Evolution of Natural Terrain Hazard Assessment Strategy in Hong Kong

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Abstract: Since the early 1990s, there has been increased awareness of potential hazards from natural terrain failures in Hong Kong. The Geotechnical Engineering Office (GEO), in collaboration with geotechnical practitioners, has been undertaking technical development work for dealing with natural terrain hazards in Hong Kong. This has led to an improved understanding of the characteristics and behaviour of natural terrain landslides and their potential risk. The technical development has evolved from studies of notable individual landslides or landslide clusters and compilation of a comprehensive natural terrain landslide inventory in the early to mid-1990s, through regional studies in identifying landslide susceptibility factors and developing methodologies for engineering geomorphological mapping, to the development of a systematic natural terrain risk management strategy today. Although much experience has been gained in understanding natural terrain hazards, much effort is still required to enhance our current state of knowledge and practice.

1 INTRODUCTION

Natural terrain covers over 60% of the total land area in Hong Kong (i.e. about 670 km^2). Much of it is steeply sloping and mantled by weak saprolitic or residual soils, or colluvial deposits derived from past landslides and erosion processes. The vast majority of the terrain is underlain by volcanic and granitic rocks, which were formed over 100 million years ago. Being shaped to its present form as part of the on-going natural geological, geomorphological and weathering processes, much of the natural terrain is often only marginally stable. The common forms of natural terrain landslides comprise open hillslope landslides, debris flows, channelized debris flows, rock falls and boulder falls.

Most of natural terrain landslides in Hong Kong are triggered by intense rainfall whilst in some cases very short-duration rainstorm can trigger numerous landslides. Hong Kong's natural terrain is especially susceptible to shallow (typically <3 m), small to medium-sized (typically several hundred cubic metres) landslides (Fig. 1), which could develop into debris flows when the debris enters into drainage lines (Wong *et al.,* 1998, Wong & Ho, 2000). Sizeable failures are rare but when they occur, they are mostly related to the presence of adverse geological conditions (e.g. Shum Wan Road Landslide in 1995) or significant entrainment along the debris flow path (e.g. Tsing Shan Debris Flow in 1990). In densely developed hillsides, there could be serious consequences even if the volume of the landslide is relatively small (Fig. 2).

Fig. 1. Landslide-prone natural terrain in Hong Kong

Fig. 2. A relatively modest 50 m^3 landslide in 1998 had resulted in damage to property

Most developed areas extend from the limited areas of level ground onto sloping ground. As demand for new land for development continues, land nearer to natural slopes has to be considered for building and infrastructure projects. With increased awareness of the potential hazards from natural terrain failures, the Geotechnical Engineering Office (GEO), in collaboration with geotechnical practitioners, has been undertaking technical development work on the subject since the early 1990s. This has led to an improved understanding of the nature and characteristics of natural terrain landslides, the potential risk and approaches for risk management (e.g. Wong, 2009; Ho & Lau, 2010; Martin & Ng, 2011).

This paper summarises the technical development of natural terrain hazard assessment strategy in Hong Kong since the early 1990s and discusses the key insights and experience gained during the development process. The work described is covered in four phases: (i) the early phase of landslide studies, (ii) the territory-wide landslide data compilation and analysis phase, (iii) the regional and site specific studies phase, and (iv) the systematic natural terrain landslide risk management phase.

2 EARLY PHASE OF LANDSLIDE STUDIES

The 1990 Tsing Shan debris flow, involving about 20,000 m^3 of landslide debris, was a significant incident in Hong Kong (King, 1996). In November 1993, a severe rainstorm over Lantau Island led to widespread landslides with over 800 natural terrain failures recorded (Wong *et al.*, 1998). Detailed studies of these landslides have helped to examine the characteristics and understand the mechanisms of natural terrain failures in Hong Kong.

2.1 *1990 Tsing Shan debris flows*

The landslide started off as a relatively modest debris avalanche of about 350 m^3 at the landslide source. It developed into a 20,000 m^3 mobile debris flow through material entrainment along the drainage line, with a total runout distance of about 1 km (Figs. 3a, 3b, 3c). This debris flow is regarded locally as an example of a low-frequency, large-magnitude landslide (King, 1996), and has been referenced internationally as a case that illustrates very high debris flow entrainment (e.g. Jakob & Hungr, 2005).


Fig. 3a. General view of the 1990 Tsing Shan debris flow


Fig. 3b. Trigger landslide


Fig. 3c. Eroded remains of the valleyside fan

Before the debris flow occurred, the foothills had been planned for residential development. The debris flow could have resulted in serious consequences if the site traversed by the debris flow had already been developed at the time. After the debris flow, the land use at the site was amended from residential development to a golf driving range in order to minimise the risk exposure. The case is a vivid illustration of the risk of debris flows and the importance of taking account of natural terrain landslide hazards in land use and development planning.

2.2 *1993 natural terrain landslides on Lantau Island*

In early November 1993, over 800 natural terrain landslides on Lantau Island (Figs. 4a, 4b) were triggered by a severe rainstorm. The landslides resulted in blockage of roads and catchwaters. As Lantau Island was largely undeveloped at that time, there were no landslide related casualties. In early 1994, the GEO commenced a study on the natural terrain landslides, with the objectives to collect information on the landslides, assess the characteristics and mechanisms of the failures, and to examine the mobility of the debris movement.


Fig. 4a. The 1993 natural terrain landslides on Lantau Island


Fig. 4b. View of a landslide scarp from the debris trail

The study established that a high density of natural terrain landslides could be triggered in a severe rainstorm (about 7 landslides/km^2 occurred in this rainstorm), and that terrain at a gradient of 30^o to 35^o underlain by volcanic rocks appeared to be particularly susceptible to failure. The field inspections have shown that the majority of the landslides inspected were shallow failures involving loose bouldery colluvium (Wong *et al*., 1998). 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 1993 landslides that flanked the Tung Chung New Town, which was being developed at that time, also arrived at similar conclusions.

3 TERRITORY-WIDE LANDSLIDE DATA COMPILATION AND ANALYSIS PHASE

The Natural Terrain Landslide Study (NTLS) comprised a series of integrated GEO studies of the risks associated with natural terrain in Hong Kong that were undertaken in the 1990s. The aims of the NTLS were to investigate the distribution, nature and probable causes of landsliding on natural terrain in Hong Kong and to assess the hazard from such events. In early 1995 the GEO commenced development of a natural terrain landslide inventory (NTLI) for Hong Kong as the first phase of the NTLS. This dataset would be the starting point for a better understanding of the global distribution and nature of natural terrain landslides in Hong Kong, so as to better assess the hazards. A large landslide study was conducted in 1998 to review primarily the large landslides (scarp width >20m) contained in the NTLI. These datasets were later developed in a Geographic Information System (GIS) which facilitates analyses of the data to determine correlations between landslide distribution and possible causal factors, and a preliminary assessment of hazard. A systematic landslide investigation programme was established in 1997 to study significant landslides including those that occurred on natural terrain (Ho & Lau, 2010).

3.1 *The Natural Terrain Landslide Inventory*

In order to develop a methodology using interpretation of high-flight aerial photographs (>2,400 m flight-height), a pilot study of three 1:5,000-scale map sheets was carried out in early 1995 by consultants from the New South Wales Department of Land and Water Conservation, Australia. Following the pilot study, compilation of the NTLI commenced in September 1995 and was completed in February 1996 (King, 1999). This was followed by a recognition factor study to quantify the number of landslides that may have been missed or misidentified due to constraints of the API techniques, and a revegetation study to record the rate of landslide scar revegetation in late 1996.

The landslide data were recorded on a set of 1:5,000-scale map sheets, with a unique reference number given to each landslide (Fig. 5a). Information including width of the landslide scarp, vegetation cover, ground slope angle across the landslide scarp, date of the aerial photograph on which the landslide can be first observed, and the date of the last available aerial photograph on which the landslide does not appear were recorded for the landslide identified.

All the landslide information, including the NTLI map and the data table, were digitised in 1996. Fig. 5b is a graphical display of the NTLI, showing the natural terrain landslide crowns and debris trails. The inventory was updated regularly and by 2003, the NTLI had catalogued some 30,000 landslides, about 11,000 and 19,000 of which are recent landslides (i.e. with determinable year of occurrence) and relict landslides respectively.

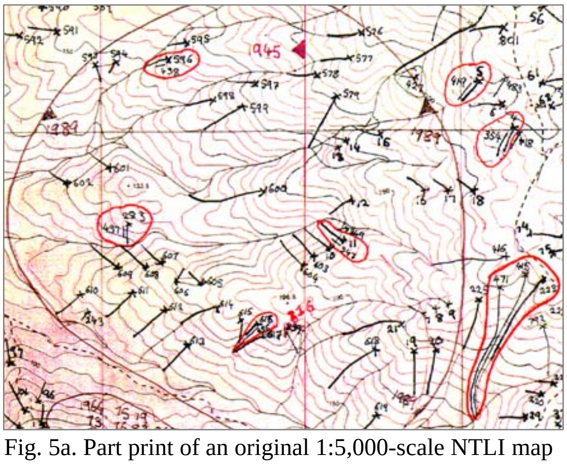


Fig. 5a. Part print of an original 1:5,000-scale NTLI map (King, 1999)

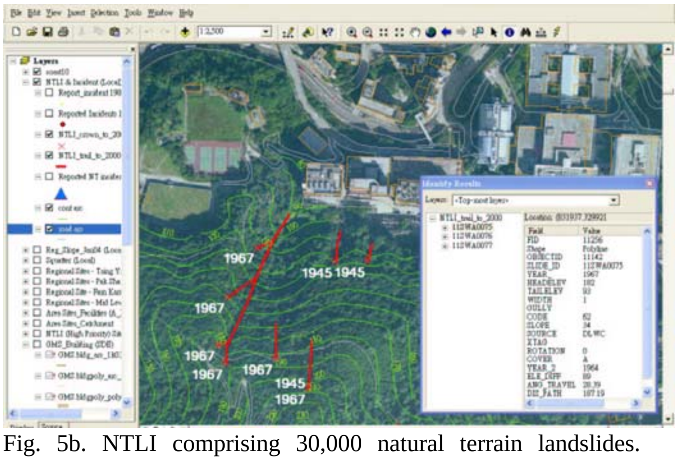


Fig. 5b. NTLI comprising 30,000 natural terrain landslides. Landslide source, trail and year are shown on a geo-referenced, orthorectified image

Factors such as photograph coverage, cloud cover, ground shadows, vegetation cover, and scale and resolution of the high-flight aerial photographs imposed certain limitations on the dataset. Consequently, some landslides may have been missed, whilst some shown in the inventory may be other features mis-identified as landslides (e.g. small fill slopes, excavations, paths and graves). Despite these constraints, the NTLI was the most comprehensive catalogue of natural terrain landslides that had been compiled at the time. It provided important data for future studies of natural terrain hazards, and was widely used by the local geotechnical profession until it was replaced by the Enhanced Natural Terrain Landslide Inventory (ENTLI) in 2007, as described in Section 5.1 below.

3.2 *Large landslide dataset*

Large landslides are defined as having a scarp width of more than 20 m. These were classified as large landslides in the NTLI. Furthermore, the NTLI recognised that multiple-source failures, that are each less than 20 m in scarp width, may represent a larger feature which may not have been recognised as such from the high-flight aerial photographs. Most of these features have been recorded in the NTLI from aerial photographs taken during or before 1963/64. Aerial photographs taken at various times up to the 1960s were mainly high-flights, with the first territory-wide systematic coverage providing exceptionally good quality low altitude imagery in 1963/64. Thus, the low-flight 1963/64 aerial photographs allowed the larger landslide features to be examined in greater detail, in terms of their size, distribution, interpretation and classification, and their geomorphological context. The study included:

(a) a review of large and cross-tagged landslides contained in the NTLI;
(b) a review of landslides and slope instability shown on the Hong Kong Geological Survey (HKGS) and Geotechnical Area Studies Programme (GASP) maps respectively; and
(c) identification of landslide features not contained in any of these datasets.

About 1,900 large natural terrain landslides were compiled based on the interpretation of aerial photographs and hillside geomorphology (Scott Wilson, 1999a, b). These large landslides included large relict morphological features, as well as recent natural terrain failures. Some examples of the identified large relict landslides are shown in Figs. 6a, 6b, 6c.

Fig. 6a. Large coastal landslide on Lamma Island

Fig. 6b. Massive debris lobe at Sham Wat, Lantau Island

Fig. 6c. Large relict landslide above Tung Chung Road, Lantau Island

3.3 *Landslide susceptibility analysis*

As with other natural geological hazards, given the current state of knowledge and available geotechnology, prediction of where and when hillside failure will occur remains a distant goal. Landslide susceptibility in the present context refers to the likelihood of the hillside to landslide occurrence, and excludes the consideration of debris runout and retrogression of the slope failure. Landslide susceptibility zoning usually involves classifying the terrain into different zones of landslide susceptibility.

In the late 1990s, Evans & King (1998) carried out a territory-wide landslide susceptibility zoning, based on correlation of natural terrain landslides (the NTLI which was compiled in the mid-1990s) with slope angle and geology. The work focused on developing useable techniques for the preliminary identification of areas of natural terrain that may be particularly susceptible to the initiation of debris avalanches. Nineteen geological groups and thirteen slope angle classes were adopted, which resulted in 247 different types of terrain unit. A Digital Elevation Model (DEM) was compiled from the 1:5,000-scale 10 m contour topographical maps, and a susceptibility zoning map was prepared in 1:20,000-scale. Based on the results of susceptibility analysis, terrain units were categorized into five susceptibility classes, with an average annual landslide frequency ranging from <1 landslide per km^2 (very low) to >10 landslides per km^2 (very high) (Fig. 7).

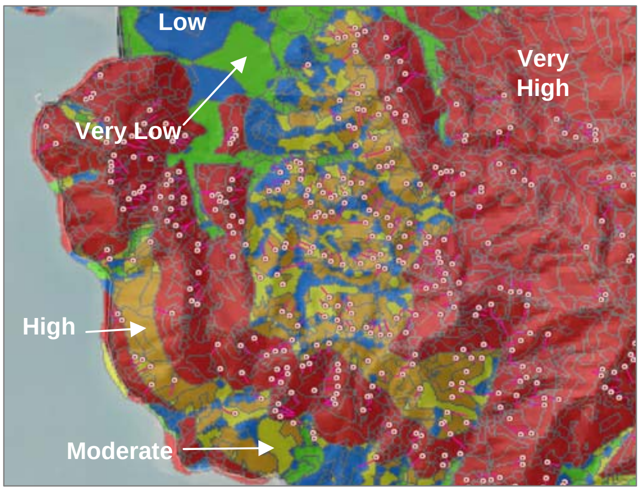


Fig. 7. Part print of the landslide susceptibility map

Wong (2003) discussed the implications of the limited resolution in the calculated landslide frequency among the different susceptibility classes, which is only within about one order of magnitude between the least and most susceptible classes. Such a resolution was considered insufficient for differentiation of vulnerable hillsides, especially in view of the potentially high consequence of landslides given Hong Kong's dense development in the foothills setting. It should be noted that landslide susceptibility analysis can be subject to much uncertainty given the typical scenario of very limited ground investigation because of practicality considerations. There can be a wide range of landslide initiation factors (e.g. topographical factors, geological influences, hydrogeological boundaries, etc.), which may combine in different ways such that the assessment of the relative propensity of a site to instability is not a straightforward exercise. The low resolution probably demonstrated a lack of understanding of the combination of factors that control landslide susceptibility. It may also reflect the possibility that the natural hillsides in Hong Kong are generally susceptible to shallow failures, with a relatively small difference in the landslide susceptibility between the 'more problematic' and 'less problematic' terrain.

3.4 *Systematic landslide investigation*

Since 1997, significant natural terrain landslides have been systematically investigated under the GEO's landslide investigation programme (Ho & Lau, 2010). Some notable cases investigated include: the distressed hillside at Queen's Hill (FSW, 1999), the 1999 Sham Tseng San Tsuen debris flow (FMSW, 2000), 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 large scale very slow moving landslide in Leung King Valley (Parry & Campbell, 2003), and the 2005 Kwun Yam Shan landslide (MGSL, 2007). The studies have provided further insights into the causes, mechanisms and characteristics of natural terrain landslides. Table 1 summarised some key observations of these notable natural terrain landslides investigated.

Table 1. Summary of the notable natural terrain landslides investigated

Cases	Year	Slide Type [(1)]	Landslide Volume (m^3)	Consequence	Key Observations
Queen's Hill	1997[(2)]	Signs of distress	n/a	Some low-rise blocks were evacuated.	Hillside distress in the form of localized landslides, tension cracks and disturbed ground were identified.
Sham Tseng San Tsuen	1999	DF	20-600	Demolished several dwellings. 1 fatality and 13 injured.	Four landslides occurred at the natural hillside, the largest of which (600 m^3) was the primary source of the debris flow.
Tsing Shan	2000	CDF	1,600	Floodwater and debris deposited on LRT track, golf centre & Lung Mun Road.	Elevated pore pressure in colluvium triggered the failure at source area. Accumulation of loose boulder deposits on steep slopes above the incised drainage line contributed additional material to the debris flow.
Leung King Estate	2000	CDF	70-600	Inundation of alluvial outwash debris into the perimeter road of Leung King Estate.	Series of natural terrain landslides occurred on the hillside under one severe rainstorm. Most failures located below exposed rock cliffs at the heads of natural drainage lines on steep hillsides (gradient 30°-40°) that have instability history.
Lei Pui Street	2001	CDF	780	Demolished two squatter structures. Lei Pui Street was closed for 3 days.	The debris flow was triggered by a 250 m^3 landslide above a 25m high cliff. Probable causes of the instability include infiltration through talus and development of cleft water pressures within the underlying rock joints; unfavourable orientation of sheeting joints and steeply dipping major joint set forming potential release surfaces and tension cracks.
Cloudy Hill	2000-2001	DS, DA, DF	12-630	Nil.	Over 45 natural terrain landslides occurred in the vicinity of Cloudy Hill. It was found that the critical factors controlling landslide susceptibility at Cloudy Hill relate primarily to the nature of regolith and terrain morphology.
Leung King Valley	2002[(3)]	very slow moving	40,000	Nil.	The area of the distress was about 10,000 m^2 and the total mass undergoing deformation is in the order of 40,000m^3. The unusual characteristics of this landslide are that the deformation features are fresh, relatively complete, and the fact that the landslide is entirely within natural terrain.
Kwun Yam Shan	2005	CDF, signs of distress	2,350	Approximate 10 m section of the MacLehose Trail was severed.	The landslide involved failure of up to 5m of colluvium, primarily along the old colluvium/CDT interface, giving rise to fast-moving debris. Debris travelled a total distance of 330 m down the drainage line. Development of the extensive tension cracks and other displacement structures are suggestive of a large ground mass undergoing a complex mode of instability.

(1) DF: debris flow; CDF: channelized debris flow; DS: debris slide; DA: debris avalanches
(2) Hillside distresses were identified in 1997 during a slope upgrading works in the vicinity. The instability has been identified in aerial photographs dating back to 1924 during the landslide study.
(3) Extensive ground deformation in the form of surface cracks was apparent following a hill fire occurred in April 2002.

4 REGIONAL AND SITE SPECIFIC STUDIES PHASE

The momentum for further developments on the subject was further boosted from 2000 onwards by incorporating natural terrain hazard regional studies and discrete packages of Natural Terrain Hazard Study (NTHS) and mitigation measures into consultancies under the Landslip Preventive Measures (LPM) Programme. The Tsing Shan foothill regional study formulated a process-based regolith classification and mapping methodology (Fletcher *et al.*, 2002; MFJV, 2002) and highlighted the merits of geomorphological assessments in NTHS (e.g. Parry & Ruse, 2002). The methodology of natural terrain geomorphological mapping was 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.

4.1 *Regional study - Tsing Shan foothill area*

During a rainstorm on 14 April 2000, a swarm of some 100 natural terrain landslides occurred in the Tsing Shan foothills. A regional study covering *c.* 6.5 km^2 was initiated to examine landslide problems in this area in the context of their geomorphological setting (Fig. 8). An area-based susceptibility analysis of the Tsing Shan foothills at 1:2,000-scale was undertaken. Positive correlation was established with three terrain attributes, viz. regolith type, lithological boundaries and proximity to the head of drainage lines, as obtained from detailed field mapping (MFJV, 2003a). The landslide densities were then grouped into classes of <100 landslides/km^2, 100 to 200 landslides/km^2, 200 to 400 landslides/km^2 and >400 landslides/km^2 (Fig. 9). This regional study extended the susceptibility between the least and the most susceptible classes to two orders of magnitude.

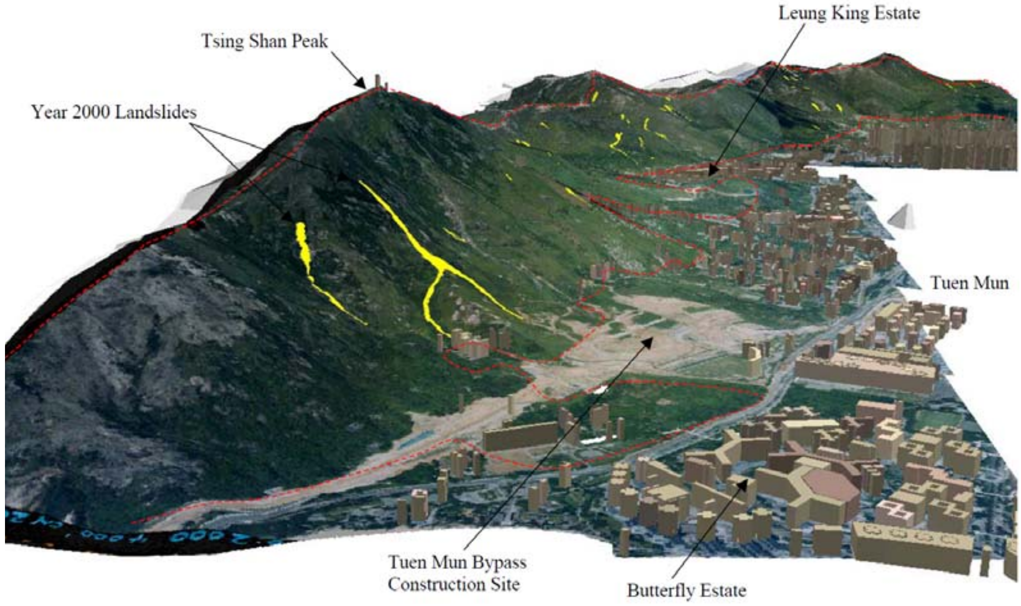


Fig. 8. 3-D oblique aerial view of the Tsing Shan foothill Study Area (MFJV, 2003c)

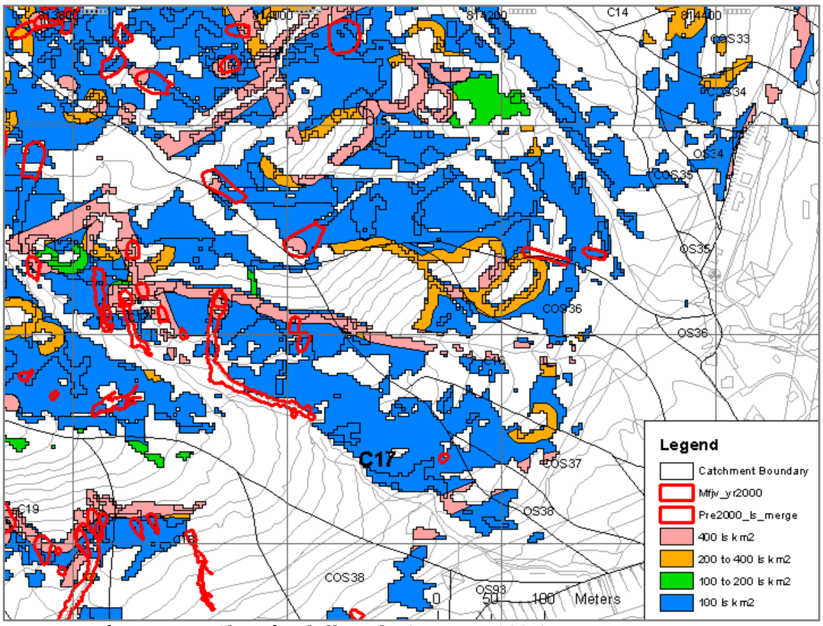


Fig. 9. 1:2,000 susceptibility zoning from Tsing Shan foothill study (MFJV, 2003a)

It was noted that the study of natural terrain hazards involved consideration of the site in the context of its regional geological and geomorphological settings, any man-made influences that may have modified this setting, and the history of landsliding in the area (Ng *et al*., 2003). Geomorphological maps are therefore a fundamental part of natural terrain hazard studies. By placing the site and its surroundings in a framework that integrates form, materials and process, the geomorphological map helps the practitioner assess the influence of such factors as lithology, structure, materials and processes on past landform development, and hence facilitates the analysis of future behaviour.

4.2 *Regional study - north-eastern Hong Kong Island*

Given the current state of knowledge and available geotechnology, it is not possible to predict with full confidence where and when hillside failures will occur. However, it is important that state-of-the-art techniques and best practice should be applied, as far as practicable, to help identify potentially problematic hillsides that may pose a significant risk to existing developments.

In 2006, a pilot study was carried out for the north-eastern Hong Kong Island covering *c*. 19km^2 (MFJV 2009a, b), with an aim to develop a suitable regional natural terrain hazard review methodology, supplementing the approach of identifying vulnerable hillsides based on past hillside failures alone. The hazard maps produced take cognizance of the relationships between the information gathered from 1:2,500-scale engineering geomorphological mapping and the identified hazards (hazard type, location, volume range, etc.), together with consideration of historical landslide records and topographical data based on the results of the LiDAR survey. The morphographical (e.g. regolith) information are also used in the hazard maps, typically to assess potential areas of erodible material (e.g. confined colluvium) along potential channelised debris flow paths (Fig. 10).

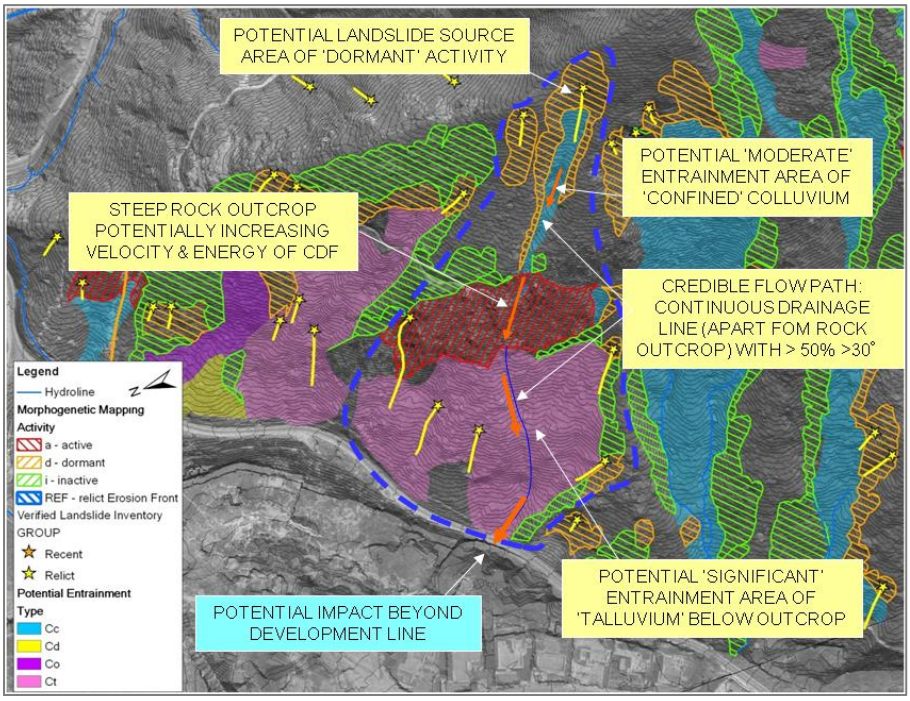


Fig. 10. Example of hazard map showing combination of landform units that generate potential hazard models (MFJV, 2009b)

The study provided an improved means of identifying natural terrain units that may be more susceptible to failure in general. It also offered insights that facilitated development of models for assessing where relatively rare but significant landslide hazards may be present, such as channelized debris flows originating on upper hillsides, with downslope cliffs along the drainage channel to boost the kinetic energy of debris in entraining materials along the stream course and significantly increase the debris volume (MFJV, 2009).

4.3 *Site specific NTHS*

In the early 2000s, discrete packages of NTHS and mitigation measures had been incorporated into LPM consultancies, following the react-to-known-hazard principle for sites affected by very recent (i.e. occurred in the last few years) natural terrain failures. The potential hazards posed by the natural terrain sites were studied so that appropriate mitigation measures were incorporated where necessary. As such, guidelines on recommended good practice for Natural Terrain Hazard Studies (NTHS) were prepared by the GEO.

The interim natural terrain hazard assessment guidelines were published in 2000 (Ng *et al*., 2000) to recommend appropriate practice and procedures, in particular for application of the Design Event Approach. Based on the experience gained and feedback received, a revision of the guidelines was carried out in 2002 with updates on the criteria for screening of sites subject to natural terrain hazards, explanation of the differences between Design Event and Quantitative Risk Assessment (QRA) approaches, the requirement of a detailed aerial photograph interpretation at an early stage of the study, review of notable natural terrain landslide studies, relevance of geomorphology to natural terrain hazard studies, and environmental considerations and maintenance requirements of mitigation measures (Ng *et al*., 2003).

The natural terrain hazard assessment may be conducted using either the QRA approach or the Design Event approach. Regardless of the approach, engineering geological / geomorphological assessment was considered essential in assessing the potential landslide hazards for the sites. There has been continual development of natural terrain related engineering geological / geomorphological mapping techniques in this period. Valuable results were reported with the use of geomorphological assessments, e.g. Arup (2004) (Fig. 11). Along with various regional and site specific NTHS, valuable experience and enhanced engineering geological / geomorphological mapping skills were developed which led to consolidation of knowledge and experience on geomorphological mapping for NTHS (GEO, 2004; Parry & Ng, 2010; Parry, 2011).

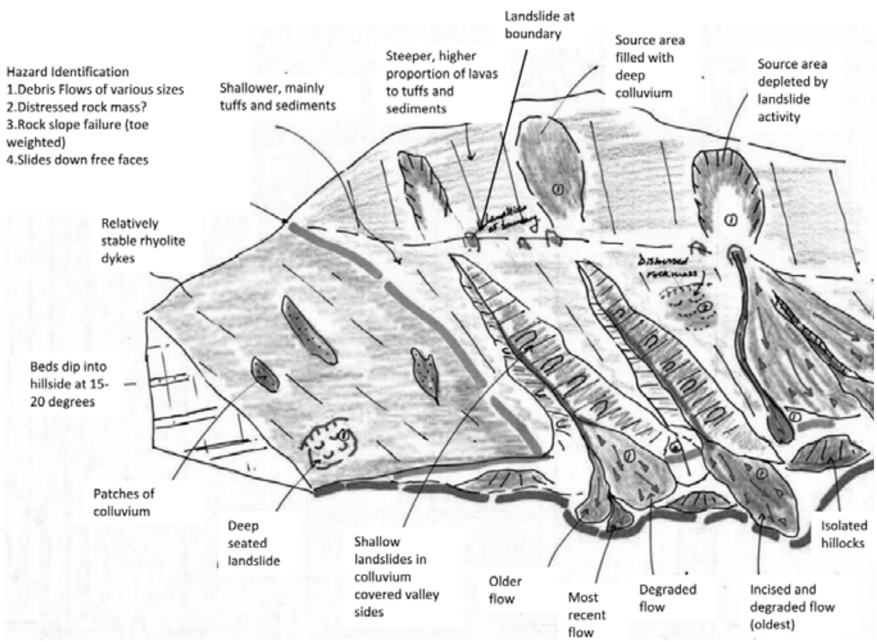


Fig. 11. Reconnaissance geomorphological map for North Lantau (Arup, 2004)

4.4 *Technical development*

In support of the NTHS, various technical development studies have been carried out including soil bioengineering, digital and remote sensing technologies, dating of natural terrain landslides and geotechnical instrumentation works.

4.4.1 Soil bioengineering

After natural terrain failures, bare soil is exposed at the landslide scars and loose debris may have accumulated down slope. Repair works to these scars are generally not warranted because of the high cost and adverse effect on the environment associated with the inaccessibility of most of the scars. In situations where the long-term repair of natural terrain landslide scars are called for, soil bioengineering measures offer a low cost, less heat- and light-reflective, potentially effective, largely maintenance-free, sustainable, and environmentally acceptable alternative to conventional hard surfacing works.

In April 2003, the GEO undertook a pilot project to assess the suitability of soil bioengineering measures for minimising the deterioration of natural slopes in areas of natural terrain affected by recent, shallow landsliding and related gully erosion. The objectives were: (i) to identify measures that are capable of reinforcing the soil mass, and thereby increase the resistance of the slope to further erosion, and (ii) to identify means of accelerating the natural re-vegetation of deteriorating slopes, which in turn would enhance the local ecosystems. This project, which included field trials on several natural hillsides (Fig. 12), has led to the development of the 'Guidelines for Soil Bioengineering Application on Natural Terrain Landslide Scars' (Campbell *et al*., 2008).

(a) Lining the hedgelayer bench with degradable erosion control mat

(b) Laying out rooted plants for hedgelayer installation

(c) Established hedgelayer after one year

Fig. 12. Some bioengineering works carried out in Cloudy Hill as part of the soil bioengineering study

4.4.2 Digital and remote sensing technologies

Significant advances have been made in the application of digital and remote sensing technologies to enhance the capability and efficiency of NTHS. These include Geographic Information System (GIS), digital photogrammetry, Global Positioning System (GPS), and terrestrial and air-borne LiDAR, which have provided promising results. A summary of the technological development and applications in digital technology is given by Wong (2004) and Ng & Wong (2007).

The significant efforts made by the GEO over the years have paid valuable dividends as digital and remote sensing technologies are playing an increasingly important role in landslide risk management in Hong Kong, ranging from data management and dissemination, analysis and interpretation of geospatial data, to providing critical information for problem solving and decision making (Ng & Wong, 2007). The scope of application will continue to expand as these technologies make further advances and become more accessible.

4.4.3 Pilot study on dating of natural terrain landslides

The Design Event approach to hazard risk assessment involves a qualitative assessment based on the likelihood of natural terrain hazards and their consequences. In particular, the relevance of the large relict landslides plays an important role in the assessment of the design event, i.e. the likely volume of failures that could occur. In 2005, a pilot study on dating of natural terrain landslides at 19 sites concluded that direct age determination of carefully selected natural terrain landslides in Hong Kong was viable using dating techniques of Radiocarbon (C14), Optically Stimulated Luminescence (OSL) and Cosmogenic Nuclide surface exposure (Sewell & Campbell, 2005). For instance, the large coastal landslide on Lamma Island (Fig. 6a) had an estimated volume of about 30,000 m^3 and probably occurred within the last few hundred years based on the OSL dating technique. The massive debris lobe at Sham Wat in Lantau Island (Fig. 6b) 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 at 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 (Fig. 6c) was found to have occurred about 8,000 years ago. These landslide ages could have implications of the relevancy of the relict landslides with respect to the present day climatic conditions.

4.4.4 Field instrumentation

As geotechnical instrumentation techniques continue to improve and practitioners gain a better understanding of the possible influence of progressive slope deterioration, slope instrumentation for long-term performance monitoring of hillsides can provide valuable information on the understanding of ground and groundwater behavior during rainstorms. The GEO has undertaken some technical development work to study the performance of various instruments and arrange pilot instrumentation schemes to set up prototype real-time instrumentation networks in Hong Kong (Millis *et al*., 2008).

Four hillsides (Tsing Shan, Pa Mei, Tung Chung and Ching Cheung Road) were selected for the instrumentation study for their variety of geological / hydrogeological conditions and the differing landslide mechanisms offered by these sites. These allowed a variety of instrument types and monitoring scenarios to be tested. As none of these sites presented an immediate risk to the general public, the findings could be considered for application to other slopes where potentially more hazardous conditions may exist.

The field instrumentation works were completed in late 2007 and the real-time monitoring system at the four selected hillsides was operational from March 2008 for a period of three years. The monitoring data collected included records from several notable rainstorms in 2008. A wide range of conventional and state-of-the-art geotechnical sensors, e.g. multi-antenna type differential global positioning system (DGPS) (Fig. 13a), ground movement Time Domain Reflectometry (TDR), in-place inclinometers (Fig. 13b), real-time data communication and geotechnical data processing system were installed. Collaborative studies were also carried out with local tertiary institutions (e.g. Leung *et al*., 2011).

Fig. 13a. DGPS (top) monitoring equipment and (bottom) multi-antenna system (Millis *et al*., 2008)

Fig. 13b. Inclinometer monitoring system (Millis *et al*., 2008)

5 SYSTEMATIC NATURAL TERRAIN LANDSLIDE RISK MANAGEMENT PHASE

Around the mid 2000s, the GEO began technical development work to support the formulation and implementation of a natural terrain risk mitigation strategy for the post-2010 Landslip Prevention and Mitigation Programme (LPMitP). The Enhanced Natural Terrain Landslide Inventory (ENTLI) was prepared by 2007 (MFJV, 2007a, Dias *et al*., 2009). In parallel, a systematic hazard identification exercise was also undertaken, involving compilation of an inventory of hillside catchments with historical natural terrain landslides that had occurred close to existing buildings and important transport corridors (denoted as Historical Landslide Catchments (HLC)) (MFJV 2007b). Based on the pilot HLC data prepared in 2004, a risk-based HLC priority ranking system was developed by Wong *et al*., (2006).

5.1 *Enhanced Natural Terrain Landslide Inventory*

The limitations of the NTLI (King, 1999) and discrepancies between site specific landslide studies and the features contained within the NTLI have been discussed by practitioners, e.g. Parry (2001), Pinches *et al*., (2002) and MFJV (2003b). In particular, the high-flight aerial photography, on the basis of which the NTLI was compiled, has a limited resolution. Many natural terrain landslides that are of small size or that occurred sometime before the aerial photographs were taken cannot be recognized from photographs taken at high altitude.

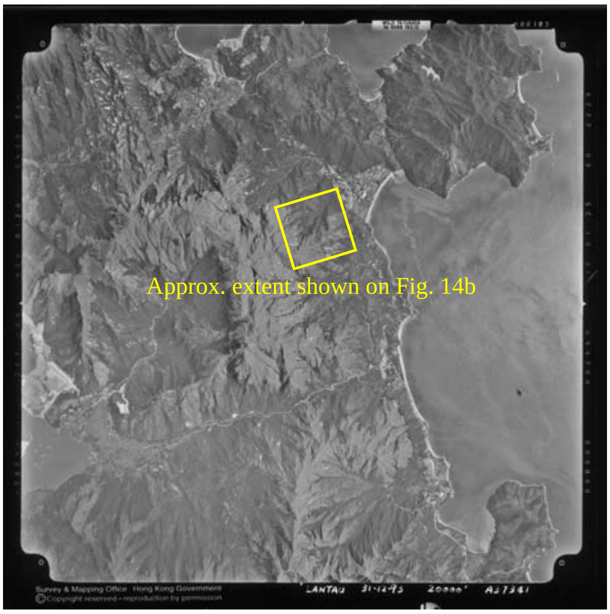


Fig. 14a. Example of a high-flight aerial photograph taken at 6,000 metres

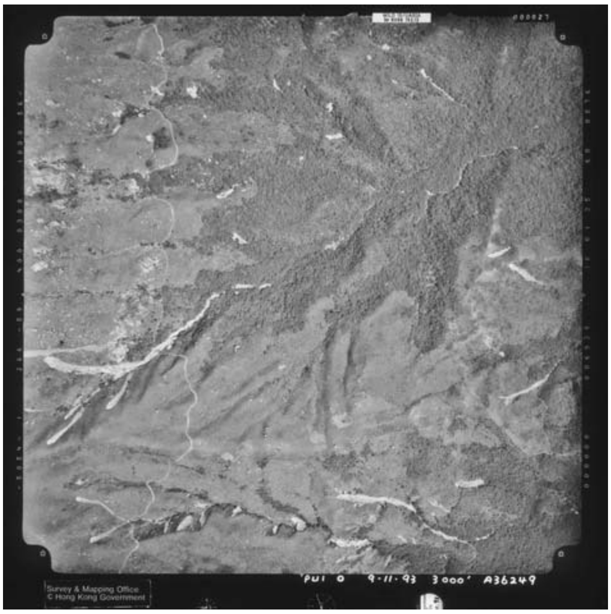


Fig. 14b. Example of a low-flight aerial photograph taken at 900 metres

In early 2004, the GEO commenced compilation of an updated natural terrain landslide catalogue for Hong Kong, using both high and low-flight aerial photographs (ranging from about 500 to 6,000 m flight-height), in recognition of the limited resolution and temporal coverage of the high-flight aerial photographs. To develop a methodology and to evaluate required resources, a pilot study was carried out covering Hong Kong Island, Kowloon and the Sha Tin foothills. In July 2005, consultants were commissioned to compile the catalogue for the whole of Hong Kong. The inventory was first prepared in March 2007 and is updated regularly to maintain its currency.

The improved inventory (ENTLI) supersedes the NTLI. The ENTLI is presented in a GIS data format that contains the locations and attributes of more than 100,000 landslides identified on natural terrain (MFJV, 2007a; Dias *et al*,. 2009). Up to 2009, about 19,000 and 90,000 recent and relict landslides respectively have been recorded. Identification of the landslides by API using low-flight aerial photographs provided additional information on the mapped features and, on a comprehensive basis, was instrumental in identifying vulnerable catchments with historical landslide activities that may pose a risk to the community.

5.2 *Inventory of Historical Landslide Catchment*

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 vulnerable catchments, which are posing a notable risk, are denoted as Historical Landslide Catchments (HLC). Fig. 15 shows the HLC selection criteria. The inventory comprises about 2,700 HLC (Fig. 16 shows examples of some HLC), and is the basic dataset for planning the priority ranking and implementation of risk mitigation works for vulnerable hillsides flanking existing developments in Hong Kong. The GEO has completed a global QRA to evaluate the risk levels of the HLC, diagnosed their risk characteristics and projected the overall risk of natural terrain landslides for the whole of Hong Kong (Wong *et al*., 2006, Cheng & Ko, 2010). This provided key information for the formulation of the prevailing natural terrain risk management strategy. Using the global QRA results, a risk-based ranking system was devised for establishing the relative priority of the 2,700 HLC for systematic follow-up actions under the LPMitP since 2010.

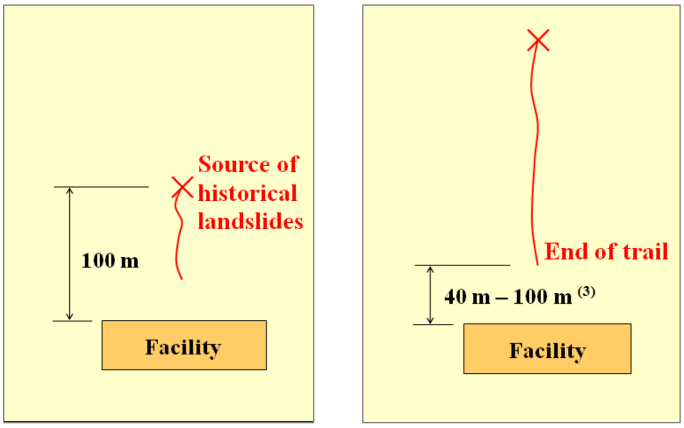


Fig. 15. Existing HLC selection criteria

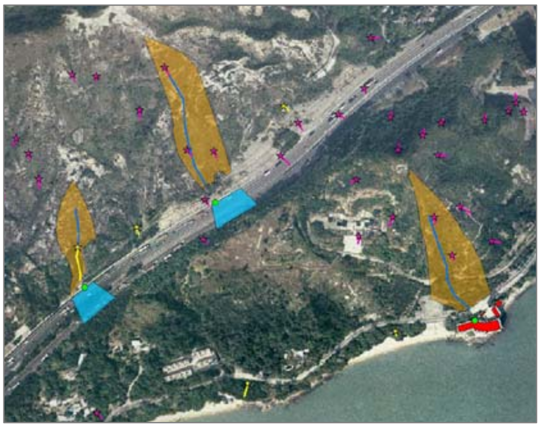


Fig. 16. Example of HLC delineated

The severe rainstorm of 7 June 2008 has highlighted the potential vulnerability of developments located close to natural terrain. The rainstorm, which centred over the western part of Lantau Island, caused over 1,000 natural terrain landslides in the region including many debris flows with long runout distance. Table 2 shows the runout distance of debris flows that occurred in June 2008 on Lantau Island compared with that recorded in the ENTLI up to 2006.

Table 2 Comparison of runout distance of debris flows that occurred in June 2008 with those recorded in the ENTLI

Runout distance of debris flow	No. of cases recorded in the ENTLI (up to 2006)	No. of cases identified in Lantau Island (June 2008)
Runout ≥ 200 m	162	105
Runout > 200 - 500 m	149	87
Runout > 500 - 1000 m	12	14
Runout > 1000 m	1	4

Taking cognizance of the lessons learnt from the June 2008 landslides and with the experience gained from the LPMitP, the HLC selection criteria are being reviewed. Some sizeable catchments with major drainage lines (refers to catchments with a plan area ≥10,000 m^2 and a drainage line of length ≥500 m) have also been delineated in order to identify vulnerable catchments, in particular those with the potential for causing low-frequency, large-magnitude channelized debris flows (CDF). Further review will be conducted for those sizeable catchments affecting high consequence facilities.

5.3 *Area-based approach*

Noting the significantly increased output of natural terrain work under the LPMitP, Chan (2007) and Wong (2009) highlighted a number of issues in tackling natural terrain landslide risk management. Those specifically relevant to geological aspects included possible underestimation of the design event, inadequate prediction of the nature of landslide debris, mis-interpretation of debris flowpaths, and occurrence of landslides in low-ranked HLC or non-HLC. Whilst the nature of landslide debris can be better appreciated through careful field mapping and characterisation, and prediction of debris flow paths can be improved with the help of terrain models generated from LiDAR data, other aspects cannot be readily defined or codified because of their wide scope and partially implicit nature. A pragmatic approach was therefore required.

To overcome the limitations of the HLC framework, which is based on known failures, an area-based approach to natural terrain hazard studies was adopted, whereby HLC are combined in study packages with adjoining hillside catchments that have similar topographical, geological, geomorphological and environmental settings, and affecting the same unit of development. Fig. 17 shows an example of a study area. This is necessary to take account of some lower-ranked and/or non-HLC hillsides flanking developed areas that may also be susceptible to failure. In addition, studying larger hillside areas is more amenable to systematic application of engineering geomorphology for hazard assessment.

Using this approach, some 900 study areas were delineated. This dataset provided a better appreciation of the scale of the natural terrain work required for planning of the LPMitP consultancy agreements, and to monitor the progress of addressing the deserving HLC in a holistic manner. The approach to engineering geomorphological and hazard mapping developed since the early 2000s has been routinely applied to many study areas under the LPMitP consultancy studies in an area-based approach (Fig. 18).

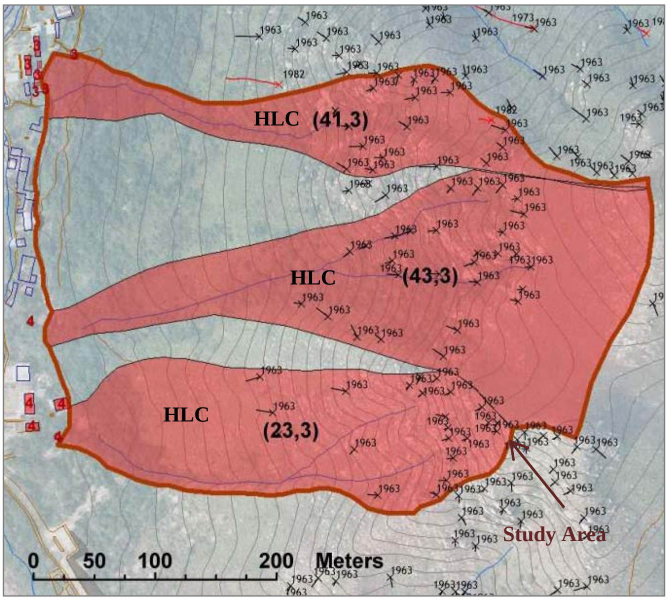


Fig. 17. Example of a study area under LPMitP
(Note: the first number within the bracket refers to HLC ranking, second number refers to the HLC class)

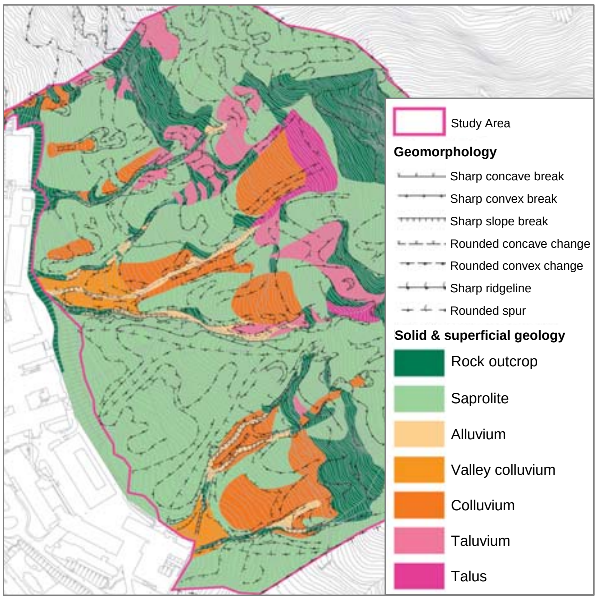


Fig. 18. Example of engineering geomorphological map developed for a study area (Parry, 2011)

5.4 *Out-of-Turn action*

Subject to endorsement by the GEO's technical review, injection of deserving natural hillside catchments into LPMitP for out-of-turn action is allowed based on the 'react-to-known-hazard' principle. For example, after the 7 June 2008 rainstorm, the GEO reviewed various landslide cases and considered that the West Lantau Region as well as five notable cases, namely Fui Yiu Ha in Sheung Ling Pei, Shatin Pass Road, Ewan Court, San Francisco Towers and Fung Fai Terrace, met the 'react-to-known-hazard' principle and deserved out-of-turn action in the interests of public safety.

5.4.1 West Lantau regional study

The severe rainstorm of 7 June 2008 had its peak over the western part of Lantau and caused over 1,000 natural terrain landslides in the region. Many of the sizeable natural terrain failures developed into debris flows and affected developed areas (Fig. 19), resulting in evacuation of village residents and road closures. Following this rainstorm, the GEO commissioned a regional natural terrain hazard study of West Lantau (*c*.18.5 km^2). Its main purpose was to undertake a regional scale natural terrain hazard review for the study area with the purpose of ranking landslide risk within natural hillside catchments and prioritising the implementation of more detailed hazard studies and where necessary, mitigation works.

Fig. 19. Example of landslide clusters in West Lantau from the June 2008 rainstorm

In this study, comprehensive engineering geomorphological mapping (AFJV, 2010; Millis *et al*., 2010) was carried out to extract relevant geological and topographical information of the natural terrain (Fig. 20). The observations made during the API and field inspections indicated that the terrain within the study area could be broadly sub-divided into four 'Terrain Units' (viz. Incising Terrain Unit, Lower Terrain Unit, Middle Terrain Unit and Upper Terrain Unit) based on their regional scale, shape and form (Fig. 21). These units reflect different stages and means of landscape evolution within the study area.

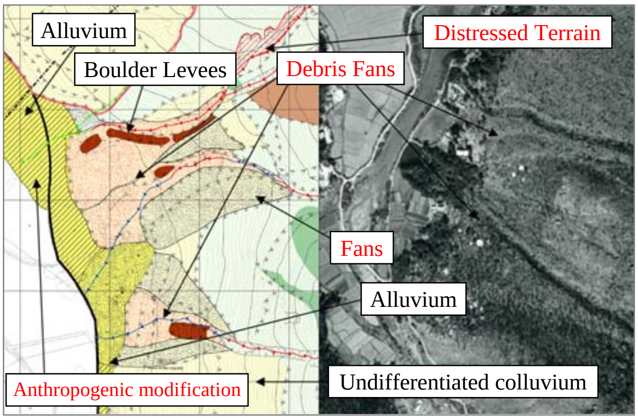


Fig. 20. Example of superficial deposit and their grouping into landforms (Parry *et al*., 2010)

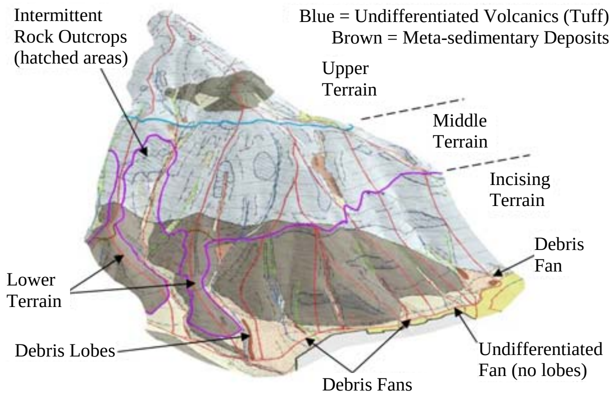
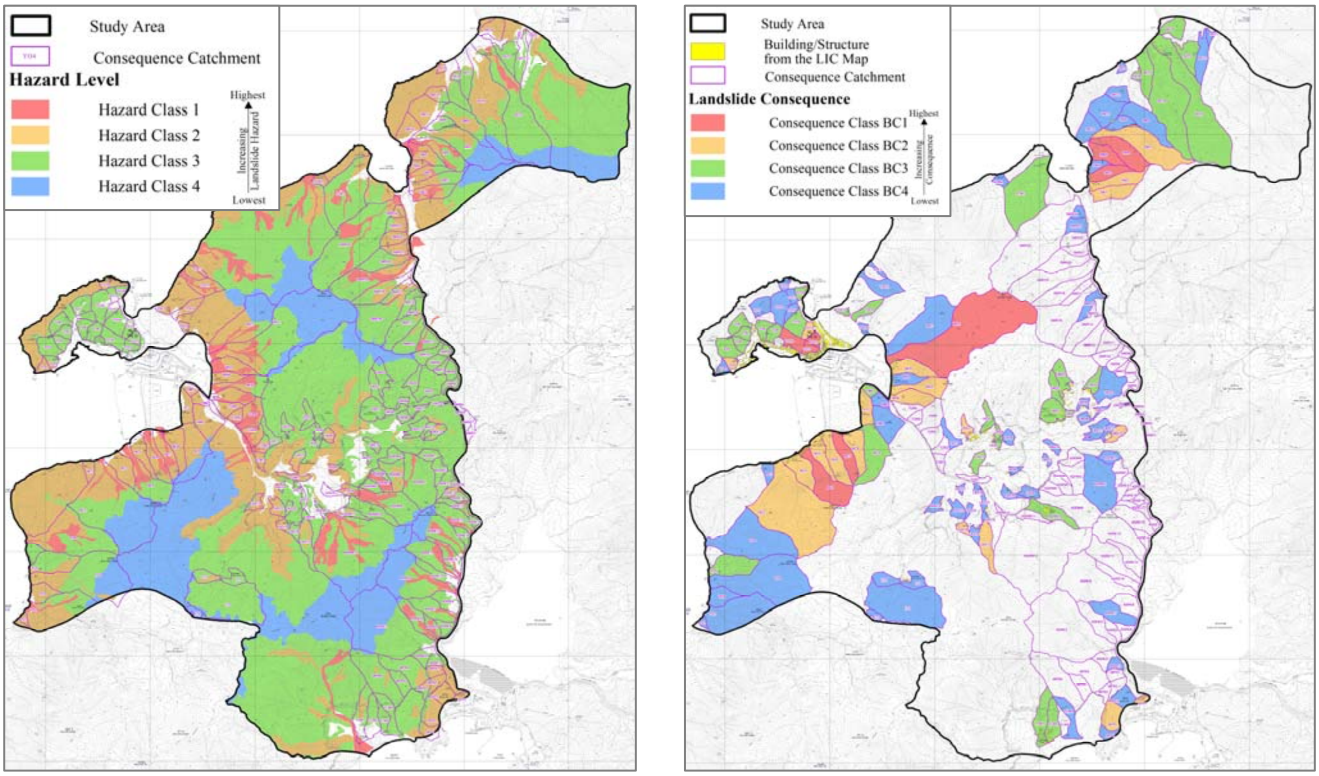


Fig. 21. Subdivision of 'terrain units' (Millis *et al*., 2010)

Landslide hazards within the study area were assessed based on the various components recorded within the engineering geomorphological maps, including the slope morphology, type and extent of superficial geological deposits, landform, drainage line characteristics and the 'Terrain Units'. The spatial distribution of the more hazardous zones was found to be in good agreement with the locations of both the historical landslide records and the June 2008 landslides (Fig. 22a).

The consequence of landslides within the study area has been evaluated based on two groups, viz. the occupied buildings within existing villages and key transportation routes. By evaluating the relative landslide hazards in a given catchment against the corresponding landslide consequence (Fig. 22b), risk matrices of hazard versus consequence for villages and transportation routes have been produced to allow screening and ranking of the hillside catchments.



(a) Landslide hazard map (b) Consequence map

Fig. 22. Regional hazard and risk mapping of the natural terrain at West Lantau (Millis *et al*., 2010)

5.4.2 Other notable cases

Following the June 2008 landslides, the following five cases were also considered to have met the 'react-to-known-hazard' principle for out-of-turn action under the LPMitP. An area-based approach was adopted.

(i) Fui Yiu Ha in Sheung Ling Pei – The debris from the landslide (*c.* 150 m^3) caused damage to the low-rise structures at the toe of the hillside. The ENTLI revealed a history of failures and clustering of landslide scars, and the hillside contained several relatively high ranking HLC.

(ii) Shatin Pass Road – A landslide (*c.* 1,500 m^3) occurred above a man-made slope within the natural terrain, with the landslide debris being channelized down a stream course and reaching the compound of Tsz Ching Estate. Owing to the proximity of the debris flow to the public housing estates, the case attracted extensive public and media attention.

(iii) Ewan Court – The landslide (*c.* 100 m^3) was initiated as an open hillside failure and became channelized below Bowen Road. The ENTLI revealed a history of past instability in the general vicinity of the hillside, which contained several relatively high ranking HLC.

(iv) San Francisco Towers - The landslide (*c.* 150 m^3) occurred on a hillside below Broadwood Road. There were a number of past landslide incidents recorded on the hillside. Owners of San Francisco Towers reported excessive surface runoff from the hillside in the previous years. The fill material above San Francisco Towers and the landslide scar were injected into the LPMP for upgrading.

(v) Fung Fai Terrace – The landslide (*c.* 150 m^3) occurred on a hillside below Stubbs Road. Residents of nine flats temporarily moved out voluntarily. The landslide scar was injected into the LPMP for upgrading.

5.5 *Technical support works*

Previous technical development studies (Section 4.4) were found to be applicable to the works being conducted under the systematic natural terrain landslide risk management phase, and have been further developed as described below.

5.5.1 Soil bioengineering

Under the West Lantau regional study, detailed review of the potential for the implementation of soil bioengineering works has been conducted for those catchments selected for implementing mitigation works (Arup, 2010). This built on the experience gained in using bioengineering measures for repairing landslide scars between 2003 and 2006. The review specifically focussed on the identification of shotcrete portions of the catchments where soil bioengineering measures could be utilised to restore the hillside and prevent future degradation.

The review indicated that a study area at Upper Keung Shan has potential for the implementation of soil bioengineering measures. The study area was subjected to extensive landsliding during the June 2008 rainstorm, resulting in a large portion of the catchment (some 3,900 m^2 in plan area) being covered in shotcrete as a result of landslide emergency works (Fig. 23). As such, it provides an ideal site for comprehensive implementation and long-term monitoring of the effectiveness of soil bioengineering measures. Following the implementation of soil bioengineering measures, detailed review of the performance and effectiveness of the works will be carried out. The completion of such works will enhance the state of knowledge regarding the effectiveness of soil bioengineering works in Hong Kong and will facilitate further review and updating of existing guidelines, where appropriate.

(a) General view

(b) Landslide scar

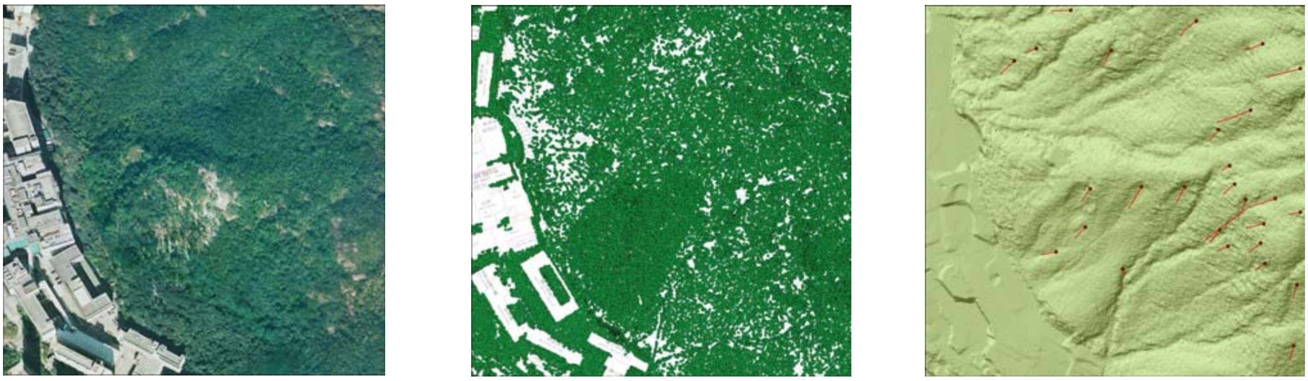
(c) Landslide trail

Fig. 23. Shotcreting works on the landslide scar in Upper Keung Shan

5.5.2 Territory-wide LiDAR survey

A pilot airborne LiDAR (Light Detection and Ranging) survey of Hong Kong Island in 2006 demonstrated that LiDAR data would be beneficial in deciphering ground features under a thick vegetation cover (Ng & Chiu 2008). Apart from facilitating preparation of engineering geomorphological and subsequent hazard maps, LiDAR data also allows generation of high-resolution terrain models which are crucial for accurate mapping of landslide scars and prediction of debris flow paths from mobility modelling (Fig. 24). With the experience gained from the pilot survey in 2006, a territory-wide survey was conducted in December 2010.

LiDAR technology, with multi-return capability, can produce 'bare-earth' ground profiles or digital terrain models through a data processing technique known as 'virtual deforestation'. It has proven to be useful in natural terrain hazard studies where much of the hillsides are covered with vegetation. The 'bare-earth' models facilitate identification of ground features, such as relict landslides and subtle terrain morphology that are disguised under thick vegetation cover. With the availability of the good quality and high resolution LiDAR data, wider applications of the LiDAR technology have been further explored, including delineation of geomorphological and geotechnical features, detection of changes in landform, enhancing visualization of landslides in 3-D, as well as identification of anthropogenic features. Recent developments in the application of the LiDAR data are outlined in Lai *et al*. (2012).



(a) Hillside in December 2006 (b) Ground points from LiDAR survey (c) Digital elevation model

Fig. 24. Example of digital elevation model generated using LiDAR Data (Ng & Chiu, 2008)

5.5.3 Age determination of natural terrain landslides

An age dating programme of natural terrain landslides, which is aimed at building a comprehensive database of numerical landslide age data in order to establish a better framework in determining the design events for implementation of hazard mitigation works, commenced in October 2010. Most of the ages obtained so far are from debris deposits using the OSL dating technique. Only a few samples suitable for Cosmogenic Nuclide surface exposure dating and C14 dating have been undertaken.

Thus far, some 50 ages on debris deposits from seven sites have been obtained. In contrast to the dated samples previously reported which have come from relatively shallow excavations in debris fans (Sewell & Campbell, 2005), recently analysed samples have come mostly from boreholes and trial trenches in thick colluvial lobes on Lantau Island (e.g. Wang Hang). Samples currently being dated come from LPMitP sites on Hong Kong Island. The age data from these sites will be compared with those from Lantau Island, and well as data from previous studies to further test landscape evolution and climate models. This will also allow further analysis of age versus depth relationships, and frequency versus magnitude relationships.

5.5.4 Landslide monitoring work

The West Lantau regional study has provided an opportunity to install suitable field instruments, to investigate the type, rate and frequency of ground movement, the role of hydrogeology and its effects on slope instability (Arup, 2012; 2013a, b). The sites include three adjacent open hillslope catchments at Tai O Cemetery and a major drainage line at Keung Shan Road West. The field instrumentation works build on the experience gained in the previous works (see Section 4.4.4).

Following the June 2008 rainstorm, field inspections in the Tai O Cemetery site have identified networks of tension crack extending across several portions of the hillside. This suggests that areas of active deformation are present and that further ground movements may occur in the event of significant rainstorms. As such this area is considered suitable for studies of ground deformation together with detailed assessments of the geological and hydrogeological conditions. This location also contains a large relict landform interpreted as being a rotation failure (Fig. 25). The proposed instrumentation works include sensors to monitor surface and sub-surface ground movements, groundwater conditions and rainfall.

Under the same rainstorm, the drainage catchment at Keung Shan Road site experienced some 18 landslides (Fig. 26). As a result, a rigid barrier was built at the mouth of the drainage line which is considered sufficiently robust to mitigate hazards within the catchment. Given the propensity of the terrain above the rigid barrier to channelised debris flows and the fact that such hazards have been mitigated against, this catchment is considered suitable for instrumentation purposes. The proposed instrumentation works include surface and sub-surface ground movement, rainfall, groundwater levels, fluvial activity along the drainage lines and potential debris flow behavior.

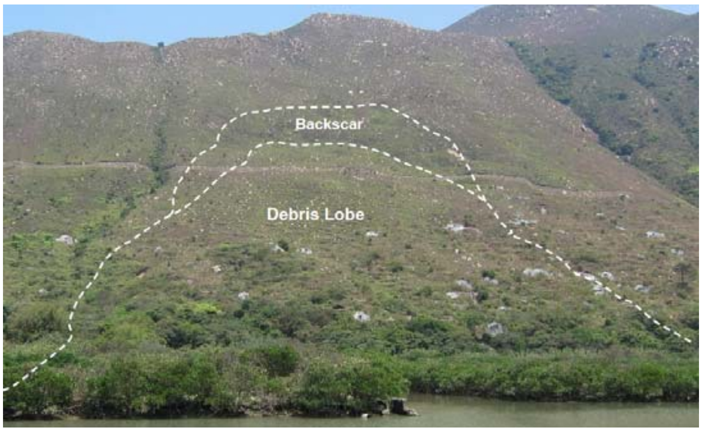


Fig. 25. General view of landslide complex at Tai O Cemetery site

Fig. 26. Oblique photo of the Keung Shan Road site after June 2008 rainstorm

5.6 *Enhanced technical approach for NTHS*

Since the publication of the NTHS guidelines (Ng *et al*., 2003), much experience has been gained in the study and mitigation of natural terrain hazards in Hong Kong, particularly from systematically dealing with Historical Landslide Catchments (HLC) under the LPMitP since 2010. By consolidating the experience gained and incorporating the findings from technical development work, and following extensive consultation with practitioners, key areas for enhancement to the approach for dealing with natural terrain hazards in Hong Kong were identified. The enhancements aim to place hazard mitigation at a level that is more appropriate and practicably achievable given the current state of knowledge and technology, and serve to provide a more cost-effective and practical approach to dealing with natural terrain landslide hazards.

The enhanced approach is described in three separate GEO Technical Guidance Notes. TGN 36 (GEO, 2013a) covers the classification of hillside catchments, the rationalization of the Design Event Approach (DEA), and the application of the enhanced approach in dealing with natural terrain hazards. TGN 37 (GEO, 2013b) gives recommendations on the use of empirical design of flexible barriers for mitigating open hillslope landslides. TGN 38 (GEO, 2013c) provides guidance on the assessment of debris mobility for hillside failures within catchments with the presence of pronounced topographic depression but without well-defined drainage channel which potentially may lead to debris flow hazards. The enhanced approach will be reviewed, following experience gained in its application.

5.7 *Study of hillside pockets*

Given the history of infrastructure and building developments at Hong Kong's foothills, small tracts of hillsides flanking developed areas (referred to as 'hillside pockets') are common. These hillside pockets are affected by human disturbance to varying degrees (e.g. construction of roads or building platforms). Landslides are found to occur at the hillside pockets from time to time, e.g. landslide that occurred below Broadwood Road and above San Francisco Towers as well as landslide below Stubbs Road and above Rockwin Court, Fung Fai Terrance (Fig. 27) during the severe rainstorm on 7 June 2008 (see Section 5.4.2). For the one at San Francisco Towers, a subsequent landslide investigation revealed that the failure was initiated from an unregistered fill body below Broadwood Road.

Fig. 27. Examples of failures within hillside pockets

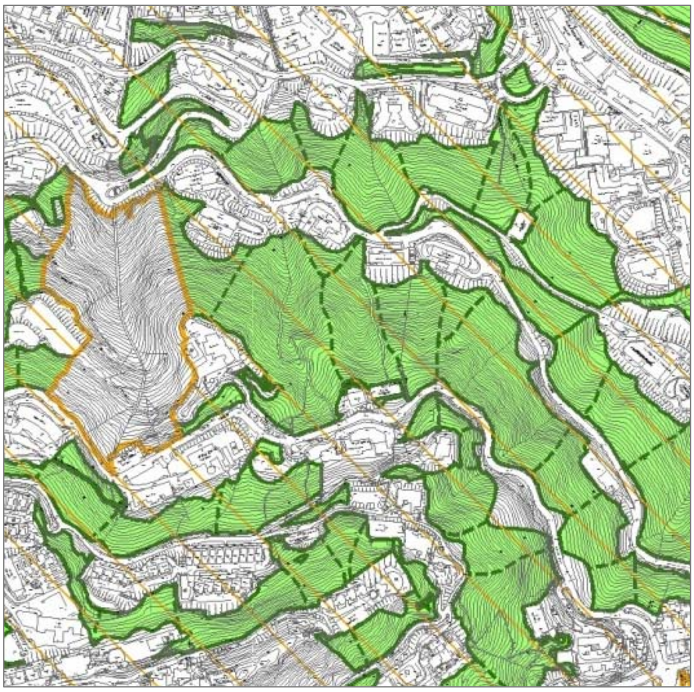


Fig. 28. Examples of hillside pockets (those in green)

Due to concerns that other 'missed' fill bodies may exist and pose a public safety concern, a review was carried out in the late 2000s to examine possible approaches for identifying unregistered fill bodies. The review concluded that sizeable pockets of hillside in the urban areas can be identified based on a GIS search using a set of criteria (e.g. height, slope gradient and plan area). Based on a detailed review of the relevant aerial photographs, it is possible to determine whether the hillside pockets may contain registerable man-made features. These features are then confirmed by field inspection.

A pilot study on the approaches and measures for dealing with these pockets, commenced in March 2010 and was completed in early 2013, which aimed at identifying hillside pockets and examining the possible strategy for dealing with the hazard posed by hillside pockets (Arup, 2013c). The pilot study developed a set of criteria for identifying the hillside pockets within the predominantly developed area as well as the methodology for delineating the development line. A hillside pocket is defined as an area of hillside that is located within the predominantly developed area and satisfies all of the three criteria: (i) maximum slope gradient >20°; (ii) elevation difference >8 m; and (iii) plan area >400 m². Some examples of hillside pockets are given in Fig. 28. A GIS search routine was developed for systematic and automatic identification of hillside pockets that satisfy the criteria above.

A QRA was conducted to assess the global risk from the hillside pockets. The estimated risk was presented in terms of the annual Potential Loss of Life (PLL) and was determined through detailed hazard and consequence assessments for the two study areas in Hong Kong Island and Sha Tin. These two study areas were considered representative of the full range of hillside pocket conditions likely to be encountered throughout Hong Kong and account for approximately 10% of the projected hillside pocket areas in Hong Kong. Territory-wide projections of the overall landslide risk from hillside pockets in Hong Kong were made which indicated that the best estimated risk to life from landslides originating within Hillside Pockets is 0.56 PLL per year, which is an order of magnitude lower than the PLL from the natural terrain. The GEO has commissioned a further study recently to catalogue the hillside pockets for whole of Hong Kong and to develop a system for a combined ranking of hillside pockets and HLC to facilitate appropriate follow up actions.

6 CONCLUSIONS

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. Since the 1990s, the natural terrain hazard assessment strategy and the associated technical development works for dealing with natural terrain hazards in Hong Kong has gradually evolved, comprising four distinct phases: (i) the early phase of landslide studies, (ii) the territory-wide landslide data compilation and analysis phase, (iii) the regional and site specific studies phase, and (iv) the systematic natural terrain landslide risk management phase. However, it is apparent that further insightful engineering geological development work will be required to help reduce the large uncertainties which still exist in making hazard predictions.

Despite NTHS apparently becoming routine work under the LPMitP, there is no room for complacency. Much effort is still needed to enhance the current state of knowledge and practice for assessing natural terrain hazards, in order to implement more cost effective and appropriate mitigation works.

ACKNOWLEDGMENTS

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