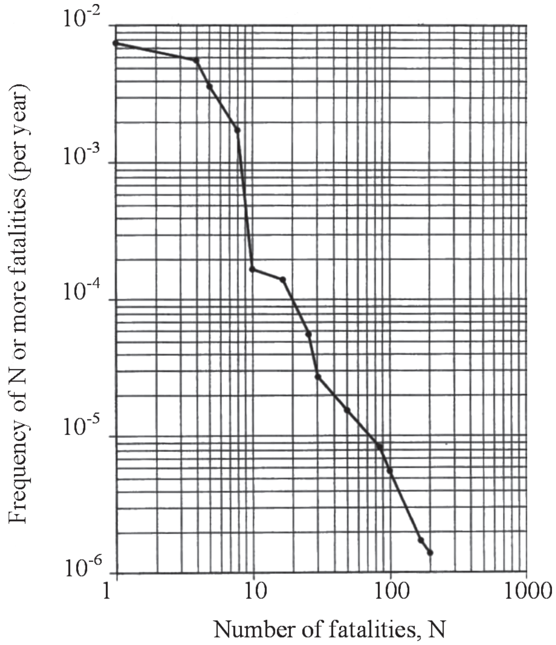

Figure 12. Calculated F-N curve for the Fei Tsui Road landslide (Wong et al. 1997)

The abandoned quarry faces of the slopes flanking the Lei Yue Mun squatter villages in Hong Kong were between 20 m and 40 m high, and typically sloping at 65° to 80° (Figure 13). The slopes had a history of instability. QRA was adopted to quantify the landslide risk and to assist in decision-making with regard to the extent of re-housing of the squatter residents.

(a) Hazard identification

This was carried out through a comprehensive geotechnical study. The principal hazards threatening the squatter village included rock falls and debris slides arising from failure of the un-engineered cut and fill slopes. The hazards were categorized according to the volume of failure.

(b) Frequency assessment

Interpretation of aerial photographs, which dated back to 1945 at this site, identified a total of 115 landslides. 'Recognition factors' of 30% and 90% were adopted for small and medium landslides, respectively. This factor represented the proportion of landslides that could be recognized, to address the problem that some of the smaller failures could have been missed by aerial photograph interpretation. The base-line annual landslide frequencies for the site were found to be 3.3 for small (<50 m^3), 1.3 for medium (50-500 m^3), 0.24 for large (500-1,000 m^3), 2.4 x 10^{-3} for very large (1,000-5,000 m^3), and 2.4 x 10^{-4} for extremely large failures (>5,000 m^3). The frequency was spatially apportioned to different 20-m wide slope segments via an empirical slope rating scheme.

(c) Consequence assessment

Consequence was defined in terms of three different groupings, each with its own level of associated casualties. The groupings took into account the type

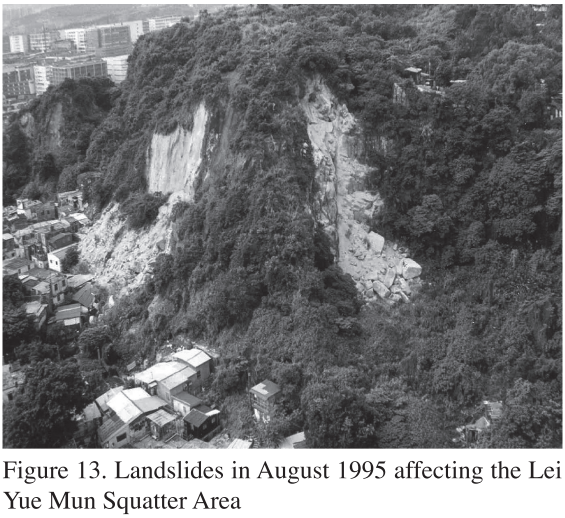

Figure 13. Landslides in August 1995 affecting the Lei Yue Mun Squatter Area

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of landslides and debris travel distance, as well as the proximity of the dwellings. Site surveys were carried out on about 10% of the population and 45 dwellings, to identify the numbers of people at risk and their temporal distributions at different types of facility.

(d) Risk calculation and evaluation

The dwellings were grouped into 20 m by 20 m grid cells. The number of people and the temporal presence in each grid were determined from a population survey. An Event Tree was generated for each of the reference grids, which traced the different credible scenarios by combining the hazard grouping, timing of failure, responses to landslip warning, level of emergency services, secondary hazards, etc.

The site-specific risk acceptance criteria were determined through a review of different safety acceptance criteria and consideration of the situation involving squatters at Lei Yue Mun. The proposed individual risk criteria ranged from an upper boundary (unacceptable) of 10^{-4} to a lower boundary (acceptable) of 10^{-6}. The risk criteria that are currently adopted in Hong Kong (ERM 1998) had not been developed at the time.

The results of the QRA indicated that a large area of the squatter area fell within the unacceptable region in terms of individual risk (Figure 14). The assessed societal risk was also found to be unacceptable (Figure 15). Risk calculations further showed that if the squatter residents within the area recommended for clearance were re-housed, the societal risk would reduce to the ALARP region. Cost-benefit calculations indicated that the residents in areas where the landslide risk was within the ALARP region did not justify immediate re-housing. Quantification of risk provided a rational basis for decisions to be made on risk mitigation and squatter clearance in this case.

5.4 *Shatin Heights QRA*

Hong Kong's natural terrain is susceptible to shallow, small-to-medium-sized landslides (Figure 16), which can develop into debris flows after entering drainage lines. Should the debris reach densely developed areas, serious consequences may occur, even if the volume of the landslide is relatively small (Figure 17). The strategy that is being adopted in Hong Kong for management of natural terrain landslide risk entails

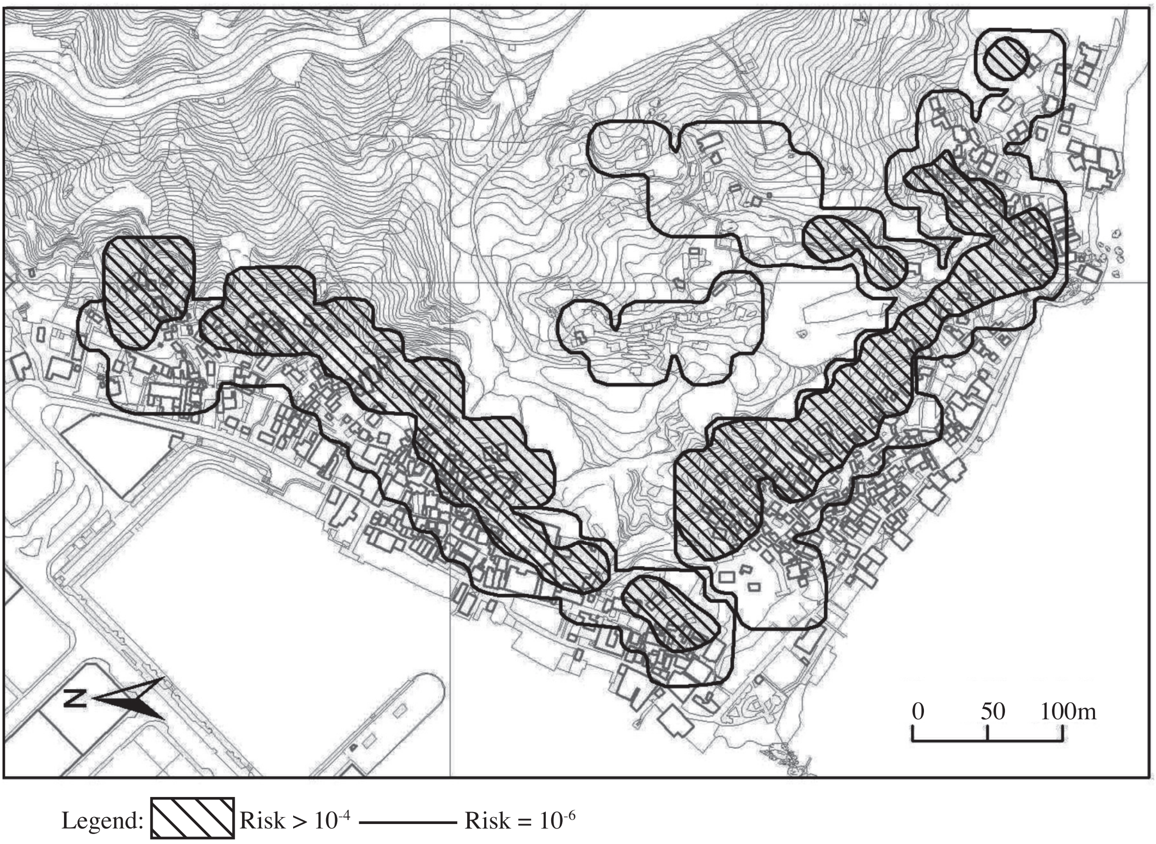

Figure 14. Individual risk contours for the Lei Yue Mun Squatter Area (Hardingham et al. 1998)

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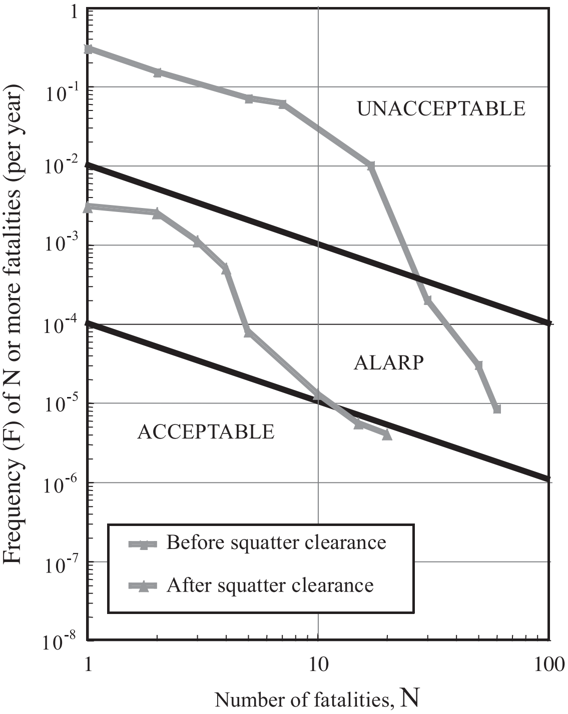

Figure 15. Societal Risk for the Lei Yue Mun Squatter Area (Hardingham et al. 1998)

Figure 16. Landslide-prone natural terrain in Hong Kong

Figure 17. A 20 m^3 landslide in 1998 resulted in damage to property

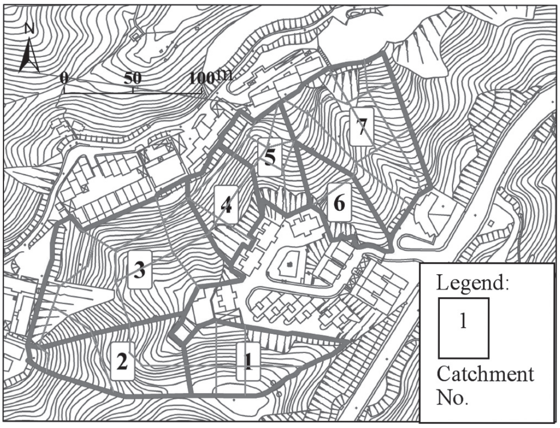

Figure 18. Natural terrain catchments in Shatin Heights, Hong Kong

(a) Before risk mitigation

(b) After risk mitigation

Legend:

■ Risk > 10^{-4} ▨ Risk >10^{-5} to <10^{-4} –·– Risk = 10^{-6}

Figure 19. Personal Individual Risk at Shatin Heights (FMSW 2001)

two principles (Chan 2003):

- For existing developments, deal with natural terrain landslide risk following a ‘react-to- known-hazard’ principle, i.e. to carry out studies and mitigation actions where significant risk becomes evident.
- For new developments, contain the increase in

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overall risk through studying and undertaking any necessary mitigation actions on sites subject to natural terrain landslide hazards.

Use of QRA as an accepted approach for studying natural terrain landslide risk and determining the required mitigation actions was formally introduced in Hong Kong in 2000.

The natural terrain landslide problem at the Shatin Heights site is described in Section 4.4 above. The QRA of the site, which is documented in FMSW (2001), is one of the earliest QRA applications to natural terrain landslide risk in Hong Kong. The GEO selected the case for risk assessment based on the 'react-to-known-hazard' principle, following six natural terrain landslides that occurred on the hillside in 1997.

The study area (Figure 18) was sub-divided into seven catchments and a total of 45 segments, based on topographic conditions. The QRA included the following key tasks:

(a) Hazard identification

This was carried out with a desk review of the available data, interpretation of historical aerial photographs, study of the 1997 landslides, ground investigations, geological mapping, geotechnical appraisal and use of engineering judgment. The landslide hazards were classified according to two types of mechanism (open hillslope landslide and channelized debris flow) and three failure scales ('small' for volumes within 50 m^3, 'medium' for between 50 m^3 and 200 m^3, and 'large' for between 200 m^3 and 1,000 m^3).

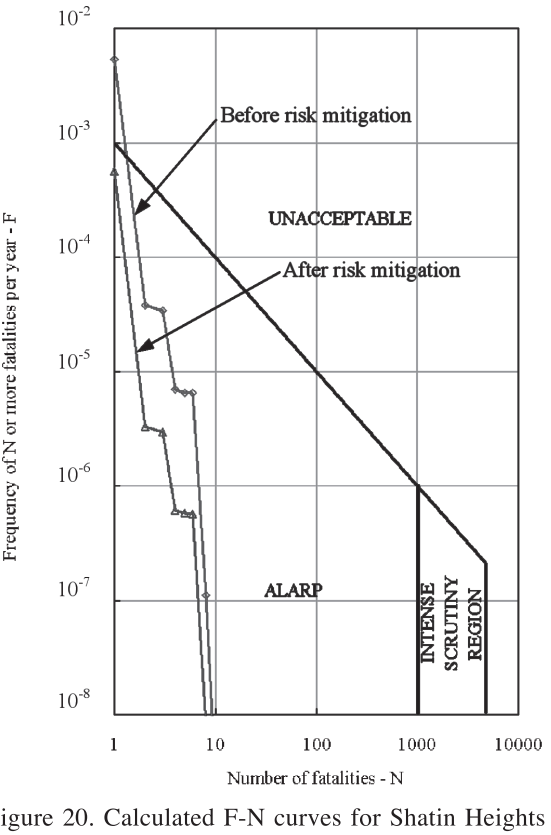

Figure 20. Calculated F-N curves for Shatin Heights (FMSW 2001)

(b) Frequency assessment

The base-line landslide frequency was assessed from historical landslide data collated from detailed interpretation of aerial photographs dating back to 1963, with allowance being made for 'recognition factors'. Volume-frequency relationship was established from the landslide data, together with a consideration of the data available from elsewhere in Hong Kong (Wong & Lam 1998, Franks 1998). Probabilistic slope stability analyses were carried out to provide a basis for spatial distribution of the landslide frequency to the different segments. The distributed landslide frequency was further adjusted by a Bayesian approach to take account of any historical landslide frequencies occurring in the segment.

(c) Consequence assessment

A site-specific consequence model was formulated, based on the generalized model developed by Wong et al (1997). This modified consequence model entailed the use of site-specific data on debris mobility, an empirical runout model, and vulnerability factors for different types of facility at different proximity zones. Scaling factors were applied for adjusting the vulnerability factors under different circumstances. Landslide consequence was quantified by multiplying the expected number of people with the relevant vulnerability factor.

(d) Risk calculation and evaluation

The distribution of the calculated Personal Individual Risk (PIR) at Shatin Heights is shown in Figure 19. PIR adopted in Hong Kong refers to the frequency of harm to a theoretical individual who is exposed to the hazard with account being taken of the temporal factors which expose the individual to the hazard. Parts of the site had an unacceptable PIR, i.e. exceeding 10^{-4} per year for an existing facility (ERM 1998). The societal risk in terms of potential loss of life (PLL) was found to be 5.7 x 10^{-3} PLL per year. The corresponding F-N curve is shown in Figure 20. The societal risk criteria apply to a consultation zone that is equivalent to a maximum 500 m long segment of natural hillside. The societal risk was within the ALARP region except for the single-fatality portion which was in the unacceptable zone (ERM 1998).

(e) Risk mitigation strategy

The mitigation strategy that was adopted included a qualitative assessment of the design hazard, which was followed by risk-cost-benefit analysis based on the ALARP principle. The design hazard was established with the use of the Design Event Approach (as described in Section 4.2 above), which indicated that a worst credible event (i.e. notionally a 1,000-year event) was to be mitigated. From analysis

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of the magnitude-frequency data, the design landslide volumes were estimated to be 600 m^3 for catchment No. 3, and 500 m^3 for catchments No. 5 and No. 7. Possible risk mitigation schemes, including use of debris-resisting barriers and local slope stabilization, were examined. The cost of risk mitigation was found to be about US$ 0.7 million, which would result in mitigation of about 80% of the societal risk. After risk mitigation, the PIR distribution (Figure 19) and F-N curve (Figure 20) would be well below the unacceptable zone. The risk mitigation was found to be justified from risk-cost-benefit analysis, based on consideration of an equivalent value of life of US$ 3 to 4 million and an aversion factor of unity. The risk mitigation works were implemented in close liaison with the local residents in 2004.

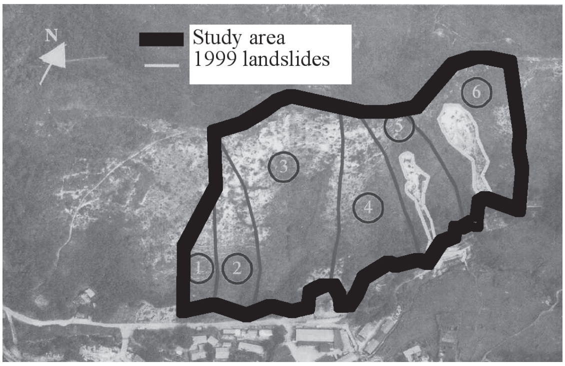

Figure 21. The August 1999 landslides at Pat Heung, Hong Kong

5.5 *Pat Heung QRA*

In August 1999, two landslides occurred on the natural hillside above No. 92 to 94 Ta Shek Wu Kiu Tau, Pat Heung, Hong Kong (Figure 21). Based on the 'react-to-known-hazard' principle, the GEO arranged a QRA of the natural terrain landslide risk on the existing developments at the site. The study was documented by OAP (2003).

The QRA at Pat Heung followed methodology that was similar to those developed and adopted in the Shatin Heights study. Use of GIS techniques enabled a more refined sub-division of the hillside into regular 10-m grid cells, which facilitated spatial analysis.

(a) Hazard identification

The landslide history, geology, geomorphology and hydrogeology were evaluated by aerial photograph interpretation, field mapping, and ground investigation comprising boreholes, trial pits and gravity surveys. The landslides occurred mainly in the surface layer of colluvium, and occasionally with part of the slip surface extending into the underlying weathered volcanic tuff. The landslide hazards were identified as shallow landslides, either in the form of an open hillslope failure or channelized debris flow. Landslide volume was categorized into different ranges.

(b) Frequency assessment

The base-line landslide frequency was established from the historical landslide data, with allowance for 'recognition factors'. The relevant terrain attributes, including slope gradient, slope aspect and regolith type, were analyzed to examine their correlation with the historical landslide distribution. A grid-based landslide susceptibility analysis was carried

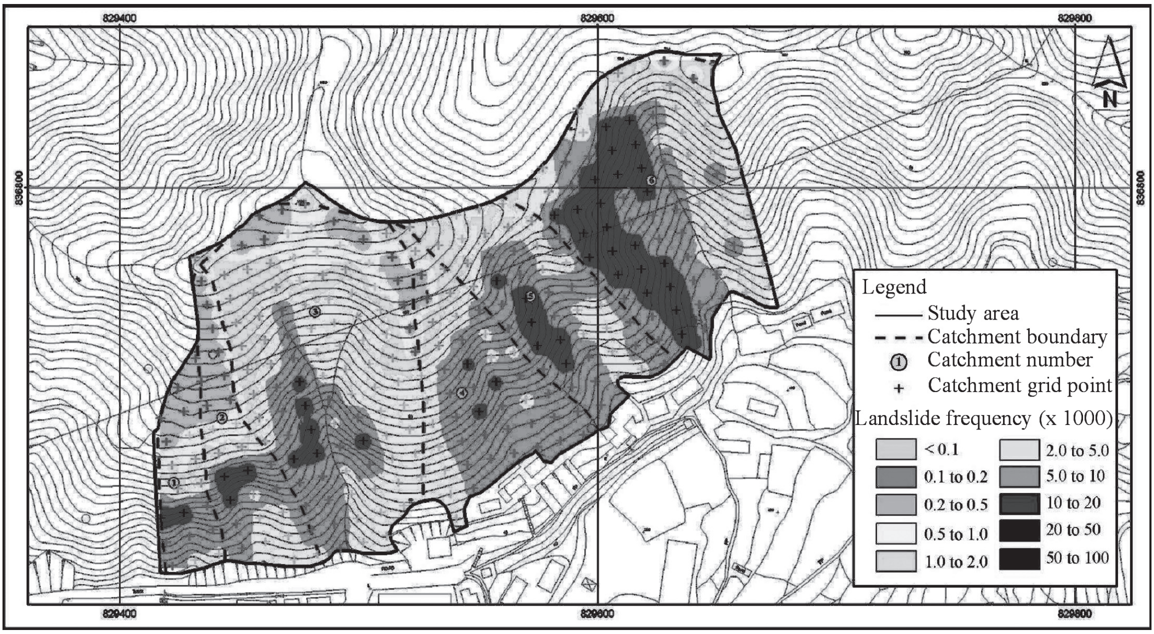

Figure 22. Annual landslide frequency (OAP 2003)

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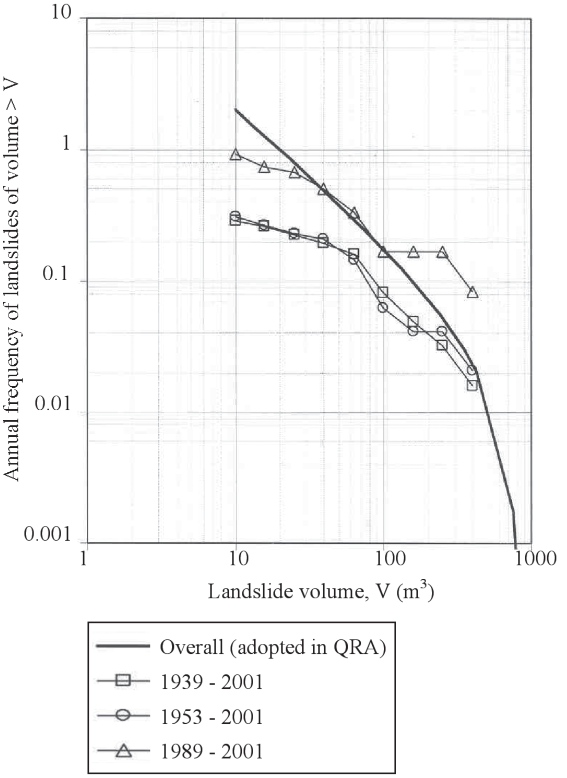

Figure 23. Volume-frequency distribution for landslides at Pat Heung (OAP 2003)

out to distribute the landslide frequency to each grid cell (Figure 22). The landslide volume-frequency distribution was established from historical landslides (Figure 23). The worst credible volumes (i.e. notional 1,000-year event) for open hillslope failure and channelized debris flow were assessed as of 400 m^3 and 550 m^3, respectively.

(c) Consequence assessment

Historical debris runout data at the site were analyzed to establish the mean and standard deviation relationships of debris runout for open hillslope failures and for channelized debris flows (Figure 24). Runout distance was adopted as an empirical indicator of the probabilistic distribution of debris mobility, whereas the mean travel angle minus two standard deviations was taken as the upper limit of debris runout.

For houses including dwellings and industrial buildings, the expected number of vulnerable people and their temporal distribution were identified from field surveys and interviews. For roads and footpaths, it was estimated from vehicle and pedestrian densities. The vulnerability factor was calculated as the product of a base-line factor, a volume factor and a protection factor (Figure 25).

(d) Risk calculation and evaluation

The risk arising from landslides originating from each grid cell was calculated and summed. The PIR at houses No. 92 and 93 ranged from 1.2 x 10^{-4} to 2 x 10^{-4} per year, which was unacceptable. The societal risk was found to be 2.1 x 10^{-3} PLL per year. About 77% of this came from people in buildings, 18% from pedestrians and 5 % from vehicle occupants. The derived F-N curve (Figure 26) showed that the single-fatality portion was within the unacceptable zone.

(e) Risk mitigation strategy

Possible risk mitigation options were examined. The recommended option comprised debris deflector walls together with local soil nailing to protect the houses. These would reduce the societal risk to about 5 x10^{-4} PLL per year, i.e. by over 80% (Figure 26). The cost of the mitigation works was about US$ 1 million. The maximum justifiable expenditure was assessed to be US$ 0.6 to 1.5 million, based on use of 120-year design life, an equivalent value of life of US$ 3 to 4 million (ERM 1998) and aversion factor of 1 to 2. The mitigation measures were being constructed in 2004/05.

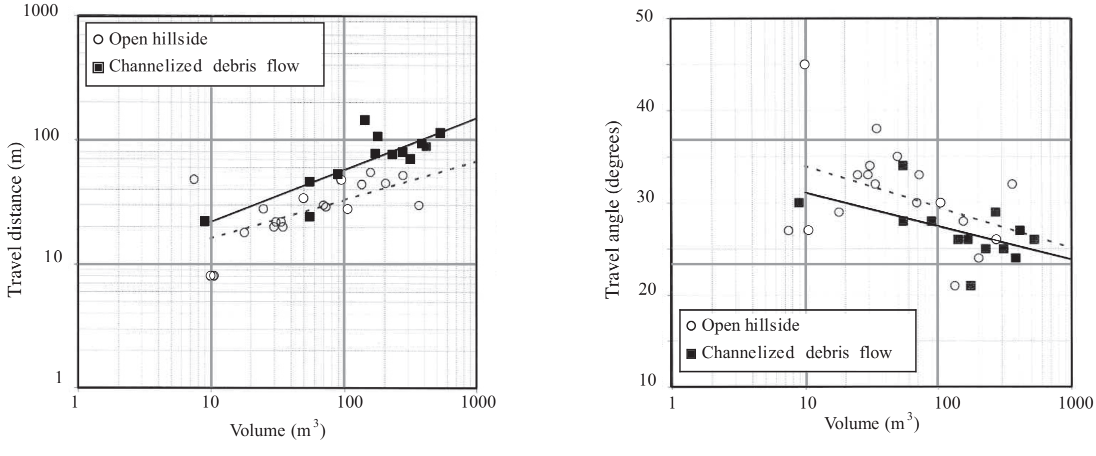

Figure 24. Mobility of landslides in Pat Heung (based on OAP 2003).

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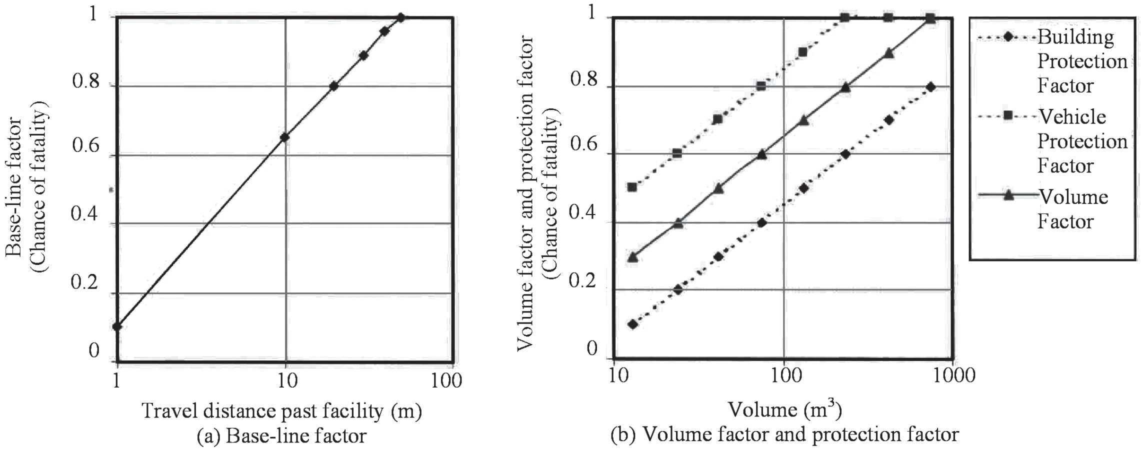

(a) Base-line factor

(b) Volume factor and protection factor

Notes: (1) The base-line factor is applied to a facility located at a given distance from the distal end of the debris runout

(2) Vulnerability factor = Base-line factor × Volume factor × Protection factor

Figure 25. Vulnerability factor adopted in Pat Heung QRA (based on OAP 2003)

5.6 *North Lantau Expressway QRA*

The North Lantau Expressway is the sole vehicular access to the Hong Kong International Airport and the adjacent Tung Chung New Town, Lantau, Hong Kong. The road is a two-way highway with 3 lanes each way. It runs for about 20 km along the toe of the steep natural hillside of north Lantau. The hillside has numerous records of historical natural terrain failures, and some of these have reached the present position of the highway.

A qualitative hazard assessment was carried out (Ng & Wong 2002). The assessment included a review of the historical landslide records and the geological and terrain conditions, consideration of the historical landslide activity, proximity of the highway to the hillside and empirical debris runout criteria, a 4 km long section of the highway near the Tung Chung New Town (Figure 27) was found to require a QRA. The QRA findings were documented in OAP (2005).

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

(a) The natural hillside to be assessed covered a large area, and involved more variable geological conditions and landslide types. Hence, in this QRA, particular attention was given to geological assessment of the terrain morphology and landslide process, which formed an integral part of hazard identification and frequency assessment. The information was synthesized into detailed morphology-based regolith maps and landslide process models (Figure 28).

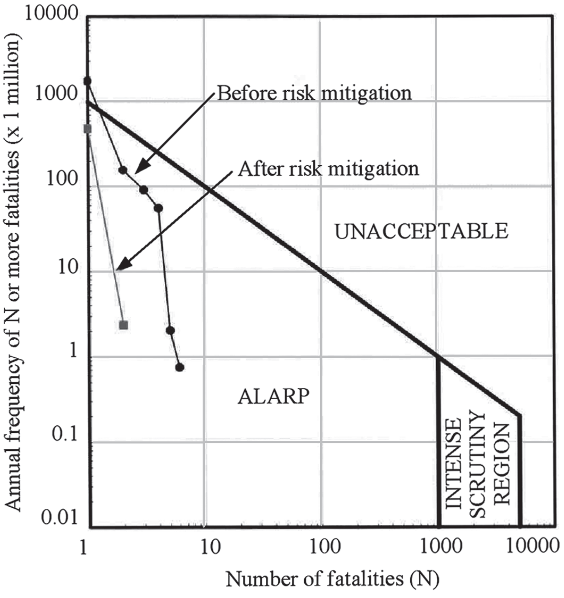

Figure 26. Calculated F-N curve for Pat Heung (OAP 2003).

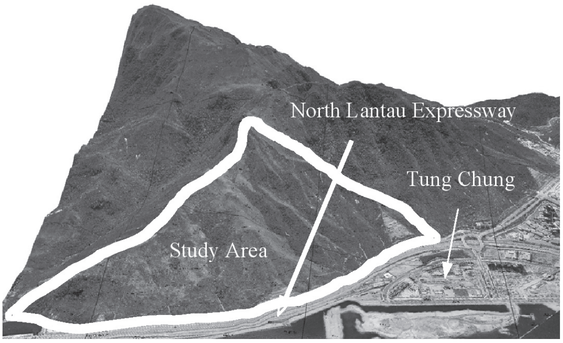

Figure 27. Natural hillside overlooking North Lantau Expressway, Hong Kong

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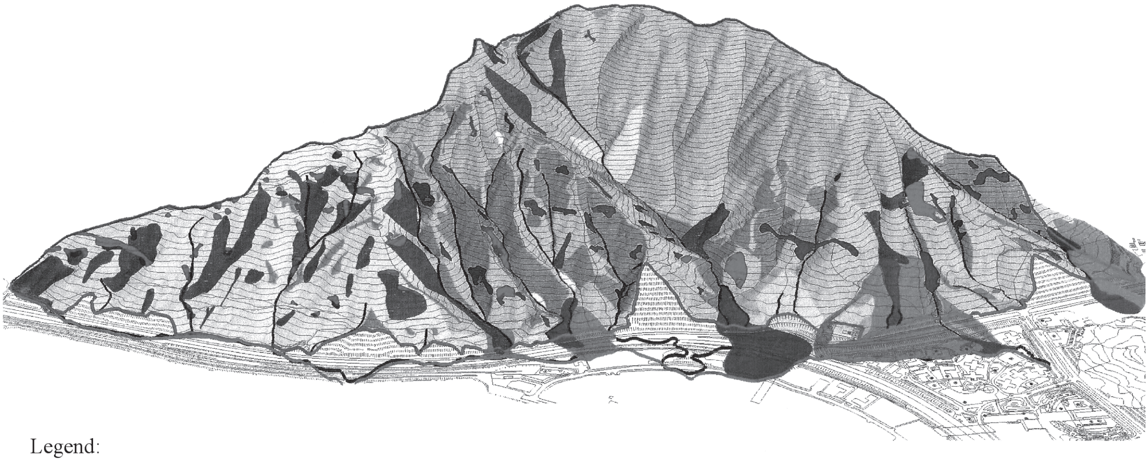

Legend:

- ■ Distressed ground (with tension cracks and slow moving landslides).
- ■ Area of landslide clustering.
- ■ Alluvium, channelized debris flow dposit, colluvium and taluvium boulder accumulate along the drainage channels.
- ■ Shallow landslides deposit colluvium on gully side slopes. Many landslides.
- ■ Taluvial lobes downslope from intermittent rock outcrops.
- ■ Rockfall debris at the toe of rock outcrops.
- □ Accumulation of colluvium in topographic depressions.
- ■ Landslides occur on former steep coastal slopes.
- □ Open hillslope colluvium accumulates on relatively shallow hillslopes. In feldsparphyric rhyolite/ porphyritic microgranite terrain. Very few landslides.
- □ Open hillslope colluvium on relatively shallow hillslopes (younger terrain) in the rhyolite lava/ tuff terrain as a result of creep. Few landslides.
- ■ Relatively steep hillslopes in the upper portion of the rhyolite lava/ tuff terrain (older terrain). Drainage channels generally have well defined convex breaks of slope at their heads but very few recent landslides.

■
■
■ Incised and degraded
■
□

↑ Younger

Debris fans, comprising coalescing bodies of colluvium/ alluvium, have developed at the hillslope toe.

— Study area boundary
— Former shoreline
— Former cliffline

- ■ Areas of saprolite along hillside spurs. Very few landslides.
- ■ Rock outcrops

Figure 28. Landslide process model (OAP 2005)

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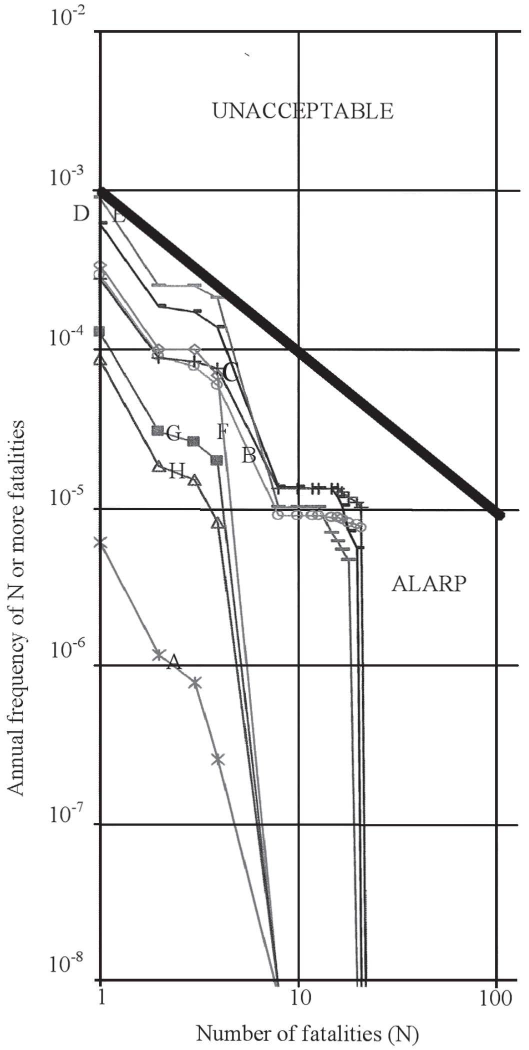


Legend:

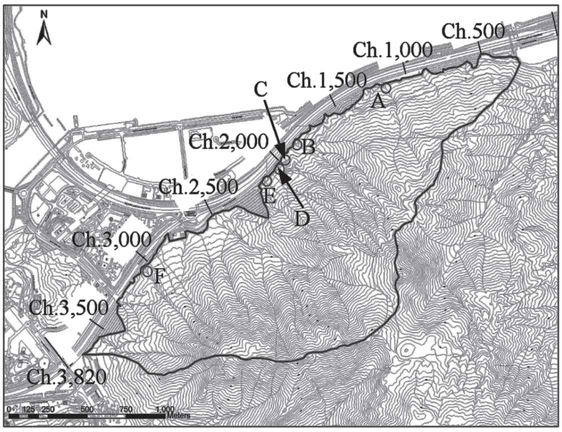
A - Chainage 0-500 m
B - Chainage 501-1000 m
C - Chainage 1001-1500 m
D - Chainage 1501-2000 m
E - Chainage 2001-2500 m
F - Chainage 2501-3000 m
G - Chainage 3001-3500 m
H - Chainage 3501-4000 m

Figure 29. Calculated F-N curves for North Lantau Expressway (OAP 2005)

(b) The highway was located at some distance from the steep natural hillside and was partly protected by buffer zones, which included open spaces, road reserves and drainage ditches and chambers. The QRA showed that both the PIR and societal risk in terms of risk-to-life were not in the unacceptable zone. The PIR for the most affected people (i.e. bus drivers) was found to be 1.7 x 10^{-7} per year, which is well within the acceptable limit of 10^{-4} for an existing facility. For societal risk, the total calculated PLL is 6.8 x 10^{-3} per year, which comes

Table 15. Potential 120-year economic loss for North Lantau Expressway (extracted from OAP 2005)

Type	Scope	Potential economic loss
Damage to vehicles	Economic loss associated with direct damage to vehicle on North Lantau Expressway due to debris impact	US$0.2 million
Air travel passengers delay	Economic loss associated with potential delays to air travel passengers due to temporary closure of the expressway and thereby causing delayed traffic access the Hong Kong International Airport	US$12 million
Air cargo delay	Economic loss associated with potential delay to air cargo due to temporary closure of the expressway and thereby causing delay to good vehicles' access the Hong Kong International Airport	US$42 million



Location	Design requirement for risk mitigation		
	Debris volume (m^3)	Debris velocity (m/s)	Debris height (m)
A	500	13	2.5
B	500	13	2.5
C	1,000	15	3.0
D	1,000	15	3.0
E	1,000	15	3.0
F	1,700	16	3.5

Figure 30. Mitigation strategy (OAP 2005)

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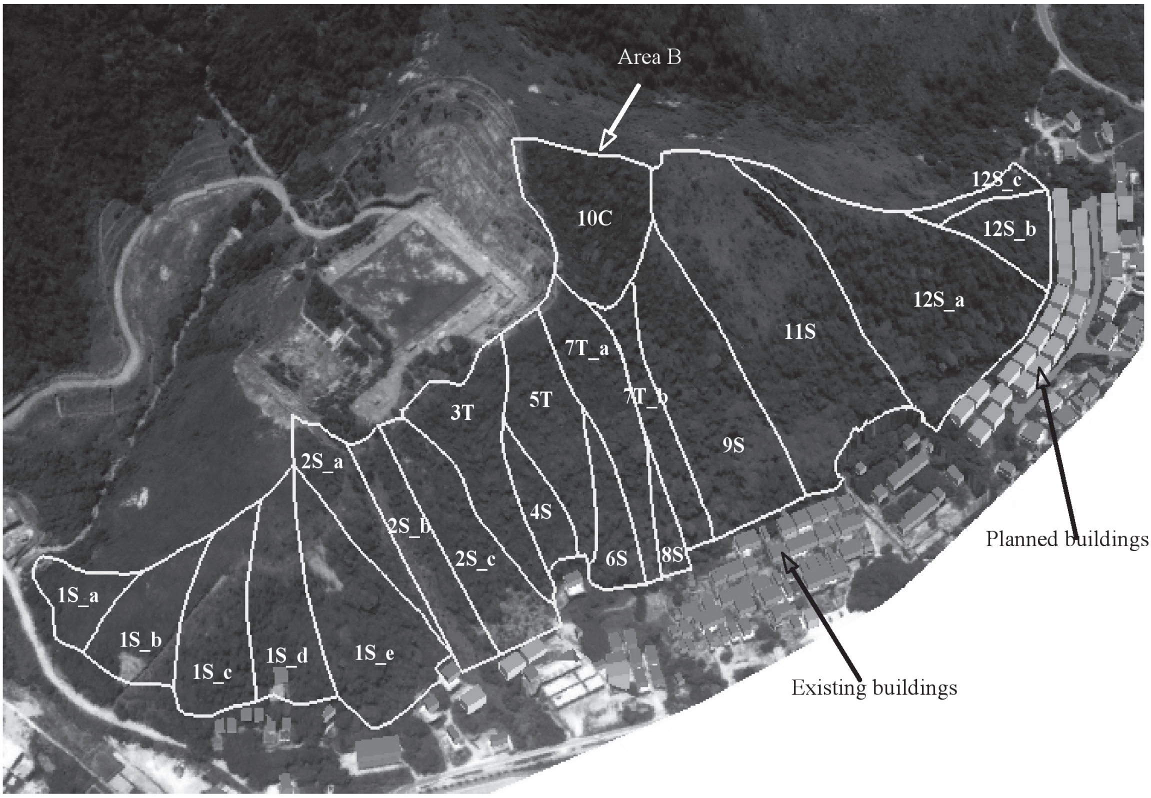

Figure 31. Catchments and sub-catchments in Area B, Ling Pei, Hong Kong (Wong et al. 2004c)

from channelized debris flows. The F-N curves for the eight sections (each 500 m long) of the highway are all within the ALARP region (Figure 29).

(c) While risk-to-life was found to be in the ALARP region, it was perceivable that the potential economic loss arising from landslides could be significant. This was confirmed by quantifying the risk in respect of different types of economic loss (Table 15). The total potential economic loss was found to be about US$ 54 million in 120 years.

The preferred risk mitigation scheme comprised provision of check dam basins at six vulnerable debris flow channels (Figure 30). The cost of the mitigation works was about US$ 3.5 million. Based on the ALARP principle, the maximum justifiable expenditure for mitigating loss of life alone was found to be within US$ 3 million, which was less than the cost of the preferred scheme. However, with account also taken of the significant potential economic loss, risk mitigation was considered justified. This case illustrates that for major highways and infrastructures, economic loss can be substantial and may have significant effects on the risk-cost-benefit analysis.

5.7 *Ling Pei QRA*

In 2004, a land-use concept plan was drafted by the Government of the Hong Kong Special Administrative Region (HKSAR) to guide the development of the Ling Pei area, Tung Chung, Hong Kong. The planned development comprised construction of 76 nos. of 3-storey houses at the toe of the hillside that overlooks the existing village in Ling Pei (Figure 31). Wong et al (2004c) carried out a QRA to quantify and evaluate the risk. The case was a notable development in the application of landslide QRA in Hong Kong in the following respects:

- This is a case that extends the application of formal landslide QRA to land-use and development planning at a specific site in Hong Kong.
- As an attempt to standardize the QRA process and further improve practice of QRA on natural terrain landslides, a recent review on the use of QRA has identified 16 key modules of work, as listed in Table 16. The Ling Pei QRA served as a reference case that was undertaken in alignment with the 16 key modules of work.
- As part of the work, further enhancements of site-specific QRA techniques were made. The enhancements helped to improve the rigor of the assessment and to overcome some known technical problems that have been encountered in previous QRA.

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

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Table 16. Key modules of work in natural terrain landslide QRA (based on Wong 2005)

Module of Work	Scope
(1) Determine study objectives and approach	– Identify the background and purposes of the study, and any special requirements – Determine the objectives and the level of details required – Select the approaches to be adopted
(2) Delineate study area	– Identify the extent of the site that may be at risk from landslide hazards – Set out the extent of the study area
(3) Validate historical landslides	– Collate information on historical landslides based on documentary records, aerial photograph interpretation, and findings from field mapping and geomorphological assessment – Validate the data and compile a dataset of landslides and related attributes
(4) Examine rainfall records and effects	– Collate information on the rainfall history – Examine any relevant rainfall-landslide pattern/correlation – Establish any need to adjust figures on the historical landslide activity to account for rainfall effects
(5) Demarcate boundaries and types of catchments	– Delineate the boundaries of catchments – Sub-divide the catchments where necessary, e.g. based on topographic conditions and mechanism of debris movement – Match the catchments with the facilities at risk
(6) Identify facilities and population at risk, and their degree of proximity	– Identify the types and locations of the facilities at risk – Establish degree of usage and temporal distribution of population at risk – Examine degree of proximity with reference to GEO's screening criteria, empirical models, relevant historical runout data, etc.
(7) Geological assessment	– Carry out field mapping to establish the engineering geological and geomorphological conditions – Examine landslide processes and mechanisms, regolith type and distribution, signs of distress, and other relevant terrain attributes – Classify terrain, and develop geological and landslide process models
(8) Formulate hazard and hazard models	– Identify potential landslide hazards and the relevant hazard scenarios that require risk quantification – Formulate hazard models for use in QRA and in assessment of Design Events
(9) Identify possible debris runout paths and influence zones	– Divide potential landslide sources into cells – Identify possible debris runout paths for each cell – Match the cells with the facilities at risk – Assess the degree of proximity and the degree of damage to the facilities at risk
(10) Carry out frequency assessment	– Formulate frequency model – Establish the frequencies of occurrence of different types of hazard – Assess the spatial distribution of the landslide frequency, together with the use of susceptibility analysis and Bayesian methodology as appropriate – Assess the frequency of occurrence of special hazard scenarios, e.g. building collapse and events with knock-on effects
(11) Carry out consequence assessment	– Formulate consequence model – Assess the consequence of occurrence of different types of hazards – Assess the consequence of occurrence of special hazard scenarios, e.g. building collapse and events with knock-on effects
(12) Analyze risk	– Calculate the risk by integrating frequency and consequence – Evaluate the distribution of risk – Carry out sensitivity analysis and examine the reliability of the findings of the risk assessment
(13) Assess design events	– Assess the magnitudes of Design Events
(14) Evaluate risk management strategy	– Compare risk results with risk criteria – Formulate possible risk management options – Evaluate the pros and cons of different risk management options and identify the preferred risk management strategy – Interact with and obtain feedback from stakeholders
(15) Draw conclusion and recommendation	– Conclude the findings of the study – Recommend risk management strategy and follow-up actions
(16) Document findings	– Document the findings of the study – File the relevant information, data and calculations – Update the relevant documentary and digital records

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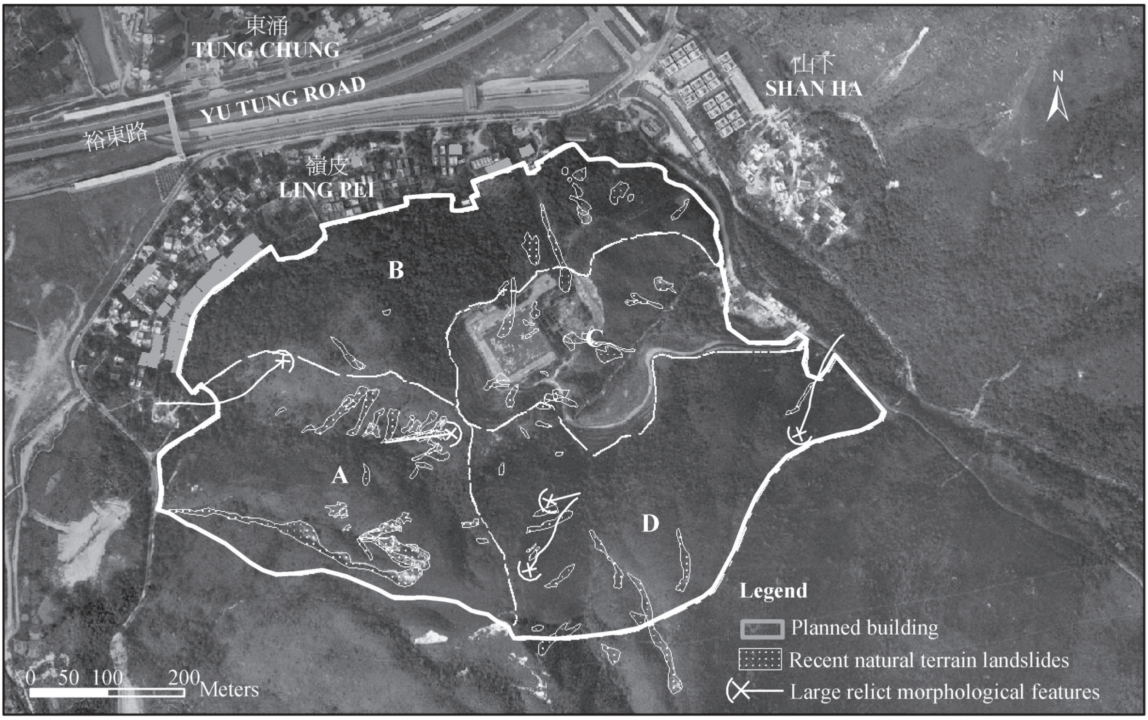

Figure 32. Historical landslides in Ling Pei (Wong et al. 2004c)

(a) Study objectives, approach and area (Module Nos. 1 & 2)
The study served to assess the risk on the planned development and to guide the development strategy. The hillside that overlooked the planned buildings is denoted as Area B in Figure 32. As good practice in site-specific QRA on natural terrain landslides, a larger region was studied for thorough examination of the landslide process and characteristics (Areas A to D, Figure 32).

(b) Landslide history and rainfall effects (Module Nos. 3 & 4)
Historical landslide activities and characteristics in the region were evaluated from an interpretation of aerial photographs, field inspections and geomorphological mapping. A total of 91 recent natural terrain landslides and five large relict landslide-related morphological features were identified (Figure 32). The correlations of natural terrain landslide density with normalized rainfall intensity in Hong Kong established by Ko (2003) and Wong et al (2004c) were applied to the site. The landslide and rainfall histories at the site were found to be broadly consistent with the Hong Kong-wide trend, and the available historical landslide data gave a reasonably conservative base-line landslide density for use in frequency assessment.

(c) Catchment and facility identification (Module Nos. 5 & 6)
The topographic conditions of the hillside was assessed with the use of a 2-m grid digital elevation model (DEM), together with terrain evaluation based on field mapping and interpretation of aerial photographs. This resulted in demarcating the hillside in Area B into a total 21 sub-catchments (Figure 31). The sub-catchments were classified into three types according to the mechanisms of debris movement (Table 17).

(d) Geological assessment and hazard identification (Module Nos. 7 & 8)
The geological assessment comprised geological mapping, investigation and appraisal to establish the landslide processes at the site, examine the landslide mechanisms, classify the terrain, formulate geological models, diagnose possible hazards, etc. The work provided a technical basis for formulating terrain and hazard models.

(e) Debris runout path and influence zone (Module No. 9)
There are two main aspects of evaluation of debris runout for use in consequence assessment. Firstly, the mobility of the landslide debris has to be assessed. In the Ling Pei site, this was done by statistical analysis of the historical runout data. Secondly, the debris runout path has to be predicted. To do so, sub-catchments in Area B were further divided into small hillside units (Figure 33). Each hillside unit should have practically the same landslide susceptibility and debris runout path. Based on 3-D GIS analysis and terrain evaluation, the possible debris paths originating from each hillside unit were determined. Each unit

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Table 17. Hazard classification (Wong et al. 2004c)

Hazard	Classification	Definition
Mechanism of debris movement (which was related to catchment characteristics)	C	Channelized debris flow
	T	Mixed debris flow/avalanche at topographic depression
	S	Open hillslope debris slide/ avalanche
Scale of landslide (which was established from volume-frequency relationships for different classes of catchment)	H1a	30 m^3 notional (20 m^3 to 60 m^3)
	H1b	100 m^3 notional (60 m^3 to 200 m^3)
	H2a	300 m^3 notional (200 m^3 to 600 m^3)
	H2b	1,000 m^3 notional (600 m^3 to 2,000 m^3)

was then matched with the segments of the lower boundary of the catchments, and with the existing and planned houses. A Fault Tree methodology was adopted in the matching to cater for the uncertainties in predicting the debris flow paths.

(f) Frequency assessment (Module No. 10)

This followed standard volume-frequency correlation and spatial distribution of the base-line landslide densities to each hillside unit via susceptibility analysis (Figure 34). In this QRA, different susceptibility models were adopted for different terrain types, to cater for the fact that their landslide processes were different.

(g) Consequence assessment (Module No. 11)

An enhanced consequence model, which incorporated consideration of the hazard type, runout mechanism, runout path, debris mobility and vulnerability formulation, was developed for use in this QRA. Vulnerability factors for the buildings were derived from integrating the probabilistic function of debris runout distance and a model for the degree of damage (Figure 35).

(h) Risk analysis and evaluation (Module Nos. 12 & 13)

The assessments and risk integration were carried out on a GIS platform. The calculated PIR of an individual in the planned buildings ranged from 3.3 x 10^{-7} to 8.9 x 10^{-6} per year (Figure 36), which was within the maximum permissible level of 10^{-5} per year for new developments (ERM 1998). The societal risk for the planned houses was 1.8 x 10^{-4} per year. The corresponding F-N curve (Figure 37) was within the ALARP zone.

The PIR on the existing houses was also assessed and found to be within the maximum permissible level. The societal risk on the existing houses was 4.3 x 10^{-4} per year. Hence, the planned development would result in more than 60% increase in societal risk. The F-N curve of the total societal risk for both the existing and planned houses was within the ALARP zone (Figure 37).

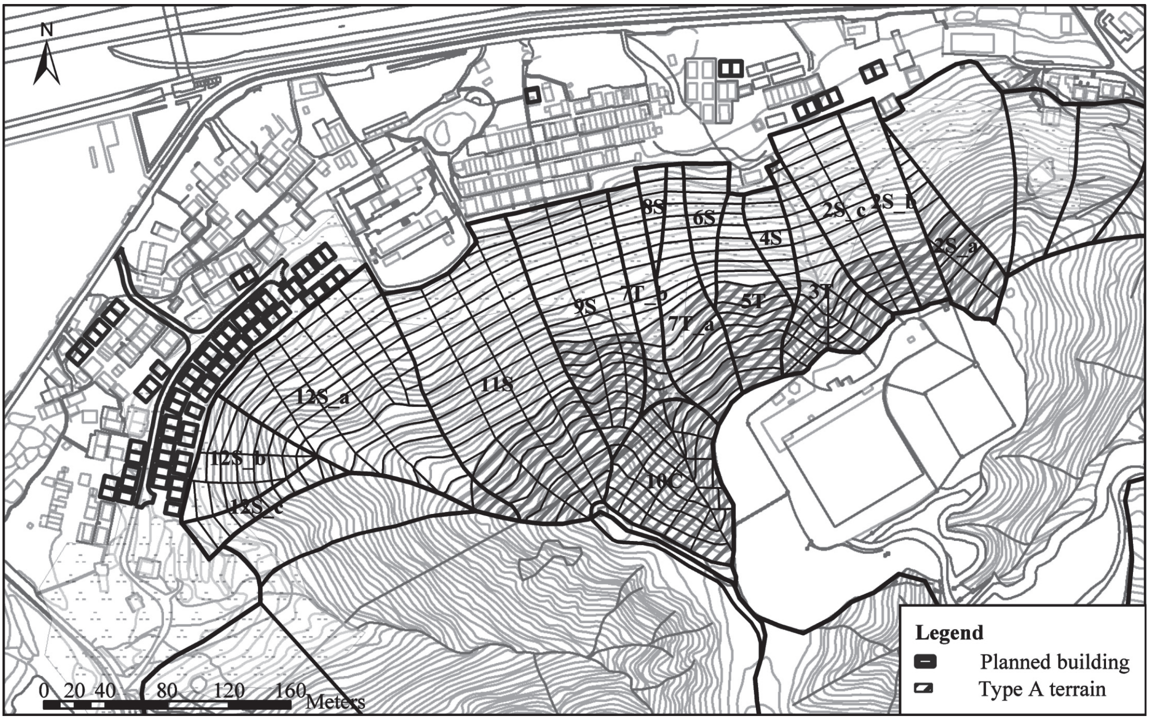

Figure 33. Hillside units (Wong et al. 2004c)

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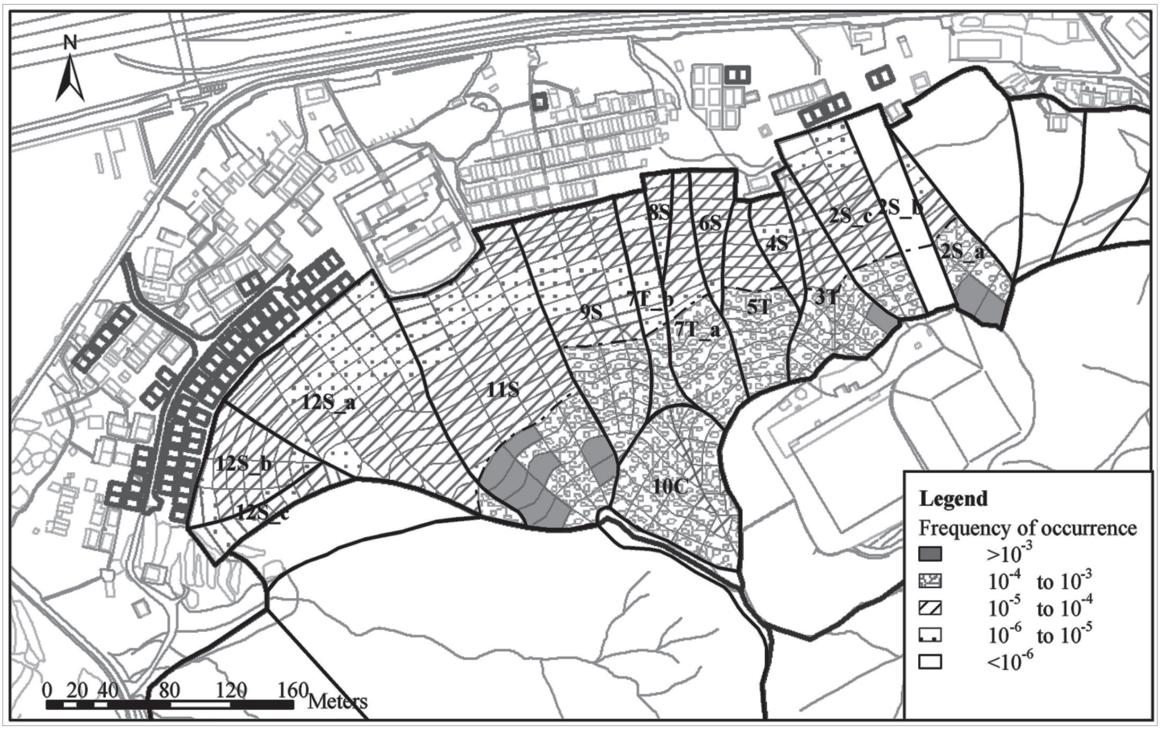
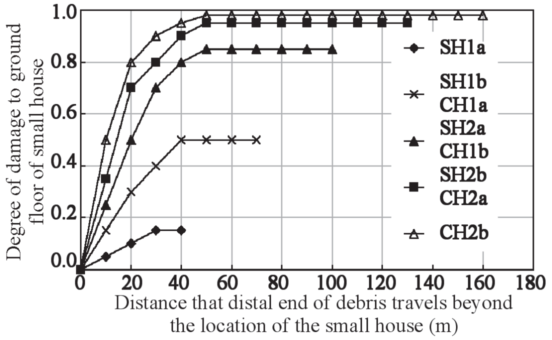


Figure 34. Calculated annual frequency of landslide hazard H1a (20 m^3 to 60 m^3) (Wong et al. 2004c)



Note: SH1a, etc. as defined in Table 17.

Figure 35. Degree of damage to ground floor of building (Wong et al. 2004c)

(i) Risk management strategy (Module No. 13)
The maximum justifiable expenditure calculated from the ALARP principle was found to be about US $ 0.1 million. At this order of maximum expenditure, adopting extensive slope stabilization measures (e.g. soil nailing) and provision of heavy debris-retaining structures would not be practical. Two possible risk mitigation options were evaluated (Figure 38). Both schemes were within the order of the maximum justifiable expenditure. The total cost of the planned houses was assessed to be about US$ 30 million. Hence, provision of the landslide mitigation measures would only amount to about 0.3% of the total cost.

(j) Risk communication and documentation (Module Nos. 14, 15 & 16)
The QRA findings were presented to the stakeholders and the two possible risk mitigation options provide a guide for formulating the development strategy at the site.

5.8 *Commentary on Site-specific QRA*

5.8.1 Application

QRA has been applied to many sites in Hong Kong to quantify and evaluate natural terrain landslide risk. The F-N curves derived from some the sites, which are representative of the Hong Kong conditions, are shown in Figure 39. From the wealth of experience and QRA results available, some observations on the current state of applications can be made:

(a) The QRAs are carried out by geotechnical professionals as an integral part of geotechnical assessment. The geotechnical practitioners have acquired the skills, and input from risk analysts and QRA specialists is generally not required. QRA is becoming part of local professional practice in slope engineering and landslide risk mitigation.

(b) The QRA results have been taken as a sufficiently reliable estimate of the landslide risk, to support risk management decisions to be made at individual sites. This reflects a general recognition among

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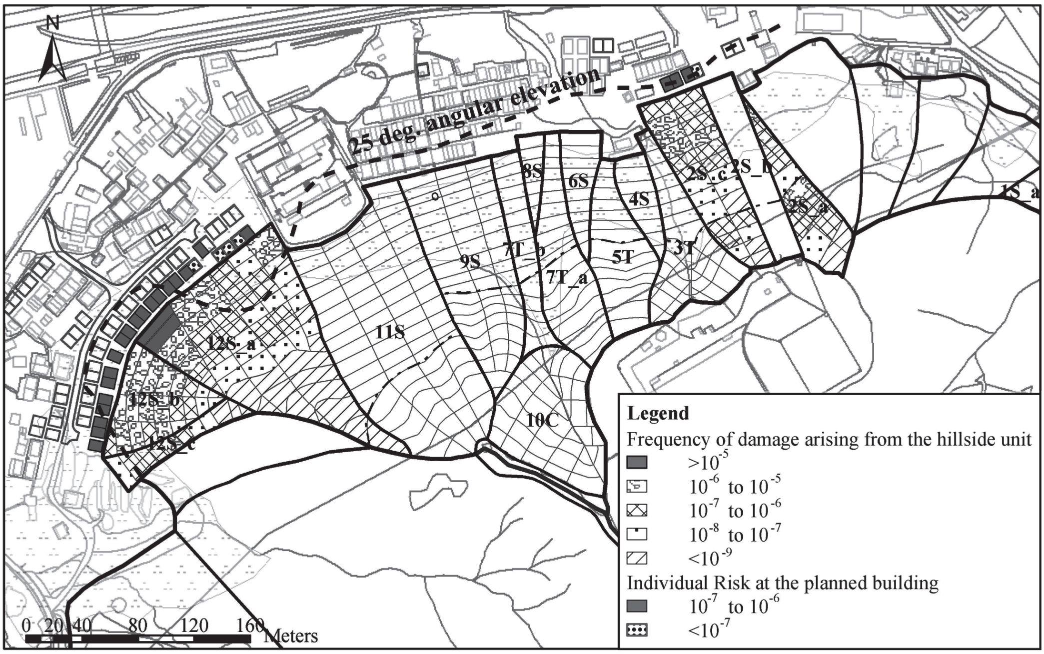
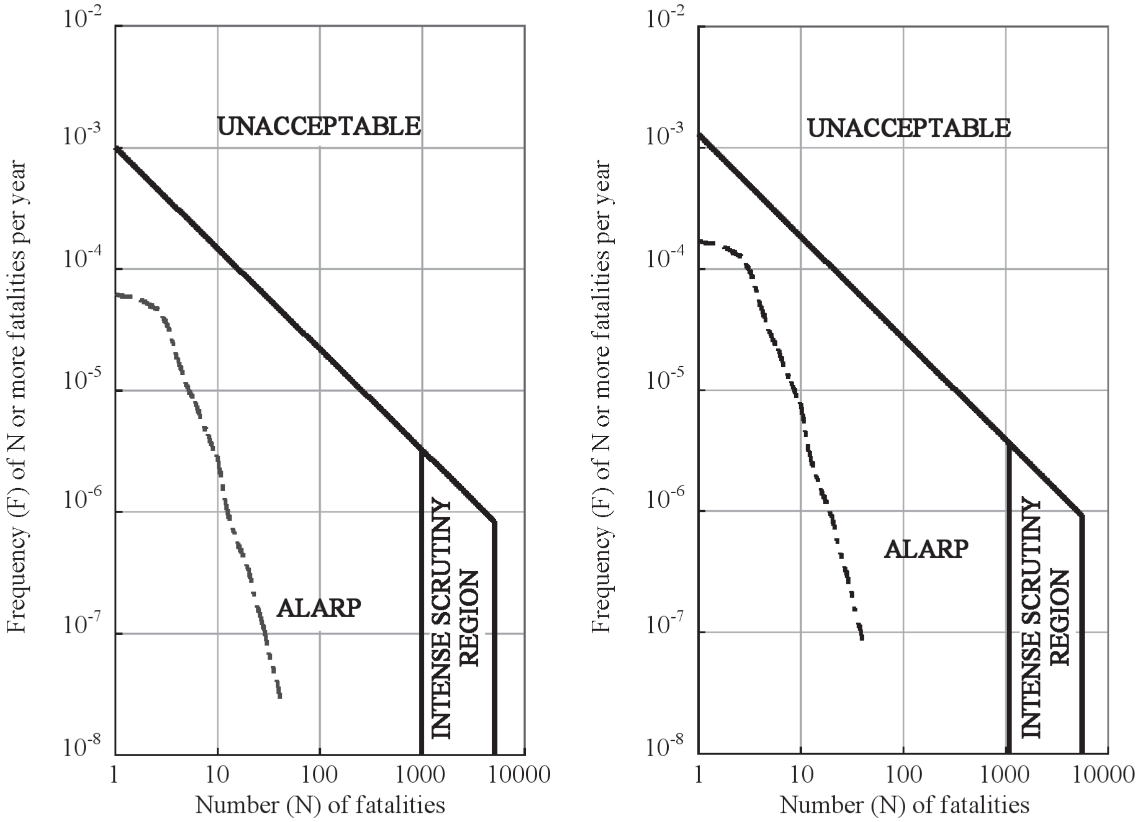


Figure 36. Individual Risk at planned buildings (Wong et al. 2004c)



(a) For planned buildings

(b) For existing and planned buildings
(Note: Risk criteria scaled up according to consultation boundary length = 560 m)

Figure 37. Calculated F-N curves for Ling Pei (Wong et al. 2004c)

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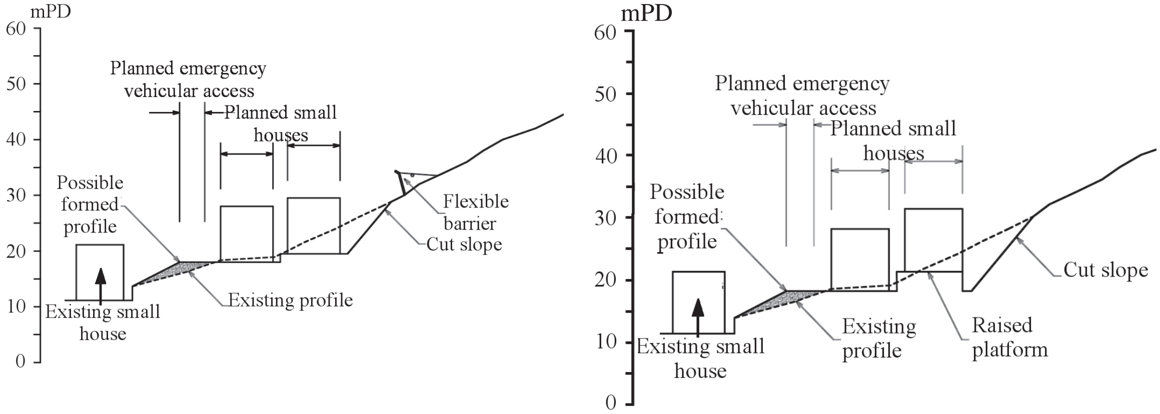
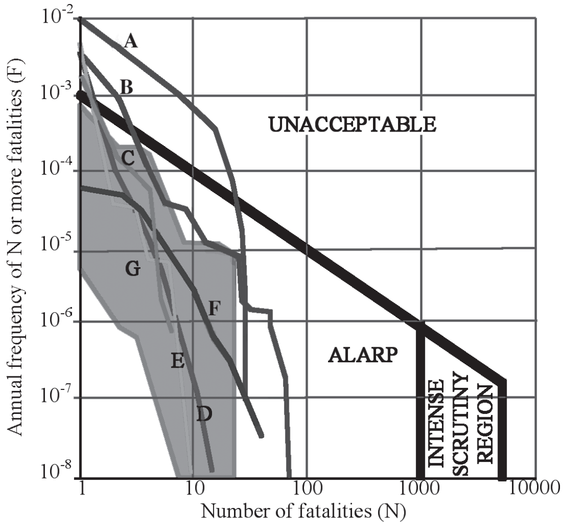


(a) Provision of flexible barriers

(b) Provision of raised building platform

Figure 38. Evaluation of risk mitigation options (Wong et al. 2004c)



Legend:
A - Luk Keng (OAP 2004)
B - Lei Pui (Halcrow 2005)
C - Pat Heung (OAP 2003)
D - Victoria Road (Halcrow 2004)
E - Shatin Heights (FMSW 2001)
F - Ling Pei (Wong et al 2004)
G - North Lantau Expressway (OAP 2005)
(different 500 m sections)

Figure 39. F-N curves of selected natural terrain landslide QRA in Hong Kong

the geotechnical profession that the risk levels assessed by QRA are consistent with professional judgment of the scale of the problem, and that the risk mitigation actions found necessary by QRA are reasonable and practical to implement. This also shows the practicality of use of the risk criteria.

(c) The calculated risk levels for the sites cover a broad range, which spans from the unacceptable zone to well within the ALARP region. Comparison of the site-specific QRA results with those of the global QRA (Section 6.5.1) shows that they are in reasonable agreement. This gives reassurance that the site-specific QRA results are of the right order of magnitude.

(d) Most of the QRA cases were triggered by the 'react-to-known-hazard' principle adopted in Hong Kong for managing natural terrain landslide risk for existing developments. The QRA results reveal that the PIR and the societal risk for these cases fall into the unacceptable zone. Substantial risk mitigation (typically reducing about 80% of the risk) has been found to be justified by the ALARP principle. These cases indicate that the 'react-to-known-hazard' principle has been exercised with consistent professional judgment in identifying sites with a genuine risk concern. Also, QRA can provide an effective and practical means for assessing and managing their natural terrain landslide risk.

(e) QRA has been applied to a lesser number of new development sites affected by natural terrain landslide risk. Some new development sites in Hong Kong are known to be subject to significant natural terrain landslide risk. For these sites, use of QRA should be as effective as the 'react-to-known-hazard' cases. However, many other new development sites may only be marginally affected by natural terrain landslide hazards. The Ling Pei site is an example, with the risk found to be well within the ALARP zone. At Ling Pei, relatively minor risk mitigation provisions were found to be justified from the ALARP consideration. It is not entirely clear as to whether the use of a simplistic risk-cost-benefit evaluation to formulate the risk mitigation strategy is defensible and prudent in such cases, where the calculated risk-to-life is

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low. The North Lantau Expressway QRA has demonstrated that for strategic roads and major infrastructures, the requirements for risk mitigation may be governed by socio-economic factors.

(f) A number of factors have been essential to the progress made in natural terrain landslide QRA in Hong Kong. These include:

- The public's high expectation of slope safety and the landslide-prone setting of Hong Kong call for vigilant risk management in order to meet the public’s expectation.
- Good quality data are more readily available, in particular historical landslide data and other geotechnical and geological information that are required for use in QRA.
- QRA has already been formally used in assessing and managing the risk of Potentially Hazardous Installations.
- Guidelines on natural terrain landslide risk tolerability criteria have been formulated.
- Other approaches cannot deal with the natural terrain landslide problems more effectively.
- Continued development and enhancement of techniques during QRA applications.

(g) Despite the significant progress in using QRA to deal with natural terrain landslide problems, there have only been limited site-specific QRA applications to man-made slopes in Hong Kong. The availability of other established and effective approaches (factor of safety approach and other qualitative methodologies) is a key factor. The lack of agreed risk criteria for landslide risk from man-made slopes is also relevant.

(h) There is less experience in quantification of the potential landslide socio-economic loss. The techniques are not very well developed.

5.8.2 Practice

The distinct advantages of QRA over qualitative assessment rest on the ability to quantify risk instead of analyzing risk in relative terms, and on the explicit consideration of risk tolerability and the ALARP principle to provide a rational basis for evaluating the risk mitigation strategy. To realize the full benefits, the following two fundamental conditions must be fulfilled:

(1) The relevant quantified risk criteria must be available (and endorsed for use in QRA). Otherwise, a common basis for risk evaluation is lacking. Hence, for places without any agreed risk criteria, or where there is strong objection to using quantified risk criteria, QRA application would be significantly constrained.

(2) The quantified risk levels must be sufficiently reliable. The quantified risk levels should never be taken as precise numbers. However, the figures should at least be adequately representative to ensure that their use in risk evaluation and formulation of risk mitigation strategy is meaningful and would not be misleading. Sensitivity analysis would help to assess the reliability of the risk results. Achievement of reasonable accuracy is critically dependent on the availability of reliable data to support the required risk quantification work and on the use of rigorous risk assessment methods. While the rigor of the risk analysis is typically a matter methodology and skill, lack of data is critical and difficult to overcome.

Detailed discussions about each of the key components of QRA are given in the relevant SOA. Experience gained from QRA applications reveals some noteworthy developments:

(a) Hazard identification

Hazard identification may be regarded as the most important component of landslide QRA. It is not only concerned with classifying the hazards for risk quantification, but also a thorough assessment of the available data and site conditions, landslide processes and mechanisms, and potential hazards. Such work is not new to the geotechnical profession. It has long been undertaken in geotechnical assessments, although in the past, the assessments would not normally proceed as far as risk quantification. Integration of the good practice in geotechnical assessments with QRA, particularly in hazard identification, is essential to the success of a QRA. However, if the landslide process and the nature of the potential hazards are not understood, there is little hope that their risk can be reliably quantified.

In Hong Kong, progress has been made in recent years in improving geotechnical assessment techniques for use in QRA. Examples include landslide investigations, regolith and process-based geomorphological mapping (GEO 2004), age-dating of landslide and debris (Sewell & Campbell 2004), rainfall-landslide correlations (Ko 2003), and applications of remote sensing and GIS technology (Wong et al. 2004a).

(b) Frequency assessment

Use of historical landslide data, if available, in frequency assessment is the most common and probably most reliable. However, properly assessing landslide frequency would often require attention to the following area:

- Consideration should be given as to whether the historical landslide data are complete and sufficiently representative for use in frequency assessment. In a more detailed QRA, addressing this issue could involve assessing the extent of depletion at the potential landslide sources, rainfall history and historical landslide activity, effects of ‘recognition factors’, etc.
- Where the site that is being assessed is relatively small in size, it may have to study a larger area with a similar geological setting in the geotechnical

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assessment. This would provide more data for statistical analysis and for assessment of the relevant landslide processes and mechanisms.

- Where only limited or incomplete historical data are available, use of other methods (e.g. probabilistic analysis and expert judgment) becomes more important. However, their reliability should be considered.
- The potential hazards should be properly classified, typically based on the scale and mechanisms of failure. It should avoid lumping frequency data of different types of hazard, which would adversely affect the resolution and accuracy of the frequency assessment. Proper classification also supports a more refined consequence assessment.
- Spatially apportioning the base-line frequency to different parts of the slope/hillside would often involve the use of susceptibility analysis. It is preferable to perform the susceptibility analysis using site-specific data, instead of adopting general susceptibility correlations that may be of limited direct relevance to the site. In addition, use of Bayesian methodology may help to give a balanced consideration of the theoretical susceptibility correlation and historical slope performance.
- The base-line landslide frequency is often spatially distributed before applying the volume-frequency relationship. This simplifies the frequency assessment, but the rationale may be questionable. There are technical merits in applying the volume-frequency split first, followed by spatial distribution of landslides of different volumes. However, this would require separate susceptibility analyses be carried out for landslides of different volumes, which may not be practical for sites with few data available.
- Frequency assessment for low-frequency large magnitude events is more difficult. Use of expert judgment based on findings from geotechnical assessment of the relevant relict events, geomorphology, rainfall-landslide correlation and worst credible failure volume, is a possible approach. Benchmarking with regional data and results of modeling may provide useful information.

(c) Consequence assessment

Models for consequence assessment are available. These models typically follow a standard framework, which includes consideration of the proximity of the element at risk, the average number of vulnerable people, their temporal distribution and vulnerability factors. Experience in formulating and applying consequence models suggests the need to give heed to following:

- Landslides with different mechanisms and scales would affect an element at risk to differing degrees, and should be analyzed separately in consequence assessment. The methodology adopted in consequence assessment should duly cater for the effects of landslide mechanism and scale, and particularly on the average number of people at risk and the vulnerability factors adopted in the assessment.
- Sub-dividing the potential landslide sources into small units is preferable. Previously, the sub-division was primarily aimed at improving the frequency assessment by separating the slope or hillside into cells according to their landslide susceptibility. More recently, the sub-division is also aimed at a more rational consequence assessment, particularly in respect of the debris runout path and influence zone. This may necessitate the use of irregular cells, instead of grid cells with a standard size. It would also require that the consequence model be set up as early as the frequency assessment stage, to ensure that the sub-division would produce cells that meet the requirements of both the frequency and consequence assessments.
- Consideration of debris mobility is a key component of consequence assessment. However, attention should be given not only to assessing the runout distance, but also the potential runout paths. The latter was often not very well addressed in many landslide QRA, and this could lead to gross mistakes. Predicting the potential debris runout paths requires reliable topographic information (e.g. a high resolution DEM), which may be difficult to obtain. For instance, presence of thick vegetation may hinder detailed topographic survey and terrain mapping. The available topographic maps may not be entirely reliable and sufficiently accurate. Remote-sensing technology, in particular multi-return air-borne Light Detection and Ranging (LIDAR), has shown promising results in producing high resolution DEMs that can 'see through' vegetation (e.g. NRC 2004).

Figure 40. The Tsing Shan debris flow in 2000

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- In addition, landslide debris would not always travel downslope along the steepest path. Other factors, such as the orientation of the sliding surface at the landslide source, momentum of fast-moving debris, presence of drainage channels and building platforms, etc, would affect the debris runout path. The example of a bifurcated debris flow in Figure 40 illustrates the uncertainties in predicting the debris runout path. Event-tree analysis has been adopted, together with a cell-facility matching procedure, as a tool in consequence assessment to cater for such uncertainties.
- The assessment of the width of a landslide and its effects on the average number of people at risk, vulnerability factors, etc. is coarse in many of the existing consequence models. Further work is required to improve the assessment and its integration with the consequence model.
- Less experience is available in quantification of the consequence of building collapse and socio-economic loss. This is an area where input from specialists in the relevant field would be useful.

(d) Risk calculation and evaluation

Risk calculation in QRA is relatively straightforward. Integration of QRA with GIS techniques, which significantly enhances the capability and efficiency of analysis of spatial data in QRA, is the trend.

Sensitivity analysis has been carried out in many QRAs to examine the effects of the assumptions made and uncertainties involved on the calculated risk results. There is scope for further improving the practice in that many of the sensitive analyses that have been carried out only cover selected aspects of the QRA, and not a complete assessment of the likely order of accuracy of the calculated risk figures.

Furthermore, no provisions are available in the existing risk criteria for formally addressing uncertainties in QRA. The current practice of not using the calculated risk figures and risk criteria in absolute terms is a preferred approach (IUGS 1997). QRA is only one input to the risk management process. Apart from the uncertainties in the risk quantification, other socio-economic and political factors can play a key role in making risk decisions. The practicality and credibility of the use of risk criteria are to be tested with time. There is no established practice in evaluating economic loss, which requires further attention to ensure that the full range of risk is adequately addressed by QRA.

6 GLOBAL QUANTITATIVE RISK ASSESSMENT (QRA)

6.1 *Overview*

The advantages of QRA are evident when it is used to guide risk management decisions at individual sites. However, QRA is not confined to site-specific applications. QRA can be applied to a large group of slopes for quantifying and evaluating the overall risk. This is referred to as 'global' QRA (Wong et al. 1997, Wong & Ho 2000, Ho et al. 2000). It typically serves to examine the overall scale of a problem and to identify the relative contributions from different components.

Global QRA has been used fairly extensively in Hong Kong, and has proven to be crucial to landslide risk management, particularly in formulating risk management strategy. However, it has not been as popular elsewhere, where landslide-related issues are conventionally addressed by qualitative means.

Global QRA differs from site-specific QRA in a number of aspects:

(a) Unlike site-specific QRA, global QRA is not aimed at quantifying the risk on individual site basis, nor evaluating site-specific risk management actions. Global QRA quantifies risk for the purposes of formulating risk management strategy and identifying risk-based actions that affect a large number of sites. Site-specific QRA is of interest to designers and slope owners. Global QRA, if carried out properly, would provide quantified risk results that are of interest to policy makers and organizations tasked with an overall landslide risk management mission. However, site-specific QRA and global QRA are not entirely independent of one another. They often provide a benchmark for calibrating each other's results.

(b) As a large number of slopes are assessed in a global QRA, carrying out detailed investigations and geotechnical appraisals at each slope in the QRA is normally not practical. This limits the types and quality of data that may be used in global QRA. Hence, simplified frequency and consequence models, which are less data-demanding, are typically adopted in global QRA.

(c) Use of simplified models and less detailed data would not necessarily degrade the reliability and useful functions of global QRA. As global QRA is intended for quantifying and evaluating overall risk, the QRA results are less sensitive to the models, data and assumptions adopted, as compared with site-specific QRA.

Several applications of global QRA are described in the following Sections to illustrate how it has contributed to strategic landslide risk management.

6.2 *Assessment and Application of Quantified Overall Landslide Risk*

6.2.1 Background

As noted in Section 3.3.1 above, the mid 1990s was a time of major development of landslide risk management in Hong Kong. After many years of investment in retrofitting sub-standard slopes, there

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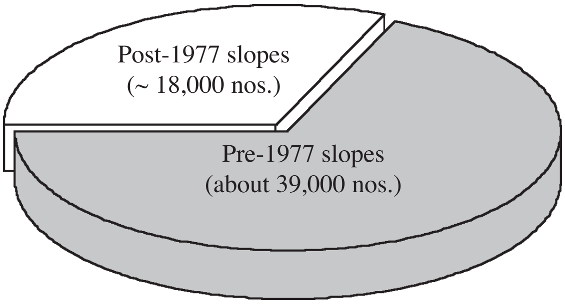

Figure 41. Catalogue of Slopes comprising 57,000 nos. sizeable man-made slopes in Hong Kong

was a need to consolidate the practice and review progress. The compilation of a new and comprehensive Catalogue of Slopes, with the number of identified old, un-engineered man-made slopes increasing from about 12,000 to over 35,000 (subsequently known to be 39,000, Figure 41), showed that potential landslide problems could be of a much larger scale than previously envisaged. Also, an increasing slope safety expectation among the public was evident from the strong public reaction to the fatal landslides that occurred in the early 1990s. Improved awareness and capability in risk assessment also brought about an impetus to use formal risk assessment in landslide risk management. In this context, and as a pioneer application at the time, QRA was formally adopted in a global framework to quantify the overall risk of the old, un-engineered man-made slopes in Hong Kong. The work was described in Wong et al (1997) and Wong & Ho (1998).

6.2.2 Methodology of the global QRA

The hazard model (Figure 42) adopted reflected the different types of hazard assessed in the QRA. The frequency of occurrence of each type of hazard was calculated from a detailed analysis of the historical landslide data collected systematically in Hong Kong since 1985. The analysis included matching the landslides with the slopes, evaluating the base-line frequency for each category and spatially distributing the frequency to each slope via a frequency model. The large body of information on over 5,000 landslides in Hong Kong was essential to the use of this approach.

A generalized consequence model was developed and this was described in Wong et al (1997). The consequence model included consideration of the categorization of the facility at risk (Table 4), the expected number of fatalities for each category of facility, size of failure, landslide mechanism, proximity of the facility, vulnerability factor and any aversion effects due to multiple fatalities. The consequence in terms of PLL was evaluated for each type of hazard on each slope. The relevant slope attributes and data on the facilities were obtained from the Catalogue of Slope.

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 – 1,000 m^3 – 1,000 – 10,000 m^3 – >10,000 m^3
Facility affected	– Consequence model

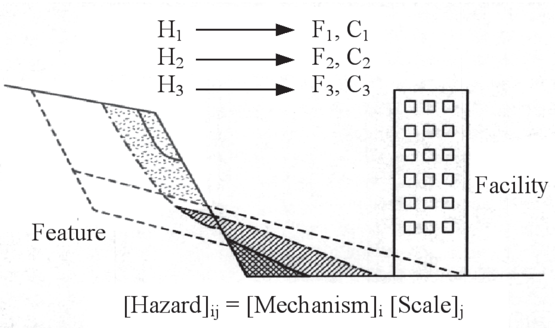

Figure 42. Hazard and frequency model (Wong et al. 1997)

6.2.3 Findings and application of the global QRA

The global QRA assessed a total of 35,000 un-engineered man-made slopes that were registered in the Catalogue of Slopes at the time. The calculated PLL figures for different classes of slope are shown in Table 18. The total PLL of the slopes (as at 1997) was estimated to be about 11 per year. By projection, it was estimated that the risk of all un-engineered (i.e. pre-1977) slopes should have been over 20 per year as at 1977.

Apart from giving an estimate of the over risk level, the global QRA also provided invaluable information on the risk distribution and characteristics. Examples of applying the information to formulating the risk management strategy for the LPM Programme include:

(a) Application of the calculated risk distribution to priority ranking – The global distribution of the quantified risk from cut slopes, fill slopes and retaining walls is in the ratio of 6:1:1 (Table 19). In terms of average risk per slope feature, the corresponding ratios were about 3:1:1. Experience from the LPM Programme suggested that the stabilization costs of a cut slope, fill slope and

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Table 18. Results of global QRA of unengineered man-made slopes in Hong Kong (Wong & Ho 1998)
(a) PLL for cut slopes (per year)

Group no.		1	1	2	2	3	4	5	Building collapse	Total
Type of facility		Buildings	Roads	Buildings	Roads	Roads & open space	Roads & open space	Roads & open space		
Slope height	< 10 m	1.53	0.43	0.51	1.07	0.86	0.215	4.66×10^{-3}	0	4.62
	10 – 20 m	0.61	0.23	0.20	0.58	0.46	0.111	2.36×10^{-3}	0	2.20
	> 20 m	0.26	0.20	8.60×10^{-2}	0.49	0.39	6.88×10^{-2}	1.15×10^{-3}	0.171	1.67
	Total	2.40	0.86	0.80	2.14	1.72	0.395	8.17×10^{-3}	0.171	8.49

(b) PLL for fill slopes (per year)

Group no.		1	1	2	2	3	4	5	Total
Type of facility		Buildings	Roads	Buildings	Roads	Roads & open space	Roads & open space	Roads & open space	
Slope height	< 10 m	0.14	0.05	0.05	0.13	0.10	1.81×10^{-2}	3.03×10^{-4}	0.49
	10 – 20 m	0.12	0.03	0.04	0.07	0.06	1.00×10^{-2}	1.71×10^{-4}	0.32
	> 20 m	0.31	2.38×10^{-2}	1.03×10^{-1}	5.95×10^{-2}	4.76×10^{-2}	9.00×10^{-3}	1.61×10^{-4}	0.55
	Total	0.57	0.10	0.19	0.26	0.21	3.71×10^{-2}	6.35×10^{-4}	1.36

(c) PLL for retaining walls (per year)

Group no.		1	1	2	2	3	4	5	Total
Type of facility		Buildings	Roads	Buildings	Roads	Roads & open space	Roads & open space	Roads & open space	
Wall height	≤ 5 m	3.76×10^{-1}	2.21×10^{-2}	1.25×10^{-1}	5.53×10^{-2}	4.42×10^{-2}	7.31×10^{-3}	1.15×10^{-4}	0.63
	> 5 m	4.44×10^{-1}	6.32×10^{-3}	1.48×10^{-1}	1.58×10^{-2}	1.26×10^{-2}	1.93×10^{-3}	2.74×10^{-5}	0.63
	Total	8.20×10^{-1}	2.84×10^{-2}	2.73×10^{-1}	7.11×10^{-2}	5.69×10^{-2}	9.24×10^{-3}	1.42×10^{-4}	1.26

retaining wall were comparable. Hence, the ratio of risk per feature reflected the relative proportions of different slope types to be retro-fitted under the LPM Programme, as an optimal risk-cost-benefit strategy for effective reduction of the landslide risks associated with different slope types. This has formed the basis for allocation of retro-fitting resources to different slope types under the LPM Programme since the mid 1990s.

(b) Application of the calculated risk profile to formulating quantified risk reduction targets – The risk profile in Figure 43 shows the overall risk distribution among slopes in different groups, based on the categorization of the facilities at risk. About half of the overall risk came from approximately 10% of the slope population that had the highest potential risk. This indicated that upgrading of a relatively small proportion of the

Table 19. Risk distribution according to type of slope (Wong & Ho 1998)

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

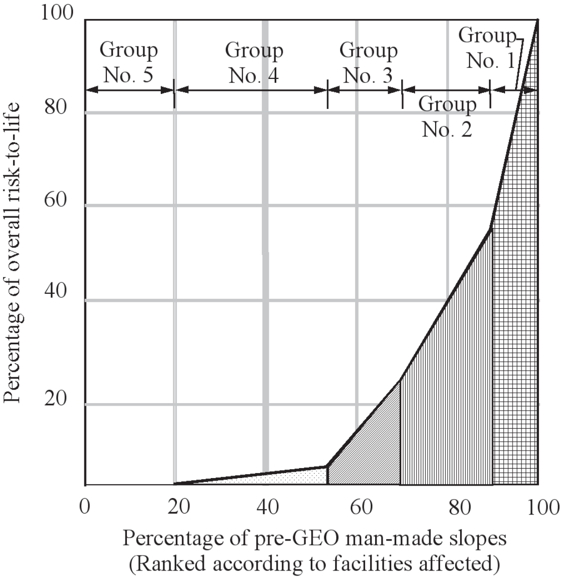

Figure 43. Risk profile of un-engineered man-made slopes in Hong Kong in 1997 (Wong & Ho 1998)

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old slopes that posed the highest potential risk would result in a major global risk reduction. This risk reduction ratio (i.e. reduction of 50% risk by retro-fitting the worst 10% slopes) reflected the likely order of the beneficial return of the retrofitting programme, which could be achieved by implementing a risk-based slope rating system. This has been formally adopted as quantified risk reduction targets pledged by the HKSAR Government. The LPM Programme was tasked to upgrade about 10% of the pre-1977 slopes by year 2000, and another 10% by 2010. The pledged risk reduction targets entailed: (a) by the year 2000, the overall landslide risk from the pre-1977 man-made slopes would be reduced to 50% of the level in 1977; and (b) by 2010, the risk would be further reduced to 25% of the level in 1977 (Works Bureau 1998).

(c) Application to cost-benefit evaluation and risk communication – Using the global QRA methodology, the overall theoretical annual fatalities can be predicted with some confidence to determine longer-term trends and project future performance, as well as to quantify the effectiveness of the risk mitigating actions over time. Cost-benefit calculations were performed to evaluate the investment made relative to the projected number of lives saved as a result of the efforts of the LPM Programme. It was found that for the 10-year period from 2000 to 2010, the LPM Programme would be operating at about US$ 2 million per statistical life saved. This figure was within the limit of maximum justifiable expenditure as derived from the ALARP principle using the risk guidelines (ERM 1998). There has been strong and unanimous public opinion that the GEO should implement the 2000 to 2010 LPM Programme. Hence, the findings of the global QRA provided a means of quantifying and benchmarking the expectation of the public in terms of landslide risk tolerability and ALARP deliberation.

6.3 *Evaluation of Risk Mitigation Performance*

6.3.1 Performance from 1977 to 2000

The global QRA described in Section 6.2 above was updated in year 2000. The update was aimed at assessing whether the pledged 50% landslide risk reduction target from 1977 to 2000 was achieved by the LPM Programme. The methodology adopted in the update followed that of Wong & Ho (1998), and the findings were presented in Cheung & Shiu (2000).

In this update, the overall landslide risk of all registered pre-1977 slopes in 2000 was quantified. This included the risk of the remaining pre-1977 slopes that had not yet been upgraded by 2000 and the residual risk of the pre-1977 slopes that had been upgraded by 2000. The total PLL in 2000 of all pre-1977 slopes was found to be 10.3 per year. The PLL of all the pre-1977 man-made slopes as at 1977 was back-analyzed, and was assessed to be 21.8 per year. These indicated that the risk reduction from 1977 to 2000 as a result of the LPM Programme was 53% (Table 20), which met the pledged risk reduction target.

Table 20. Landslide risk reduction from 1977 to 2000 by the LPM Programme (Cheung & Shiu 2000)

Slope type	Landslide risk (PLL per year)		
	As at 1977	As at 2002	Risk reduction from 1997 to 2000
Soil cut slopes	18.52	8.51	10.01 (55%)
Rock cut slopes	1.18	0.74	0.44 (37%)
Retaining walls	0.62	0.41	0.21 (34%)
Fill slopes	1.51	0.61	0.90 (60%)
Total	21.8	10.3	11.5 (53%)

6.3.2 Performance from 2000 to 2004

The 10-year LPM Programme from 2000 to 2010 is currently in progress. A global QRA was completed in 2004 by the GEO as an interim review of the progress made in the overall landslide risk reduction.

The methodology adopted in the previous global QRA was adopted, with enhancement made in expressing the landslide frequency in terms of the number of landslides per year per unit slope area, instead of the number of landslides per year per slope. This refinement improved the reliability of applying the frequency model to slopes of different sizes. In addition, systematic landslide investigations carried out by the GEO on failures of engineered slopes provided improved data for estimating the landslide frequencies of different types of engineered slopes (Wong & Ho 2000). This improved the assessment of the residual risk of engineered slopes, i.e. slopes formed or upgraded to the required geotechnical standards after 1977.

The QRA findings are presented in Lo & Cheung (2004). It was found that by 2010, the risk of all the pre-1977 registered man-made slopes, based on a projection from the progress made in the current LPM Programme, would be reduced to about 25% of the risk in 2000 (Figure 44). This indicated that the pledged risk reduction for the 2000 to 2010 LPM Programme was achievable, and that the LPM Programme was making satisfactory progress towards achieving this target.

The overall risk level of all of the 57,000 registered man-made slopes in 2010, including pre- and post-1977 slopes, was also assessed in this global

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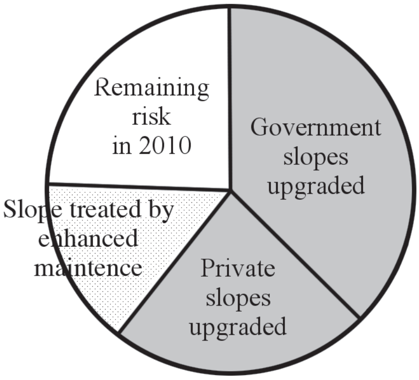
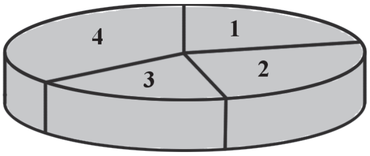
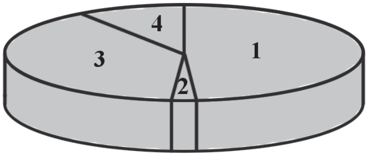


Note: Remaining risk of un-engineered slopes in 2010 is about 25% of the risk in 2000

Figure 44. Reduction of risk of un-engineered man-made slopes from 2000 to 2010 (based on Lo & Cheung 2004)



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



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

Legend:
1 =Un-engineered slopes affecting Groups No. 2(b) & 3 facilities and unplanned structures
2 =Un-engineered slopes affecting Groups No. 4 & 5 facilities
3 =Engineered slopes treated by old technology (see Note (4) of Table 25)
4 =Engineered slopes treated by robust technology (see Note (4) of Table 25)

Figure 45. Breakdown of risk of 57,000 man-made slopes in the Catalogue of Slopes by 2010 (based on Lo & Cheung 2004)

QRA. The risk was found to be about 5 PLL per year. The numbers and risks of different classes of slope are shown in Figure 45.

6.4 *Development of Risk Management Strategy*

6.4.1 Global risk from natural terrain landslides

Hong Kong has about 650 km^2 area of natural hillsides that have not been significantly modified by man-made activities. The natural hillsides were not registered in the Catalogue of Slopes, but they posed a landslide risk to the community. Previously, the landslide risk in Hong Kong was predominantly associated with the large stock of un-engineered man-made slopes that existed within the developed areas. Following years of landslide risk reduction efforts, landslide risk from the un-engineered man-made slopes is reducing. This highlights the need to assess the risk of other types of landslide hazards, in particular natural terrain landslides, for formulating the post-2010 risk management strategy.

Wong et al (2004b) completed a global QRA of the overall risk of natural terrain landslides in Hong Kong. The key components of the global QRA are described below to illustrate the work involved in a task of this kind:

(a) Review of natural terrain landslides and data compilation and analysis – An inventory of over 30,000 natural terrain landslides (Figure 46) from interpretation of historical aerial photographs was compiled (King 1999). Rainfall-natural terrain landslide correlation was established by Ko (2003) and Wong et al (2004c) from spatial analysis of the 5-minute rainfall data available since 1985 (Figure 47). Susceptibility analysis was carried out (Evans & King 1998) to establish the base-line landslide density for terrains with different characteristics.

(b) Identification of vulnerable catchments – While many of the natural hillsides adjoin developed areas, not all of them would pose a significant risk. As part of the global QRA, a search of vulnerable catchments was carried out. This included identification of the following two types of catchments:

– Historical landslide catchments – these refer to catchments with known historical natural terrain landslides occurring close to existing important facilities, including buildings, major roads and mass transportation facilities. With the use of GIS spatial analysis supplementary by field validation, a total of 453 historical landslide catchments were identified. These 453 catchments had a total area of about 5 km^2, i.e. within about 1% of the natural terrain in Hong Kong.

– Supplementary catchments – these refer to catchments without any known historical natural terrain landslides occurring close to existing important facilities (Figure 48). It was estimated that more than 10,000 of such catchments are present in Hong Kong, bordering the development boundaries. It was not practical to record and evaluate all these catchments in the global QRA. Hence, only samples of supplementary catchments were recorded and analyzed in the QRA. A total of 1,018 supplementary catchments (about 23 km^2) in five selected regions were compiled. In addition, 43 catchments (about 1.5 km^2) in six selected

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areas, where site-specific natural terrain landslide QRA had been carried out, were also registered for benchmarking purposes.

(c) Hazard identification – A total of 12 types of hazard were analyzed in the QRA, based on a combination of the scale of failure and mechanism of debris movement (Table 21). Four rainfall scenarios, with normalized maximum rolling 24-hour rainfall up to 35%, were explicitly considered in the analysis (Table 22).

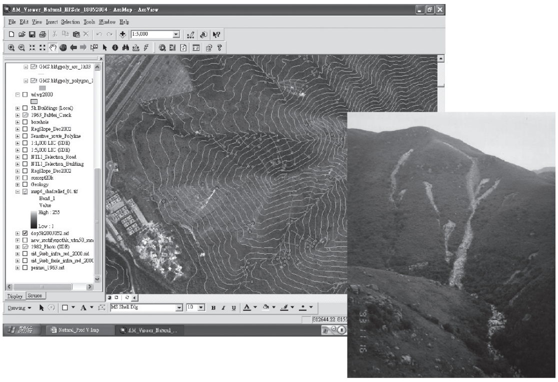

Figure 46. Natural terrain landslide inventory, Hong Kong (comprising over 30,000 historical natural terrain landslides)

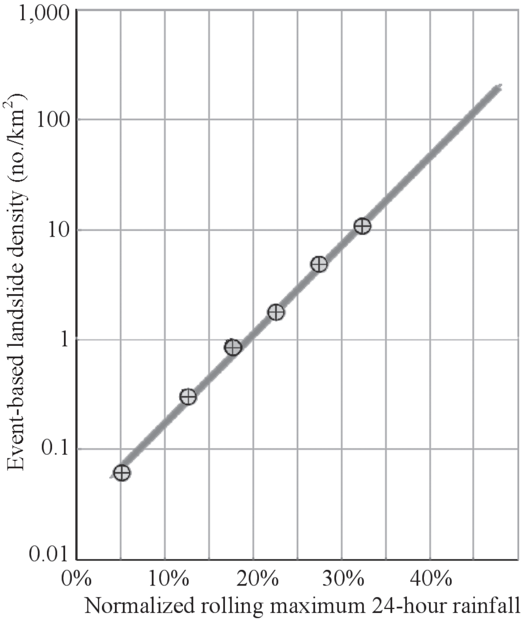

Figure 47. Rainfall-natural terrain landslide correlation (based on Ko 2003, Wong et al. 2004b)

Figure 48. GIS inventory of (a) historical landslide catchments and (b) supplementary catchments

Table 21. Hazard classification (Wong et al. 2004b)

Hazard combination	Classification	Definition
Mechanism of debris movement (which was related with catchment characteristics)	C	Channelized debris flow
	T	Mixed debris flow/avalanche at topographic depression
	S	Open hillslope debris slide/avalanche
Scale of landslide (which was established from volume-frequency relationships for different classes of catchment)	H1	50 m^3 notional (20 m^3 to 200 m^3)
	H2	500 m^3 notional (200 m^3 to 2,000 m^3)
	H3	5,000 m^3 notional (2,000 m^3 to 20,000 m^3)
	H4	20,000+ m^3 notional (>20,000 m^3)

Table 22. Rainfall scenario (Wong et al. 2004b)

Rainfall scenario	Normalized maximum rolling 24-hour rainfall	Landslide density (no./km²)	Annual frequency of occurrence
A	≤10%	0.0593	0.8130
B	>10 – 20 %	0.4387	0.4785
C	>20 – 30 %	2.3354	0.0608
D	>30 – 35 %	10.6811	0.0035

Note: An extreme Rainfall Scenario E, with normalized 24-hour rainfall >35% at 500-year return period, was assessed by extrapolation of the QRA results.

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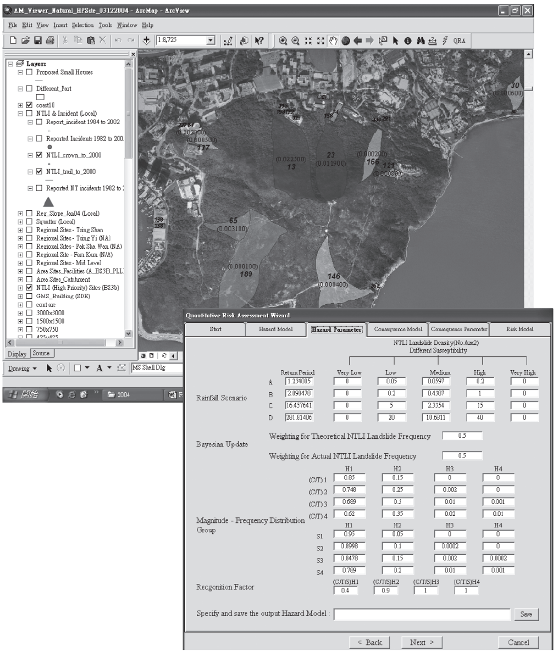
In view of the significant uncertainties involved and the lack of reference data, the risk arising from extreme rainfall events with normalized rainfall exceeding 35% was assessed separately by extrapolation of the QRA results.

(d) Risk assessment - The frequency model and consequence model adopted, which were enhanced from the previously developed global models, were described in Wong et al (2004b). Integration of the frequency and consequence models gave the landslide risk of each catchment and for each of the affected facilities. The calculation involved a large volume of work on spatial analysis, and was performed by GIS (Figure 49). To ensure performance, the global QRA was calibrated with results from sites where detailed site-specific QRA were carried out.



NTLI Landslide Density(No./km2)
Different Susceptibility

Rainfall Scenario	Return Period	Very Low	Low	Medium	High	Very High
A	1.234005	0	0.05	0.0597	0.2	0
B	2.090478	0	0.2	0.4387	1	0
C	16.457641	0	5	2.3354	15	0
D	281.81406	0	20	10.6811	40	0

Bayesian Update
Weighting for Theoretical NTLI Landslide Frequency: 0.5
Weighting for Actual NTLI Landslide Frequency: 0.5

Magnitude - Frequency Distribution Group

	H1	H2	H3	H4
(C/T) 1	0.85	0.15	0	0
(C/T) 2	0.748	0.25	0.002	0
(C/T) 3	0.689	0.3	0.01	0.001
(C/T) 4	0.62	0.35	0.02	0.01

	H1	H2	H3	H4
S1	0.95	0.05	0	0
S2	0.8998	0.1	0.0002	0
S3	0.8478	0.15	0.002	0.0002
S4	0.789	0.2	0.01	0.001

Recgonition Factor

(C/T/S)H1	(C/T/S)H2	(C/T/S)H3	(C/T/S)H4
0.4	0.9	1	1

Specify and save the output Hazard Model :

Figure 49. Global QRA undertaken on a GIS platform

The overall risk of natural terrain landslides in Hong Kong, based on the state of development at 2004, was assessed to be about 5 PLL per year. As shown by the breakdown of risk (Table 23), the total PLL of the 453 historical landslide catchments was 1.8 per year. This included a contribution of 0.4 PLL per year (i.e. 22%) from the extreme rainfall scenario based on extrapolation. The risk results showed that the 453 historical landslide catchments constituted about one-third of the overall risk, i.e. the other two-thirds of the overall risk would come from supplementary catchments. The risk of the supplementary catchments was projected from analysis of the samples of supplementary catchments in the global QRA using the risk model (Figure 50). This two-thirds of the overall risk was dispersed among a large number of supplementary catchments. Neither the exact locations of these supplementary catchments nor the risk distribution among them were known.

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

6.4.2 Risk management strategy

The global QRA on natural terrain landslides revealed the nature and distribution of natural terrain landslide hazards in Hong Kong. The risk distribution according to the scale of landslide showed that H2 (200 m^3 to 2,000 m^3, see Table 21) constituted about 75% of the overall risk (Table 24). This is consistent with the fact that the risk mitigation works undertaken by the GEO in recent years based on the 'react-to-known-hazard' principle has primarily been dealing with natural terrain landslide hazards at such a scale.

The distribution of the calculated risk for the historical landslide catchments is shown in Figure 51. Also shown in the Figure are the PLLs assessed from some recently completed site-specific QRA on sites that met the 'react-to-known-hazard' principle.

The results showed that the historical landslide catchments were of comparable risk-to-life level as those of the 'react-to-known-hazard' cases. In particular, about 75% of the historical landslide catchments were within the range of risk for the 'react-to-known-hazard' cases that were found to require substantial landslide risk mitigation from risk tolerability and ALARP considerations. The remaining 25% of the historical landslide catchments would probably fall within the ALARP region, and the extent of any necessary risk mitigation might be affected by other factors. These included aversion effects due to multiple fatalities, social-economic factors and political considerations, as is illustrated by the North Lantau Expressway case (Section 5.6).

The quantified natural terrain landslide risk has been compared with the risk of other types of landslides quantified from the global QRA on man-made slopes. The estimated profile of different types of landslide risk in year 2010 is shown in Table 25. The overall risk of natural terrain landslides and man-made slope failures in Hong Kong would be at comparable levels by 2010. By that time, the historical landslide catchments would be a distinct batch with the highest average risk-to-life per feature, as well as the highest risk-cost ratio per feature. This batch would deserve priority for allocation of resources for risk mitigation. This would be followed by un-engineered

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Table 23. Summary of results of global QRA (based on Wong et al. 2004b)

Component		Method of quantification	Risk (PLL per year)
453 historical landslide catchments	Rainfall Scenarios A to D (≤ 35% normalized rainfall)	Global QRA on the historical catchments using the QRA models	1.4
	Rainfall Scenario E (> 35% normalized rainfall)	~30% increase, from extrapolation of QRA results using rainfall-landslide correlation	0.4
Supplementary catchments		~ 200% increase, from projection based on global QRA using the risk model (Figure 50)	3.2
Total			5.0

Notes:

(1) Other consequences, e.g. economic loss, disruption to community and public aversion to multiple fatalities, not reflected in the calculated PLL.

(2) No. of historical landslide catchments would increase at about 10 no. per year. Risk could increase with more developments taking place near steep hillsides.

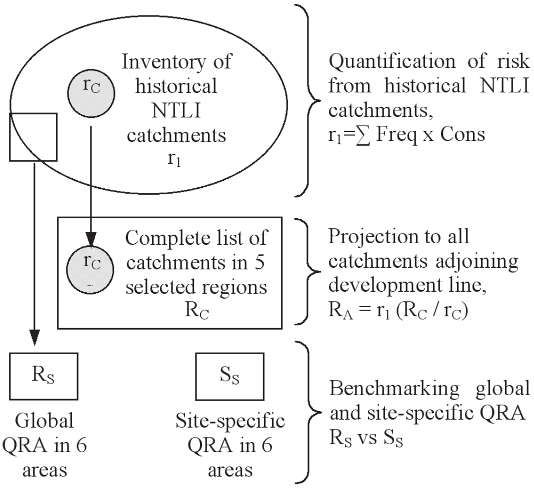

Figure 50. Risk model of global QRA for natural terrain landslides in Hong Kong

Table 24. Risk distribution according to scale of landslide (Wong et al. 2004b)

	Percentage of total risk value			
	H1	H2	H3	H4
Sensitive routes and mass transportation facilities	21.2%	74.1%	3.4%	1.3%
Building structures including collapse	13.1%	75.5%	8.3%	3.1%
Collapse of building structures only	0.0%	4.1%	4.7%	1.3%
Total risk	13.7%	75.4%	7.9%	3.0%

man-made slopes affecting Groups No. 2(b) and 3 facilities (see Table 4) and engineered slopes treated by old technology. Un-engineered man-made slopes affecting Groups No. 4 and 5 facilities have a much lower risk per feature because of the negligible failure consequences. Although these slopes are susceptible to landslides, they should be given the lowest priority for retro-fitting based on risk-to-life consideration. The global QRA findings provided a rational and consistent basis for formulating risk management strategy.

7 CONCLUDING REMARKS

Landslide risk assessment that is undertaken at a large scale, in which the facilities at risk are individually recognized and assessed, is described in this paper. Selected applications cases are presented to illustrate the approaches adopted and the developing trend in risk assessment practice.

Risk assessment at this scale may be regarded as the most detailed form of landslide risk assessment. The professional practice has clearly evolved to the stage that landslide and slope engineering is no longer confined to an investigation of slope stability. The consequence of landslides has to be examined, and landslide risk has to be assessed and evaluated in totality. This risk-based perspective is fundamental to addressing and managing landslide problems, and it aligns the geotechnical profession with many other fields that explicitly practice risk management.

There is a broad spectrum of landslide risk assessments, in terms of the objectives, methodologies and levels of detail of the assessment. In particular, there is a choice between using a qualitative or quantitative approach. There are also significant differences between applying the assessment to a few individual sites and to a large number of sites. The trend of increasing use of a quantitative approach is evident, and will continue. The available cases of QRA applications have demonstrated the advantages of QRA. They have also helped to refute misunderstandings and misconceptions about

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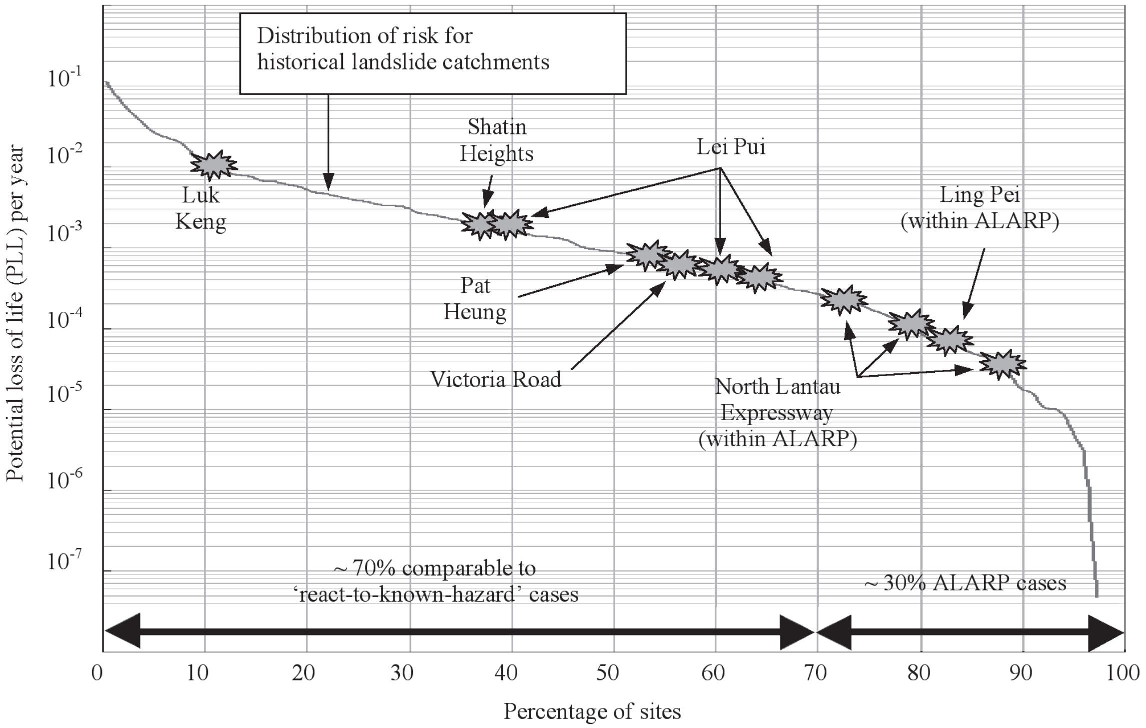

Figure 51. Risk profile of historical landslide catchments

Table 25. Landslide risk profile in year 2010 (based on Wong et al. 2004b, Lo & Cheung 2004)

Type of slope		Approximate no.	Proportion of risk	Average PLL per no.	Relative risk-cost ratio
Natural hillside	Historical landslide catchments	450 catchments	~ 15%	3.3×10^{-2}	10
	Supplementary catchments	Many (exact no. not known)	~ 35%	Not known	Not known
Unengineered man-made slopes	Affecting Groups No. 2(b) & 3 facilities and unplanned structures	12,000 slopes	~ 25%	2.1×10^{-4}	1
	Affecting Groups No. 4 & 5 facilities	14,000 slopes	< 1%	$< 7 \times 10^{-6}$	0.03
Engineered man-made slopes	by old technology	10,000 slopes	~ 20%	2.0×10^{-4}	1
	by robust technology	20,000 slopes	~ 5%	2.5×10^{-5}	0.13

Notes:

(1) See Table 4 for definitions of Facility Groups.

(2) Un-engineered man-made slopes affecting Groups No. 1 & 2(a) facilities would have been retro-fitted by year 2010, i.e. they become engineered slopes.

(3) In calculating the relative risk-cost ratio, it is conservatively assumed that the average cost of risk mitigating for a natural terrain catchment is 10 times as that for a man-made slope.

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

QRA. However, this should not detract from the importance also of qualitative assessments. The level of complexity of the analysis should be compatible with the nature of the problem to be solved, as well as with the resources available for solving the problem. Qualitative risk assessment will continue to be the most appropriate solution for some types of problem (e.g. slope risk rating), and it can also be complementary to, or be used in combination with, a detailed QRA.

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With the increasing awareness that landslide risk has to be managed, slope owners, regulators and the public as a whole, have become more ready to consider the balance between risk and cost, and less tolerant of any perceived risk that can be reduced without excessive cost. This brings a diverse range of landslide problems to the agenda of risk assessment. The challenge is for the geotechnical profession to master the diverse range of landslide risk assessment techniques and to choose the right tools for the right problems.

While use of QRA is fashionable, the profession must not lose sight of the fact that quantification does not necessarily improve accuracy and reliability. When risk is expressed in subjective and relative terms, it is by nature qualitative and intended to be indefinite. When risk is quantified, it can be expressed and communicated as exact figures, even though these may be far from accurate. The quantitative framework can provide quantified figures, but it cannot guarantee that the QRA will give reliable results. The accuracy and reliability of QRA come only with the rigor of the assessment and with the use of data, techniques and procedures that are appropriate to the specific problem being analyzed. In many practical cases, the resources available for QRA are less than satisfactory, so rendering the results unreliable, potentially misleading, and likely to do more harm than good. In such circumstances, it is imperative that the assessor should maintain good professional discipline in clearly communicating the limitations of the assessment and not overselling the QRA results. This is not at all an impediment to use of QRA. Instead, it forms part of the momentum for the geotechnical profession to further improve the skills and practice in quantified risk assessment, and to become more effective in risk communication with stakeholders.

8 ACKNOWLEDGEMENTS

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