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Managing landslide risk systematically using engineering works

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The dense urban development on a hilly terrain, together with intense seasonal rainfall, gives rise to acute slope safety problems in Hong Kong. This is reflected by a death toll of over 470 fatalities due to landslides since the 1940s. Site formation works form an integral part of infrastructure and building development in a steeply sloping terrain. In the mid-1970s, the Hong Kong government embarked on a slope retrofitting programme, known as the landslip preventive measures programme, systematically to reduce landslide risk by upgrading substandard man-made slopes to modern safety standards. By 2010, some 4500 high-risk government man-made slopes had been upgraded through the implementation of engineering works. In 2010, the government launched the landslip prevention and mitigation programme to dovetail with the completion of the previous programme. The new rolling programme aims to contain the overall landslide risk to an 'as low as reasonably practicable' level by upgrading the remaining substandard man-made slopes and systematically mitigating the landslide risk posed by vulnerable natural terrain catchments. In this paper, the advances and innovations arising from this unique systematic slope safety programme are described.

1. Introduction

Hong Kong has a population of over 7 million in a small land area of approximately 1100 km^2, some 60% of which comprises natural terrain. The scarcity of flat land necessitated dense urban hillside development in the past. At the time of rapid economic expansion in the 1960s to 1970s, there was no geotechnical control in regulating slope formation works. As a result, about 40 000 potentially substandard man-made slopes were formed.

The two dominant rock types in the urban areas of Hong Kong are granitic and volcanic rocks (Sewell and Campbell, 1997). These rocks have been deeply weathered – locally in excess of 60 m, or 100 m in more extreme cases. The ground conditions are typically highly variable and heterogeneous. Erosion pipes can exist in the weathered rocks as well as colluvium, and such preferential flow paths can greatly complicate the local hydrogeology. Rapid build-up of transient and spatially variable groundwater conditions is the norm under intense rainfall. Rainfall intensities of 50 mm/h to 100 mm/h and 250 mm/day to 350 mm/day are common. Intense rainstorms can trigger numerous landslides, which are liable to cause loss of life and significant socioeconomic damage given the dense urban development.

Landslides in Hong Kong typically comprise shallow failures of less than 3 m in depth with a debris volume of less than 50 m^3. Sizeable landslides of several hundred cubic metres or more, many of which involve structure-control failures, can also occur. Because of the dense urban setting, even a relatively small-scale landslide could result in significant impact. This vulnerable setting, together with the high public expectation, calls for a high level of slope safety.

The occurrence of several disastrous landslides, which led to multiple fatalities in the 1970s (Figure 1), culminated in the setting up of the Geotechnical Engineering Office (GEO) in 1977 as a

Figure 1. Disastrous landslides on 18 June 1972 in Hong Kong: (a) Sau Mau Ping (71 fatalities); (b) Po Shan (67 fatalities). From 1977 to 2010 approximately HK$19 billion (about £1·9 billion) was spent on landslip prevention measures

central government body to regulate slope safety in Hong Kong. Since its establishment in 1977, GEO, now housed under the Civil Engineering and Development Department, has implemented a comprehensive slope safety system to manage landslide risk in Hong Kong. One of the key components of this holistic system comprises a systematic programme to retrofit existing substandard man-made slopes using engineering works. The scope of this programme was subsequently expanded to cover risk mitigation works for vulnerable natural hillside catchments. This paper presents the key technical advances made in respect of landslide risk management and slope engineering practice in Hong Kong, and highlights the achievements of the systematic slope retrofitting programme.

2. Systematic slope retrofitting programmes

2.1 Landslip preventive measures programme (1977–2010)

In the aftermath of the disastrous landslides in the 1970s, GEO embarked on a long-term programme in 1977, known as the landslip preventive measures (LPM) programme, systematically to retrofit substandard government man-made slopes and undertake safety screening studies of the stability of private man-made slopes. Chan and Lau (2008) present the scope of the LPM programme and how slopes under different jurisdictions are dealt with.

The LPM programme had evolved progressively to cope with the growing expectations of the general public for enhanced slope safety and aesthetics. Following the fatal Kwun Lung Lau landslide in 1994 (Wong and Ho, 1997), the LPM programme was accelerated with the injection of additional resources. The annual output in terms of upgraded government slopes and expenditures are shown in Figures 2 and 3, respectively.

Typically, over 150 sites scattered in different places are active at any one time under different works contracts.

By 2010, the overall risk to life posed by substandard man-made slopes had been reduced to less than 25% of the 1977 level, as demonstrated by novel quantitative risk assessment techniques (Wong, 2005).

2.2 Landslip prevention and mitigation programme (2010–present)

In 2010, the GEO launched a new rolling landslip prevention and mitigation (LPMit) programme to dovetail with the LPM programme on its completion. The strategy of the LPMit programme is to contain the remaining landslide risk within the ‘as low as reasonably practicable’ region (Figure 4) through enhancement of the remaining substandard man-made slopes and systematic mitigation of landslide risk posed by vulnerable natural hillside catchments, in accordance with the ‘react-to-known-hazard’ principle (i.e. to carry out studies and mitigation actions where significant hazards become evident).

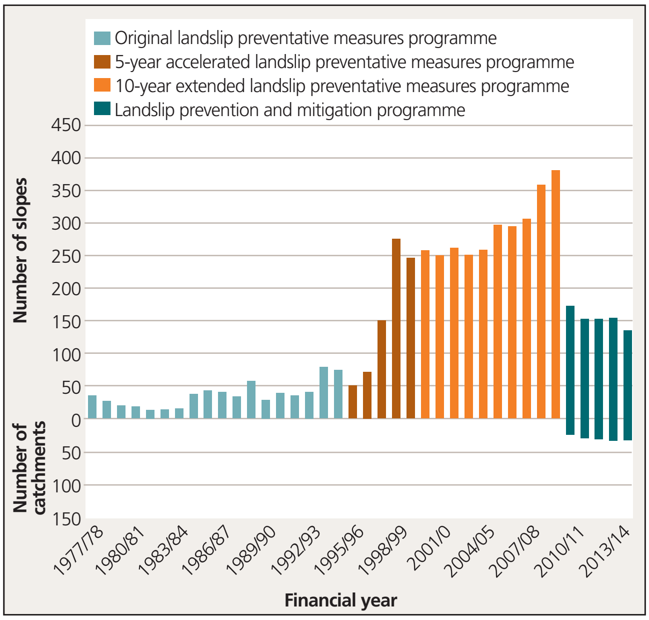

Figure 2. Number of slopes upgraded and number of catchments with mitigation measures implemented from 1977 to 2015

Contrary to the LPM programme, which adopted a 'total retrofit' approach focusing on high-risk slopes affecting occupied buildings and major roads, an 'asset management' approach has been adopted under the LPMit programme. A comparison of the two approaches is given in Table 1.

The pledged annual target outputs of the LPMit programme are: (a) to upgrade 150 substandard government man-made slopes; (b) to complete safety screening studies on 100 private man-made slopes, and (c) to undertake landslide risk mitigation works for 30 vulnerable natural hillside catchments. The annual expenditure is approximately HK$1000 million (about £100 million).

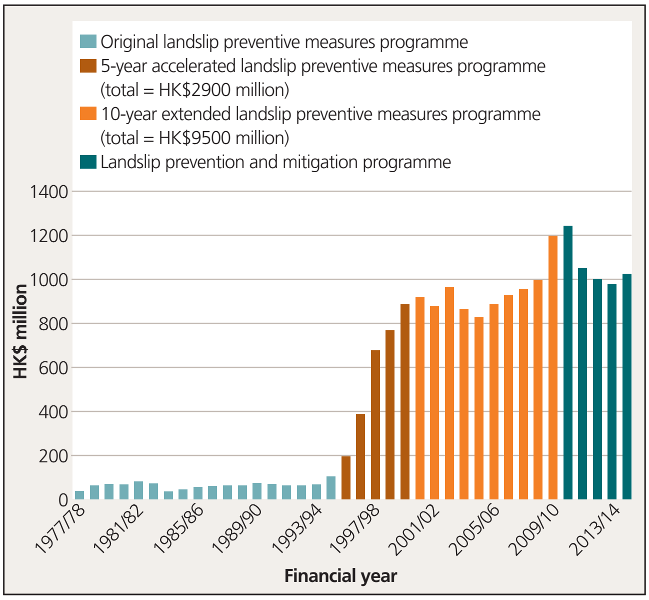

Figure 3. Expenditure under the landslip preventive measures and landslip prevention and mitigation programmes from 1977 to 2015 (HK$10 = £1)

'Total retrofit' approach (landslip preventive measures programme)	'Asset management' approach (landslip prevention and mitigation programme)
Focused on slopes posing high risk – e.g. old substandard slopes with serious failure consequences	Risk is moderate to low (within 'as low as reasonably practicable' zone) – for example slopes with less serious failure consequences
Involved a manageable number of slopes – 'total fix' is practical	Risk is spread over a large number of slopes – total fix within a short time is neither practical nor cost-effective
Upgrading is required if the slope is assessed to be substandard. Slope ranking is to set the priority order for assessment/retrofitting, to maximise the rate of risk reduction	Upgrading is required if the slope is at an advanced stage of deterioration or of known instability problem. Slope ranking is to identify the most deserving slopes for action, to deal with known hazards and optimise use of limited resources
Implemented as a retrofitting task to reduce a notable risk proportion by a target date	Implemented as a rolling enhancement programme to contain risk level as otherwise risk will increase progressively due to slope degradation, population increase and encroachment of more urban development or redevelopment on steep hillsides, and potential impacts of extreme weather conditions as a result of more frequent and more severe rainfall due to climate change

Table 1. Comparison of 'total retrofit' and 'asset management' approaches

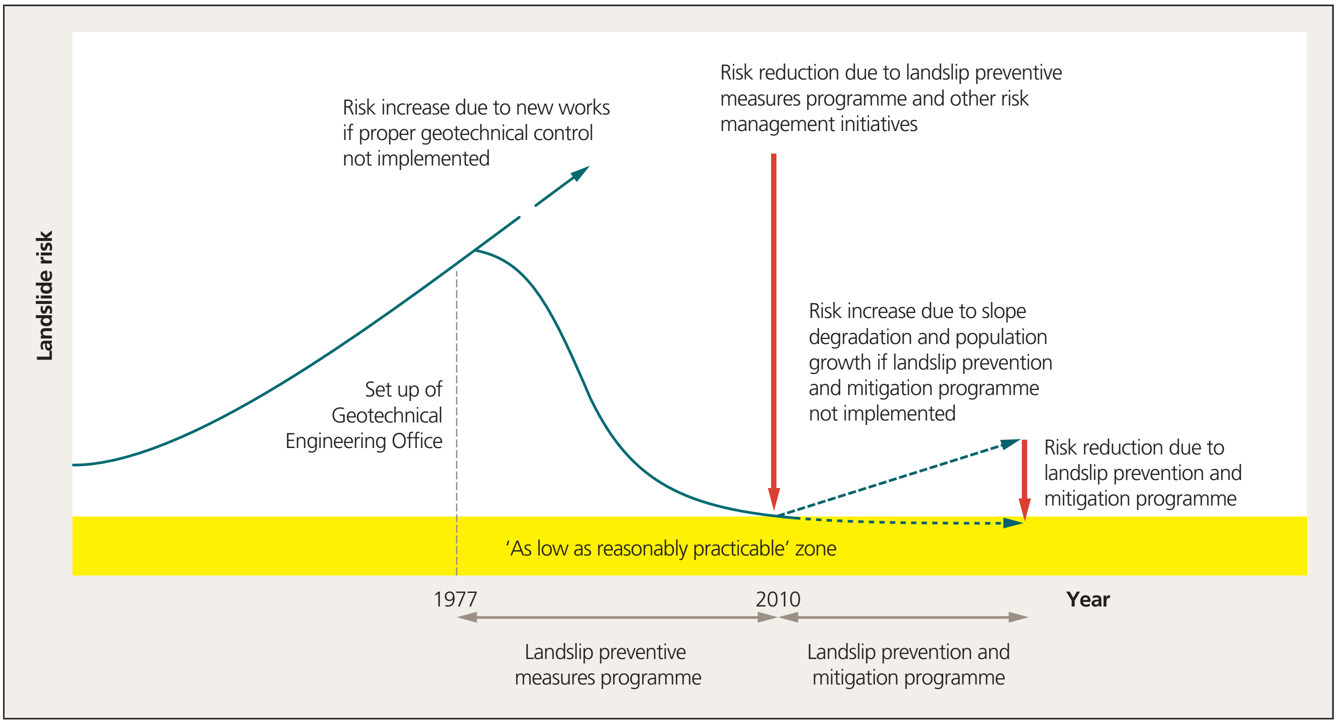

Figure 4. Notional landslide risk curve trend

3. Promoting regular slope maintenance

Regular slope maintenance contributes to reducing the chance of landslides caused by surface infiltration and wash-out (i.e. erosion) failures due to uncontrolled and concentrated surface water flow. Such failures are common in a dense urban setting and can be aggravated by blockage of surface drainage channels or defective slope surface protection due to lack of maintenance. The recommended good practice for slope maintenance is given in GEO (2003). Regular routine inspections by technical staff and engineering inspections by a qualified geotechnical professional provide a mechanism for early detection of signs of distress and slope deterioration, as well as changes in site setting that may adversely affect slope safety. In addition to routine maintenance, the concept of preventive maintenance, which involves the use of prescriptive measures – such as pre-determined, experienced based and suitably conservative standard modules of slope improvement or drainage enhancement works without the need for detailed ground investigation and stability assessment – is also promoted by GEO (2009) to enhance asset management.

4. Advances in landslide risk management

4.1 Holistic slope safety system

As the specialist geotechnical arm of the Hong Kong government and the landslide risk manager, GEO formulated a holistic slope safety system to manage landslide risk, which incorporates the application of fundamental risk management concepts at the policy administration level. The system has been subject to progressive improvement over the years. It has now evolved into a comprehensive regime, which embraces a range of initiatives that serve to manage the landslide risk through an explicit risk-based strategy and approach in a holistic manner (Wong, 2009a).

The principal goals of the slope safety system are to reduce landslide risk to the community through a policy of priority and partnership, and to manage public perception and tolerability of landslide risk in order to avoid unrealistic expectations.

The system is primarily a framework for systematic and multi-pronged management of landslide risk. It adds value to the sustainable development of Hong Kong through averting landslide fatalities, and improving the built environment. This entails the use of both engineering (hard) and non-engineering (soft) approaches. The key components are summarised in Table 2.

4.2 Risk-based priority ranking systems for slopes

Risk-based priority ranking systems, which consider both the likelihood and consequence of slope failure, have been developed to ensure that the most deserving slopes are selected for priority action under the slope retrofitting programmes. The ranking systems (Cheng, 2013; Wong, 1998) incorporate extensive local experience and insights into failure mechanisms. To support the implementation of the expanded LPMit programme, a separate risk-based priority ranking system for vulnerable natural hillside catchments was also developed (Chan and Kwan, 2012). Readers should consult the above references for details of the various ranking systems, including how different types of facilities and infrastructures are considered.

4.3 Quantitative risk assessment

The GEO has pioneered the development of quantitative risk assessment techniques to manage landslide risk as well as to evaluate the performance and cost effectiveness of the government's efforts in reducing landslide risk using engineering works (Wong, 2005).

Territory-wide quantitative risk assessments carried out by GEO served to define the scale of the respective landslide hazards, evaluate the risk portfolio and distribution and provide a basis for formulating appropriate risk reduction strategies and the setting of realistic slope safety goals for the systematic programmes to retrofit existing substandard slopes. In addition, quantitative risk assessment allows monitoring of the progress of the LPM programme and evaluation of its cost effectiveness through cost–benefit calculations (Ho and Ko, 2009).

Quantitative risk assessment has also shown that by 2010 the overall landslide risk of natural terrain would become comparable to that posed by the remaining substandard and non-robust man-made slopes (Cheng and Ko, 2010). This finding formed the basis for expanded efforts to cover systematic mitigation of the natural terrain landslide risk under the LPMit programme.

Slope safety system components	Contribution by each component		
	to reduce landslip risk		to address public attitudes
	hazard	vulnerability	
Policing			
Cataloguing, safety screening and statutory repair orders for slopes	✓		
Checking new works	✓	✓	
Slope maintenance audit	✓		
Inspecting squatter areas and recommending safety clearance		✓	
Input to land use planning	✓	✓	
Safety standards and research	✓	✓	
Specialist works projects (slope safety programme)			
Upgrading existing government man-made slopes	✓		
Mitigating natural terrain landslide risk	✓	✓	
Regular slope maintenance			
Routine and preventive slope maintenance	✓		
Education and information			
Maintenance campaign	✓		✓
Personal precautions campaign		✓	✓
Awareness programme	✓	✓	✓
Information services	✓	✓	✓
Landslip warning and emergency services	✓	✓	✓
Maintenance of registered government man-made slopes and natural terrain defence/stabilisation measures is carried out by the responsible government departments			

Table 2. Key components of the Hong Kong slope safety system

4.4 Systematic landslide investigation programme

Landslide investigations provide an invaluable source of information for enhancing the understanding of failure and slope behaviour. Considerable insights have been gained from studies of slope failures, which have led to improvement in the slope engineering practice and publication of enhanced technical standards and guidance (Ho *et al.*, 2009).

For example, the 1994 Kwun Lung Lau landslide investigation (Wong and Ho, 1997) revealed the adverse effects of leakage from buried water-carrying services on slope stability, and advanced the understanding of the mechanism of brittle failure of a slender masonry wall (aspect ratio ≥5). The former has resulted in the *Code of Practice on Inspection and Maintenance of Water Carrying Services* (Works Bureau, 1996), whereas the latter has necessitated a revised standard of professional practice for the assessment of old masonry walls.

A systematic landslide investigation programme was introduced in 1997. The findings arising from landslide studies have greatly enhanced the technical know-how and understanding of the nature of landslide problems in Hong Kong (Ho and Lau, 2010).

5. Advances and innovations in retrofitting of substandard man-made slopes

5.1 Soil cut slopes

From the late 1970s to late 1980s, substandard soil cuts in Hong Kong were commonly upgraded by trimming to a gentler angle in order to achieve the required factor of safety (Geotechnical Control Office, 1984). However, studies of failures of engineered slopes (i.e. those designed or upgraded to the required standard with geotechnical input) have shown that such unsupported cuts are not robust and notable failures have occurred, as they can be especially sensitive and vulnerable to uncertainties such as the geological defects and groundwater anomalies.

Soil nailing started to be used in Hong Kong in the early 1990s for upgrading substandard soil cuts. The early design approach and construction practice of the drill-and-grout soil nails were discussed by Watkins and Powell (1992). Because soil nails are usually installed at a close spacing (typically 1·5–2·5 m), they can reduce the vulnerability of a slope to undetected weak geological defects by binding the soil together to form an integral groundmass. In addition, the use of soil nails is an attractive solution from a logistic, programming and cost point of view, as it is a relatively simple operation. To improve and optimise the soil nailing technology, extensive studies comprising field tests, site trials, laboratory tests, numerical modelling and physical modelling were conducted by GEO. These resulted in enhanced cost effectiveness, increased robustness, improved durability and better quality works, and culminated in the publication of a new technical standard on soil nailing (GEO, 2008).

For more sizeable slopes, hand-dug caissons have been adopted as the upgrading measure in some past projects (Figure 5).

5.2 Loose fill slopes

Existing loose fill slopes (with inadequate compaction) are liable to fail by means of static liquefaction upon water ingress due to rainfall infiltration. These substandard slopes were traditionally stabilised by removing and re-compacting the upper 3 m of loose material and provision of a subsurface drainage layer (Hong Kong Government, 1977). The corresponding good performance records since 1977 have vindicated this approach. However, this re-compaction method often involves diversion of buried services, clearance of existing mature trees and vegetation on the slopes, and extensive earthworks, which require adequate access and working space.

To minimise the disturbance to the environment, various alternative stabilisation methods were examined, including grouting, installation of displacement piles, installation of soil nails with concrete grillage beams (Figure 6) and pit-by-pit fill replacement (Chan and Chan, 2008). The latter two options have proved to be effective in upgrading substandard loose fill slopes.

The use of soil nails, which has now become a common practice for upgrading loose fill slopes with relative compaction values ranging from 75 to 95%, called for the formulation of a novel design methodology that addresses various potential failure modes including static liquefaction and interface liquefaction (Cheuk *et al.*, 2013; GEO and Hong Kong Institution of Engineers, 2011).

Figure 5. Construction of hand-dug caissons at Sai Wan Estate, Hong Kong

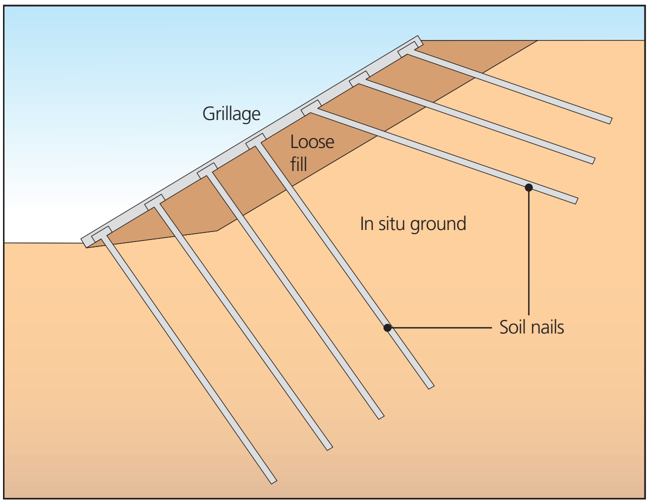

Figure 6. Soil nails with concrete grillage beams

5.3 Masonry walls

The investigation and assessment of the stability of old masonry retaining walls is not straightforward because of their variable and non-monolithic construction (Chan, 1996). Guidance on assessment of well-proportioned masonry walls and slender masonry walls is given by GEO (2004).

A special feature of many old masonry walls in Hong Kong is the presence of 'wall trees' (mostly Chinese Banyan), which grow into the open joints or crevices between the stone blocks and/or above the wall crest. These wall trees need to be preserved in view of their amenity and heritage values.

Wong and Jim (2011) recommended soil nailing as one of the suitable stabilisation measures for old masonry walls in order to preserve both existing wall trees and the masonry facade fabric (Figure 7).

5.4 Novel use of time domain reflectometry for quality control of soil nails

Like other buried works, it would be difficult to verify the actual quality of soil nails once they have been installed into the ground. To enhance the quality control of soil nails, GEO has pioneered the development of non-destructive testing methods for assessing both the length of installed steel bar and the integrity of grout annulus.

Among the various potential testing methods considered, time domain reflectometry (TDR) was found from comprehensive field trials to be a simple, sufficiently reliable, quick and inexpensive tool for the above purposes (Cheung and Lo, 2011). GEO has promulgated the novel use of TDR to audit soil nailing works since 2004 and a quality assurance framework was developed (GEO, 2008). More than 53 000 soil nails have been successfully tested to date using TDR.

5.5 Landscaping and greening of slopes

A holistic approach in slope landscaping and greening, together with the provision of a suitable erosion control mat, is promoted by GEO. Special emphasis is given to rendering the appearance of engineered slopes as natural as possible, to make them blend in with their surroundings. Existing vegetation covers on slopes are preserved wherever possible. The surface of the upgraded slopes would be vegetated with native shrub species (or tree species if the slope gradient is less than 35°), with a view to developing an eco-friendly environment (Figure 8).

Where a hard surfacing is required for steep slopes or slopes with notable past failures because of safety concerns, suitable landscape treatments (such as applying subdued colour, masonry facing and providing planter holes and proprietary greening product on the slope surface for screen planting) will be adopted to minimise visual impact.

Comprehensive technical guidance on landscape treatment and bioengineering is promulgated by GEO (2011a).

6. Advances in natural terrain landslide risk management

6.1 Natural terrain hazard study

A comprehensive framework and methodology for managing natural terrain landslide risk has been developed by GEO (Wong, 2003). A natural terrain hazard study (NTHS) is carried out to formulate the engineering geological and engineering geomorphological models for a natural hillside and evaluate the landslide hazards.

The natural terrain landslide hazards are classified into five main types taking due account of the mechanism of landslide debris transportation, nature of displaced material and catchment topographic characteristics. These comprise open hillslope failure, debris flow, deep-seated failure, boulder fall and rockfall.

Three different technical approaches, namely design event, quantitative risk assessment and factor of safety, may be used either individually or in combination for the evaluation of natural terrain hazards. Technical development work was instrumental in formulating these approaches for application to NTHS. This led to the publication of a technical guidance document on natural terrain hazard assessment (Ng *et al.*, 2003), which has recently been updated (Ho and Roberts, 2016).

Further technical development work was carried out in 2014 based on a consolidation of more recent experience, which resulted in the development of an enhanced approach for NTHS (GEO, 2014a). These enhancements aim to pitch at a level of hazard mitigation that is more appropriate and practically achievable, and is commensurate with the current state of knowledge and technology. In addition, the enhanced methodology provides a more cost-effective approach in dealing with natural terrain landslide hazards.

Figure 7. Old masonry wall upgraded with the use of soil nails

Figure 8. Landscape treatment on an upgraded roadside cut slope

6.2 Application of digital and remote sensing technology

Significant advances have been made in the practical application of advanced digital and remote sensing technologies to meet the challenges posed by natural terrain (Wong, 2007). These include digital photogrammetry, geographic information system (GIS) and remote sensing technologies such as air-borne and terrestrial light detection and ranging (Lidar) and interferometric synthetic aperture radar, which enhance the capability and efficiency of NTHS.

The conventional aerial photographic interpretation and photogrammetric analysis using stereoscope and stereo-plotter are now undertaken by digital means by way of digital photogrammetry, with improved efficiency, resolution and analytical capability.

Notable advances made by GEO in respect of GIS technology and capability include GIS search, browsing, editing and publications, GIS-based geotechnical analyses (e.g. landslide susceptibility analyses, rainfall–landslide correlations, etc.) and GIS modelling (e.g. modelling of runout of landslide debris and quantitative risk assessment of natural terrain landslides and three-dimensional (3D) visualisation).

Since 2003, GEO has been using a land-based Lidar for topographic surveys where access is difficult or dangerous (e.g. survey of fresh landslide scars). Lidar technology with the multi-return capability can produce 'bare-earth' ground profiles or digital terrain models even in heavily vegetated terrain through a data processing technique known as 'virtual deforestation'. It has proved to be exceedingly useful in NTHS. The bare-earth models facilitate the identification of ground features such as relict landslides or subtle terrain morphology.

In 2012, GEO conducted a territory-wide airborne Lidar survey of the whole of Hong Kong to produce fine-scale topographical maps and a digital elevation model typically with a grid size of about 1 m. This has enabled the delineation of geomorphological and geotechnical features, detection of changes in landform, enhanced visualisation of landslides in 3D, and identification of anthropogenic features to a resolution that cannot be achieved by means of conventional aerial photographs.

Recently, GEO has successfully applied mobile laser scanning technology as well as hand-held laser scanning technology to conduct topographic surveys at selected man-made slopes and natural terrain.

The application of Lidar technology has been shown to be a cost-effective and reliable tool, particularly for NTHS, and has provided high resolution spatial data (i.e. digital terrain model) that are essential for landslide hazard assessment and debris runout evaluation.

6.3 Advances in debris mobility modelling

One of the key factors that can affect the design of risk mitigation works is debris mobility. This requires the use of dynamic analysis to assess the probable debris runout distance, debris velocity and debris thickness of natural terrain landslides, with due regard to the likely scale of the failure and modes of debris transportation. Computer codes based on continuum models, which have been calibrated against local well-documented natural terrain landslides, are commonly used in routine practice.

The GEO developed two in-house numerical models, namely 2dDMM and 3dDMM, for landslide debris mobility analysis. These algorithms have been used to back analyse channelised debris flow and open hillside failure in Hong Kong as well as published case studies in other countries. Advances in numerical modelling of landslide debris movement has greatly enhanced the capability of assessing debris influence zones and the rational design of risk mitigation works.

Based on the findings of back analyses of past natural terrain landslides, guidelines on the assessment of debris mobility of future natural terrain landslides for design purposes are available from GEO (2011b, 2012a, 2013) for reference by practitioners.

A benchmarking exercise on landslide debris mobility modelling was held in Hong Kong during the 2007 International Forum on Landslide Disaster Management (Hungr *et al.*, 2007). Thirteen groups of researchers and practitioners from different parts of the world participated in this exercise. A range of numerical models was used for the debris mobility analysis of the selected benchmark cases. The outcome of this exercise showed that the simulation results obtained by GEO's landslide runout simulation models were reasonably accurate as compared with the analytical solutions, laboratory flume test measurements and field observations. The results were also generally consistent with those determined from some other numerical models.

6.4 Rational design of debris-resisting barriers

Instead of carrying out extensive landslide preventive works on natural terrain, which would often be impractical and environmentally undesirable, defence measures are typically constructed at the toe of the hillside. For example, a concrete check dam may be constructed at the toe of a drainage line to contain the landslide debris discharged from the natural terrain (Figure 9).

Figure 9. Concrete check dams at the toe of natural hillside

6.4.1 Rigid barriers

Rigid barriers are typically constructed using reinforced concrete and are deployed mostly to intercept channelised debris flow. They are designed to resist the impact force of the debris and occasional boulders embedded in the debris front. Lo (2000) recommended the use of the hydrodynamic pressure approach to estimate the debris impact load. The author also suggested using the Hertz equation, with an appropriate load reduction factor of 10, to estimate the boulder impact load.

Kwan (2012) updated the above recommendation in respect of the value of dynamic pressure coefficient to be adopted. Kwan (2012) also recommended the consideration of multiple phases of landslide debris impact on the barrier. The recommendations on the assessment of design debris impact velocity and design retention volume for debris-resisting barriers were further refined by Kwan and Koo (2015) and published in GEO (2015a) and GEO (2015b), respectively.

The recommended good practice for detailing of rigid debris-resisting barriers is given in GEO (2012b).

6.4.2 Flexible barriers

Flexible barriers, in the form of steel ring nets mounted between horizontal steel ropes spanning over steel posts and anchored to the ground, are one of the common natural terrain landslide mitigation measures. Their advantages include relatively easy installation on steep natural terrain, less visually obtrusive and less environmental impact as compared with rigid barriers. While flexible barriers have been in use for over 20 years mainly as a defence measure against boulder falls and rockfalls, the application of flexible barriers to resist the impact of landslide debris is a novel approach that lacks an internationally recognised standard for design.

The design methodology for rockfall fences is based on the energy approach whereby a falling rock or boulder is stopped in one go by the barrier, which is designed to absorb the kinetic energy of the rock mass. The design usually entails the use of proprietary flexible barrier systems with specified energy absorbing capacities that have been verified by full-scale field testing in accordance with the relevant national or international standards. This technology for rockfall fences is relatively mature. In contrast, the impact of landslide debris on a flexible barrier may be delivered in the form of consecutive pulses, and the loading on the barrier is affected by the compressibility and mobility of the debris. Therefore, the design methodology for rockfall barriers is not directly applicable to the design of debris-resisting flexible barriers.

The GEO initiated technical development work with a view to improving the understanding of the interaction between landslide debris and a flexible barrier. Based on numerical experiments using particle flow code in three dimensions, Sun and Law (2012) recommended the consideration of two principal modes of debris impact mechanisms, namely pile-up and run-up mechanisms (Figure 10), in the design of flexible barriers. They further proposed simplified analytical solutions for calculating the energy loading arising from impact by landslide debris, with due account taken of the energy loss (e.g. due to basal resistance) experienced by the landslide debris, for the above two mechanisms. Recommendations on rational design approaches (i.e. force approach and energy approach) for flexible debris-resisting barriers were made by Kwan and Koo (2015).

As part of the development work, an empirical design methodology for prescribed flexible barriers for open hillslope failure was also developed by the GEO based on a review of the energy capacity of barriers and a probabilistic consideration of the scale and mobility of historical landslides in the landslide inventory (GEO, 2014b). This has helped to streamline the design of debris-resisting barriers in practice.

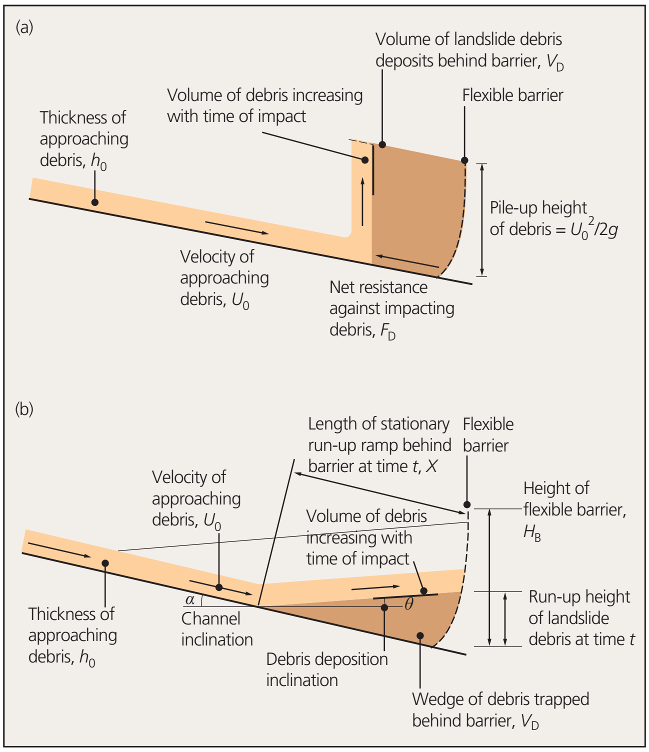

Figure 10. The pile-up (a) and run-up (b) mechanisms proposed by Sun and Law (2012) in assessing the energy loading by landslide debris for the design of flexible barriers

6.5 Innovative risk mitigation schemes

Other innovative schemes have been developed by GEO to mitigate natural terrain landslide risk where the use of conventional debris-resisting barriers is inappropriate. An example is given by the Po Shan natural hillside catchments, which are known to have high transient groundwater tables in a thick layer of bouldery colluvium (>30 m) and a history of landslides.

To combat the risk of deep-seated landslides, a robust groundwater control system, which comprised two 3·5 m diameter drainage tunnels, together with 172 sub-vertical drains (24–100 m long), was provided (Figure 11). Details are described by Lo *et al.* (2011).

6.6 Technical development work

The GEO continues to undertake extensive technical development work relating to NTHS and design of natural terrain landslide risk mitigation measures. Examples of some of the ongoing technical development work include:

- laboratory flume tests to investigate the use of baffles for energy dissipation
- field tests on a range of cushioning materials intended to reduce boulder impact load on rigid barriers (Figure 12(a))

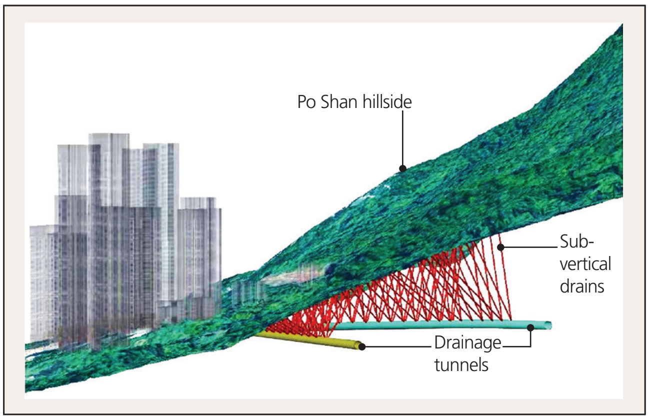

Figure 11. Construction of drainage tunnels at Po Shan natural hillside, Hong Kong

- improved algorithm of debris mobility analysis for design of multiple barriers (Kwan *et al.,* 2015)
- review of numerical codes for analysis of flexible barriers subject to debris impact (Kwan *et al.,* 2014, 2015)
- centrifuge tests to investigate debris impact on flexible and rigid barriers, respectively (Figure 12(b))
- design of full-scale tests of debris impact on flexible barriers (design volume up to 500 m^3 and typical impact velocity of 8–10 m/s).

7. Ongoing challenges

The LPMit programme manages landslide risk proactively through the implementation of engineering works to reduce risk to life. The scope of the systematic retrofitting programme has been expanded to cover natural terrain, which represents a formidable challenge. This calls for continual technical development work to enhance slope engineering practice and promote innovations.

Despite the achievements made with regard to landslide risk reduction, there is no room for complacency. It is pertinent that all stakeholders should remain vigilant about landslide risk. An acute challenge is the potential climate change impact and the projected increase in extreme rainfall events. This was highlighted by the devastation caused by the severe rainstorm of 7 June 2008 in Hong Kong, which was the most intense rainstorm since rainfall records began in 1884. This resulted in a large number of natural terrain landslides, many of which were sizeable scale and mobile (Wong, 2009b).

More recently, scenario-based assessments of the potential impact of extreme rainfall on slope safety and stress testing of the prevailing emergency response system have provided insight into the risk profile and strategic areas that deserve improvement in the government's landslide emergency system (Ho *et al.,* 2015). There is an eventual need to improve the slope safety preparedness and crisis management for extreme rainfall, and enhance community resilience.

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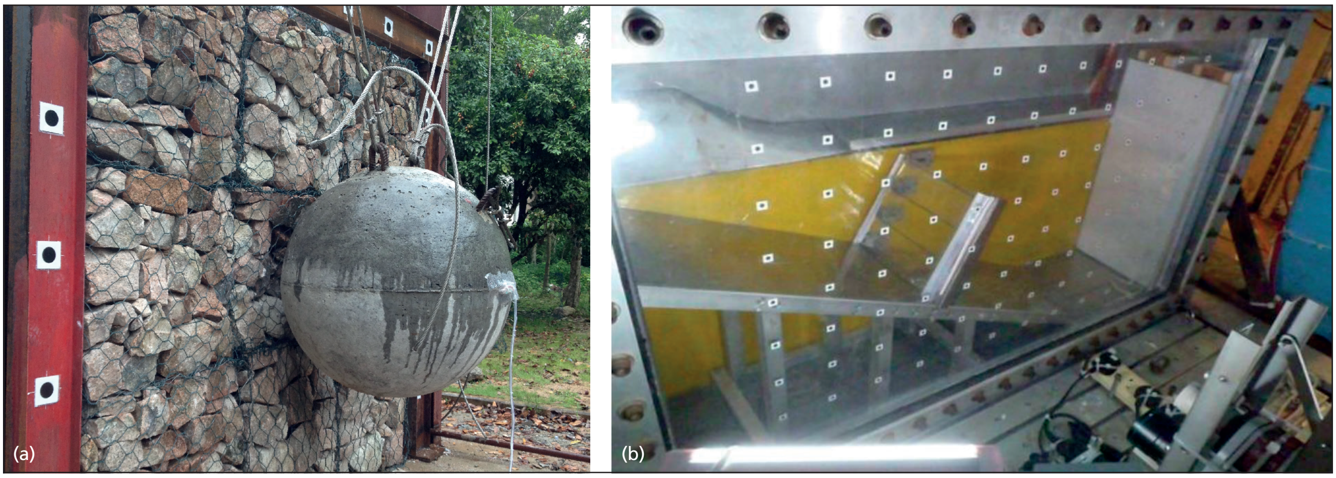

Figure 12. (a) Large-scale physical impact test on a rigid barrier with a gabion cushioning layer, and (b) centrifuge test to examine debris dynamic impact loading on a simulated flexible barrier

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