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Is landslide risk quantifiable and manageable?

H.N. Wong
Civil Engineering and Development Department, Geotechnical Engineering Office, Government of the Hong Kong Special Administrative Region, Hong Kong, China

ABSTRACT: Quantitative Risk Assessment (QRA) enables decision-makers to exercise informed and rational judgement in evaluating and managing risk. It is commonly acknowledged that Hong Kong has showcased not only the state-of-the-art in, but also the practicability of, quantification and management of landslide risk. The author would caution that this is a simplistic view. With reference to Hong Kong's experience, it is highlighted that there are different categories of landslide problems, each with its own factors that combine to give rise to risk. As to whether the risk is quantifiable and manageable, different categories have their particular circumstances and the answers are not the same. It is credible to manage landslide risk without quantification, although risk quantification can undeniably aid risk management. Landslide risk quantification may not be practicable in all cases. Even if landslide risk is quantifiable, it is important not to lose sight of the degree of uncertainty involved.

1 INTRODUCTION

Landslide risk management and Quantitative Risk Assessment (QRA) have been undergoing rapid development in the past 20 years. Notable recent developments and applications of landslide QRA are described in Fell & Hartford (1997), Wong et al. (1997), Ho et al. (2000) and Wong (2005). Separately, under funding from the European Commission, the integrated research project 'SafeLand' has been conducted in Europe by 27 institutions from 13 countries, aiming at developing generic quantitative risk assessment and management tools and strategies for landslides.

The quantitative approach in landslide risk assessment and management has gained wider use, both in global and site-specific assessments, as illustrated by successful applications in Hong Kong and elsewhere.

This paper aims to discuss whether landslide risk is quantifiable and how landslide risk is being managed in practice, with and without quantification. Particular reference is made to the practice and experience in Hong Kong, which is recognised as a role model in urban landslide risk management.

2 LANDSLIDE AND SLOPE SAFETY MANAGEMENT IN HONG KONG

2.1 *Landslide problems in Hong Kong*

While landslides are widespread in many parts of the world, landslides in Hong Kong interact intensely with human activities in urban areas. Landslides pose particularly grave challenges to densely populated built-up areas like Hong Kong because:

- landslide consequences are serious due to the close proximity to and the high concentration of population and vulnerable facilities;
- urban development, when carried out without adequate geotechnical input, results in the formation of potentially unstable slopes and increases landslide frequency;
- landslide problems in an urbanised setting are aggravated by human factors, including concentrated surface water flow and localised cutting and filling; and
- relocation of existing facilities to avoid landslide hazards is often not viable, while at the same time landslide prevention and mitigation works are difficult and costly given space and access constraints.

In the early years of Hong Kong's rapid urbanisation, a large number of cut and fill slopes and retaining walls were formed to pave the way for housing and infrastructure developments. Typically formed with little geotechnical input at the time, these unengineered man-made slope features continue to pose landslide risks to the community to this day. Against this background, the Landslip Prevention and Mitigation (LPMit) Programme (known as Landslip Preventive Measures, LPM, Programme before 2010) has been implemented by the Geotechnical Engineering Office (GEO, formally the Geotechnical Control Office) of the Civil Engineering and Development Department, with significant headway made in risk reduction.

The severe weather conditions experienced in Hong Kong and the increasing urban development close to natural hillsides have also called for attention to managing the risk of landslides originating from natural terrain.

2.2 *Slope safety management system*

Following a number of disastrous landslides with serious fatalities in the 1970s in Hong Kong, the GEO was established in 1977. Over the years, a comprehensive Slope Safety System has been developed and implemented by the GEO to combat landslide problems.

The key components of the Slope Safety System in Hong Kong together with their functions in a risk management context are summarised in Table 1. A range of initiatives are included in the System to manage landslide risk in a holistic manner.

The goals of the System are: (i) to minimise landslide risk to the community through a policy of priority and partnership for reducing landslide frequency and consequence, and (ii) to address public attitude and tolerability of landslide risk to avoid unrealistic expectations. The System also adds value to the society through averting potential fatalities and improving the built environment.

The Slope Safety System has proven successful in containing landslide risk within an As Low as Reasonably Practicable (ALARP) level, via: (i) improving slope safety standards, technology and administrative and regulatory frameworks, (ii) ensuring safety standards of new slopes, (iii) rectifying substandard Government slopes and maintaining them, (iv) ensuring that private owners take responsibility for slope safety, and (v) promoting public awareness in and response to slope safety. Besides slope safety, the improved aesthetics and ecology of engineered slopes have also contributed to enhancing the built environment.

Retrofitting of the old unengineered slopes is carried out in the pre-2010 LPM Programme and post-2010 LPMit Programme. The Programmes serve to systematically assess the stability of old man-made slopes according to their ranked

Table 1. The slope safety system in Hong Kong (based on Malone 1998).

	Primary contribution of each component to		
	Reduce landslide risk		Address public attitude and tolerability
Components of slope safety system	Reduce likelihood	Reduce consequence	
Policing			
– Checking new slope works	✓		
– Slope maintenance audits	✓		
– Recommending safety clearance of vulnerable squatters and unauthorised structures threatened by hillsides		✓	
– Exercising geotechnical control through input in land use planning		✓	
– Safety screening studies and recommending statutory repair orders for private slopes	✓		
Works projects			
– Retrofitting substandard government man-made slopes	✓		
– Natural terrain landslide mitigation and boulder stabilisation works	✓		
Research and setting standards	✓	✓	✓
Education and information			
– Slope maintenance campaigns	✓		✓
– Risk awareness programmes and personal precaution campaigns	✓	✓	✓
– Information services	✓	✓	✓
– Landslip warning and emergency services		✓	✓

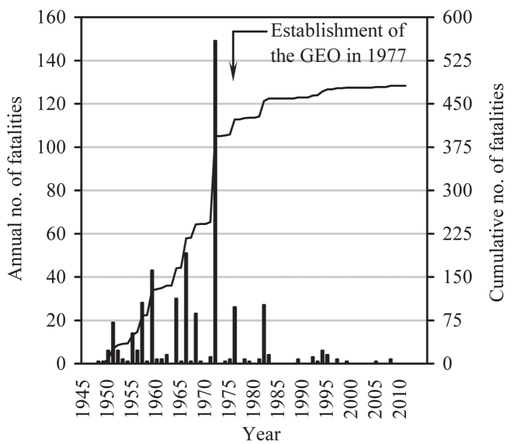

Figure 1. Historical annual landslide fatalities in Hong Kong.

order of priority and to upgrade substandard Government slopes to the required standards.

2.3 *Risk trend*

A detailed analysis of the landslide risk trend in Hong Kong is given in Wong (2009a). Two types of landslide risk trend have been assessed: historical and theoretical. They illustrate how the holistic landslide risk management framework has contributed to reducing landslide risk in Hong Kong.

Since the 1940s, documentary records have been available in Hong Kong for reliably tracing historical landslide fatalities. Figure 1 shows the annual landslide fatality figures. Although historical fatalities reflect the risk that has actually been realised, they do not necessarily represent the true (or theoretical) level of landslide risk, because such figures are affected by the actual rainfall conditions, spatial distribution of heavy rain with respect to that of existing facilities, near-miss events, etc. QRA has therefore been applied in Hong Kong to quantify the levels of theoretical landslide risk. The historical and theoretical landslide risk trends in Hong Kong are further described in Section 5.2 below.

3 CLASSIFICATION OF LANDSLIDES

Proper classification of landslides is important for risk assessment and management. Common practice is to classify landslides based on either the physical characteristics of the slope (e.g. whether man-made or natural; whether cut slope or fill slope) or the landslide mechanism (e.g. whether sliding, liquefaction or washout; whether debris flow or slide or avalanche). Proper classification prevents fundamentally different landslide types and their related data from being lumped together. As different fault trees and event trees are involved in assessing the risks of different types of landslides, mixing them together is not conducive to meaningful analysis and diagnosis of risk patterns and trends.

Factors other than physical characteristics could also be critical to landslide classification. For example, the landslide susceptibility of cut slopes formed before and after 1977 in Hong Kong is markedly different due to different levels of geotechnical input in their design and construction. Changes in slope design standards and processing systems applied to slopes should also be taken into account in the classification of slopes and landslides.

In terms of landslide classification, three notable categories of landslides have contributed to the landslide risk in Hong Kong: (i) landslides induced by construction activities, (ii) landslides triggered by heavy rain on slopes that do not meet engineering standards, and (iii) landslides under severe weather conditions, on slopes that meet engineering standards. The answers to the question about whether landslide risk is quantifiable and manageable are different for each of the categories. Their respective risk quantification and management issues for each class of landslides are explored in the following sections.

4 LANDSLIDES INDUCED BY CONSTRUCTION ACTIVITIES

4.1 *Description of problem*

Construction activities that are improperly carried out may cause failure of both temporary and permanent slopes. Slopes that are poorly designed or built may fail during or soon after its formation. Construction activities such as unauthorised excavation may also cause failure of the adjacent slopes even if the slopes have been designed to a high safety standard. Such failures could involve system deficiency (e.g. poor design guidelines and construction practice), malpractice (e.g. unauthorised construction activities), and human error (e.g. design fault).

Heavy rainfall is often one of the aggravating factors of construction-induced landslides. The most notable example in Hong Kong is the Po Shan landslide on 18 June 1972 (Fig. 2), which resulted in the collapse of the 15-storey Kotewall Court and 67 fatalities. The cause of the landslide was attributed to poorly executed site formation works which undermined the stability of the hillside and resulted in a catastrophic failure when hit by heavy rain.

Figure 2. The Po Shan landslide on 18 June 1972.

4.2 *Risk quantification*

The risk of construction-induced landslides is very difficult to quantify. Such landslides are typically the result of multiple causes that are highly variable. In many historical cases, the causes of failure are poorly documented and detailed design information is not available. As construction practice evolves with time, so do construction problems. There is often a lack of reliable data that can be consistently analysed for landslide frequency assessment. Risk quantification of this kind of failures has therefore not been conducted in Hong Kong, with the narrow exception of a preliminary review of trench excavation-induced failures by Kwong (2003). While construction-induced landslides are also commonplace in other parts of the world, to the author's knowledge, there is hardly any systematic, comprehensive risk quantification carried out.

4.3 *Risk management*

Despite the difficulty in risk quantification, the risk of construction-induced landslides is nonetheless manageable. The primary factors causing such landslides are reasonably well understood and can be regulated by improved system and practice.

This has been done in Hong Kong through the geotechnical control of Government and private developments. All permanent geotechnical works including man-made slopes and retaining walls formed under public works developments are submitted to the GEO for checking (ETWB 2002), and there is also an established independent checking system for temporary works. Geotechnical control over private developments is also exercised by the GEO through the statutory powers of the Buildings Authority. Design submissions made by developers or owners are subject to approval before construction commences.

Geotechnical control needs to be supported by regulatory and administrative systems to ensure effective enforcement. Also of importance is good professional ethics and accountability in upholding good practice in design and construction.

Given the system in place, extensive landslides triggered by construction activities are no longer expected in Hong Kong. However, the possibility of isolated incidents arising from unforeseen circumstances or exceptional irregularities at individual sites cannot be entirely ruled out. Also, smaller failures may still result from localised unauthorised construction, e.g. in squatter and village areas.

5 LANDSLIDES TRIGGERED BY HEAVY RAIN, ON SLOPES THAT DO NOT MEET ENGINEERING STANDARDS

5.1 *Description of problem*

On average, approximately 300 landslides are reported in Hong Kong every year, most of which involve failure of substandard man-made slopes triggered by rain when the Landslip Warning is in force. Issue of Landslip Warning is decided by the GEO based on rainfall forecasts from the Hong Kong Observatory and the landslide frequency-rainfall model established by the GEO using historical data. Normally three to four Landslip Warnings are issued in Hong Kong every year. The rainfall concerned is heavy, but usually not extreme.

Slopes not meeting engineering standards refer to unengineered man-made slopes formed without proper geotechnical design and control. This occurred prior to the establishment of the GEO in 1977. In those days, slopes in Hong Kong were designed and formed empirically by experience: cut slopes typically constructed to 55° and fill embankments to 35° were deemed to be satisfactory. A total of 39,000 sizeable unengineered slopes (>3 m high) have been registered in the GEO's catalogue of man-made slopes. After 1977, good practice and regulatory system were put in place, which virtually eliminated the formation of new substandard slopes. However, due to the presence of the large number of these old unengineered slopes, they are the principal source of landslide risk in Hong Kong after 1977.

A notable example of failure of unengineered slope triggered by heavy rainfall was the collapse of a fill embankment at Sau Mau Ping in 1976 where landslide debris punched through the ground floor of Block 9 of Sau Mau Ping Estate

Figure 3. Fill slope failure at Sau Mau Ping on 25 August 1976.

killing 18 people (Fig. 3). Subsequent investigation revealed that the loose sandy fill materials in the surface 3 m of the slope had undergone liquefaction failure when it became saturated in the heavy rain (Morgenstern 1978).

Natural hillsides that have marginal stability and are active in landsliding may also fall into this category. From the interpretation of the comprehensive inventory of historical aerial photographs, it is found that an average of about 300 natural terrain landslides occur on the natural terrain in Hong Kong each year. However, most of these landslides do not result in any major consequences and are not reported to the GEO.

5.2 *Risk quantification*

The landslide risk associated with this kind of slopes can be more readily quantified, provided that comprehensive data are available on:

i. historical landslides, their locations, time, scale and consequence; and
ii. the characteristics of the slopes, i.e. their type, size, gradient, etc.

The above conditions are favourably met in Hong Kong, which renders risk quantification practicable. Comprehensive and good quality failure data are available, and all existing, sizeable man-made slopes have been registered and surveyed. In Hong Kong, the instability problem of this category of slopes is principally controlled by the deficiency of empirical-based design, which displays a probabilistic pattern of failure associated with: (i) presence of geological weaknesses, and (ii) occurrence of heavy rain. Historical landslide data, together with local knowledge and information on ground and rainfall conditions, provide a good basis for analysing both of these factors, and thereby establishing the frequency of landslides. The numerous historical landslide data together with detailed inventory of slopes and the facilities affected in the event of failure also enable the development and application of landslide consequence models for quantifying the consequence of failure (Wong et al. 1997).

Global QRA has regularly been carried out to quantify the landslides risks for this category of slopes, as an integral part of landslide risk management in Hong Kong. The effect of construction activities is excluded in the quantification of rainfall-induced landslides for this category of slopes, given that landslide risk from construction activities has been largely managed.

Figure 4 shows the rolling 15-year average values of the annual fatalities, which depict the historical landslide risk trend in Hong Kong. Figure 5 presents diagrammatically the calculated

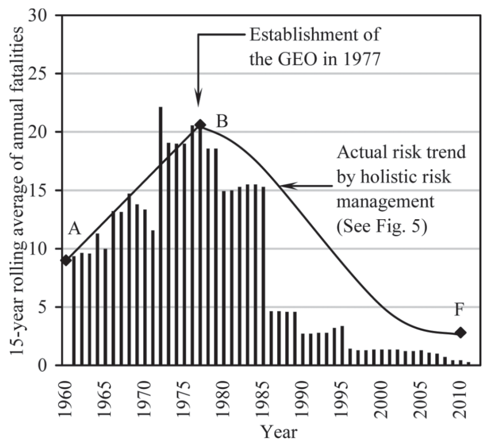

Figure 4. 15-year rolling average of historical annual landslide fatalities in Hong Kong.

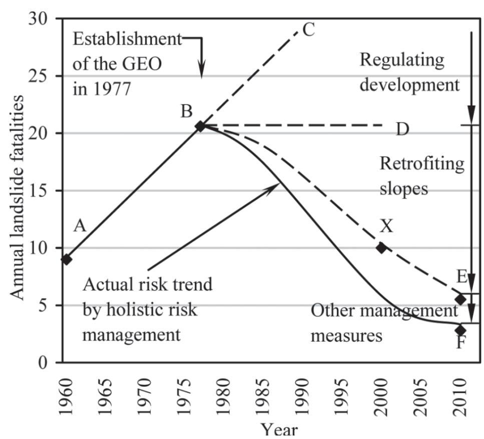

Figure 5. Landslide risk trends in Hong Kong.

landslide risk trend for this category of slopes in Hong Kong, as assessed by global QRA.

In 1977, territory-wide geotechnical control was introduced by the GEO to ensure that newly formed slopes in Hong Kong are designed and built to the required standards of safety. Since then, the increasing risk trend has levelled off, i.e. turned from line BC to line BD in Figure 5, despite that an additional more than 20,000 sizeable man-made slopes have been formed as a result of urban development in Hong Kong. Since 1977, the outcome of the retrofitting effort under the LPM Programme is progressive risk reduction along Line BE (Fig. 5). From a global QRA, the calculated overall landslide risk in year 2000 is 50% of that in 1977 (Cheung & Shiu 2000), i.e. Point X in Figure 5. It was also found that by year 2010, the retrofitting works should have brought the overall risk level to within 25% of that in 1977 (Cheng 2011), i.e. Point E.

The global QRA conducted on the unengineered slopes in Hong Kong has given results with good reliability, as is also illustrated by the good match of the calculated risk figures with the historical landslide risk trend (Fig. 4).

Wong (2005) also describes the application of QRA at individual sites in Hong Kong, for the quantification and management of the risk at site-specific level. In general, given the use of the same set of data, the reliability of the risk quantification would decrease from global to site-specific QRA. Hence, in practice, site-specific QRA normally calls for more detailed information and assessment.

5.3 *Risk management*

Hong Kong's Slope Safety System is instrumental in its success in managing landslide risks arising from old substandard slopes. This has however not come easily. The process has called for a strong commitment in resources, time and strategy. In contrast with forming new slopes that are up to standard, retrofitting existing substandard ones is resource-demanding and is subject to many other engineering, environmental and social constraints. It takes a long time to achieve notable results. A system manager, a role taken on by the GEO, is required to devise good strategy and organisation, involving the compilation of catalogues, prioritisation, systematic study and retrofitting, etc.

Global QRA has been successfully used to identify the scale of the landslide problem and to facilitate the formulation of strategy and prioritisation. It has formed the basis for resource allocation and assessment of relative priority between different slope types under the LPM and LPMit Programmes, as incorporated into the prevailing risk-based priority ranking system.

On natural terrain, the distribution of risk amongst different types of catchments has been assessed, including open slopes, topographic depression and channelised debris flow (Wong et al. 2006, Cheng & Ko 2010). These results have been instrumental in formulating the post-2010 LPMit Programme, which implements risk mitigation works for 30 natural hillside catchments annually apart from retrofitting old man-made slopes.

Global QRA has also provided useful figures on the amount of risk reduction achieved and the effectiveness of risk management effort, which aids risk communication.

Site-specific QRA, on the other hand, facilitates a rational consideration of risk tolerability and evaluation of risk mitigation strategy at a particular locality. This is where state-of-the-art quantified risk management is usefully applied. For example, a natural terrain landslide hazard study has been carried out at Sha Tin Heights, Hong Kong (Fig. 6) following six landslides in 1997, three of which developed into debris flows that affected residential buildings. QRA was used to evaluate the acceptability of risk levels (Fig. 7) and the cost effectiveness of risk mitigation strategies. Risk mitigation works were completed in 2004.

In parallel, besides landslip prevention and mitigation works, non-works measures such as public education, landslide warning, etc. have helped reduce the consequence of landslides. The GEO runs a public education and publicity campaign on slope safety to promulgate the importance of slope maintenance and educate the public on personal precautionary measures to be taken during heavy rainstorms. The GEO also provides a 24-hour emergency service to attend to landslip incidents and to advise on emergency and follow-up actions,

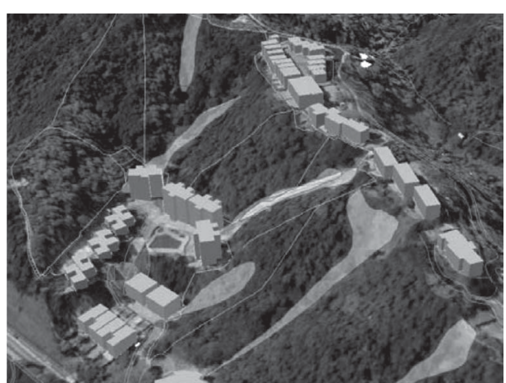

Figure 6. Residential buildings affected by landslide hazards at Sha Tin Heights (after Wong & Ho 2005).

such as building evacuation and road closure, to minimise the impact of landslides on the public.

The non-works initiatives form an integral part of holistic landslide risk management. They have proven to be effective in reducing the landslide risk to the ALARP level. This is shown diagrammatically as Line BF in Figure 5, reflecting a further reduction in landslide risk from the theoretical level (Line BE) that accounts only for the effect of slope retrofitting works. Over the past 20 years, the actual annual landslide fatalities in Hong Kong have been consistently less than the theoretical risk level by at least 50%. The overall risk trend suggests that the contribution of the non-works initiatives to reduction of landslide risk in Hong Kong could be fairly significant. As an illustration, in the past 20 years, the number of Landslip Warnings issued, landslide incidents reported, buildings and people temporarily evacuated, and sections of road closed as a result of the landslide emergency responses of the GEO and the community are shown in Table 2.

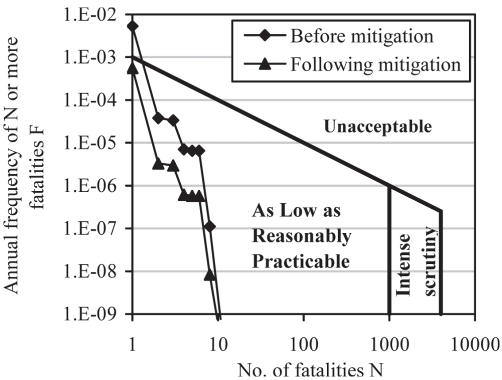

Figure 7. Comparison of societal risk in terms of F-N pairs with societal risk criteria at Sha Tin Heights. societal risk was reduced from 5.67×10^{-3} PLL/year to 4.44×10^{-3} PLL/year following the implementation of risk mitigation measures (after Fugro Maunsell Scott Wilson JV 2004).

6 LANDSLIDES UNDER SEVERE WEATHER CONDITIONS, ON SLOPES THAT MEET ENGINEERING STANDARDS

6.1 *Description of problem*

An account of the key lesson learnt from the systematic landslide investigation in Hong Kong that engineered slopes still have a finite chance of failure is given in Wong & Ho (2003). Such failures are typically related to the progressive degradation of man-made slopes under repeated rainfall conditions or to geological defects not identified in slope design by the current state of knowledge and practice.

Table 2. Breakdown of landslides affecting different facilities in Hong Kong since 1994.

Year	No. of landslip warning issued	No. of reported landslide incidents	No. of buildings* evacuated			No. of sections of road affected/closed
			Block	House	Flat/unit	
1994	4	436	4	24	207	225
1995	6	295	5	8	170	163
1996	2	153	0	7	58	87
1997	8	491	0	19	176	253
1998	1	216	0	6	43	120
1999	3	402	4	10	128	166
2000	6	322	0	3	15	184
2001	8	214	0	6	48	98
2002	3	138	0	7	5	73
2003	1	201	0	2	3	98
2004	2	69	0	0	3	18
2005	2	481	7	4	46	219
2006	4	193	0	1	8	85
2007	1	83	0	0	4	36
2008	5	849	1	22	80	420
2009	2	124	0	0	2	45
2010	3	266	0	0	7	93
2011	0	99	0	0	0	27

*A ‘block’ is a multi-storey building, which may comprise up to several dozen of flats/units. A ‘house’ is typically within 3 storeys, which comprises several flats/units.

Between 1997 and 2002, 106 landslide incidents involved man-made slopes with past geotechnical engineering input and geotechnical design submissions checked and accepted under the slope safety system, 24 of which were major failures (i.e. ≥50 m^3 in volume). All the 106 failures were subject to the GEO's detailed landslide investigation to enable a systematic diagnosis of the probable causes of failure. Of the 106 cases, 53 affected engineered soil cut slopes, 15 of which were major failures. All these 53 failures involved unsupported soil cuts, with no structural support such as soil nails or earth retaining structures. The comprehensive analysis showed such engineered man-made slopes that were formed with old technology before the 1990s, known as 'old technology slopes' in Hong Kong, are not sufficiently robust in withstanding degradation and could fail under severe rainfall conditions.

During the severe rainstorms between May and July 2008, 28 landslides occurred on engineered man-made slopes, of which two were major failures (Li et al. 2012). The one at Pak Fuk Road was an unsupported soil cut slope formed between 1976 and 1980. The one at Tsing Yi Road involved a wedge failure in its rock portion. These failures on engineered slopes are typical of the residual landslide risk problem associated with old technology slopes in Hong Kong.

Unengineered slopes have a much higher failure frequency than engineered ones, and they tend to show instability under much less intense rainfall. In contrast, the risk of failure of engineered slopes tends to become evident under severe rainfall conditions. The dire consequences of such failures can be illustrated by the following two examples:

i. The 13 August 1995 landslide at Fei Tsui Road (GEO & Knill 1996) involved a large-scale failure (14,000 m^3) of a 27 m high engineered cut slope that had no structural support (Fig. 8). A total of 370 mm rainfall was recorded at the site within 24 hours before the landslide, and the 31-day rainfall of 1303 mm exceeded the highest calendar monthly rainfall ever recorded by the rain gauge at the Hong Kong Observatory since records began in 1884. The landslide consisted of a translational failure with the detached ground mass sliding on a surface dipping gently out of the slope. Large failures of this type are unusual in Hong Kong. The post-failure investigation established that the basal slip surface of the landslide developed along a laterally extensive (>50 m) weak layer of kaolinite-rich altered tuff, which was about 15 m below the crest of the cut slope and dipping out of the slope at about 10° to 25°. The failure caused one fatality.

ii. The adverse effect of significant geological defects on slopes previously subjected to engineering studies was evident in the Shek Kip Mei landslide of 25 August 1999 (Fugro Maunsell Scott Wilson JV 2000). The 4-day rainfall before the landslide was most severe, with a total of 641 mm of rain and was the heaviest recorded since slope formation. The slope displaced forward by about 1 m at the slope toe. The total volume of the displaced mass was about 6000 m^3. A laterally-persistent (over 60 m long) discontinuity dipping at a shallow angle out of the slope formed the basal plane of the southern part of the landslide. This discontinuity was infilled with polished, slickensided kaolin and manganese oxide deposits up to 15 mm thick only (Fig. 9), which was not mapped in the past geotechnical studies. As a result of the landslide, two public housing blocks were permanently evacuated.

Figure 8. Failure of cut slope at Fei Tsui Road on 13 August 1995.

Natural terrain in Hong Kong also exhibits instability that resembles this category of landslide problem, in that natural terrain tends to respond vigorously to severe rainfall. Ko (2005) established from detailed rainfall and natural terrain landslide correlations that the density of natural terrain landslides increases exponentially with rainfall intensity (Fig. 10). Under moderate to heavy rainfall conditions, there are generally few failures on natural terrain in Hong Kong. However, when rain becomes severe, e.g. when 20% or more of the average annual rainfall is recorded within 24 hours, widespread natural terrain landslides tend to occur. For instance, in the June 2008 rainstorm, Lantau Island was subjected to a maximum of 623 mm rainfall in 24 hours, with a statistical return period of about 200 years. The 4-hour rainfall of 384 mm in the rainstorm was most severe, which measured over 1000-year return period. More than 2400 natural terrain landslides occurred during the

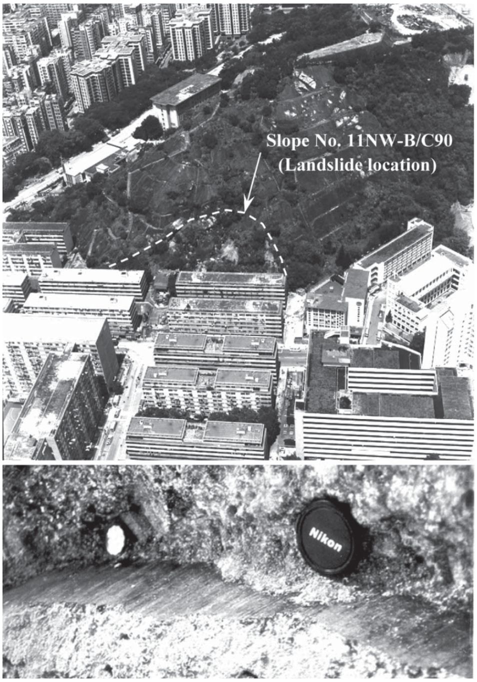

Figure 9. Failure of cut slope at Shek Kip Mei on 25 August 1999 (top); laterally persistent discontinuity infilled with slickensided kaolin and manganese oxide deposits (bottom).

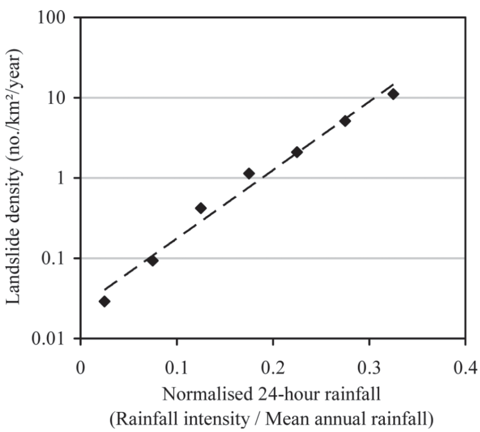

Figure 10. Correlation between rainfall and natural terrain landslide density.

rainstorm (Fig. 11). Furthermore, it was evident that the scale of the natural terrain landslides and the mobility of the landslide debris also increased drastically under such extreme rainfall (Wong 2009b).

Figure 11. Natural terrain landslides at Tung Chung, Lantau Island during the June 2008 rainstorm.

6.2 *Risk quantification*

Quantifying the landslide risk under severe weather conditions is difficult and is subject to significant uncertainty. First, only limited data are available on the landslide frequency in severe rainfall conditions, given the limited observation period for relatively rare events. For instance, the current natural terrain landslide inventory maintained by the GEO is primarily based on low-level aerial photographs which reveal historical natural terrain landslides over the past 60 years. Caution is needed when using the historical data as a basis for assessing extreme, or low-frequency-high-magnitude events by simple projections. Large and mobile landslides are potentially underrepresented.

Second, the quantification of landslides occurring during severe weather conditions requires extensive extrapolation, which increases uncertainty. There is little information available on the presence and extent of geological defects that could subvert slope stability, even for man-made slopes that have been properly engineered. The phenomenon and process of slope degradation are not well understood. There is limited knowledge of how landslide scale and mobility increase under extreme rainfall conditions.

Third, effects of climate changes could alter both the frequency of occurrence as well as the severity of extreme rainfall conditions. However, this is an area awaiting further study and analysis to ascertain the effects, their potential influence on the severity and frequency of extreme rainfall, and how slope instability would respond to such changes.

In short, risk quantification may be attempted for landslide risk under severe weather conditions but the findings should be interpreted with care and with due consideration of the significant uncertainty involved.

6.3 *Risk management*

Managing landslide risks that may be brought about by severe weather conditions poses some of the greatest challenges for the geotechnical profession today. The difficulty is two-fold. Firstly, the uncertainties in risk quantification reflect the lack of understanding of the nature and severity of the problem, which hinders the formulation of risk management strategy and deployment of resources. Secondly, given the present state of knowledge and technology, pragmatic solutions to curb landslides in extreme weather conditions may not always be available.

For man-made slopes, robust design solutions have already been adopted in Hong Kong. This includes the use of structural support such as soil nailing and prescriptive measures such as enhanced drainage provisions. Engineered slopes formed with old technology could be vulnerable to failure in severe rainfall conditions. However, it is notable that no mobile, high consequence or major failures have occurred on soil nailed cut slopes in Hong Kong to date. This indicates the robustness of soil nailed systems in preventing large scale instability even in the face of severe weather conditions. Minor failures do occur, and these may be reduced by improved slope surface protection and drainage measures (Ng et al. 2008).

For natural terrain landslides, on the other hand, existing technology has limited capability in coping with the hazards that may arise under severe rainfall conditions. There is thus a pressing need for the development of better mitigation measures and innovative solutions. Some thoughts on enhanced risk management and mitigation strategy for natural terrain arising from observations and lessons learnt from the June 2008 rainstorm are given in Wong (2009b). For instance, in dealing with sizeable debris flows exceeding several thousand cubic metres, there may be a need to explore the use of multiple layers of debris resisting barriers rather than a single layer.

Non-works options will also continue to feature prominently in the management of landslide risk under severe weather conditions, including public education, landslip warning and emergency preparedness as discussed earlier. At the same time, closer collaboration with the meteorological profession is required in assessing the effects of climate change and its implications in slope safety.

7 CONCLUDING REMARKS ON RISK QUANTIFICATION AND MANAGEMENT

A range of factors affect the practicability of risk quantification. These need to be evaluated before deciding whether or not it is practicable to perform QRA and whether or not risk quantification can be expected to give reliable results. Even where it is possible to quantify the risk, it is important not to lose sight of the degree of uncertainty involved.

Proper classification, including consideration of both the physical and system aspects of the landslide hazards, is important in risk quantification and management. Different types of landslides should not be lumped together in analysis. The availability of good documentation and data of historical landslides and slopes are prerequisites to QRA.

The main challenge in risk quantification often lies with the assessment of landslide frequency (including the scale and mobility of failure). Consequence assessment is generally less difficult, although existing consequence models do warrant further review of their applicability and reliability under different circumstances. This is beyond the scope of this paper.

It is possible to manage landslide risks without quantification, but risk quantification can undeniably aid risk management. The problem of construction-induced landslides in Hong Kong illustrates how the multiple uncertainties involved could render risk quantification difficult, even though there are a wealth of data, good understanding of landslide mechanisms and ample experience in use of QRA.

Where risks cannot be quantified with reasonable confidence, it is difficult to apply the quantified risk assessment and management framework. However, the relevant risk assessment principles and considerations are still useful in general terms. Applied in a qualitative manner together with expert judgment, they can still facilitate management of risk.

In Hong Kong, the risk of rainfall-induced landslide on old, unengineered slopes has been reduced to a low level. As the risk level reduces, risk quantification becomes increasingly sensitive to the uncertainties involved. In the past, this category of landslides was the predominant component of the overall landslide risk in Hong Kong. Upon reduction of the risk to a relatively low level, other factors have come into play, e.g. the effect of construction activities and risk associated with extreme weather conditions, which originally would not contribute significantly to the overall landslide risk.

Therefore, it may become more difficult and unreliable to further quantify the actual risk reduction that could be achieved by a certain risk management initiative, when the risk is at a low level already and is sensitive to changes associated with other factors.

Viewed from another perspective, containing risk within the ALARP level calls for continual effort to curb various factors that may increase risk. This in turn requires risk management efforts which may not necessarily achieve a noticeable or quantifiable risk reduction.

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