Rising to the Challenges of Natural Terrain Landslides

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ABSTRACT

Systematic study and mitigation of natural terrain landslide risk is a core component of Government's post-2010 Landslip Prevention and Mitigation Programme (LPMitP). Tackling natural terrain landslide hazards marks a new chapter in Hong Kong's landslide risk management, and the geotechnical profession must rise to the challenges of its enhanced responsibilities. This paper summarises the technological development work on natural terrain in the past twenty years, which has led to the formulation of the LPMitP. Technical issues that may confront the profession as we venture into this new field of work are described, with particular focus on natural terrain failures, debris movement and risk management strategies. Lessons learnt from ongoing studies, including those from the June 2008 landslides, and their implications are highlighted.

1 NEW CHAPTER OF LANDSLIDE RISK MANAGEMENT IN HONG KONG

1.1 History of Landscape Evolution in Hong Kong

Hong Kong has a population of over 7 million and a land area of about 1,100 km^2. The terrain is hilly, with some 75% of the land steeper than 15º and over 30% steeper than 30º. Intense urban development has taken place on flat ground and in foothill areas, and is progressively encroaching on the steep hillsides where landslides from man-made slopes and natural terrain could pose a significant hazard (Figure 1).

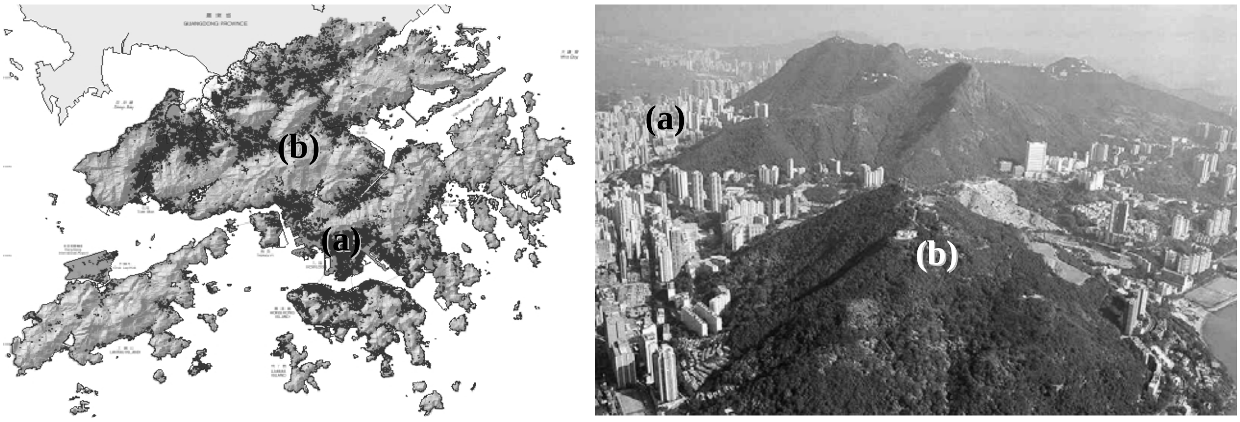


Figure 1: High concentration of developments in Hong Kong mingled with man-made slopes and natural hillsides
(Note: (a) urban development fringing (b) steep natural hillsides)

Natural terrain occupies about 60% of the land in Hong Kong. Much of it is steeply sloping and mantled by weak saprolitic or residual soils, or colluvial deposits derived from past landslide and erosion processes. The vast majority of the terrain is underlain by volcanic and granitic rocks, which were formed over 100 million years ago (Sewell et al. 2000). The details of the present day landscape are thought to have formed mainly during the Quaternary Period, from about 1.4 million years ago to the present. The subtropical deep weathering of the rocks probably began during the Tertiary period as long as 60 million years ago under relatively stable, warm and humid climatic conditions (Ruxton & Berry 1957). The last glaciation commenced about 25,000 years ago, reaching a maximum about 17,000 years ago. At this time, sea level was around 130 m below the current level, and the coastline was about 120 km south of Hong Kong (Figure 2). When global deglaciation accelerated about 12,000 years ago, the sea level rose and the coastline moved northward. A postglacial sea level high, possibly reaching 1 to 3 m above its present level, was attained about 7,000 years ago (Fyfe et al. 2000). Substantial erosion and mass movements probably occurred at the new coastal region. These involved coastal landslides and reactivation of relict failures, which modified the landscape. Erosion and mass movements would have also taken place on mountain slopes, particularly during wetter periods, which are postulated at about 12,500 to 11,000, 10,500 to 8,000, and 7,000 to 5,500 years ago (Ng et al. 2003).

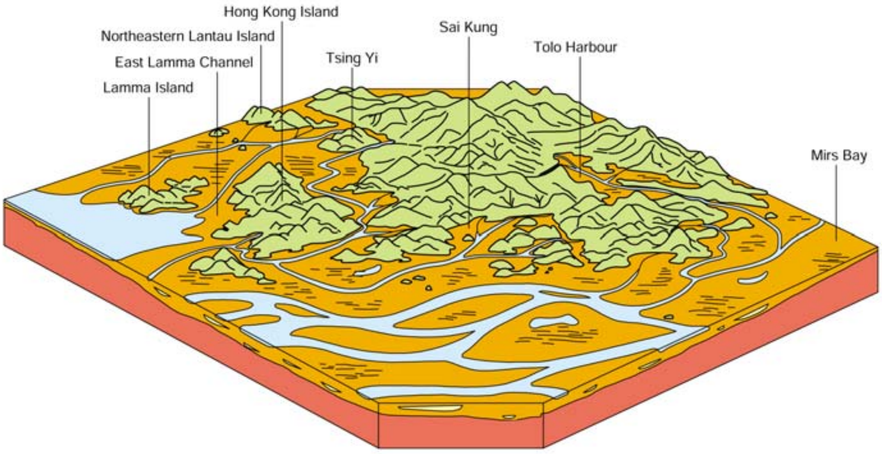


Figure 2: Topography of Hong Kong during a low sea level stand (from Fyfe et al. 2000)

While Hong Kong’s natural hillsides have experienced a long history of landscape evolution, they remain highly susceptible to rain-induced landslides (Figure 3), which could develop into debris flows upon entering drainage lines. Sizeable failures on steep open hillslopes could also result in discharge of fast-moving debris downslope. Should the debris reach developed areas, serious consequences may occur.

Figure 3: Landslide-prone natural terrain in Hong Kong

1.2 Natural Terrain-related Studies in Early Years

Lumb (1975) summarized in his paper the state of knowledge on landslides in Hong Kong at the time, with attention given mainly to man-made slope failures.

In 1977, the Geotechnical Control Office (GCO, renamed Geotechnical Engineering Office in 1991) was set up as the central body to regulate geotechnical engineering and slope safety in Hong Kong. Since then, Hong Kong landslip preventive works have primarily focused on landslide risks associated with man-made slopes, which posed a much greater overall risk to the community than natural terrain hazards. Knowledge of natural terrain landslides was rather limited in Hong Kong in the 1970s.

Some pioneering studies on Hong Kong's natural terrain were pursued in the 1980s. These included the territory-wide geological survey mapping (Fletcher 1997), which succeeded the earlier work by Allen & Stephens (1971), and the terrain classification mapping published under GCO's Geotechnical Area Studies Programme (Styles & Hansen 1989). The above provided useful information, at a regional scale, on the geology of Hong Kong and the general terrain characteristics. Apart from these major mapping programmes, the Mid-levels Study (GCO 1982) was a landmark in regional slope studies, comprising three years of extensive ground investigation, hydrogeological monitoring and subsequent analysis. Some technical publications in the 1980s also covered aspects of the hillside processes, e.g. recognition of soil piping in colluvium and saprolites as a widespread near-surface process (Brand et al. 1986), and engineering geomorphology of Hong Kong's terrain (Hanson 1984; So 1986). Information on recorded natural terrain landslides was summarised in GCO's reports on rainfall and landslides. These include reports on two major rainstorms of 1982 (Hudson 1982; Tang 1982), in which many natural terrain landslides were observed. Engineering methods for treatment of unstable boulders (Au & Chan 1991) and design of boulder barriers were developed (Chan et al. 1986).

1.3 Technology Development Since the 1990s

With increased awareness of the potential hazards from natural terrain failures, the Geotechnical Engineering Office (GEO) (now, part of the Civil Engineering and Development Department), in collaboration with geotechnical practitioners and researchers, has been undertaking technical development work on the subject since the early 1990s. This has led to improved understanding of the nature and characteristics of natural terrain landslides, their potential risk and approaches for risk management. Some initiatives that are either milestones in the technological development or have notable impact to professional practice are described below:

(a) **Study of the 1990 Tsing Shan debris flow**: This large channelised debris flow (Figure 4) was studied in detail by the GEO, and reported by Chan et al. (1991) and King (1996). The incident started as a debris slide of about 350 m^3 at the landslide source. It developed into a 20,000 m^3 debris flow through material entrainment, with a runout distance of about 1 km. The debris flow has been regarded locally as an example of a low-frequency, large-magnitude natural terrain landslide event, and quoted internationally as a case that illustrates high debris flow entrainment (Jakob & Hungr 2005). Before the debris flow, the planned development in the region was encroaching on the Tsing Shan foothills. The debris flow could have resulted in serious consequences if the site traversed by the debris flow had been developed at the time. After the debris flow, development at the site was changed to a golf driving range to minimise risk exposure. The case is a vivid illustration of the risk of debris flows and the importance of proper land-use and development planning in controlling undue increase in the risk of natural terrain landslides.

(b) **Study of the 1993 Lantau landslides**: In the rainstorm of November 1993, over 860 natural terrain landslides occurred on Lantau Island (Figure 5). The landslides resulted in blockage of roads and catchwaters. As Lantau Island was largely undeveloped at the time, there were no landslide casualties. The landslides were mapped and the data collected analysed (Wong et al. 1998). The study established that a high density of natural terrain landslides could be triggered in a severe rainstorm (about 7 nos./km^2 in the region affected by high rainfall intensity in this rainstorm), and that terrain at a gradient of 30° to 35° underlain by volcanic rocks was most susceptible to failure. Empirical assessment of landslide debris runout data showed that debris mobility was affected by the mechanism of debris movement, with channelized debris flows being more mobile than open hillslope failures. The study carried out by Franks (1998) on the landslides overlooking Tung Chung New Town, which was being developed in 1993, also arrived at similar observations.

Figure 4: The 1990 Tsing Shan debris flow

Figure 5: Natural terrain landslides on Lantau Island in the November 1993 rainstorm

(c) **Natural Terrain Landslide Inventory (NTLI)**: In the mid 1990s, the GEO compiled the Natural Terrain Landslide Inventory (NTLI), a Geographic Information System (GIS)-based inventory of historical natural terrain landslides identified from interpretation of high-flight aerial photographs (2,400 m or above) taken since 1943 (King 1999). Figure 6 shows a graphical display of NTLI, including the identified natural terrain landslide crowns and the debris trails. Up to the year 2000, the NTLI has catalogued some 30,000 landslides, about 11,000 and 19,000 of which are recent and relict landslides respectively. Factors such as photograph coverage, cloud cover, ground shadows, vegetation cover, and scale and resolution of the high-flight aerial photographs impose certain limitations on the dataset. Consequently, some landslides may have been missed, and some landslides shown in the inventory may be other features mis-identified as landslides. Despite these constraints, the NTLI was one of the most comprehensive catalogues of historical natural terrain landslides that had ever been compiled at the time. It provided important data for studies of natural terrain hazards, and was widely used by the geotechnical profession until it was replaced by the enhanced inventory described in Item (o) below.

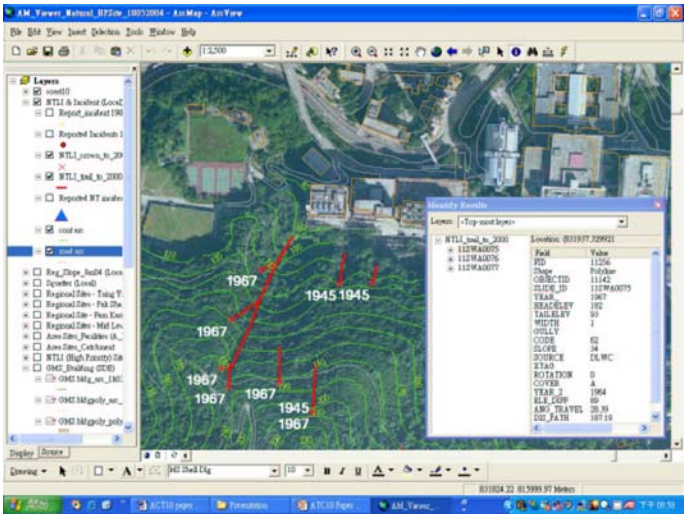
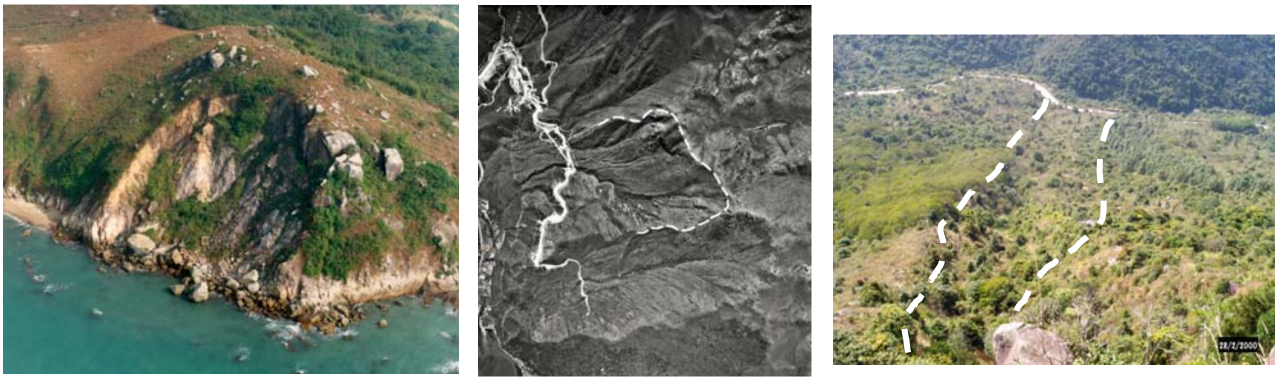


Figure 6: Natural Terrain Landslide Inventory in GIS Format

(d) **Large Landslide Dataset**: A database of about 1,900 nos. large natural terrain landslides was compiled based on interpretation of aerial photographs and hillside geomorphology (Scott Wilson 1999a, b). These large landslides include large relict morphological features and recent natural terrain failures with a scar width exceeding 20 m. Some examples of the identified large relict landslides are shown in Figure 7. Studies were carried out on the possible scale and age of some of the large relict landslides. For instance, the large coastal landslide on Lamma Island had an estimated volume of about 30,000 m^3 and probably occurred within the last few hundred years. The massive debris lobe at Sham Wat, Lantau covers a plan area of about 0.3 km^2. Age-dating revealed that the main body of the hillside probably failed some 30,000 years ago, but further sizeable detachments continued to take place and the youngest one was dated as only about 2,000 years old (Sewell & Campbell 2005). The large relict landslide scar that was left in place after a massive debris flow near the present Tung Chung Road was found to occur about 8,000 years ago. These landslides are relatively young in geological time scale. They could have implications to the assessment of the current landslide risk.



(a) Large coastal landslide on Lamma Island

(b) Massive debris lobe at Sham Wat, Lantau

(c) Large relict landslide above Tung Chung Road

Figure 7: Examples of large relict landslide features

(e) **Landslide susceptibility analysis**: Evans & King (1998) carried out a territory-wide landslide susceptibility zoning, based on correlation of natural terrain landslides with slope angle and geology. Nineteen geological groups and thirteen slope angle classes were adopted, which resulted in some 247 different types of terrain units. Natural terrain landslide data from the NTLI up to the year 1994 were used in the analysis. The Digital Elevation Model was compiled from the 1:5,000-scale 10 m contour topographical maps, but the susceptibility zoning map was prepared in 1:20,000 scale. More refined susceptibility analyses have subsequently been carried out at selected regions, using additional terrain attributes and more elaborate analytical techniques. Wong (2003) reviewed the state of practice in susceptibility analysis, and cautioned against the limited resolution and reliability achieved in susceptibility zoning, which affect its applicability to risk management.

(f) **Systematic landslide investigations**: Since 1997, significant natural terrain landslides were systematically investigated under GEO's landslide investigation programme. Notable cases investigated include: the 1997 Shatin Heights landslides (FMSW 2001), 1999 Sham Tseng San Tsuen debris flow (FMSW 2000), the distressed hillside at Queen's Hill (FSW 1999), the 2000 Tsing Shan debris flows (King 2001), the 2000 Leung King Estate debris flows (HCL 2001), the 2001 Lei Pui Street debris flow (MGSL 2004), landslides at Cloudy Hill (HCL 2003), the slow-moving landslide at Tsing Shan foothills (Parry & Campbell 2003), and the 2005 Kwun Yam Shan landslide (MGSL 2007). The investigations have brought about further insights into the causes, mechanisms and characteristics of natural terrain landslides.

(g) **Interim risk guidelines**: A set of landslide risk guidelines, benchmarked against that adopted for Potentially Hazardous Installations in Hong Kong, was formulated by the GEO (ERM 1998). The risk guidelines stipulate the tolerable risk criteria for natural terrain landslides in respect of Individual Risk and Societal Risk. The Individual Risk criteria apply to the annual probability of fatality for the most vulnerable person affected by landslide hazards. The maximum allowable limit is 10^{-5} for a new development, and 10^{-4} for an existing development. The Societal Risk criteria apply to the total risk-to-life posed on the community by landslide hazards within the consultation zone. The criteria were expressed as a frequency (F) versus number of fatalities (N) distribution.

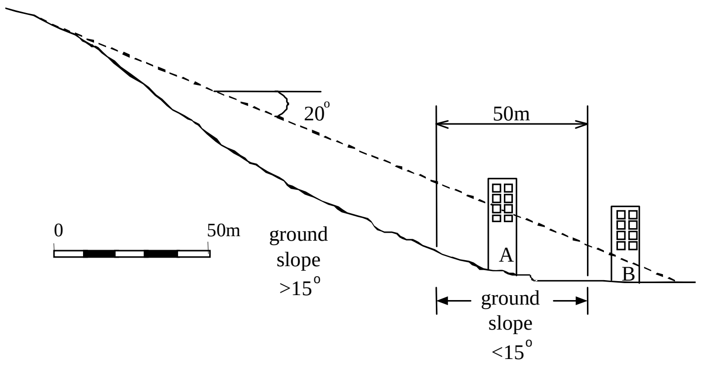
(h) **Guidelines for Natural Terrain Hazard Studies (NTHS)**: The present framework for assessment of natural terrain hazards and mitigation requirements was developed in the early 2000s (Wong 2003). Based on the framework, guidelines on recommended good practice for Natural Terrain Hazard Studies (NTHS) and the design requirements of mitigation measures are set out by Ng et al. (2003).

(i) **Guidelines for design of debris-resisting barriers**: Given the typical scale of debris flows in Hong Kong, it is often practical and cost-effective to adopt debris-resisting barriers as risk mitigation measures. Technical guidelines on assessment of debris impact forces and design of debris-resisting barriers were issued by the GEO (Lo 2000).

(j) **Development and application of Quantitative Risk Assessment (QRA)**: Technical development work undertaken in Hong Kong has been instrumental in formulating landslide QRA methodology, for application to natural terrain landslide risk management. The landslide risk assessment concepts, techniques and applications are summarised in a number of state-of-the-art papers, e.g. Wong et al. (1997), Ho et al. (2000), and Wong (2005).

(k) **Rainfall-landslide correlation**: Study of the correlations between the density of natural terrain landslides and rainfall intensity provided insights into the effects of rainfall on natural terrain landslide occurrence and assisted in risk management and disaster preparedness. The study incorporated the methodology that has been applied over the years in establishing rainfall-landslide correlations for man-made slopes in Hong Kong, together with the use of GIS and statistical techniques to further improve the assessment (Ko 2003; Wong et al. 2004). The detailed rainfall records available in Hong Kong since 1985 and the NTLI data provided the essential data for the study.

(l) **Assessment of debris mobility**: The GEO has commenced empirical assessment of debris mobility since the study of the 1993 Lantau landslides (Wong & Ho 1996). This was followed by analysis of the additional data collated from landslide investigations and from the NLTI. In the early 2000s, a set of simple and conservative guidelines was established, on the basis of runout characteristics of landslide debris. The guidelines have been used in initial screening of land-use planning and development proposals, to assess whether a given site may be subject to natural terrain hazards and may require hazard study and mitigation as part of the development (Figure 8). Development of 2-D and 3-D numerical modelling of debris movement has enhanced the capability of assessment of the debris influence zone and design of risk mitigation works.



Site	Natural Terrain Hazard Study Requirement Criteria		Natural Terrain Hazard Study Required ?
	Within 20° Angular Elevation of Natural Terrain ?	Within 50m of Ground Sloping at > 15°?	
A	Yes	Yes	Yes
B	Yes	No	No

Figure 8: Screening criteria for assessing the requirement for NTHS in new development projects

(m) **Engineering geological assessment**: Engineering geological assessment is essential to NTHS. There has been continual development of natural terrain-related engineering geological mapping techniques in Hong Kong. Process-based regolith classification and mapping methodology was formulated in the Tsing Shan foothills regional study (MFJV 2002; Fletcher et al. 2002). Useful results were reported with the use of geomorphological assessments, e.g. Parry & Ruse (2002), HCL (2003), Mott Connell (2003) and OAP (2004). More recently, the methodology of natural terrain geomorphological mapping has been further developed in the north-eastern Hong Kong Island regional study, incorporating geomorphological interpretation and use of historical landslide data and air-borne Light Detection and Ranging (LiDAR) survey results.

(n) **Novel technology**: Significant advances have been made in the application of digital and remote sensing technologies to enhance the capability and efficiency of NTHS in Hong Kong. Among these, digital photogrammetry, Geographic Information System (GIS), Global Positioning System (GPS), and terrestrial and air-borne LiDAR (Figure 9) have provided promising results. A summary of the technological development and applications is given by Wong (2007). Recent progress made in air-borne LiDAR survey in Hong Kong is described in Ng & Chiu (2008). The improved capability in real-time slope monitoring is also notable (Lau et al. 2008; Solomon et al. 2008).

(a) Hillside in December 2006

(b) Ground points from LiDAR Survey

(c) Digital elevation model generated using LiDAR data

Figure 9: LiDAR data (from Ng & Chiu 2008)

(o) **Enhanced Natural Terrain Landslide Inventory (ENTLI)**: In recognition of the limited resolution and temporal coverage of the high-flight aerial photographs, the GEO completed in 2007 a major enhancement of the NTLI to incorporate results from mapping of historical natural terrain landslides using the available low-flight (taken at less than 2,400 m) and high-flight aerial photographs (MFJV 2007a). The improved inventory is known as the Enhanced Natural Terrain Landslide Inventory (ENTLI), which replaces the NTLI.

(p) **Inventory of Historical Landslide Catchments (HLC)**: Based on the ENTLI, an inventory of hillside catchments with historical natural terrain landslides that occurred close to existing buildings and important transport corridors was compiled (MFJV 2007b). These catchments are denoted as Historical Landslide Catchments (HLC). The inventory comprises about 2,700 HLC, and is the basic dataset for planning the future risk mitigation works for hillsides flanking existing developments in Hong Kong. The GEO has completed a global QRA to assess the risk levels of the HLC, diagnose their risk characteristics and project the overall risk of natural terrain landslides in Hong Kong (Wong et al. 2004). This provided key information for formulation of the natural terrain risk management strategy. Using the QRA results, a risk-based ranking system was devised for establishing the priority of the 2,700 HLC for systematic follow-up actions (Cheng & Ko 2008).

(q) **Studies of June 2008 landslides**: A severe rainstorm hit Lantau Island in June 2008 and caused about 1,600 natural terrain landslides (Figure 10). Many of the landslides were sizeable and resulted in a much greater runout distance than those that have previously occurred in Hong Kong. Detailed mapping of the landslides and the related technical development studies are being carried out. The landslides serve as a vivid reminder of the risk associated with natural terrain landslides in the densely developed setting of Hong Kong.

Figure 10: Landslides in Tai O, Lantau in the June 2008 rainstorm

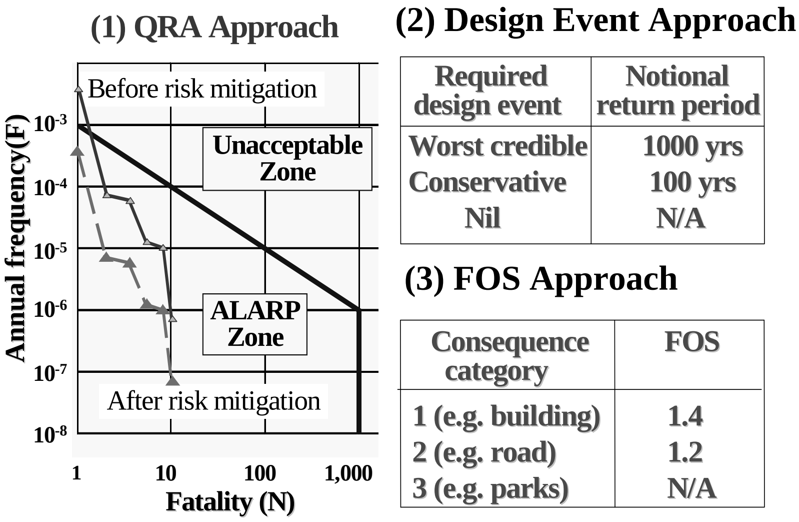
1.4 1977 to 2010 Landslip Preventive Measures (LPM) Programme

Prior to the establishment of GEO in 1977, there was very limited geotechnical control of slope formation both in the private and public sectors. Many old man-made slopes formed before 1977 did not meet the current safety standards, and they constituted the main share of the landslide risk in Hong Kong. Since 1977, the Government has been implementing the Landslip Preventive Measures (LPM) Programme to retrofit substandard government man-made slopes and to conduct safety-screening studies on private slopes, according to their ranked order of priority.

Government's concerted effort in the past 30 years has brought about substantial improvement in the safety of man-made slopes and a significant reduction in the number of landslide fatalities. When the current phase of the LPM Programme is completed in 2010, a total of about 7,000 man-made slopes will have been dealt with under the Programme and the overall landslide risk from man-made slopes will be substantially reduced to less than 25% of that which existed in 1977, reaching a reasonably low level that is commensurate with the international best practice in risk management.

With improved awareness of the potential natural terrain hazards and trend of increasing development close to steep hillsides, administrative measures were introduced in the early 2000s to control undue risk increase from new developments, through avoidance of development in hazardous areas as far as possible, and study and mitigation of hazards as part of the developments where necessary. Ad-hoc studies and mitigation of natural terrain landslide hazards affecting existing developments have also been undertaken following the ‘react-to-known-hazard’ principle, i.e. when significant hazard becomes evident, the case is injected into the LPM Programme for study and risk mitigation. In practice, the majority of the ‘react-to-known-hazard’ cases dealt with under the LPM Programme since 2000 comprised sites affected by newly occurring landslides, and the expenditure incurred constituted a small proportion (within 3%) of that of the LPM Programme.

The insights gained on natural terrain hazards through the technical development work have resulted in rationalisation of the technical approach for dealing with the hazards. Three different approaches, viz., Factor of Safety, QRA and Design Event (Figure 11), are recommended for dealing with natural terrain hazards in Hong Kong. The ‘react-to-known-hazard’ cases dealt with under the LPM Programme and other cases as part of new development works have provided the geotechnical profession with experience in applying the approaches:



(2) Design Event Approach

Required design event	Notional return period
Worst credible	1000 yrs
Conservative	100 yrs
Nil	N/A

(3) FOS Approach

Consequence category	FOS
1 (e.g. building)	1.4
2 (e.g. road)	1.2
3 (e.g. parks)	N/A

Figure 11: Different approaches adopted in assessment and mitigation of natural terrain landslide hazards in Hong Kong

(a) **Factor of Safety Approach**: The conventional engineering approach, which is commonly applied to man-made slopes, has been to design the slopes to the required factor of safety. The relevant slope design requirements are stipulated in the Geotechnical Manual for Slopes (GCO 1984). This approach aims to avert landslides by ensuring a prescribed margin of safety, and is also applicable to natural terrain if the design objective is to reduce the likelihood of slope failure. A typical example of such application is in the study of natural terrain below a development site to ensure that natural terrain landslides which may adversely undermine the site will not occur. However, this approach is often not suitable for use in dealing with a large area of natural terrain that poses a risk to the facilities located at its toe.

(b) **QRA Approach**: This approach is applicable when designers opt for quantification and management of natural terrain landslide risk instead of prevention of failures. Based on this approach, the designer carries out QRA to quantify the risk of natural terrain landslides. The need for any necessary risk mitigation measures is assessed by reference to GEO’s risk guidelines (ERM 1998). This approach would entail a detailed assessment of the probability and consequence of natural terrain landslides, with account taken of the uncertainties in an explicit and systematic manner, and consideration of the tolerability of the assessed risk level. It may be considered as the most rigorous and comprehensive assessment. The assessment often requires expert input and may be fairly involved and costly.

(c) **Design Event Approach**: This approach adopts a risk-based design framework and is applicable when designers opt for mitigation of natural terrain landslide risk without carrying out a formal QRA. Under this approach, the required mitigation measures (e.g. debris-resisting barriers) 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 manner through the assessment of the design event, e.g. a landslide of a certain size with a given degree of mobility. Depending on the potential landslide consequence and susceptibility of the site, the required design event may either be a 'worst credible' event or 'conservative' event, which correspond to a notional return period of 1,000 years and 100 years, respectively. The design event approach is relatively easy to apply as it does not demand formal and rigorous quantification of risk, and is favoured by many practitioners in Hong Kong. However, it gives no provision for consideration of 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.

1.5 Post-2010 Landslip Prevention and Mitigation Programme (LPMitP)

While the overall safety of man-made slopes has greatly improved with the progress of the LPM Programme, the risk of natural terrain landslides is on the rise due to increase in population and more developments taking place close to steep hillsides. From QRA, it was projected that the overall risk of landslides from natural terrain would be comparable to that from man-made slopes by 2010 (Wong et al. 2004). In particular, the identified HLC form a known target group of sites deserving attention, pursuant to the ‘react-to-known-hazard’ principle. This calls for an expanded effort to systematically combat and contain their risk to a level that is as low as reasonably achievable, in order to discharge Government’s due diligence.

In 2007, the post-2010 Landslip Prevention and Mitigation Programme (LPMitP) was endorsed as a long-term landslide risk mitigation initiative (Development Bureau 2007). The LPMitP will commence in 2010 upon completion of the current LPM Programme, as a rolling programme with the following annual output: (a) upgrade 150 Government man-made slopes; (b) conduct safety-screening studies for 100 private man-made slopes; and (c) implement risk mitigation works for 30 natural hillside catchments.

About 50% of the LPMitP resources will be deployed to deal with natural terrain landslide hazards, which is commensurate with the projected risk distribution in 2010. Following the ‘react-to-known-hazard’ principle, catchments in the HLC inventory will be selected based on their risk-based ranking order for action under LPMitP. The LPMitP marks a new chapter in Hong Kong’s landslide risk management, by incorporating systematic study and mitigation of natural terrain landslide risk as an integral part of Hong Kong’s long-term slope safety endeavour.

2 CHALLENGES AHEAD

2.1 Challenging Undertaking

The advances in technology and understanding of natural terrain landslides in Hong Kong over the years have paved the way for combating natural terrain landslide hazards under the LPMitP. However, the challenges that the geotechnical profession will face in this task cannot be overlooked, particularly in view of the following:

- Study and mitigation of natural terrain landslide risk is a relatively new undertaking in Hong Kong. Geotechnical practitioners, including geotechnical engineers and engineering geologists, need to gear up their knowledge and skills in order to meet the new challenges.

- The annual output of natural terrain landslide risk mitigation works under the LPMitP is more than 10 times of that under the current LPM Programme. To cope with the sharp increase in natural terrain work, the demand for human resources and other related provisions for delivery of the LPMitP is enormous.

- Natural hillsides cover large areas and involve highly variable ground and hydrogeological conditions. Their behaviour is affected by geomorphological processes and anthropogenic and climatic influences, which are not fully understood given the current state of knowledge and the variability and uncertainties involved. The conventional geotechnical approaches of detailed ground investigation and slope engineering are generally not applicable. The uncertainties involved need to be properly addressed in risk assessment and mitigation.

- Unlike the retrofitting of man-made slopes, it is often impractical, costly and environmentally undesirable to carry out extensive slope stabilization works on natural hillsides. Instead, natural terrain landslide risk is typically dealt with by provision of mitigation measures, such as the debris-resisting barriers and diversion channels. Hillsides after risk mitigation would remain susceptible to landslides which, in the event of occurrence, will inevitably result in social disruption and nuisance. Furthermore, residual risk will always exist because risk mitigation works are not aimed at achieving 100% risk reduction, which is not credible. The general public may not fully comprehend what can be achieved and the uncertainties involved.

- The number, scale and severity of natural terrain landslides are sensitive to rainfall conditions. Given the observed trend of climate change, it is possible that extreme rainfall conditions will occur more frequently in future. This could result in increased impact from natural terrain landslides and introduce further uncertainties to risk assessment and mitigation.

2.2 What Could Go Wrong

The geotechnical profession has to be vigilant in meeting the challenges associated with natural terrain hazards. The few years ahead may involve a critical period for building up experience and overcoming teething problems. The following are some possible scenarios of what may go wrong:

(a) **Occurrence of a landslide/debris flow with debris volume significantly in excess of the Design Event allowed for in the provision of mitigation measures**: This could result in significant damage or collapse of debris-resisting barriers, over-flow of debris from fully filled barriers, etc. The scenario may arise from under-estimation of the possible scale of the source failure volume, e.g. an unforeseen deep-seated failure, shallow but spatially extensive landslide, and multiple-source failures. Insufficient provision for a debris flow involving significant entrainment or watery debris, which can escalate the debris volume, may also give rise to this problem.

(b) **Occurrence of a landslide/debris flow discharging debris that is significantly more mobile than that considered in the design of mitigation measures**: This could result in significant damage or collapse of debris-resisting barriers, impact on areas that have been assessed as being beyond the reach of the debris, etc. Inadequate allowance for debris mobility may occur because of under-estimation of debris volume. It may also be the outcome of a lack of comprehension of the possibility of development of watery debris. Use of inappropriate rheological models and debris runout parameters may also under-predict the reach of landslide debris.

(c) **The actual debris runout path is significantly different from that considered in the design of mitigation measures**: This could result in debris hitting unprotected zones that have not been recognized as being within the debris runout path, whereas the debris-resisting barriers are placed at wrong locations that fail to intercept the debris runout. The debris runout path may be wrongly predicted if the debris runout is simply prescribed as following the direction of the steepest slope, without due consideration of other relevant factors that may change the debris runout direction. Use of unreliable digital terrain data and dynamic debris modelling algorithms, e.g. those that do not cater for possible bifurcation of the debris trail, could also result in a misleading assessment of the likely debris flow path.

(d) **Occurrence of a landslide in a low-ranked HLC resulting in serious consequences**: This could cast doubt on the reliability of the priority ranking methodology and possible human errors in assessing the ranking scores. It could also invite criticism that the LPMitP should be speeded up. The scenario may occur in association with some 'unfortunate' combinations of events that lead to dire consequences, e.g. a debris flow inundating vehicles queuing on a minor road that is blocked by flooding or a minor roadside landslide (Figure 12), as in the case of the 1995 debris flow that caused 22 fatalities at a slip road in the Genting Highland, Malaysia (Abdullah et al. 2007). The public's perception may even be worse if the failure occurs on a catchment adjoining other catchments where mitigation works have been carried out but without occurrence of any noticeable landslides in the rain storm.

Figure 12: Debris flow affecting a road with low traffic density
(Note: Consequences can be serious in case of queuing of traffic on the road during debris flow)

(e) **Serious failure at a hillside that has not been identified as an HLC**: This could arouse scepticism about the 'react-to-known-hazard' principle, and the criteria adopted and any human errors in the identification of HLC. The scenario could occur if the hillside that fails does not have any known past landslides, or the known past landslides occurred at some distance from the existing facilities (i.e. not meeting the proximity criteria adopted for identification of HLC), or where the existing facilities being affected are not categorised as important facilities (i.e. building structures and important transport corridors) as considered in identification of HLC. This may result in a demand for adopting a more proactive approach in searching for catchments that are vulnerable to landslides, or expanding the criteria adopted in compiling the HLC inventory, or both.

(f) **Inadequate emergency response**: The number of natural terrain landslides will increase exponentially with rainfall intensity. Thousands of natural terrain landslides could occur in an extreme rainstorm, and pose an acute and unprecedented strain to the landslide emergency response system. Should the emergency system become overloaded, possible drop in efficiency in attending to landslide incidents may result in delay in taking emergency actions to minimise risk exposure. Difficulty in mobilization of a large number of experienced inspection teams to ascertain the hillside conditions and the possible residual risk after widespread landslides, particularly in inclement weather conditions, could result in emergency decisions being made in the face of considerable uncertainties. Recommendations on emergency actions to be taken, which subsequently turn out to be either insufficiently safe or too conservative, could affect public safety and convenience and attract dissatisfaction. The June 2008 rainstorm that affected western Lantau is an illustration of the potential challenge. Had the rainstorm hit a more densely populated region, the demand for emergency responses would have been much more severe.

Scenarios (a) to (c) above are directly related to practitioners that are involved in natural terrain risk assessment and mitigation works. In the event of occurrence, they could result in concerns being raised about the adequacy of the risk mitigation provisions, credibility of the professional practice, and professional competence. Scenarios (d) to (f) above primarily involve the 'risk manager', i.e. the GEO. Apart from putting the natural terrain risk management strategy in question, they could potentially jeopardise the public's trust in Hong Kong's Slope Safety System.

There is no room for complacency notwithstanding the advances made in the subject of natural terrain landslides in Hong Kong over the years. As we embark on a new era of landslip prevention and mitigation works under the LPMitP, more has yet to be learnt by the geotechnical profession in improving the understanding of natural terrain landslides and capability in combating their risk. Some specific aspects of technological development concerning natural terrain failures, debris movement and risk mitigation strategy are highlighted in the next few sections.

3 INSIGHTS INTO NATURAL TERRAIN FAILURES

3.1 Some Misunderstanding

Before better knowledge about natural terrain landslides became available, there had been some early suppositions that the natural hillsides in Hong Kong are old and mature landforms and thereby should have evolved into a relatively 'stable' condition. Hencher (2000) gave a commentary on these early suppositions, with reference to the observations reported in Lumb (1975) and Ruxton (1980). These early suppositions included the views that natural hillsides show no signs of creep, all failures are first-time slips, and the concept of 'ripening' being dismissed in view of the long time needed for the degree of weathering to become significantly altered by chemical weathering.

These suppositions might sound reasonable in the light of the Second Law of Thermodynamics, which states that the entropy of an isolated system which is not in equilibrium will tend to increase over time, approaching a maximum value at equilibrium. In simple terms, it implies that over time, differences in temperature, pressure, density, etc. will tend to even out in a physical system that is isolated from the outside world. Given the longevity of the existence of the Hong Kong rocks and the relatively inactive tectonic setting, one might expect that the terrain should have reached an advanced stage of self-equilibrium (i.e. entropy). As a contrast, in the Campania Region of Italy, rain-induced natural terrain landslides occur on pyroclastic deposits (Figure 13) that have been in place for only a few hundred years (Versace et al. 2007). This notion could lead to a false sense of security about the stability of natural terrain in Hong Kong.

Figure13: Natural terrain landslides in Sarno, Campania, Italy
(Note: Photo from http://www.commissario2994.it)

Whilst acknowledging that 'natural slopes are frequently close to limiting equilibrium over very large areas', the Geotechnical Manual for Slopes (GCO 1984) stipulates that natural slopes need not meet the factor of safety requirements for slope design provided that two conditions are met: (i) the slope is undisturbed; and (ii) a careful examination is made to determine that there is no evidence of instability or severe surface erosion. There was apparently a time in the past that some practitioners presumed that these two conditions could be easily met in many places. Indeed, as far as natural terrain hazards are concerned, much of the attention was given in the past to boulder falls, instead of slope instability. In 1997, the Geotechnical Control Conference of the GEO clarified that 'evidence of instability' refers to 'evidence relevant to future instability'. It is now known that the above two criteria are very difficult to meet in reality. Hong Kong's hillsides rarely have a clean sheet in terms of past instabilities, not to mention potential future instabilities. Furthermore, disturbed hillsides are also fairly commonplace within or bordering developed areas.

3.2 Proper Perspective

In the 1990s, with the large amount of data available from the study of the November 1993 Lantau landslides, review of records of failures in the rainstorms of 1966 and 1982, together with compilation of the NTLI, it became evident that natural hillsides in Hong Kong were rather susceptible to rain-induced, shallow failures. Field investigations have revealed that failures typically occur within 1 to 2 m of the surface mantle, where erosion pipe holes, dilation and partial infilling of relict discontinuities, and localised tension cracks are often observed. The hillsides are subject to on-going degradation, and a large number of shallow landslides can be triggered by heavy rain.

Shallow landsliding is still an active process on the natural hillsides, under the prevailing climatic conditions. The potential for further failures is far from depletion, even on catchments that have many known historical landslides. This is also supported by the findings of rainfall-landslide correlations that the density of natural terrain landslides increases exponentially with rainfall intensity (Figure 14). Landslide occurrence has been found to be sensitive to rainfall intensities that cover durations ranging primarily from 4 to 24 hours, which is consistent with the observed shallow depth of failure triggered by slope saturation and transient build-up of water pressures as a result of infiltration and sub-surface seepage flows.

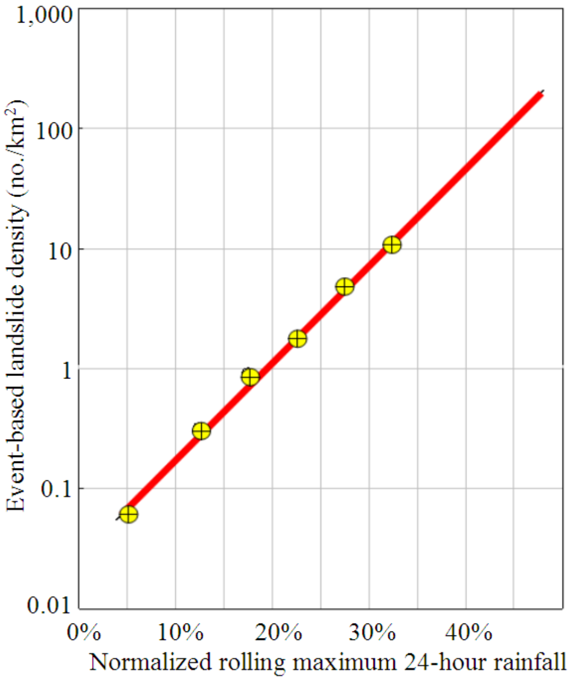
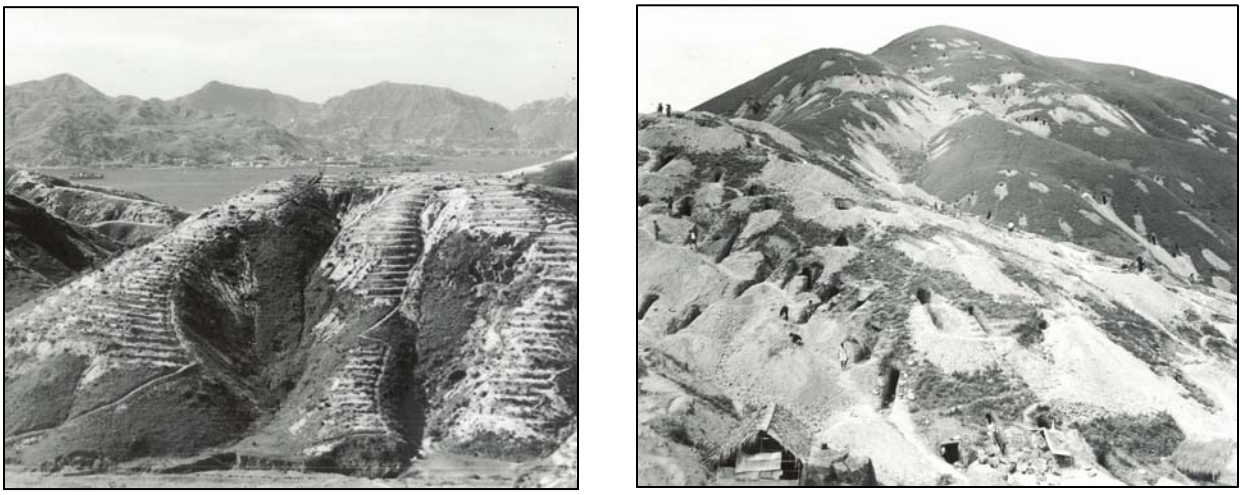


Figure 14: Rainfall-natural terrain landslide correlation

$$(\text{Note: Normalised rainfall} = \frac{\text{rainfall intensity}}{\text{mean annual rainfall}})$$

The apparent mismatch between the active landsliding process and the relatively old landform may be explained by a number of reasons. Firstly, the weathered profiles that overlie the solid rocks are much younger than the rock formation. Ruxton (1980) postulated that the weathered profiles in Hong Kong might be more than 200,000 years old, while it might take about 17,000 years for one metre thickness of rock to be weathered completely to halloysite and quartz. Hence, the surface one metre or so of the ground, which is susceptible to landslides, may be relatively young as far as its present properties are concerned. Secondly, the present-day hydrogeological and climatic conditions may be rather different from those in the geological past. This could be reflected by the drastic changes in the sea level over the past 20,000 years, with the current sea level possibly near the historical highest level. Thirdly, the hillsides may have been disturbed, to different degrees, in the recent history. Deforestation took place in Hong Kong in the past several hundred years including the Second World War period. This could have effects on slope hydrogeology, which affects slope stability. Anthropogenic activities, including formation of walking trails and roads, mining, military trenches and tracks, grazing, localised cutting and filling, cultivation, village graves, etc, could bring physical disturbance to the terrain (Figure 15).



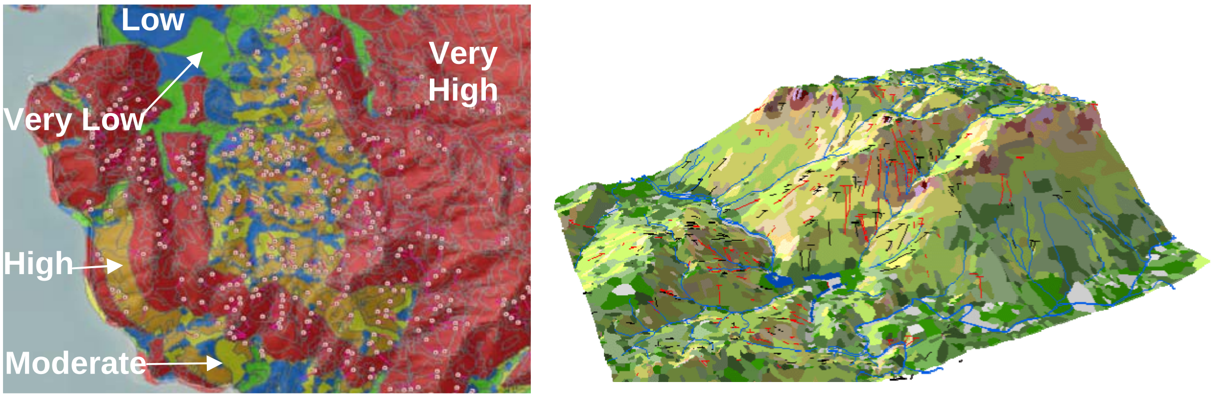
(a) Agricultural terracing

(b) Mining activities

Figure 15: Human disturbance to hillsides in Hong Kong

Statistical analyses of landslide susceptibility provide further insight into the spatial distribution of natural terrain landslides. The territory-wide landslide susceptibility analysis by Evans and King (1998), based on correlation with slope angle and geology, found that the natural terrain of Hong Kong could be differentiated into five susceptibility classes. The calculated landslide densities for the five classes vary from ≤10 to >100 landslides per km^2, which corresponds to an average frequency of failure from about ≤0.1 to >1 landslides/km^2/year (Figure 16). Wong (2003) diagnosed the implications of the limited resolution in the calculated landslide frequency among the classes, which spans only about one order of magnitude between the least and most susceptible classes. Such a resolution is considered insufficient for differentiation of vulnerable hillsides, given the potentially high consequence of landslides in Hong Kong. From a different perspective, the low resolution probably demonstrates a lack of understanding of the quantifiable factors that control landslide susceptibility. It may also reflect the possibility that the natural hillsides in Hong Kong are generally susceptible to failure, with a relatively small difference in the landslide susceptibility between the more problematic and less problematic terrain.

Combined rainfall-susceptibility analyses by GEO showed that spatial and temporal variations in rainfall intensity have a significant influence on landslide susceptibility. In particular, it was observed that at low rainfall intensity, landslides tend to occur predominately on more susceptible terrain. However, under high rainfall intensity, even less susceptible terrain would suffer from failures. This leads to the same inference: Hong Kong’s steep hillsides are actively responding to heavy rain and are far from reaching a state of high entropy against shallow failures.



(a) 2-D landslide susceptibility map

(b) 3-D presentation

Figure 16: Terrain landslide susceptibility classification.

(Note: Very High = landslide frequency > 100 no./km^2
High = landslide frequency 40 - 100 no./km^2
Moderate = landslide frequency 20 - 40 no./km^2
Low = landslide frequency 10 - 20 no./km^2
Very Low = landslide frequency ≤ 10 no./km^2)

The above observations do not apply to deep-seated failures, say, depth of landslide exceeding a few metres. Deep-seated failures rarely occur on the natural terrain of Hong Kong. Some of the isolated cases of deep-seated landslides that have taken place were significantly affected by human activities, e.g. the 1995 Shum Wan Road landslide (GEO 1996), which was affected by uncontrolled discharge of a large amount of surface water from the road that traversed the site. Some were slow-moving landslide bodies subject to prolonged deformation/displacement, e.g. the Tsing Shan debris lobe (Parry & Campbell 2003). Some appeared to be controlled by special geological structures or conditions (e.g. McMackin et al. 2009). There are no indications that the natural hillsides in Hong Kong are active in deep-seated landsliding process. It seems that, in general, such a process has reached a state of high entropy, although hillsides with latent geological weaknesses may be re-activated by major human disturbance or under very adverse weather conditions.

3.3 Recent Development

Recent studies, including those on the June 2008 landslides, are throwing further light on natural terrain failures in Hong Kong. The following are some reflections on areas for further advances in the assessment and mitigation of natural terrain hazards:

(a) **Insights from historical landslides and geomorphological assessment**: The ENTLI has provided improved data for assessment of the spatial and temporal distribution of natural terrain landslides. Analysis of the June 2008 landslides on Lantau showed that 80% of the landslides occurred within 50 m of two or more ENTLI features, and 92% within at least one ENTLI feature. When the proximity criterion is reduced to within 30 m, the calculated figures are still as high as 55% and 79%, respectively. Historical landslides appear to have certain degree of clustering, and new landslides tend to occur within or close to these clustered zones (Figure 17). Further work is required to interpret the phenomenon in geomorphological and engineering geological context, to facilitate demarcation of terrain that is more prone to failure.

(b) **Prospect of susceptibility analysis**: So far, landslide susceptibility analyses have mainly focused on consideration of landslide density, without explicit classifications that account for landslide type, scale, runout distance, etc. This would not only affect the resolution of the analysis due to lumping of different types of landslides in the analysis, but also render the results of susceptibility zoning not useful. While it is tenable that steep hillsides are all susceptible to failures, the majority of the failures are small-scale landslides with insignificant risk concern. Confining the susceptibility analysis to sizeable landslides and debris flows, i.e. excluding the more commonly occurring small-scale failures, may give more insights into the potential sources of major hazards. Many other countries are giving increasing attention to landslide susceptibility and hazard zoning for use in development planning and landslide risk management. Publication of related technical guidelines by AGS (2007) and JTC-1(2008) may further promote the work. Hong Kong's experience has shown that the susceptibility and hazard zoning methodology commonly adopted in other countries is of limited resolution and reliability for dealing with relatively small-scale failures, in Hong Kong's context. With the use of improved data and methodology, there could be some prospect of further pursuing the work and achieving better results.

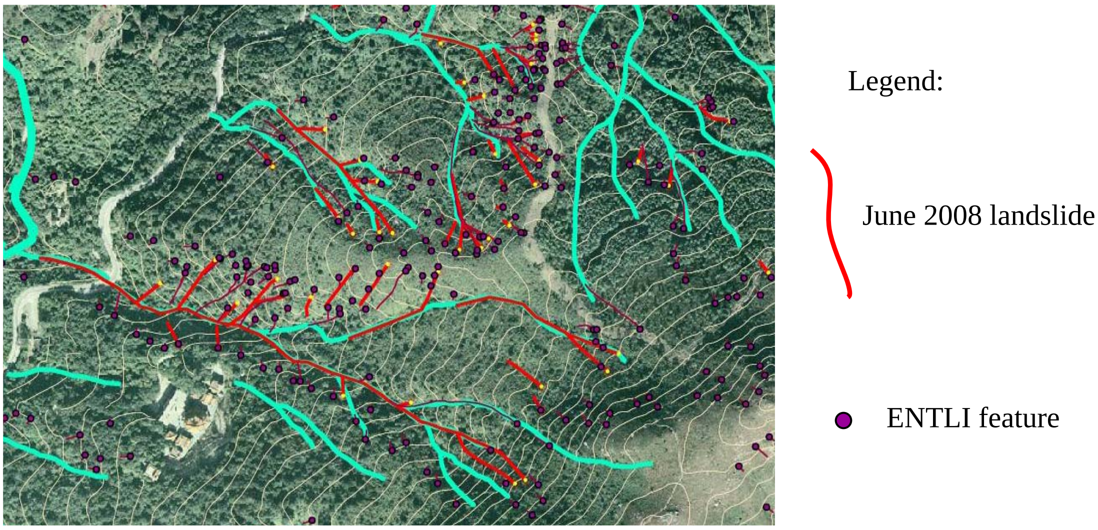
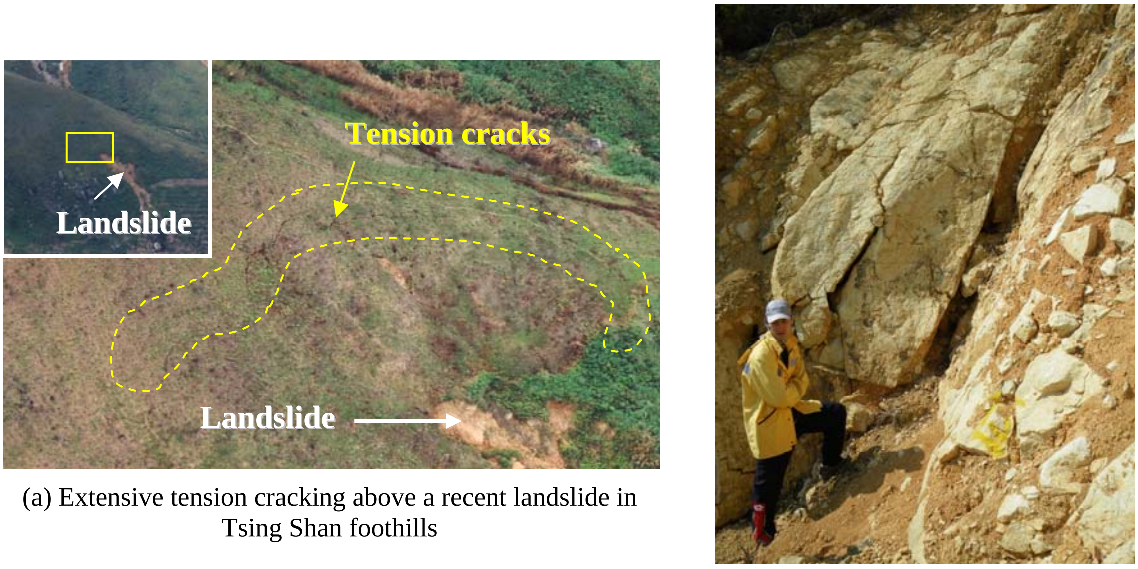


Figure 17: June 2008 natural terrain landslides occurred in closely proximity to ENTLI features

(c) **Hillside deterioration**: While field data showing evidence of hillside deterioration have become more abundant (e.g. Hughes et al. 2002; Wong et al. 2004; MGSL 2007), details of the deterioration process are still not fully known. These include possible causes and mechanisms of deterioration, time span to ripening, and factors controlling the transition from slope distress to occurrence of uncontrolled detachment. From time to time, tension cracks are found on hillsides after heavy rain or after vegetation is burnt off by hill fire (Figure 18). These may be newly formed tension cracks, or pre-existing cracks subject to intermittent movement. Development of tension cracks would affect the hydrogeology and strength of the groundmass, and significantly alter the stability conditions of the hillside. It appears that some hillsides may go through a prolonged stage of development of tension cracks, or other forms of signs of distress (e.g. slope deformation involving dilation of relict discontinuities in weathered rock, Figure 18), before occurrence of uncontrolled detachment. This offers some scope for use of continuous slope monitoring to acquire information for diagnosing the hillside behaviour and managing landslide risk. It also brings out the importance of identification of signs of distress in NTHS and the need for re-assessment after development of signs of distress on a hillside that has previously been subjected to NTHS.

(d) **Low-frequency, large-magnitude events**: Low-frequency, large-magnitude landslides pose a distinct challenge to landslide risk management, in that a large failure may lead to serious consequences and that little knowledge is available about the nature of these infrequent events and where they may take place. While the 1990 Tsing Shan debris flow and 1995 Shum Wan Road landslide may be taken as examples, there seems to be a perception that similar events rarely occur in Hong Kong. Recent mapping of the June 2008 landslides reveals that large magnitude events, in particular sizeable debris flows with long runout distance, may not be as rare as one might have perceived (Figure 19). These newly available field data indicate that a range of circumstances could result in sizeable failures or debris flows. They include: (i) deep-seated landslides controlled by geological structures or involving re-activation of relict landslide mass; (ii) shallow failures that are spatially extensive; (iii) detachment of distressed hillsides with extensive tension cracking; (iv) confluence of multiple landslides in a debris flow catchment, forming a sizeable debris flow; and (v) debris flows involving significant entrainment or watery debris, particularly at major drainage lines. Further work is needed to enhance our knowledge of these events and capability in assessing and managing their risk.



(a) Extensive tension cracking above a recent landslide in Tsing Shan foothills

(b) Open and infilled discontinuities at landslide scarp of the main source of the June 2008 Shek Mun Kap debris flow

Figure 18: Signs of deterioration of natural hillsides

Figure 19: Large debris flows on Lantau in the June 2008 rainstorm
(Note: Shek Pik No. 1 and No. 2 debris flows are shown; see Figure 5 for debris flows in the area in November 1993)

4 UNDERSTANDING DEBRIS MOVEMENT

4.1 Prevailing Knowledge

Establishing the possible reach of debris runout is essential to assessing natural terrain landslide risk. Although studies on debris mobility were started in Hong Kong several years later than in some other countries, major advances have been made over the years, which put Hong Kong on a par with other key technical leaders. This is attributed to: (i) availability of good quality landslide data on debris runout; (ii) development of numerical modelling capability in parallel with acquisition of field data, which facilitates understanding of mechanisms and calibration of numerical models; and (iii) a demand for application given the need for assessment of landslide consequences and design of debris-resisting structures.

In respect of assessment of debris mobility, the progress made and knowledge acquired over the years may be summarised as follows:

(a) **Empirical assessment**: Collection of field data on the runout of landslide debris since 1993 has enabled empirical correlations of debris mobility with landslide mechanism and volume. The work initially covered landslides on man-made slopes (Wong & Ho 1996), and was extended to include natural terrain landslides (Lau & Woods 1997; Wong et al. 1998). The correlations were principally based on consideration of the debris travel angle (Cruden & Varnes 1996), which is related to the apparent angle of friction that accounts for the energy loss in the event of a frictional material sliding along the runout path. When applied to steep hillsides, use of travel angle in assessing the reach of debris has some limitations, in that uncertainties in travel angle may result in significant difference in the predicted travel distance. Direct correlations with travel distance offer a convenient alternative, although this is not rigorous in terms of energy consideration. Attempts were made in such correlations, which have occasionally been applied in site-specific NTHS (e.g. OAP 2003). In other cases, empirical correlations were made with proximity zones defined by a combined consideration of travel angles and travel distance, using historical landslide data (Figure 20). These have been adopted in global QRA and in site-specific NTHS (Wong 2005).

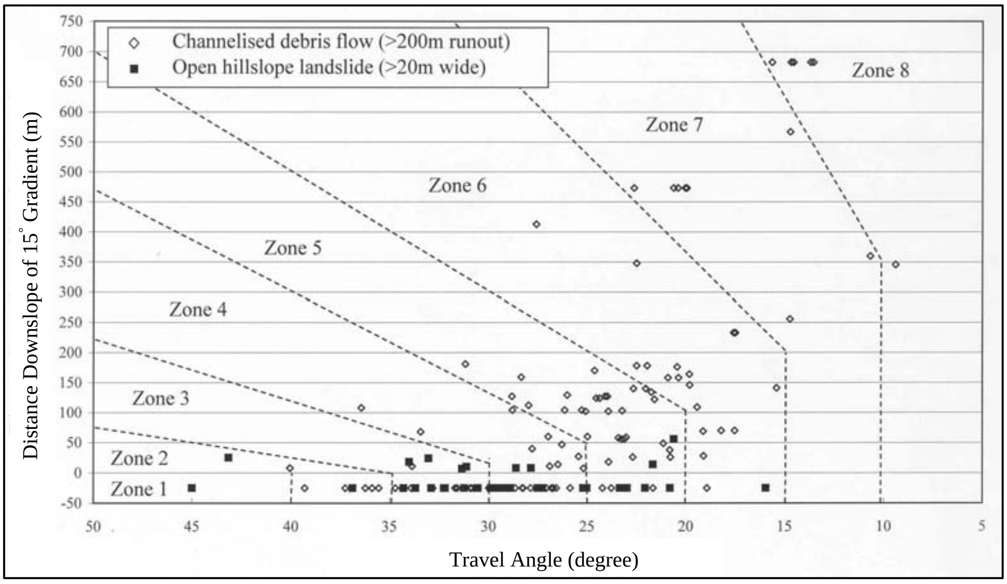


Figure 20: Empirical proximity zoning based on historical debris runout data

(b) **Analytical simulation**: In the late 1990s, analytical approaches were introduced for use in assessment of the reach of landslide debris in Hong Kong. The mass-balance approach has been adopted to evaluate the changes in the active volume of a debris flow based on empirical correlations between the rates of debris entrainment/deposition and channel characteristics, e.g. gradient and channelization ratio (Lau & Woods 1997; OAP 2004). However, this method suffers from lack of consideration of debris flow rheology and may give misleading results if the empirical data are not representative of the characteristics and site conditions of the debris flow that is being analysed. Dynamic modelling of debris as a continuum based on consideration of the principles of conservation of mass, momentum and energy has gained popularity. The method gives a more rigorous simulation of the debris flow rheology. The governing debris runout input parameters may be back-analysed from historical landslide cases. The 2-D Dynamic Analysis (DAN) model developed by Hungr (1995) was introduced for use in Hong Kong (Ayotte & Hungr 1998). Subsequently, the GEO developed its own 2-D dynamic modelling algorithm, commonly known as Debris Mobility Modeller (2D-DMM, Figure 21), based on similar formulation and solution methodology (Kwan & Sun 2006). Since then, the 2D-DAN and 2D-DMM codes have been routinely applied in the assessment of debris mobility in Hong Kong. Based on what was known at the time, Lo (2000) reviewed methods of debris mobility analysis, and gave suggestions for assessing debris mobility and debris impact loads in the design of landslide debris-resisting barriers.

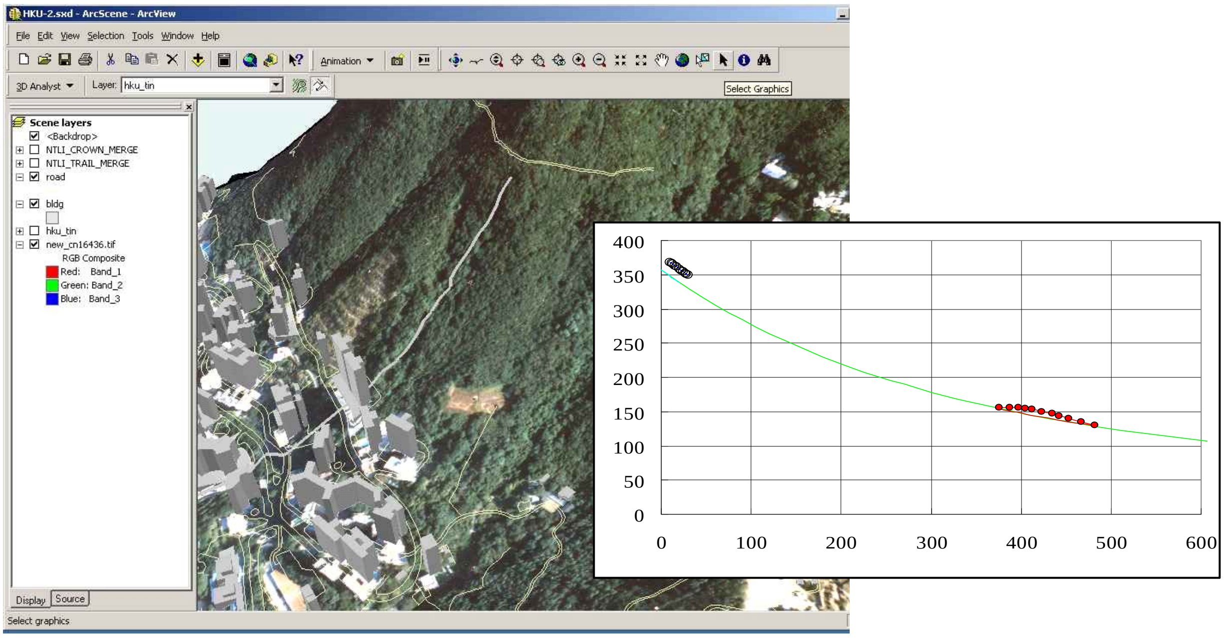
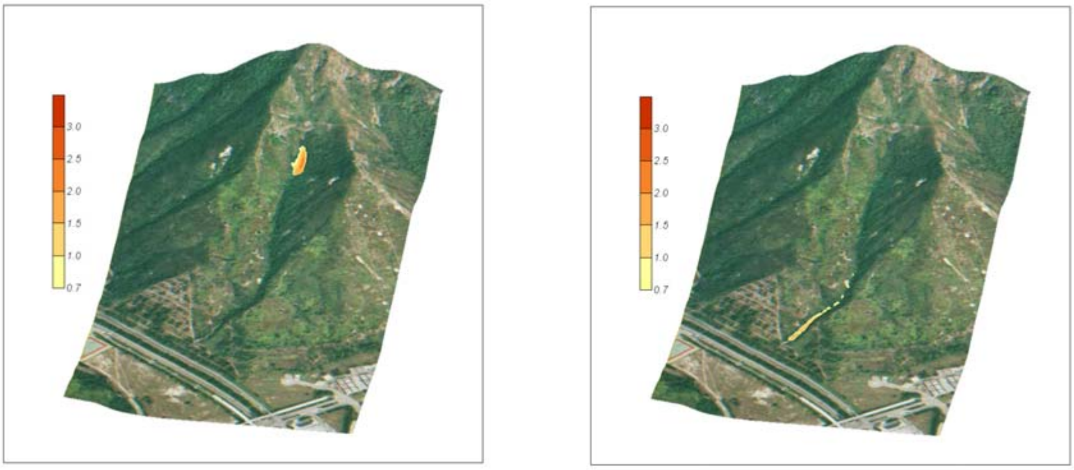


Figure 21: 2D-DMM debris runout modelling

(c) **Advanced numerical modelling**: In recent years, there was major development of 3-D dynamic continuum modelling capability. The key areas of development and performance of these 3-D algorithms are described in an expert panel review report on the international benchmarking exercise on debris mobility modelling hosted in Hong Kong in 2007 (Hungr et al. 2007a). The exercise revealed that several 3-D algorithms had the capability of simulating a wide range of cases and achieving consistent performance. These included: the DAN3D (McDougall 2006; Hungr et al. 2007b), GEO's 3D-DMM (Kwan & Sun 2007), RASH3D (Pirulli 2005; Pirulli & Scavia 2007), and the SPH code developed by Pastor et al. (2007). The finite element code MADflow developed at the University of Hong Kong (Chen et al. 2006) also gave promising results, although it could not cater for splitting and merging of landslide debris. These 3-D algorithms call for solution methodologies that are different from their 2-D counterparts, but the rheological models and debris runout parameters adopted are the same. The 3-D codes offer several distinct functionalities, which are superior to 2-D modelling and important to risk assessment: (i) the debris runout path and the lateral debris inundation zone are simulated in the modelling, instead of subjectively prescribed; (ii) splitting and merging of debris during runout, which occurred in many actual cases, can be allowed for; and (iii) effects of entrainment, presence of debris diversion and retention facilities, debris flow depth, length of the debris flow mass, 3-D profile of debris deposition, etc. can be more realistically simulated (Figure 22). Apart from these algorithms, the FLO-2D (Julien & O'Brien 1997) and PFC (ITASCA 1999) codes, which are commercially available, have also been applied in debris runout analysis in some special circumstances. FLO-2D adopts flood routing models and has been used in 3-D simulation of debris flood events in Hong Kong (Figure 23). PFC models the dynamic behaviour and interaction of discrete particles, and can be applied to simulate rock falls and avalanches.



(a) When debris entered drainage line (b) When debris was discharged at the drainage outlet

Figure 22: Three dimensional debris mobility modelling of the June 2008 Yu Tung Road debris flow using 3D-DMM (Note: Modelling results showed that the length of the debris body increased from about 50 m in (a) to about 190 m in (b), which is consistent with the video record of the debris flow)

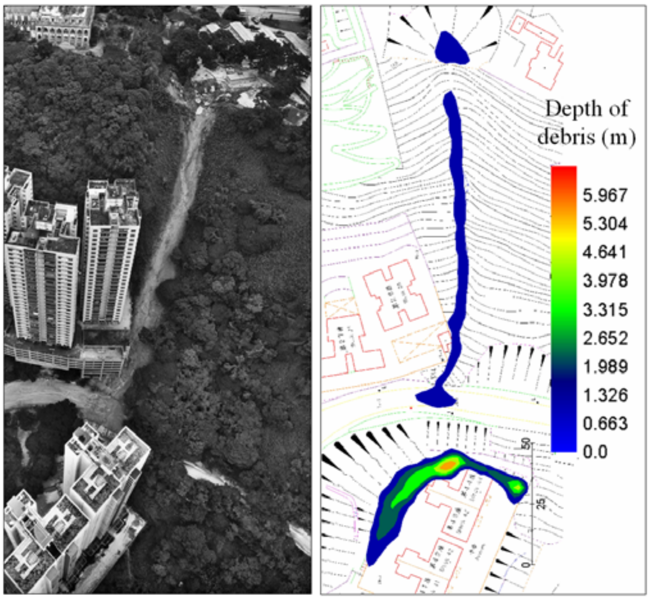
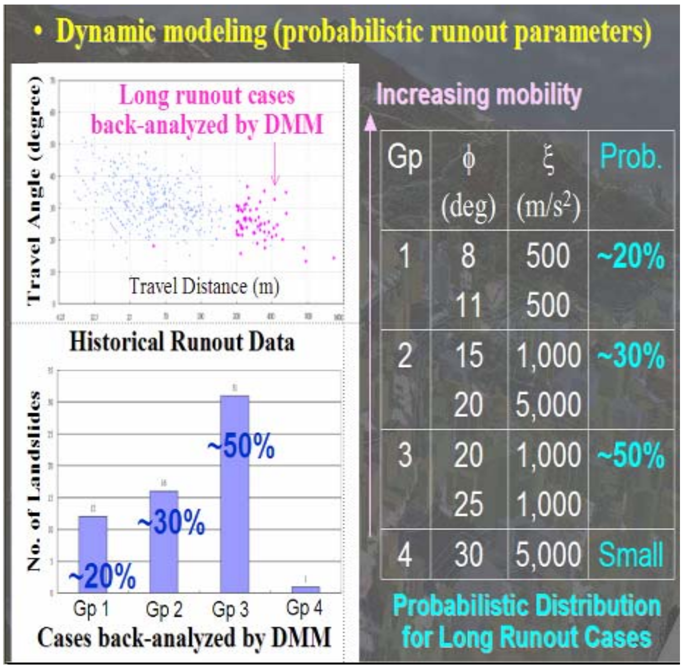


Figure 23: FLO-2D simulation of debris flow event
(Note: The 1992 Baguio Villa landslide is shown)

Based on the findings of the back-analyses of some 20 natural terrain landslide cases in Hong Kong (Ayotte & Hungr 1998), the GEO suggested the following conservative scenarios for use in the assessment of natural terrain landslide debris runout (Lo 2000): (i) for open hillside failures, the Friction rheology can be used with an apparent angle of friction of 25° for debris volumes < 400 m^3 and 20° for debris volumes ≥ 400 m^3; and (ii) for channelised debris flows, either the Friction rheology with an apparent angle of friction of 20°, or the Voellmy rheology with an apparent angle of friction of 11° and a turbulence coefficient of 500 m/s^2 can be used.

Further back-analyses were carried out by the GEO in recent years. These included review of the empirical runout data extracted from the NTLI and systematic back-analysis of about 60 known long runout cases. The work has shown that use of the Voellmy rheology is more appropriate in simulation of debris flows in Hong Kong. The probabilistic distribution of different sets of runout parameters for mobile debris flows was derived (Figure 24), which provides improved data for use in predicting the debris impact zones and assessing landslide risk under a probabilistic framework.



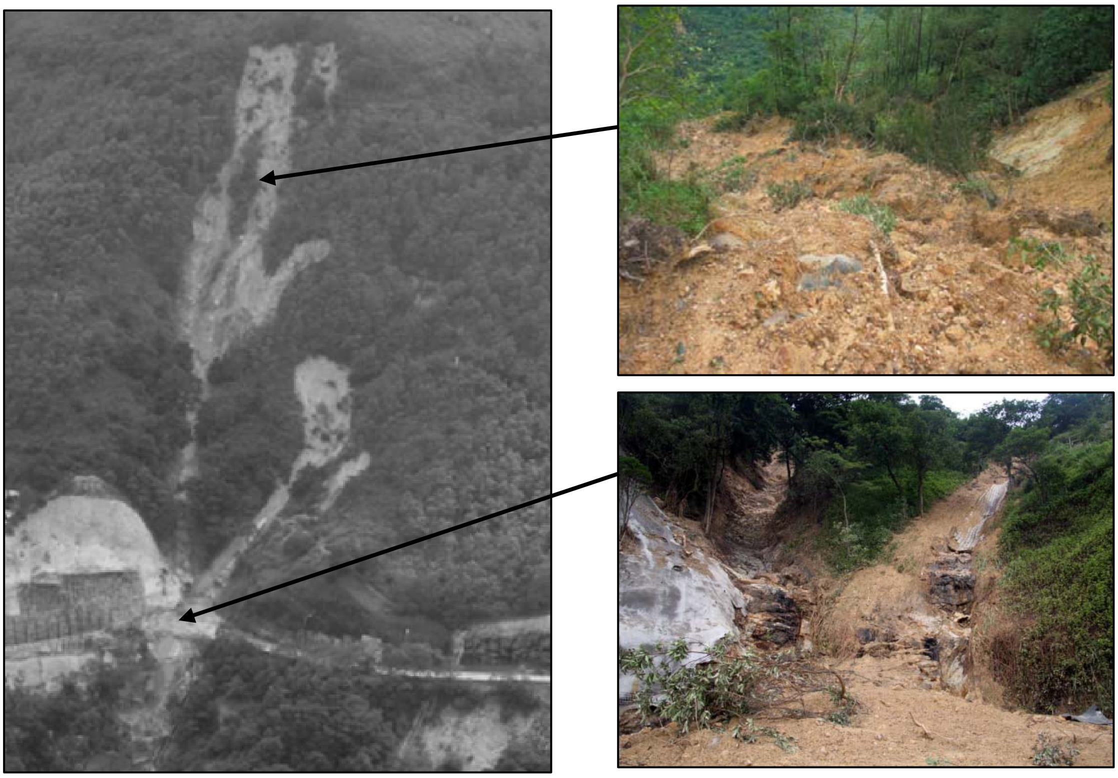
Gp	ϕ (deg)	ξ (m/s^2)	Prob.
1	8	500	~20%
	11	500	
2	15	1,000	~30%
	20	5,000	
3	20	1,000	~50%
	25	1,000	
4	30	5,000	Small

Figure 24: Probabilistic distribution of runout parameters for mobile debris flows based on back-analysis of historical long runout cases

While the potential risk of debris flows is well recognised given their mobility and concentrated discharge, there seems to be a general perception that debris flows in Hong Kong are relatively ‘dry’ events compared with those in other countries. This stems from the consideration that hillsides in Hong Kong have a limited altitude and do not contain sizeable drainage basins and large stream courses (Figure 25). This is consistent with the general observations from studies of natural terrain landslides in the past 20 years, which suggested that the debris flow events did not contain high water content. Experience acquired from NTHS in recent years also indicated that the scale of the Design Event for debris flow risk mitigation was typically in the order of several hundred cubic metres. These notions are implicit in the rheological models and runout parameters derived from back-analysis, which were benchmarked with the same dataset of known historical natural terrain landslides. However, the available dataset only covers natural terrain landslides that occurred in Hong Kong over the past few decades. This is a relatively short observation period as far as extreme events are concerned.

4.2 Recent Observations

The June 2008 rainstorm is arguably the most intense event since the setting up of the GEO. In particular, its rolling maximum rainfall intensities over the 2-hour to 4-hour duration were exceedingly high, with a statistical return period of about 500 to 1,000 years over a large part of western Lantau Island (Figure 26). The 24-hour intensity was also severe, with a return period of about 100 to 200 years. Previous work on rainfall-natural terrain landslide correlations has shown that 4-hour to 24-hour rainfall intensities are critical to triggering natural terrain landslides in Hong Kong (Wong & Ho 2006). Hence, the severity of the June 2008 rainstorm resembles a ‘worst credible event’ scenario to be considered in assessment and mitigation of natural terrain landslide risk, based on the design requirements stipulated in the Design Event Approach (Ng et al. 2003). The landslides in this rainstorm provide reference information on the possible characteristics of design events for natural terrain risk management.



(a) Hillside with a small catchment and drainage line (b) Debris flow involving relatively ‘dry’ debris

Figure 25: Typical debris flow in a small catchment
(Note: The June 2008 Keng Shan Road debris flow No. KS2 is shown)

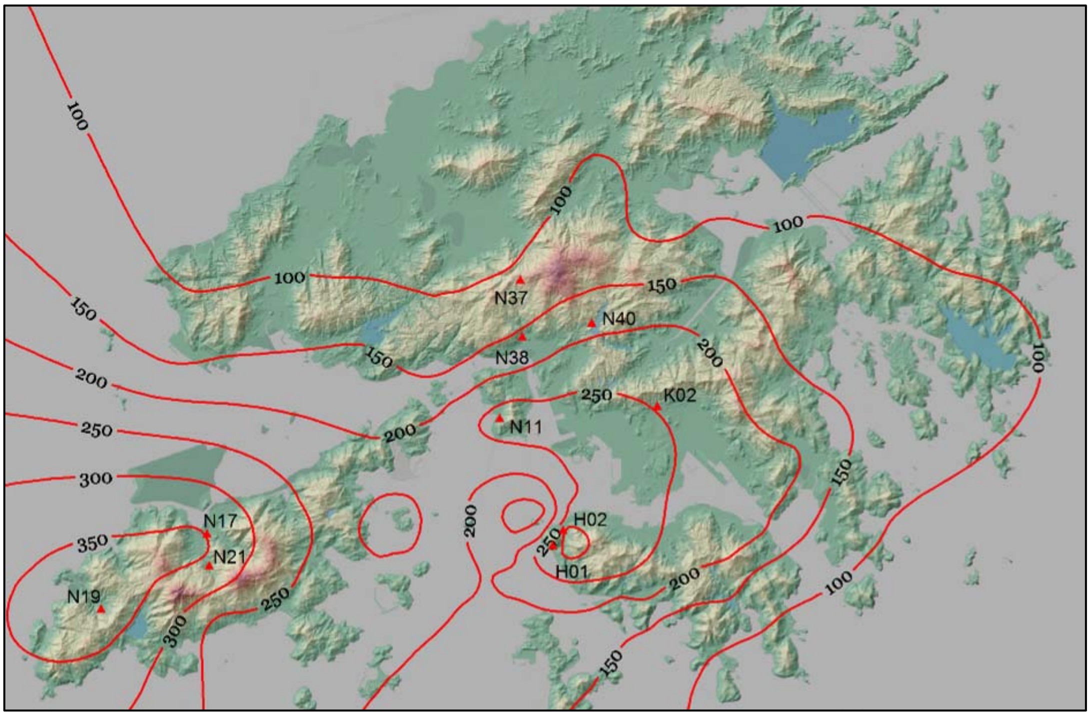


Figure 26: Isohyets of maximum rolling 4-hour rainfall in the 6 to 8 June 2008 rainstorm
(Note: Statistical return periods at raingauges No. N19, N17 and N21 are 1,100, 570 and 485 years, respectively)

Studies of the June 2008 landslides to date have brought about new observations about debris movement:

(a) **Increased debris mobility**: It is known that natural terrain landslide density escalates with rainfall intensity. Data from the June 2008 landslides, when compared with the previously available data on historical natural terrain landslides, indicate that debris flows in a severe rainstorm can also become more mobile. Figure 27 shows that the June 2008 landslides on Lantau have considerably higher mobility than that of the historical landslides in the ENTLI. Studies of debris runout form an important part of the field and analytical work that is being carried out on the June 2008 landslides. There is a need to revisit the back-analyses that have previously been undertaken on debris mobility, by incorporating the newly available data. The findings would help to improve the robustness of the assessment of the reach of landslide debris, as well as the debris velocity and impact forces to be considered in the design of mitigation measures.

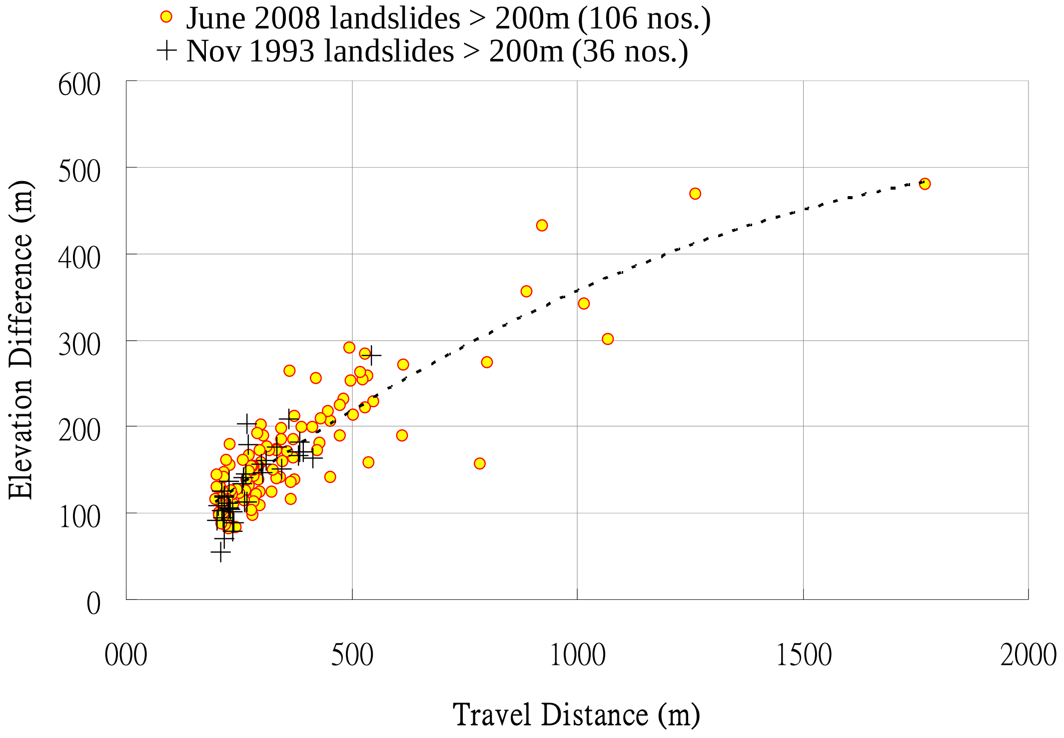


Figure 27: Data showing many long runout and high mobility landslides in the June 2008 rainstorm (Note: 18 debris flows in the June 2008 rainstorm have runout distance exceeding 500 m, while there are only 10 historical cases in the ENTLI including one case on Lantau Island; landslides with runout distance ≤ 200 m not shown for clarity)

(b) **Debris flows with watery debris**: While the high debris mobility is partly related to increase in the volume of debris flows in some cases, field mapping has found that some of the long runout landslides in the June 2008 rainstorm evidently involved flows of watery debris (Figure 28). Watery debris was mobile due to its high water content, which is contrary to the prevailing perception that debris flows in Hong Kong tend to be relatively ‘dry’. The bulked, active volume of the debris flows, with solid mixed with a large amount of water, could be much greater than the volume that is normally estimated from the size of the landslide mass. The entrainment and deposition characteristics of these watery debris flows are different from those of the less wet events. Wet debris deposited on the drainage line, e.g. forming a local landslide dam or deposited mass with high, unconsolidated pore water pressures, would be more susceptible to remobilization in the event of passage of a subsequent debris flow. These have significant implications to risk assessment and mitigation (Figure 29).

Figure 28: Deposits of a watery debris flow at the deposition zone
(Note: The June 2008 Shek Pik No. 4 debris flow is shown; the deposits have been subject to considerable sorting)

Figure 29: Grid-type steel sabo structure
(Note: The open structure would trap sizeable clasts and allow free drainage; photo from Lo 2000)

(c) **Significance of entrainment**: The 1990 Tsing Shan debris flow is known to be a case of significant entrainment, which was thought to be unusual in the past. Many debris flows with significant entrainment, e.g. entrainment ratio up to ten or even higher, occurred in the June 2008 rainstorm. Many of the long runout debris flows in the rainstorm started with a small landslide at the source, e.g. within two to three hundred cubic metres. The active volume escalated as the materials on the drainage line were entrained in the debris flows, and the eventual scale of the debris flows was largely controlled by the degree of entrainment (Figure 30). This shows the importance of assessment of the potential for entrainment in managing debris flow hazards.

Figure 30: Debris flow with significant entrainment in the June 2008 rainstorm
(Note: Debris flow above Shum Wat Road is shown; the source volume is less than 100 m^3 and the entrainment ratio exceeds 10)

(d) **Dynamic nature of drainage lines**: Mapping of the June 2008 debris flows suggests that entrainment tends to involve the materials perching on the drainage line, instead of depleting extensively into the existing side slopes and bed of the drainage line (Figure 31). This seems to suggest that the side slopes and bed of the drainage line are generally more resistant to entrainment, which may reflect their relative maturity in the formation process. Materials perching on the drainage lines, particularly in the upper part of the drainage lines within the debris flow depletion zone, are mostly sizeable boulders left in place from previous landslides. These perched materials in the depletion zone are often completely, or almost completely, swept away in the event of a mobile debris flow. The debris flow resulted in deposition of debris including sizeable boulders at the accumulation zone in the lower part of the drainage line (Figure 32). After debris deposition, and upon removal of the fines following prolonged outwash and erosion, the sizeable boulders will become perched materials again. Hence, mobile debris flows, such as those that occurred in the June 2008 rainstorm, effectively result in 'pushing' the perched materials downstream. This would significantly alter the entrainment characteristics of the drainage line and may arguably help to reduce the risk of entrainment in future events. On the contrary, less mobile landslides and debris flows would result in accumulation of debris on the upper part of the drainage lines (Figures 5 and 33). It would increase entrainment potential, as well as the risk of future debris flows. This suggests that the scale and characteristics of debris flow hazards at a given drainage line may not be static, but could change with time as landslides and debris flows take place intermittently in the catchment. In terms of entrainment potential and characteristics, some debris flow catchments may evolve with time from one stage to another within a life cycle. The dynamic nature of drainage lines should be understood and judiciously accounted for in risk assessment and mitigation.

Figure 31: Complete removal of perched materials in the depletion zone of debris flow
(Note: The June 2008 Yu Tung Road debris flow is shown; the side slopes and bed of the drainage lines not subject to significant material loss)

(a) Depletion of perched boulders in upper part of drainage line

(b) Accumulation of loose boulders at lower part of drainage line

Figure 32: Transport of perched materials in a debris flow
(Note: The June 2008 Yi O debris flow is shown)

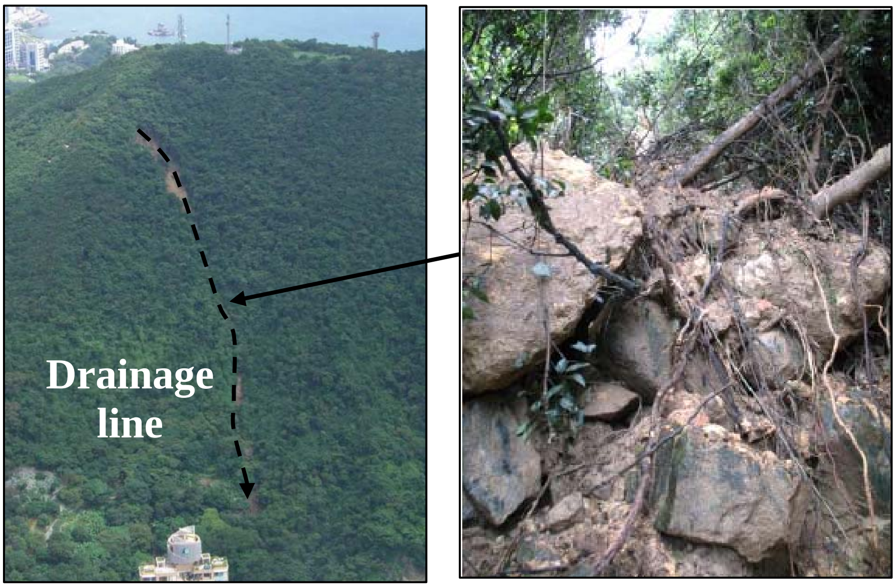


Figure 33: Less mobile landslide resulting in accumulation of loose debris on drainage line
(Note: The June 2008 Mount David debris flow above Police Quarters Block C is shown)

(e) **Deviation of debris flow path from drainage line**: A number of debris flows in the June 2008 rainstorm were found to have resulted in debris trails deviating from the drainage lines (Figure 34). As such, the debris flow did not entirely follow the drainage line, which is typically aligned with the direction of the steepest plane. This may be attributed to a number of reasons: (i) the failure at the landslide source may be subject to the control of geological structures that do not follow the direction of the steepest plane of the surface ground profile; (ii) the momentum of a fast-moving debris may cause the debris to move in the direction of the velocity vector and overshoot from the drainage line as it makes a sharp turn; (iii) run-up of a sizeable debris flow may result in overspill of debris over the watershed of the drainage line; (iv) when the debris flow hits an existing debris dam that blocks the drainage line, the flow direction may be deflected (Figure 35); (v) debris deposition in a debris flow may fill up local low points, change the topographical profile and alter the direction of the subsequent debris movement; and (vi) the existing topographical maps may not reliably represent the actual hillside topography. The above circumstances are occasionally encountered on site. It should not be taken for granted that debris flows would necessarily follow the alignment of the drainage line as indicated in the topographical map. Otherwise, the risk mitigation measures may be sited at a wrong location.

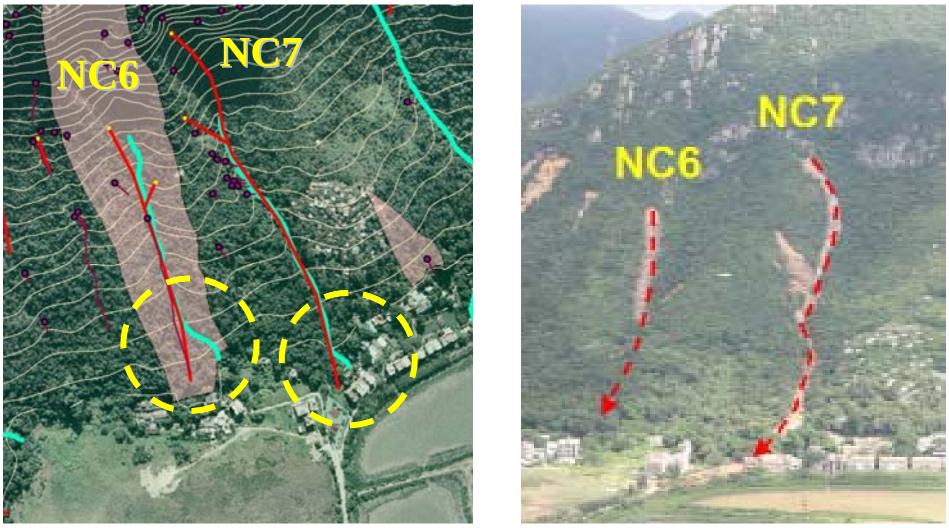


Figure 34: Examples of debris flow path deviating from drainage line
(Note: The June 2008 Nam Chung Tsuen debris flows No. NC6 & NC7 are shown)

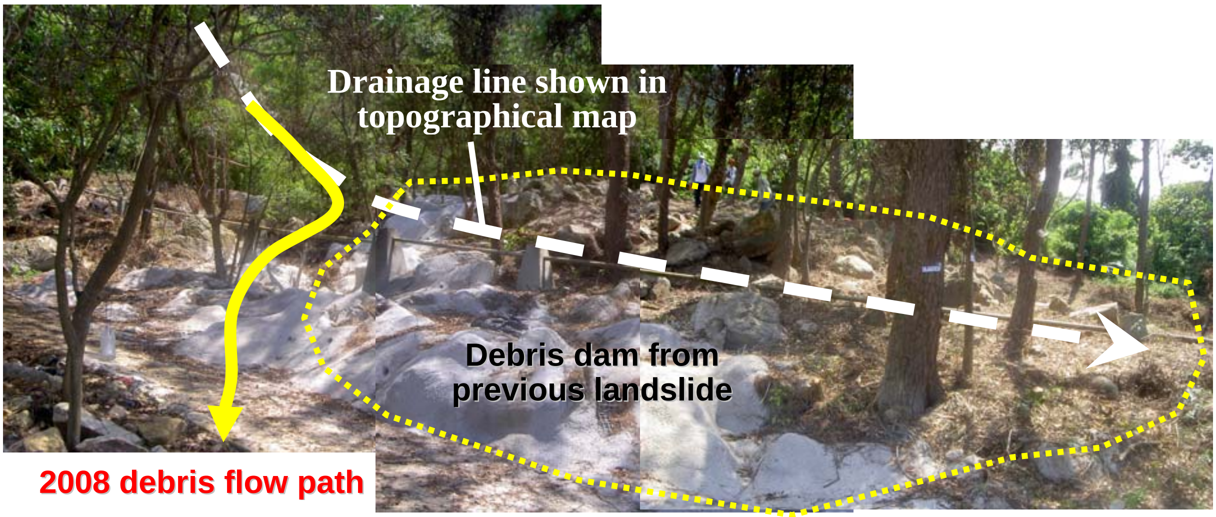


Figure 35: Debris flow diverted by an existing debris dam
(Note: The June 2008 Nan Chung Tsuen debris flow No. NC6 is shown)

4.3 Improving Understanding and Practice

In the light of the findings of presence of watery debris and their effects on the runout behaviour of debris flows, the importance of identifying the circumstances that may lead to watery debris and accounting for possible occurrence of watery debris in NTHS cannot be over-emphasised. In practice, there is a need to differentiate drainage lines that have the potential of discharging watery debris, from those where debris flows are relatively 'dry' as is commonly encountered in Hong Kong. Observations from field mapping suggest that the following settings might contribute to development of watery debris in a debris flow:

- debris flow at a major drainage line, i.e. with a large catchment and a long flow path, where a large amount of storm water may be available for mixing with the landslide debris (Figure 36)
- debris flow taking place during heavy rain, i.e. when the drainage line is full of running storm water
- debris flow with fast-moving debris, which overtakes the flow of the storm water in the drainage line and hence results in increasing water content during the debris runout
- debris flow along a main drainage line into which many tributaries of drainage lines are feeding, i.e. the water content of the debris will increase whenever the debris passes through a confluence point due to merging of storm water from the tributary onto the moving chain of debris
- other site settings, e.g. discharge of debris onto a pool of water on the drainage line, discharge of debris from a small drainage line onto a major drainage line or a catchwater channel where a large amount of storm water was running (Figure 37)

Figure 36: Major drainage lines fed by many tributaries
(Note: The June 2008 Shek Pik No. 4 debris flow is shown; the runout distance is about 1.8 km)

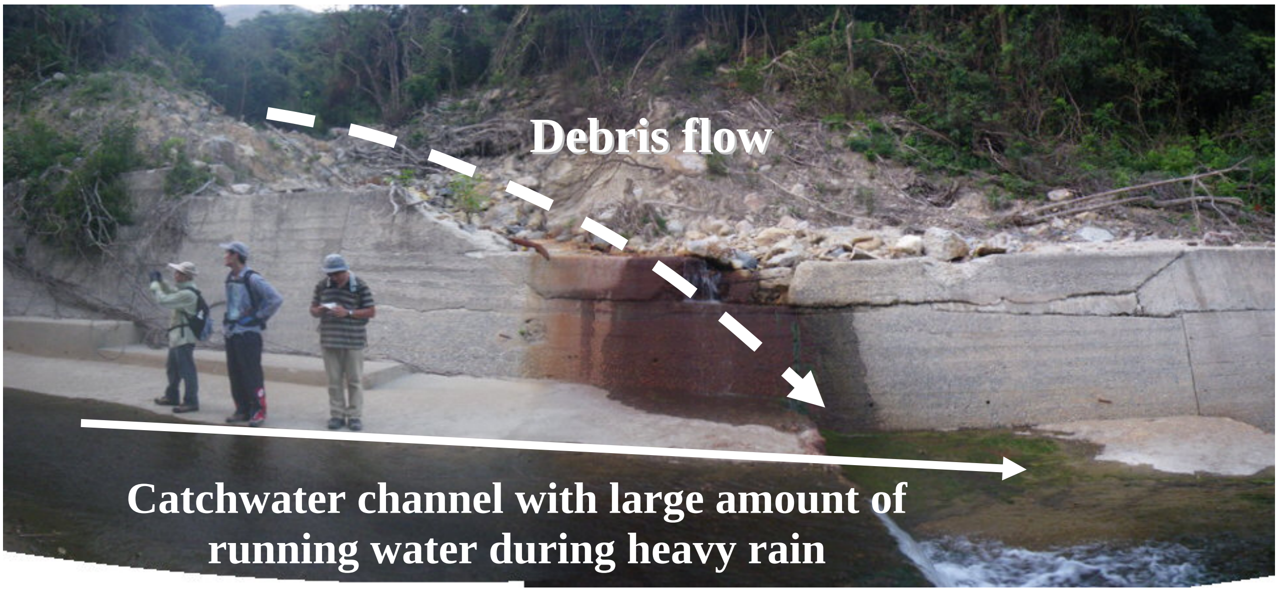


Figure 37: Debris flow entering catchwater channel
(Note: The June 2008 Shek Pik No. 1 debris flow is shown; the debris flow turned into a debris flood after entering the catchwater channel)

Apart from the possibility of discharging watery debris, the potential for major entrainment and the current life-cycle stage of a drainage line would deserve consideration in characterising debris flow catchments, for debris runout and risk assessment. From a preliminary review of the information available, it is noted that a higher degree of entrainment may be associated with the following factors:

- presence of steep terrain below the landslide source, thereby promoting acceleration of the debris after the initial detachment from the source

- presence of steep rock cliffs along the debris path, where debris velocity increases or free fall of debris may occur (Figure 38)

- debris with high rock/boulder content, which tends to involve considerable rolling and bouncing actions as the rock/boulders travel on a steep slope, particularly on a rocky channel bed

- debris flow in a drainage line with a large amount of perched boulders (Figure 39), which are susceptible to entrainment; this may coincide with a specific life-cycle stage of the drainage line, in which a large amount of entrainable materials have been stored up in the drainage line for eventual discharge downstream in a sizeable and mobile debris flow that is due to occur

- long runout debris flows with watery debris, in which the scale and mobility of the event provide sufficient energy to mobilize the entrainable materials over a long section of the drainage line

At present, knowledge of the entrainment potential and the possible characteristics and time frame of the life-cycle stages of drainage lines is rather limited. The GEO is exploring the practicality of, and strategy for, long-term monitoring of selected drainage lines, to improve the understanding of their behaviour and debris transport mechanisms.

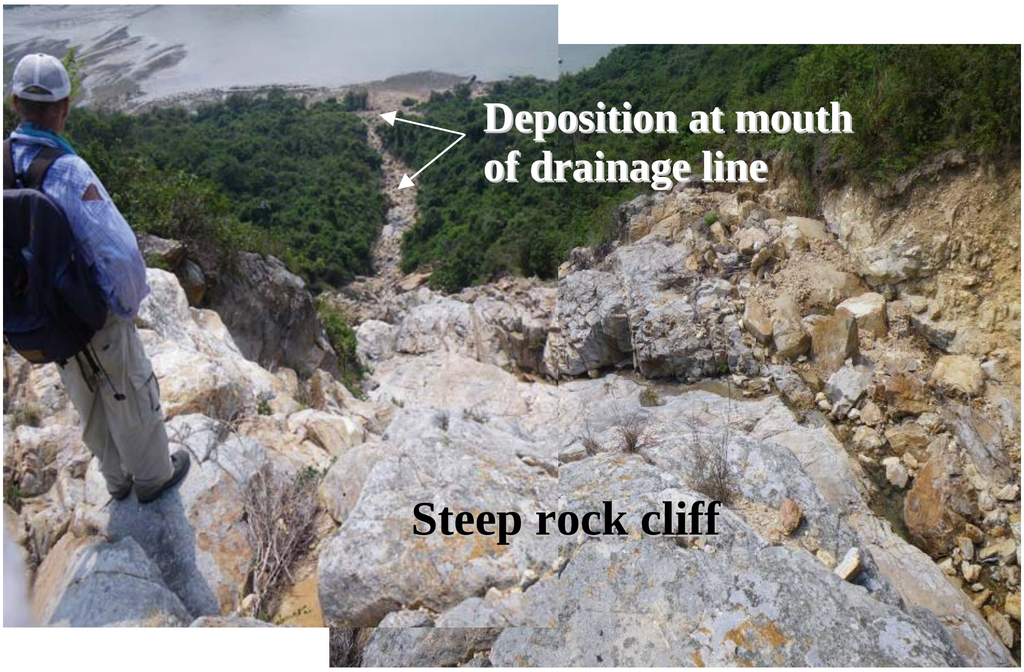


Figure 38: Steep rock cliff on drainage line
(Note: The June 2008 Yi O debris flow is shown; the debris including many sizeable boulders made their way to the mouth of the drainage with no deposition on the rock cliff)

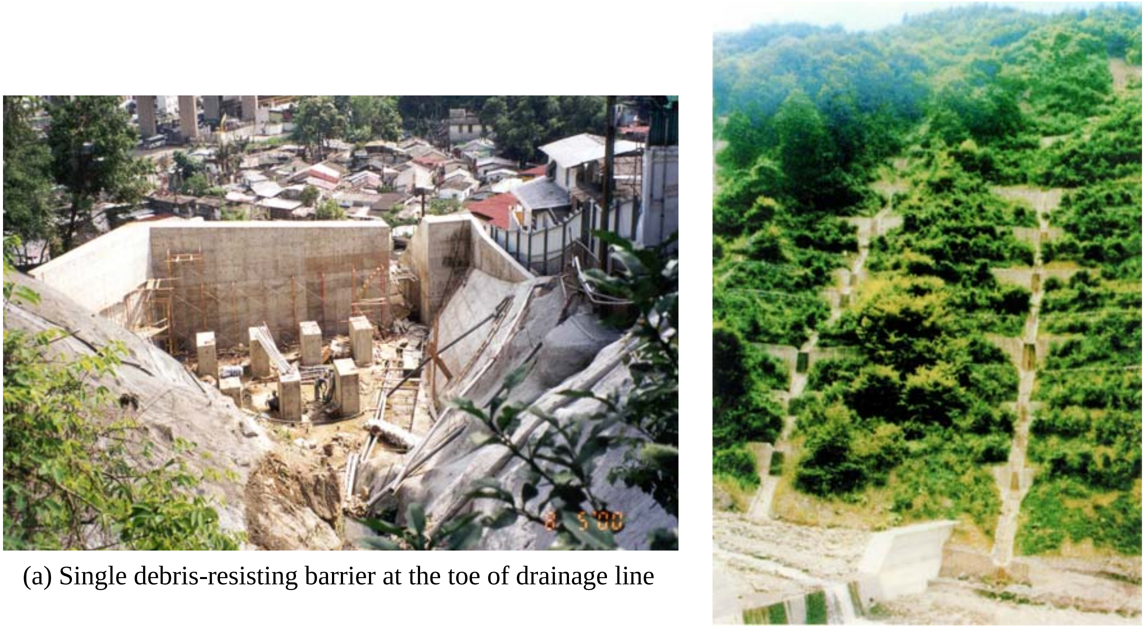
(a) Adjoining Shek Pik No. 1 (b) Adjoining Shek Pik No. 2 (c) Adjoining 1990 Tsing Shan debris flow site

Figure 39: Drainage line filled with perched bouldery deposits that are susceptible to entrainament

In respect of risk mitigation, the appreciation of the possible need to deal with sizeable debris flows (e.g. several thousands cubic metres or more) and watery debris in some circumstances has already initiated discussion and a rethink of the strategy for debris flow risk mitigation. In particular, the need to explore alternative engineering solutions to the provision of a single debris-resisting barrier at the toe of the drainage line is noted (Figure 40). For instance, building a series of barriers along the drainage line may prove to be more effective in minimising entrainment and overcoming site constraints, while construction and related maintenance issues would require deliberation. Debris diversion channels, deflection structures and protective canopies, which are rarely used in Hong Kong in the past, may be suitable solutions for some cases. Attention has to be given to minimizing disruption to the environment and landscaping the risk mitigation measures, as the works will become more widespread in the years to come. Overall, there is considerable room for engineering innovation for improving the design, construction and maintenance of natural terrain landslide risk mitigation measures.

The observation that debris runout may not entirely follow the topographical steepest slope casts doubt on the reliability of subjective determination of the debris flow path in risk assessment and design of mitigation works. Three-dimensional debris runout and mobility modelling offers a technical means of objective assessment of the possible debris runout paths. In dealing with important or sensitive cases, 3-D modelling should be carried out to supplement subjective assessment of the debris flow path and 2-D mobility modelling.

At present, 3-D modelling algorithms are not widely accessible to practitioners and are not very user-friendly. This is an area for improvement. Furthermore, use of reliable 3-D digital terrain data is essential to 3-D debris runout and mobility modelling. Remote sensing techniques, in particular multi-return airborne Light Detection and Ranging (LiDAR), is promising in acquiring 3-D topography of terrain under vegetation cover in a cost-effective manner. The geotechnical profession should be better equipped with knowledge of remote sensing technology and experience in using remote sensing data, in addition to the conventional surveying methods, to prepare for undertaking natural terrain-related assignments.



(a) Single debris-resisting barrier at the toe of drainage line

(b) Series of debris-resisting barriers along the drainage line (Photo from Lo 2000)

Figure 40: Single vs multiple debris-resisting barriers

The above calls for continual efforts in studies and research of debris flows, as well as promulgation of knowledge among the geotechnical professionals. The geology and physics of debris flows are relatively new technical fields. Typically, they are seldom covered in depth in tertiary education and in professional training. In the past, hydrologists, geologists and engineers used to approach the subject from different perspectives and with different emphasis. Lack of cross-discipline synergy and collaborative efforts is not conducive to technological advances, particularly for a complex and challenging subject like this. There is a great demand for development of engineering geological expertise in mapping and assessing debris flow hazards. For example, recognising and logging different types of debris flow-related features and deposits are akin to identification and description of soil and rock in conventional engineering geological work. Assessing potential landslide sources, volume of failure and degree of entrainment may be comparable to diagnosing geological materials and structures that affect the design and performance of slopes, foundations, excavations, etc. Likewise, engineering geological and geomorphological models need to be established for assessment of natural terrain hazards, as in the case of development of ground and design models for geotechnical assessments (GEO 2007). In terms of the engineering aspects, improved knowledge of debris flow physics is needed (Iverson 1997). The geotechnical profession is generally unfamiliar with the mechanisms of debris flow mobilization, transport and deposition, as well as the physics of viscous fluid, solid-fluid interaction, concepts of kinetic sieving (Figure 41) and granular temperature, etc. These should be included in our professional toolbox, as we rise to the natural terrain challenge.

Figure 41: Large boulders and woody debris at the snout of debris flow
(Note: Distal end of the deposition zone of the June 2008 Shek Mun Kap debris flow at about 1 km from the landslide source is shown)

5 DEVELOPMENT OF RISK MANAGEMENT STRATEGY

5.1 Evolving Nature of Strategy

A detailed evaluation of the natural terrain landslide risk mitigation strategy is beyond the scope of this technical paper, and may be premature given that the planned natural terrain works under LPMitP are only at the early stage of launching. In formulating the post-2010 landslip prevention and mitigation strategy, the Administration has pledged to conduct a review of the progress and effectiveness of the LPMitP in 2015 (Development Bureau 2007). This offers an opportunity for a formal review and refinement of the natural terrain risk management strategy, which is necessary in view of the developing nature of our technical know-how and the new insights and experience to be gained from implementing the LPMitP initiatives.

While development of natural terrain landslide risk management strategy is an ongoing process and the review of LPMitP is scheduled to be carried out some years later, the knowledge available and lessons learnt to date suggest that certain aspects may warrant further thoughts in strategy development. A number of issues that may be of interest or concern to the profession are briefly described in the following sections.

5.2 React-to-Known-Hazard Principle

The current strategy for studies and mitigation of natural terrain landslide risk on existing developments is founded on the ‘react-to-known-hazard’ principle. This is a pragmatic strategy, given that: (i) catchments with historical failures are generally more active in landslide occurrence and hence deserve priority attention; (ii) the Government has a due diligence to act on known significant hazards; and (iii) reliable means of identification of other vulnerable catchments are not yet available. As a starting point of implementation of risk mitigation works, this principle appears to be well received. However, public expectation may shift with time following occurrence of major landslide incidents. Our capability in identifying vulnerable catchments may also improve with time. Hence, the need, practicality and resource implications of adopting a more proactive approach may be an issue for deliberation in future.

5.3 *Urban Hillside Pockets*

Apart from natural terrain located outside the present development boundaries, hillside pockets within developed areas are also subject to failures from time to time (Figure 42). By nature of their location, these hillside pockets may have been subject to different degrees of human disturbance. Their close proximity to developed facilities would also render them technically different to deal with, as compared with natural hillsides outside the development lines. Furthermore, there is potentially a link between the stability of these urban hillside pockets and other urban facilities, e.g. urban drainage, construction works and land-use. Their interaction may need to be addressed in a holistic manner, instead of being dealt with separately under different portfolios.

Figure 42: Landslide on hillside pocket within developed area
(Note: The June 2008 landslide above Kennedy Road is shown)

5.4 *Output of Natural Terrain Risk Mitigation*

The planned annual output of natural terrain risk mitigation works under the LPMitP is more than ten times of the current level. This represents a sharp increase in the amount of work, and its achievement is dependent on, among other factors, the availability of personnel with suitable geotechnical expertise. Given the constraints, further increase in the output is considered not practical in the early stage of implementing the LPMitP. However, increased public awareness of natural terrain landslide risk and expectation of slope safety may turn into demand for an increase in the output of natural terrain risk mitigation. The speed with which the geotechnical profession can build up the capability and capacity for undertaking natural terrain work may remain a constraint. The effectiveness in setting up an efficient and robust LPMitP process for delivery of natural terrain risk assessment and mitigation works is also a challenge for the GEO and practitioners to tackle in partnership. On the other hand, economic downturns and complacency that may typically arise following an uneventful period may result in pressure to cut resources and investment in long-term slope safety management.

5.5 *Prescriptive Approach*

Use of prescriptive measures has played a role in dealing with man-made slopes in Hong Kong. These measures are suitably conservative, experience-based modules of slope stabilization, protective and drainage provisions. They are applied in accordance with some established prescriptive design criteria and procedures, without the need for detailed ground investigation and analytical design (Wong et al. 1999). Over the past decade, prescriptive measures have been used under the LPM Programme, and as part of Government's enhanced slope maintenance initiatives in speeding up the improvement of the safety of a large stock of old man-made slopes.

In the case of natural terrain, prescriptive design may entail prescription of the volume of the landslide debris that may be discharged from a catchment, for use in the design of risk mitigation works. The prescription may be based on consideration of the characteristics of the catchment, its historical landslide activities and potential consequence of failure, under an empirical-based framework or expert judgement procedures. Prescriptive design may serve as an alternative to the prevailing approaches for determination of the Design Event through a detailed NTHS, which takes considerable time and resources, and thereby may help to fast-track the provision of risk mitigation measures at a large number of sites in order to maximise the rate of risk reduction.

Whilst this may offer a pragmatic option of speeding up natural terrain risk mitigation works, the adequacy of the prescriptive risk mitigation provisions at individual sites may have to be reviewed at a later stage via a detailed NTHS to confirm whether additional provisions are required to further control the risk. Doubtlessly, prescriptive design is subject to potential technical constraints, particularly due to the lack of detailed assessment and optimization of design. However, many other countries are commonly adopting approaches that are largely prescriptive in nature for dealing with natural terrain hazards. In Hong Kong, even if a detailed NTHS is carried out, expert judgement will often have to be exercised in the determination of the Design Event in the face of the uncertainties involved. Hence, it is arguable that some degree of prescription is always implicit in our prevailing assessment and design process. At present, use of prescriptive approach for dealing with natural terrain hazards in Hong Kong is only at a conception stage. Further technical development work is required for formulating a practical and robust prescriptive design methodology. The prescriptive approach may have a more explicit role to play in future, particularly if there is a demand for acceleration of risk mitigation works.

5.6 Risk Communication

Dealing with natural terrain landslides would inevitably involve considerable uncertainties. Risk management initiatives are aimed at minimizing risk to an ALARP level. Our technical knowledge and capability in tackling natural terrain hazards are still fairly limited. Some circumstances, such as climate change, are not entirely within our comprehension and control. While the geotechnical profession is aware of these constraints, the public and other stakeholders may not fully appreciate the nature of the problem. In addition, their risk tolerability and expectations are sensitive to other factors, e.g. an increase in risk perception after occurrence of major landslide incidents, particularly those involving multiple fatalities and major social disruption. Effective risk communication is vital to maintaining public awareness of the nature and reality of natural terrain landslide risk, rationalizing their risk perception, and gaining their support and participation in risk management. This in turn is crucial to maintaining a healthy and realistic pace of risk mitigation works, and to facilitating the further development and enhancement of risk management strategy.

6 CONCLUSIONS

A new era of natural terrain landslide risk management is dawning. This would not have become possible without the efforts and technological advances made over the years by the geotechnical profession. However, the challenges to face in taking the work forward must be viewed in the right perception. The profession has to get geared up to meet the challenges in discharging its enhanced responsibility.

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