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Challenges in Improving Slope Safety in Hong Kong through the Landslip Prevention and Mitigation Programme

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ABSTRACT: In 1977, the Hong Kong Government embarked on a systematic retrofitting programme, known as the Landslip Preventive Measures (LPM) Programme, to systematically upgrade existing substandard man-made slopes to modern safety standards. By 2010, some 4,500 high-risk government man-made slopes have been upgraded through engineering works, and the overall landslide risk arising from man-made slopes has been reduced to less than 25% of the 1977 level. Over the years, the programme has evolved progressively in response to Government's continuous improvement initiatives and rising public expectations in respect of slope safety and slope appearance. In 2010, the Government launched the Landslip Prevention and Mitigation (LPMit) Programme to dovetail with the LPM Programme, with the focus being on retrofitting the remaining moderate-risk substandard man-made slopes and systematically mitigating natural terrain landslide risk. This paper presents the challenges, technical advances and achievements of the LPM and LPMit Programmes.

1. INTRODUCTION

Hong Kong has a hilly terrain with a scarcity of flat land. Of the total land area of about 1,100 km^2, about 63% of the land is steeper than 15^o and 30% is steeper than 30^o. It has a high concentration of urban developments in close proximity to steep man-made slopes and natural hillsides, many of which can be susceptible to landsliding during periods of high seasonal rainfall. The situation was exacerbated by the lack of proper engineering standards and input in the design and construction of man-made slopes before the late 1970s. Rain-induced landslides have occurred extensively in Hong Kong over the past century, causing significant socio-economic damage and loss of life (CEDD, 2014). The severity of the landslide problem is reflected by a death toll of over 470 people since 1947, mostly as a result of failures of man-made slopes formed in association with extensive civil engineering and site formation works due to the significant population growth.

Some notable landslide incidents with multiple fatalities include the 1972 Po Shan landslide, and the 1972 and 1976 Sau Mau Ping fill slope failures (Figure 1). These landslide disasters culminated in the setting up of the Geotechnical Engineering Office (GEO) (formerly known as the Geotechnical Control Office) in 1977 as a central body to regulate various aspects of slope safety in Hong Kong. Although serious landslides still occur from time to time, the scale and severity of the landslide problem have been reduced considerably as a result of the implementation of a comprehensive slope safety system to manage landslide risk.

Apart from substandard man-made slopes, Hong Kong is faced with the insidious natural terrain landslide hazards posed by the steep terrain, much of which is only marginally stable. For example, a review of aerial photographs taken from 1924 to 2006 has identified more than 100,000 past landslides on natural terrain (MFJV, 2007). In the severe rainstorm of 4 and 5 November 1993, over 800 landslides occurred on the natural terrain on Lantau Island. About 2,400 natural terrain landslides occurred in West Lantau during another severe rainstorm on 7 June 2008. Whilst most of these natural terrain landslides occurred in relatively remote areas, some of them had affected existing facilities including buildings and roads (Figure 2). With the growing demand for land to meet housing needs and other purposes, there is a trend to locate developments closer to steep natural hillsides with a consequential increase in landslide risk.

(a) 1972 Po Shan landslide

(b) 1972 Sau Mau Ping landslide

(c) 1976 Sau Mau Ping landslide

Figure 1 The fatal landslides at Po Shan Road and Sau Mau Ping in the 1970s

(a) 2008 landslide at Yu Tung Road, Lantau

(b) 2008 landslide at the University of Hong Kong

Figure 2 Some natural terrain landslides during the severe rainstorm on 7 June 2008

2. LANDSLIP PREVENTION AND MITIGATION PROGRAMME

2.1 Evolution of the Landslip Prevention and Mitigation Programme

Before the establishment of the GEO in 1977, there was no systematic geotechnical control of slope formation. Slopes were basically formed in an empirical manner; many cut slopes were formed at a gradient of about 60^o, and fill slopes were formed by dumping or end-tipping without any compaction, at an angle of repose of about 35^o. Many of these man-made slopes are substandard and susceptible to landsliding during heavy rainfall.

In the aftermath of the disastrous slope failures in the 1970s, the Government embarked on a long-term programme in 1977, known as the Landslip Preventive Measures (LPM) Programme, to retrofit substandard government man-made slopes and undertake safety screening and studies of private man-made slopes. For the latter, statutory orders would be served on the private owners requiring them to take necessary follow up actions if there is prima facie evidence that their slopes are dangerous or liable to become dangerous. A catalogue of sizeable man-made slopes including cut slopes, fill slopes and retaining walls was compiled by the GEO. Currently, about 60,000 man-made slopes are registered in the New Slope Catalogue. These slopes are mainly situated within developed areas close to occupied buildings or adjacent to busy roads. A risk-based ranking system was devised to accord priority of slopes for action under the LPM Programme.

During the period from 1977 to 2010, about 4,500 high-risk government man-made slopes were upgraded under the LPM Programme. The average number of slopes upgraded from 1977 to 1994 was about 35 per year and this had progressively increased to 250 per year during the Accelerated LPM Programme (1995 to 2010).

On average, there were over 150 active construction sites scattering around the territory at any one time. The scale and potential impact of the works to the general public posed a great challenge to project management, selection of design options, planning of site logistics and construction quality control.

By 2010, the overall landslide risk arising from man-made slopes has been reduced to less than 25% of the 1977 level. In 2010, the Government launched the Landslip Prevention and Mitigation (LPMit) Programme to dovetail with the LPM Programme, with the focus being on retrofitting the remaining moderate-risk substandard man-made slopes and systematically mitigating natural terrain landslide risk.

The cumulative expenditure incurred under the LPM and LPMit Programmes from 1977 to 2013 is about HK$18 billion (US$2.3 billion).

2.2 The LPM Programme (1977 to 1994)

Because of the two fatal landslides involving static liquefaction of loose fill at Sau Mau Ping in 1972 and 1976, most of the slopes included in the LPM Programme during the early years of its implementation were fill slopes affecting housing estates, schools and hospitals. Substandard fill slopes were retrofitted primarily by recompacting the top 3m of the fill bodies. Other techniques such as dynamic compaction and installation of sand compaction piles had also been experimented to identify other means of expediting the treatment of loose fill slopes (Lam, 1980) but the trials did not fruitful.

A boulder fall incident occurred in 1981 resulting in one fatality. Since then, some special LPM studies projects, e.g. the Mid-levels Boulder Field Preventive Works Pilot Scheme, were initiated under the LPM Programme to treat selected boulder fields posing a potential risk to existing developments. Techniques such as in-situ stabilization of boulders and installation of flexible boulder fence were adopted to mitigate the boulder fall hazard (Chan et al, 1986; Au & Chan, 1991).

Since 1983, some efforts were directed to treating rock cuts and soil cuts as well as retaining walls. In the late 1980s, the scope of the selection process for slopes to be included in the LPM Programme was extended to cover slopes posing a high indirect consequence to life, e.g. slopes affecting a sole access to a hospital and slopes adjoining catchwaters, etc. Nevertheless, the focus of the LPM Programme remained on treating slopes affecting occupied buildings.

By late 1980s, there was significant reduction in fatalities caused by landslides and the proportion of landslides affecting buildings had drastically reduced. It was considered by some people at the time that the LPM Programme had completed its historical role. At the same time, the expectation of the public on slope safety still continued to rise. With the resources the Government already invested in slope safety, the public was less tolerant of the occurrence of multi-fatality landslides.

2.3 The Accelerated LPM Programme (1995 to 2010)

On 23 July 1994, a fatal landslide occurred below Kwun Lung Lau in Kennedy Town. Five people were killed and three were injured during the incident. In addition, about 3,900 residents were temporarily evacuated overnight. A comprehensive investigation into the cause of the landslide was subsequently carried out by the GEO. An international renowned geotechnical engineering expert was engaged by the Government to conduct an independent review of the investigation (GEO, 2000a). A Select Committee was established by the Legislative Council in 1994 to inquire into matters relating to the fatal landslide. Prompted by the Kwun Lung Lau landslide, the Government initiated a Slope Safety Review at the end of 1994 to examine the policy, legislation and resources related to the prevention of landslides in Hong Kong, and to recommend improvement measures.

Following the investigation, inquiry and review, a number of recommendations to improve the slope safety system were made.

One of the recommendations was to accelerate the LPM Programme.

Over the 5 years from 1995 to 2000, about 800 substandard government slopes were upgraded under the LPM Programme. At the end of this period, about 250 slopes were upgraded each year, which amounted to some five to six times the average productivity before 1995. Quantitative Risk Assessment (QRA) technique has been applied at that time to evaluate and monitor the performance of the LPM Programme. The assessment found that by 2000, the overall landslide risk posed by pre-1977 man-made slopes was reduced to 50% of the level existed in 1977 (Cheung & Shiu, 2000).

The Kwun Lung Lau landslide was a milestone event in that the GEO had since taken major steps to further improve the slope safety system. For example, a systematic landslide investigation programme was launched to provide a more integrated approach for slope stability studies and the setting up of a Slope Safety Technical Review Board to assist in enhancing technical quality improvement, keeping abreast of international standards of risk-taking and other technical aspects associated with the discharge of due diligence.

From 2000 to 2010, the Accelerated LPM Programme dealt with the remaining high-risk substandard man-made slopes in the New Slope Catalogue affecting developments and major roads/footpaths. The target annual output was to upgrade 250 substandard government slopes and carry out safety-screening studies on 300 private man-made slopes. By 2010, the landslide risk posed by pre-1977 man-made slopes has been reduced to 25% of the level in 1977 (Cheng, 2011) and the number of fatal landslides has been significantly reduced.

2.4 The Post-2010 LPMit Programme

With the introduction of geotechnical control and the implementation of the LPM Programme, the landslide risk has reduced progressively and reached the "As Low As Reasonably Practicable" (ALARP) zone by 2010 (Figure 3). However, there is no room for complacency. If investment in slope safety is not maintained, the landslide risk will increase with time due to slope deterioration and encroachment of urban development or redevelopment upon steep natural hillsides. This would cause, in addition to risk to life, significant economic losses and social disruption as a result of road blockages and building evacuation due to landslides, thereby compromising public safety, sustainable development and Hong Kong's reputation as a modern metropolitan city and tourist hub.

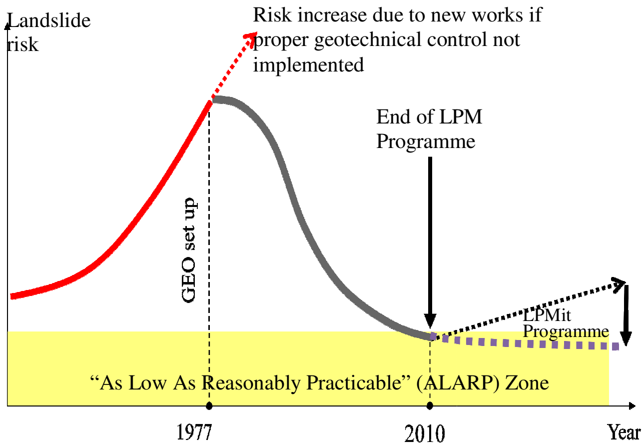


Figure 3 Landslide risk profile of Hong Kong

The majority of the remaining landslide risk comes from some 15,000 man-made slopes of moderate risk affecting development and about 2,700 natural hillside catchments with known hazards and are close to existing buildings and important transport corridors. Therefore, the Government launched the Landslip Prevention and Mitigation (LPMit) Programme since 2010 to dovetail with the LPM Programme. The strategy of the LPMit Programme is to contain this remaining landslide risk through rolling enhancement of man-made slopes and systematic mitigation of natural terrain landslide risk pursuant to the "react-to-known hazard" principle, i.e. to carry out studies and mitigation actions where significant hazards become evident. The annual target of the LPMit Programme is to complete the upgrading works for 150 substandard government man-made slopes, undertake safety screening studies on 100 private man-made slopes and carry out landslide risk mitigation works for 30 vulnerable natural hillside catchments from 2010.

3. TECHNICAL ADVANCES IN SLOPE STABILIZATION AND LANDSLIDE MITIGATION WORKS

3.1 General

Slope stabilization works are substantial engineering works based on the principles of removal (e.g. cutting back the slope to reduce its gradient), reinforcement (e.g. strengthening slopes by installation of soil nails), retention (i.e. supporting slopes with retaining structures), and replacement (e.g. excavating and reforming slopes with a denser surface soil layer). Combinations of different types of works may be used for upgrading man-made slopes. The design and construction practice for man-made slopes has evolved over time, as a result of the technical advances made in respect of slope engineering and construction techniques. In particular, the findings of the systematic landslide investigation programme initiated by the GEO since 1997 have contributed to achieving an improved understanding of the mechanisms and causes of slope failures (Wong & Ho, 2000). Areas for improvement in enhancing the reliability and robustness of slope engineering practice are identified, which are promulgated by Ho et al. (2002).

Unlike man-made slopes, the preferred approach in managing landslide risk from natural terrain is not to carry out extensive stabilization works to large areas of the natural hillside, which is impractical and environmentally undesirable, but to mitigate the risk through the provision of defense measures to contain the landslide debris from the natural hillside above. In most cases, the defense measures adopted in Hong Kong consist of the provision of a concrete barrier or flexible barrier at the toe of the natural hillside.

3.2 Fill Slopes

Many of the old fill slopes, typically comprising loosely dumped or end-tipped fill materials without compaction, are susceptible to liquefaction when they become saturated and subjected to shearing. The conventional method of treating these existing fill slopes is to excavate and re-compact the top 3 m of loose fill to a dry density of not less than 95% of maximum dry density. This is based on the recommendations made by the Independent Review Panel for fill slopes (HKG, 1977). Most of the fill slopes under LPM Programme were upgraded by means of this method because of its effectiveness and reliable performance (Figure 4). Other techniques that have been used in some cases include construction of a bored pile wall at slope crest, placement of compacted fill on the existing slope surface, removal of loose fill in conjunction with a crest retaining wall, mini-piles, dynamic compaction, grouting, etc.

Figure 4 Re-compaction of existing fill

It is, however, not uncommon that practical difficulties are encountered during the course of excavation and re-compaction of fill due to lack of working space, the need to work at height and access problems. In addition, the works would necessitate the removal of existing mature trees on the slopes, which may not be acceptable by the public. To minimize the disturbance to the environment, an alternative method of upgrading loose fill slopes using the technique of soil nailing was developed by a Working Group of the Hong Kong Institution of Engineers (HKIE, 2003; CEDD & HKIE, 2011). It entails the installation of soil nails through the fill materials together with the provision of a surface reinforced concrete grillage connecting the soil nails head. The existing trees can be preserved during the process. The soil nails are embedded in competent stratum to ensure sufficient anchorage against pull-out. The use of soil nails and concrete grillage to stabilize loose fill slopes is a cutting edge technology. Because of the construction advantages offered through the use of soil nailing, the method is now commonly used for upgrading fill slopes under the LPMit Programme (Figure 5).

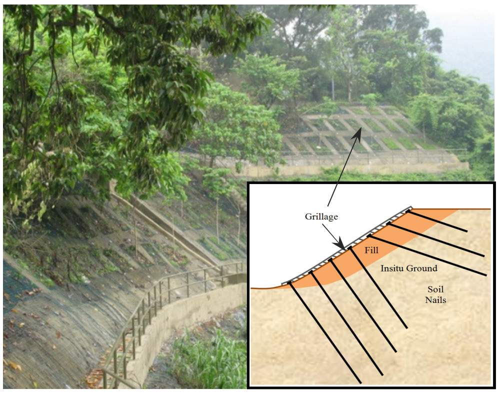


Figure 5 Upgrading of loose fill slopes by soil nail and concrete grillage

3.3 Soil Cuts

Before about 1990, the usual method of improving the stability of a substandard soil cut slope was by trimming back the slope to a gentler profile (Koirala & Tang, 1988). The major construction activity involved excavation and removal of soil materials from the slope. Because no special engineering techniques are needed, the construction cost is relatively cheap and easy to implement. Vegetation is used as the slope surface cover in order to make the slope look as natural as possible. Where there is insufficient space at the crest to accommodate the cut back profile, structural supports such as hand dug caissons or retaining walls would be used to improve the stability of the slopes (Powell et al, 1990).

Discussions on the reliability of the design of soil cut slopes were made in the 1980s (Malone, 1985). The profession recognized that there were uncertainties inherent in some of the important elements of a slope design such as the geological model, selection of slip surfaces, groundwater conditions and shear strength of the heterogeneous groundmass. Although the soil cut slopes are designed to the same factor of safety derived from deterministic analysis, the reliability in terms of the probability of failure may vary significantly. Hence the mere demonstration of an adequate factor of safety (e.g. by cutting back) carries with it no guarantee that the probability of failure is adequately low. It was necessary to improve the design of soil cut slopes that would give greater reliability and robustness for the same factor of safety.

Soil nailing, which comprises high yield steel reinforcing bars installed into the ground by means of drilling and grouting, was introduced to Hong Kong in the mid-1980s. The process of soil nailing is not unduly susceptible to weather conditions and there is flexibility to position the soil nails to avoid existing trees. The technique is simple and versatile as compared with other structural solutions, rendering it adaptable to the physical constraints commonly encountered in slope sites. In addition, because soil nails are usually installed at close spacing, they can reduce the vulnerability of the slope to undetected weak geological zones and unfavourable relict joints by binding the soil together to form an integral mass. That means the design of soil-nailed cut slopes is less sensitive to adverse ground and groundwater conditions. Following documentation of the design approach and the construction practice by Watkins & Powell (1992), soil nailing has been accepted as a robust and economical engineering solution for improving the stability of soil cut slopes in Hong Kong.

Durability is an important aspect of soil nailing system. The long-term performance of soil nails depends on their ability to withstand corrosion attack from the surrounding ground. The design for durability of a grouted soil nail with steel reinforcement entails the assessment of the corrosivity of soil at the site and the provision of corrosion protection measures. Depending on the soil corrosivity as assessed in accordance with the methodology proposed by Shiu & Cheung (2008), the required design life and the intended degree of protection, different measures may be adopted for corrosion protection. The common corrosion protection measures are cement grout, sacrificial steel thickness, sacrificial metallic coating to steel (e.g. hot-dip galvanizing with zinc coating), sacrificial non-metallic coating to steel (e.g. epoxy coating), and corrugated plastic sheathing.

In order to improve the soil nailing technology and rationalize the design standards, a series of studies were conducted by the GEO. These involved field tests, laboratory investigations, physical modeling, numerical modeling and analytical studies. The findings have led to the publication of a guidance document on soil nail design and construction (GEO, 2008).

3.4 Rock Cuts

The stability of rock slopes is mainly controlled by the characteristics and orientations of discontinuities within the rock mass, as well as the groundwater conditions. Detailed engineering geological mapping is required for the investigation, design and construction of rock slope stabilization measures. Very often, the design of the necessary works can only be finalized during the construction stage when safe access for close inspection of the rock face has been made available and obscuring vegetation and surface covers have been removed. The common stabilization measures for use in rock cut slopes include scaling, buttresses, dentition, dowels and rock bolts, drainage provisions and mesh netting.

In the design of rock slope stabilization works, it is important to identify laterally persistent discontinuities such as sheeting joints which are conducive to large-scale rock slope failures. However, dislodgement of small rock blocks by way of rotation, sliding or ravelling may occur as result of progressive deterioration and/or development of cleft water pressures within adversely oriented joints. Although the chance of direct impact by a small rock fall is not high, the consequence in the event of direct impact may be very serious given the nature of the material. Therefore, extreme care should be taken to ensure that minor but kinematically critical joints are not overlooked during the design process. Based on the key lessons learnt from studies of engineered rock-cut slope failures and a review of the practice for the investigation and design of rock cut slopes, technical guidance on enhancement of rock slope engineering practice was promulgated by GEO (2009).

3.5 Retaining Walls

Most of the substandard retaining walls comprise old masonry walls constructed during the period from 1850s to 1950s. A number of fatal landslide incidents involving masonry walls had occurred in the history of Hong Kong. In 1925, a masonry wall at Po Hing Fong on Hong Kong Island collapsed, demolishing seven houses and killing over 70 people. Most recently in 1994, the failure of a 100-year old masonry wall at Kwun Lung Lau claimed the lives of 5 persons. These tragic incidents highlight the need for understanding the structure and behaviour of old masonry walls so that appropriate stabilization measures can be implemented to improve their stability.

The assessment of stability of old masonry retaining walls is not simple because of their variable and non-monolithic construction. In order to tackle the problem, a comprehensive review on masonry retaining walls in Hong Kong, including the construction practice and structure of masonry walls, an examination of their structural behaviour, analyses of case histories of wall failures and suggestions on the approach to investigate stability of masonry walls, was carried out by Chan (1996). Further guidelines on the assessment of old masonry walls are given by GEO (2004) following a review of the lessons learnt from the Kwun Lung Lau landslide incident.

A special feature found on many old masonry walls in Hong Kong is the presence of "wall trees", which refer to trees (mostly Chinese Banyan) growing from the open joints or crevices between stone blocks. These "wall trees" constitute an important landscape element in the community and should be preserved where at all possible in view of their special amenity value. A study on masonry walls with trees was carried out by Wong & Jim (2011). The study concluded that the roots of wall trees would not induce failure of masonry walls. They would occasionally cause displacement of masonry blocks at the wall crest but the roots would also strengthen the wall face by providing a form of mesh reinforcement. However, wall trees would affect the stability of masonry walls due to its surcharge effect and this should be considered in the stability assessment. The study also identified suitable methods of stabilizing old masonry walls. One of the methods is to use soil nailing, which has the benefit of preserving both the existing wall trees and the original masonry façade (Figure 6). Other methods include the provision of conventional buttresses or flying buttresses in front of the masonry wall, and the construction of hand-dug caissons behind the wall.

Figure 6 Upgrading of an old masonry wall by soil nails

3.6 Systematic Landslide Investigations

Landslide investigations provide an invaluable source of information for enhancing the understanding of slope failures and slope behaviour. Insights have been gained from studies of slope failures into the contributory roles of adverse geology, hydrogeology and environmental settings, which have led to advances in slope engineering practice in Hong Kong. The technical findings from landslide investigations have resulted in major improvement in the slope safety system and the related technical standards or guidance. For example, the 1994 Kwun Lung Lau landslide investigation (GEO, 2000a) highlighted the adverse effects of leakage from buried water-carrying services on slope stability and advanced the understanding of the mechanism of brittle failure of thin masonry walls. The former has resulted in the issue of a Code of Practice on Inspection and Maintenance of Water Carrying Services (Works Bureau, 1996), while the latter had a profound effect on the standard of professional practice in the assessment of old masonry walls.

A systematic landslide investigation programme was introduced in 1997 as part of the LPM Programme. The findings arising from the landslide investigation programme greatly enhance the technical know-how and the understanding of the nature of slope safety problems in Hong Kong. Through these studies, practitioners can learn how slopes actually behave and perform, what the deficiencies in current practice are, and where improvements are needed in respect of slope investigation, design, construction and maintenance (Ho & Lau, 2010).

3.7 Natural Hillsides

3.7.1 Natural Terrain Landslide Inventories

As part of the hazard identification process, the GEO has compiled in the mid-1990s the Natural Terrain Landslide Inventory (NTLI), a Geographic Information System (GIS) based inventory of historical natural terrain landslides identified from interpretation of high-flight aerial photographs (2,400 m or above) taken since 1943. A major enhancement of the NTLI was completed by the GEO in 2007 in which mapping of historical natural terrain landslides using available low-flight (taken at less than 2,400 m) and high-flight aerial photographs was carried out. The improved inventory is known as the Enhanced Natural Terrain Landslide Inventory (ENTLI), which subsumes the NTLI. The ENTLI is presented in a GIS platform that contains the locations and attributes of all the 109,000 landslides identified on natural terrain up to 2009.

Studies were also carried out by the GEO on the possible scale and age of some of the large relict landslides. For instance, the large coastal landslide on Lamma Island had an estimated volume of about 30,000 m3 and probably occurred within the last few hundred years based on a variety of dating techniques, including surface exposure (Cosmogenic Nuclide) and optically stimulated luminescence dating. The massive debris lobe at Sham Wat in Lantau covers a plan area of about 0.3 km2. Age dating revealed that the main body of the hillside probably failed some 30,000 years ago, but further sizeable detachments continued to take place and the youngest one was dated as only about 2,000 years old (Sewell & Campbell, 2005).

3.7.2 Natural Terrain Hazard Study

A natural terrain hazard study (NTHS) is carried out to formulate the engineering geological and engineering geomorphological models for the hillside and evaluate the hazards involved. The natural terrain hazards have been grouped into five main hazard types on the basis of the mechanism of debris transportation, the nature of displaced material and the topographic location. These include open hillside landslide, channelized debris flow, deep seated failure, boulder fall and rock fall. Three different approaches, namely Design Event, Quantitative Risk Assessment (QRA) and Factor of Safety, may be used either individually or in combination for the evaluation of natural terrain hazards. Technical development work has been instrumental in formulating these approaches for application to NTHS. The findings have led to the promulgation of a technical guidance document on natural terrain hazard assessment (Ng el al, 2003). Further technical development work has recently been carried out resulting in the promulgation of guidelines on an enhanced approach for NTHS (GEO, 2013a).

Significant advances have also been made in the application of digital and remote sensing technologies, such as digital photogrammetry, Geographic Information System (GIS) and terrestrial and air-borne LiDAR, to enhance the capability and efficiency of NTHS (Wong, 2007).

3.7.3 Debris Mobility Modelling

One of the important factors affecting the design of defense works is debris mobility. This requires the use of dynamic analysis to assess the probable distance of debris runout and debris velocity of natural terrain landslides, based on continuum models which have been calibrated against local field observations. These continuum models utilize the principles of conservation of mass, momentum and energy to describe the dynamic motion of landslide debris and incorporate a rheological model to represent the flow behavior of the landslide debris. The findings of a study of the mobility of natural terrain landslides in Hong Kong by Ayotte & Hungr (1998) concluded that the Frictional rheology and Voellmy rheology can be used to estimate the mobility of open hillside landslides and channelized debris flows respectively. A set of conservative material parameters for debris mobility analysis in Hong Kong, including the apparent friction angle for the Friction rheology and the apparent friction angle and turbulence coefficient for Voellmy rheology was recommended.

However, the natural terrain landslides triggered by the 7 June 2008 rainstorm have provided plenty of additional information and data on debris movement. Back-analysis of selected channelized debris flows triggered by the 7 June 2008 rainstorm carried out by GEO showed that about 1% of the channelized debris flows were more mobile than that predicted using the Voellmy parameters recommended by Ayotte & Hungr (op. cit.). Based on the findings of back analyses, supplementary guidelines on the assessment of mobility of channelized debris flows are promulgated by GEO (2011a, 2013b).

The GEO has developed its own 2-D dynamic modelling algorithm, based on a formulation and solution methodology similar to that adopted in the DAN model formulated by Hungr (1995). The GEO has also developed a 3-dimensional landslide runout simulation model based on the Particle-in-Cell technique (Kwan & Sun 2007). Both modelling algorithms have been used to back analyse channelized debris flows (CDF) and open hillslope failures (OHF) in Hong Kong. The development of 2-D and 3-D numerical modelling of debris movement has greatly enhanced the capability of assessing debris influence zones and design of the corresponding risk mitigation works.

A benchmarking exercise on landslide debris mobility modeling was held in 2007 in Hong Kong during the International Forum on Landslide Disaster Management (Hungr et al, 2007). It was participated by 13 groups of researchers and practitioners from different regions of the world, including the GEO. A range of numerical models were used by the participants to complete the mobility analysis of selected benchmark cases. The outcome of this benchmarking exercise showed that the simulation results obtained by GEO's 3-dimensional landslide runout simulation model were reasonably accurate compared with the corresponding analytical solutions, laboratory measurements and field observations. The results were also consistent with those determined from other numerical models by other participants, which would mean that the debris mobility modelling capability in Hong Kong is comparable to that in other technical leaders.

3.7.4 Debris-resisting Barriers

In most cases, it is impractical and environmentally undesirable to carry out extensive stabilization works at the natural hillside. Instead, defense measures are constructed to contain the landslide debris from the natural hillside above. For example, concrete barriers may be constructed at the toe of the natural hillsides (Figure 7). In order to enhance the design of rigid barriers, a study is being carried out to identify suitable cushioning materials that could reduce the impact load from bouldery debris on the barrier. Large-scale physical impact tests on different potential cushioning materials such as cellular glass, plastic fender and dry sand are being carried out (Figure 8).

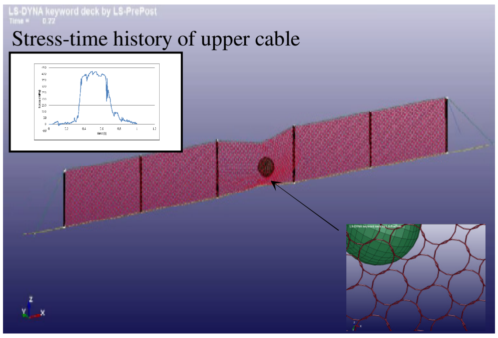
Flexible barriers, which are mainly formed of steel ring nets mounted between horizontal steel ropes spanning between steel posts and anchored into the ground, are one of the techniques that can be used to mitigate natural terrain landslides (Figure 9a). The advantages of flexible barriers are that they are relatively easy to install on steep natural terrain, less visually obtrusive and have less environmental impact as compared with reinforced concrete barriers. Whilst flexible barriers have been in use for over 20 years as a protective measure against boulder falls and rock falls, the application of flexible barriers to resist the impact of natural terrain landslide debris is a relatively new concept.

Figure 7 Concrete barriers at the toe of a natural hillside

Figure 8 A large-scale physical impact test on a concrete barrier with a gabion cushioning layer

The design methodology for flexible rock fall barriers is based on energy approach whereby a falling rock or boulder is stopped in one go by the barrier designed to absorb the kinetic energy of the rock or boulder. The design usually entails the use of proprietary flexible barrier systems with specific energy absorbing capacities that are verified by means of full scale field testing in accordance with the relevant national or international standards. The technology involved is relatively mature. In contrast to rock fall, the impact of landslide debris hitting a flexible barrier is delivered in the form of consecutive pulses due to the compressibility and mobility of the debris. Therefore, the design methodology for rock fall barrier is not applicable to the design of flexible barrier as a debris resisting structure. So far, there are no national or international standards for the design of flexible debris-resisting barriers. Suggestions on the design approaches for flexible debris-resisting barriers were made by Kwan & Cheung (2012) based on a review of the present state of knowledge, which would serve as a useful reference for practitioners. Figure 9b shows the establishment of a numerical model for a flexible debris-resisting barrier using a commercial software LS-DYNA in conjunction with the suggested "force approach" for design. As part of the development work, an empirical design methodology of flexible barriers for open hillside landslides has been developed based on a review of the energy capacity of barriers and a probabilistic consideration of the scale and mobility of landslide based on past failure cases in the landslide inventory (GEO, 2013c).

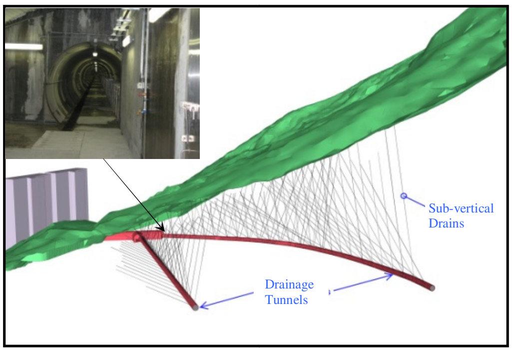
(a) Flexible barrier at the toe of a natural hillside



(b) Dynamic numerical model for a flexible barrier

Figure 9 Flexible debris-resisting barrier

(a) Construction of hand-dug caissons at Sai Wan Estate, Hong Kong



(b) Construction of two drainage tunnels at Po Shan natural hillside, Hong Kong

Figure 10 Innovative slope stabilization schemes

3.8 Other Innovative Slope Stabilization Works

For some sizeable slopes, innovative slope stabilization schemes have been adopted instead of the conventional stabilization measures. For example, 2.5m/3.0m diameter hand-dug caissons have been constructed at a 100 m high man-made slope at Sai Wan Estate as the slope stabilization measure (Figure 10a). Another example is the Po Shan natural terrain where two 3.5 m diameter drainage tunnels were constructed to provide a robust groundwater control system (Figure 10b).

3.9 Use of Novel Technology to Enhance Quality of Works

In the quest for higher LPM output, the GEO has been conscious of the need to maintain the quality of the buried works. For example, to enhance the quality control of soil nailing works, the GEO has developed non-destructive testing methods for assessing the lengths of installed steel bars and the integrity of grout for installed soil nails. Among the potential testing methods, time domain reflectometry (TDR) was found to be simple, reliable, relatively quick and least expensive (Cheung & Lo, 2011). The GEO pioneered the use of TDR to audit the soil nailing works since 2004 and more than 53,000 soil nails have been successfully tested to date.

4. ENHANCEMENT OF SLOPE APPEARANCE AND PROMOTION OF SLOPE GREENING

It is Government policy to make slopes look as natural as possible, blending them with their surroundings and minimizing their visual impact on the built environment. To implement this policy, vegetation is used as slope surface cover in the upgrading of existing man-made slopes which are not steeper than 55^{o} (Figure 11). A hard surface cover such as chunam or shotcrete may be used for steeper slopes, but suitable landscape measures such as applying subdued colour, masonry facing, providing planter holes and proprietary greening product on the slope surface for screen planting are adopted to minimize visual impact (Figure 12).

Figure 11 Typical green slope cover

For natural terrain mitigation works, the extent of works is minimised as far as practicable in order to reduce disturbance to the hillside and the environment. The existing vegetation, including trees and shrubs, is also preserved where possible during the construction of landslide risk mitigation measures. Landscape treatment such as vertical greening, screen planting and toe planters (Figure 13) would be provided to minimise the visual impact of the mitigation works and blend them with the surrounding environment.

Site trials of soil bioengineering techniques have been conducted for landslide repair works on natural terrain. The trials indicated a wide variation in the performance of the various bioengineering techniques. Based on the findings of the trials, a set of guidelines for appropriate use of bioengineering techniques for landslide repairs is developed by the GEO (2011b).

In 2000, the GEO produced technical guidelines on landscape treatment and bioengineering for man-made slopes and retaining walls (GEO, 2000b). A review was carried out in 2010 with a view to promulgating the latest best practice and expanding the scope to include landscape treatments for natural terrain mitigation works and landslide repairs. The review culminated in the new GEO Publication No. 1/2011 "Technical Guidelines on Landscape Treatment on Slopes" (GEO, 2011b). Apart from the technical aspects, the GEO Publication promotes input by professional landscape architects during the early stage of the design process to ensure that the landscaping input is integrated with the geotechnical input.

(a) Masonry-like finish on hard slope cover

(b) Provision of planter holes and toe planter

(c) Provision of propriety greening product on hard slope cover

Figure 12 Landscaping to man-made slopes with hard cover

Apart from slope appearance, the GEO is also mindful of the potential ecological impact of slope works. Special efforts are expended to achieve ecological enhancement of slope works by using native species. A good example is the adoption of ecological planting in upgrading 24 man-made slopes along South Lantau Road between 2001 and 2004 (Figure 14). Native species, either planted alone or mixed with exotic species, would attract local wildlife including birds and insects which may act as seed dispersers to enrich the plant biodiversity. A biodiversified vegetation cover is ecologically stable and hence more sustainable in the long run. Good practice on ecological planting for man-made slopes and engineering works for natural terrains with the use of native species is promulgated in GEO Publication No. 1/2011.

As part of the continuous improvement in landscape treatment of slopes, the GEO has been researching into the use of different vegetation species in slope works and experimenting with new techniques of providing erosion control measures and vegetation covers to steep slopes, with due regard to safety, cost, aesthetic quality, and long-term maintenance requirements. Field studies have been undertaken to assess the performance of different greening techniques and to identify vegetation species that can successfully establish and self-sustain on steep slopes. In collaboration with the Kadoorie Farm and Botanic Garden, the GEO has carried out a planting trial of native small tree and shrub species on steep slopes. The results provided useful information on the design and establishment of robust, cost-effective, and eco-friendly vegetation covers on man-made slopes. Further studies on the application of other vegetation species for greening man-made slopes were completed in 2007 and 2011 respectively, which have expanded the range of suitable vegetation species for landscaping of man-made slopes.

(a) Vertical greening on a concrete barrier

(b) Screening planting in front of a flexible barrier
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Figure 13 Landscaping to natural terrain mitigation measures

Figure 14 Successful example of landscaping the slopes along South Lantau Road and enhancing the biodiversity

5. DISCUSSIONS AND CONCLUSIONS

The concerted effort of the Hong Kong Government in the past 37 years has brought about substantial improvement in slope safety and a significant reduction in landslide fatalities.

The LPM Programme and the subsequent LPMit Programme have evolved progressively with time to address the slope safety needs of the community. It is noteworthy that a continuous improvement culture has been cultivated by the GEO, which contributed to many innovations and significant technical advances in slope engineering practice. This has been achieved through partnership with the geotechnical profession, contractors and local tertiary institutions. To ensure the delivery of the pledged output, the GEO exercises stringent project and financial management to facilitate smooth implementation of the slope retrofitting programme.

An added complication to slope stability is the potential impact of more frequent occurrence of more extreme rainfall events, possibly as a result of climate change. Experience in Hong Kong has emphasized the importance of adopting more robust measures (such as soil nailing or retaining wall), as opposed to non-robust measures (such as unsupported cuts) which can be sensitive to uncertainties (e.g. unforeseen adverse geological features or adverse groundwater conditions), together with the use of prescriptive drainage provisions.

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