Advances in Urban Landslide Risk Management

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ABSTRACT: The acute slope safety problems in Hong Kong are associated with its dense urban development on a hilly terrain subject to high seasonal rainfall. This vulnerable setting calls for a holistic risk management strategy and system that entails the use of both engineering and non-engineering approaches. The slope safety system, which was implemented by the Hong Kong Government in 1977, has been subjected to progressive improvement based primarily on lessons learnt from serious landslides. Over the years, the system has evolved into a comprehensive slope safety regime to manage landslide risk, involving a suite of policy, legislative, administrative, technical, emergency preparedness and public education and community-based provisions. In this paper, the key elements of the slope safety system are described and the advances made in slope engineering are highlighted.

1 URBAN LANDSLIDE RISK MANAGEMENT

1.1 Landslide Risk Management

Landslide risk refers to the combination of the probability and consequence of slope failure. It is a measure of the chance of slope failure causing a certain amount of harm, e.g. fatalities and economic losses. Landslide risk assessment involves identifying the landslide hazards and estimating the risk posed by the hazards through analyzing the likelihood and consequence of slope failure. In an overall context, landslide risk management refers to the systematic application of strategies, management policies, methodologies, procedures and practices to the tasks of identifying, analyzing, assessing, mitigating and monitoring landslide risk (Fell et al., 2005) by the responsible risk manager. For a given site, landslide risk management involves assessing the site-specific landslide risk, evaluating whether the risk is tolerable, and establishing the appropriate measures to reduce the risk to a tolerable level where deemed necessary (Wong, 2005).

1.2 Challenges in Urban Environment

Landslide risk management in an urban environment is particularly acute for the following reasons:

- Urban land-use planning, if done without proper geotechnical input, can result in developments being permitted within hazardous areas subject to severe landslide risks. This is particularly problematic if some the landslide hazards (e.g. natural terrain landslides) posed to the subsequent development are not fully assessed, hence under-estimating the risk.
- The site formation process of urban development, if carried out without adequate geotechnical input, could result in substandard slopes and increase the likelihood of landslide.
- Slope failures in an urban setting can result in serious consequences due to the clustering of developments and high concentration of population and vulnerable facilities.
- Given the close proximity of the vulnerable elements, even relatively small landslides (e.g. several tens of metres in volume) may cause notable impact. The prediction and prevention of such small scale landslides would be difficult given the many uncertainties involved.
- Landslide problems in an urban context can be aggravated by human factors, such as concentrated surface water flow, and the possibility of cascading of failures (e.g. uncontrolled surface water overflow from a road bend causing a washout failure on the downhill slope).
- In a highly developed community, particularly where there is a scarcity of developable land, relocation of vulnerable existing facilities is often not viable. At the same time, provision of landslide prevention and mitigation works can be exceedingly difficult given the space and access constraints.
- A densely urbanized city typically means high public expectation of slope safety and low tolerance of landslide fatalities. In addition, there can be severe environmental constraints in respect of undertaking investigation and

mitigation works on natural hillsides (e.g. environmental impact assessment, endangered plant and animal species, etc.).

- In a dense development involving private owners, the interpretation of the associated lease conditions vis-à-vis slope maintenance
- responsibility can be a vexed legal issue. This can impact on and pose constraints to the undertaking of regular slope maintenance works and upgrading works to substandard slopes.

The above challenges are evident in the landslide problems faced by Hong Kong, where a holistic strategy for managing urban landslide risk has been effectively implemented through a comprehensive slope safety system over the past few decades (Wong, 2009).

2 HONG KONG SLOPE SAFETY SYSTEM

2.1 Vulnerable Setting and Notable Landslide Disasters

Hong Kong has a hilly terrain. Of the total land area of some 1,100 km^2, about 63% is steeper than 15^o and 30% is steeper than 30^o. The rapid population growth and substantial economic expansion since the 1950s/1960s have resulted in a high concentration of urban developments on steep terrain in close proximity to man-made slopes and natural hillsides, which are susceptible to the occurrence of landslides during heavy rain (Fig. 1).

Fig. 1 Development on hilly terrain in Hong Kong

The severity of the landslide problem is reflected by a death toll of over 470 people since the 1940s, mostly as a result of failures of man-made slopes. Many of these substandard slopes were formed as a legacy of the extensive site formation works to facilitate urban development, the vast majority of which were unregulated by Government and with no geotechnical input.

A number of massive landslides leading to multiple fatalities occurred in the 1970s (Fig. 2). These led to public outcry and culminated in the establishment of the Geotechnical Engineering Office (GEO) in 1977 by the Hong Kong Government to regulate slope safety.

2.2 Slope Safety System

As the specialist geotechnical arm of the Hong Kong Government and the de facto landslide risk manager, the GEO faced many challenges upon its establishment, e.g. unsatisfactory state of design and construction of slope works, little geotechnical input, lack of guidance on good practice, inadequate lack of a regime to ensure proper site supervision and enforcement of specifications, and a legacy of a large number of substandard man-made slopes.

(a) 1972 Po Shan landslide (67 fatalities)

(b) 1972 Sau Mau Ping landslide (71 fatalities)

(c) 1976 Sau Mau Ping landslide (18 fatalities)

Fig. 2 Serious landslides in the 1970s

To tackle the challenges, the GEO set out to formulate a slope safety system to manage the landslide risk and regulate slope safety, which incorporates the application of fundamental risk management concepts at the policy administration level. The system has since 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.

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	✓	✓	✓
[e.g. natural terrain hazard study and mitigation			
landslide debris mobility			
landslide risk assessment and management			
slope greening]			
Specialist works projects			
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	✓	✓	✓
Note: Maintenance of registered Government man-made slopes and natural terrain defence/stabilisation measures is carried out by the responsible Government departments.			

Table 1. Key components of the Hong Kong Slope Safety System

The principal goals of the system are: (a) to reduce landslide risk to the community through a policy of priority and partnership, and (b) to address 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 (i.e. saving lives) and improving the built environment.

The holistic slope safety system entails the use of both engineering and non-engineering approaches. The key components are shown in Table 1.

The Key Result Areas of the system are as follows:

(a) Improve slope safety standards, technology, and administrative and regulatory framework.

(b) Ensure safety standards of new slopes.

(c) Rectify substandard existing Government slopes.

(d) Maintain all sizeable Government man-made slopes.

(e) Ensure that owners take responsible for slope safety.

(f) Promote public awareness, preparedness and response in respect of slope safety through public warnings and information services, public education and publicity campaigns.

(g) Improve slope appearance.

The above framework encapsulates the key components of the slope safety system in a systematic and succinct manner, which helps greatly to convey a clear message to the stakeholders (i.e. general public, private owners, media, government departments, legislative counsellors, policy bureau responsible for funding allocation, etc.).

The background of the development of the slope safety system and the roles of the key components are explained in the following.

3. EVOLUTION OF SLOPE ENGINEERING AND RISK MANAGEMENT IN HONG KONG

The slope engineering and landslide management practice in Hong Kong has evolved with time and it may be classified into three stages:

(1) Empirical slope design before 1977: Slope design and construction were based on rules of thumb, such as 55^o steep for soil cut slopes (Fig. 3) and 35^o steep for fill slopes. There was little geotechnical input, except for critical facilities such as dams, and no territory-wide geotechnical control. About 40,000 sizeable man-made slopes were formed in this period, the vast majority of which do not meet the current slope safety standards, and are vulnerable to landslide at times of heavy rain.

Fig. 3 A substandard man-made slope formed before establishment of GEO, close to existing buildings

(2) Geotechnical input to slope design and landslide prevention from 1977 to mid-1990s: In the aftermath of several disastrous landslides (Fig. 4), the GEO was set up in 1977 as the central body to regulate geotechnical engineering and slope safety in Hong Kong. Man-made slopes formed after 1977 in Hong Kong are subject to geotechnical design and checking, to ensure that they meet the required safety standards. The GEO also implements a Landslip Preventive Measures (LPM) Programme, to systematically assess the stability of the pre-1977 man-made slopes, in accordance with their ranked order of priority, and upgrade substandard Government slopes to the required standards (GCO, 1984). The conventional, deterministic approach of slope stability analysis was adopted in slope design. Landslide prevention was primarily aimed at, and based on, achieving the required design factor of safety (Table 2), although risk management concept was implicit in the strategy adopted. Risk consideration, if carried out, was made in a qualitative manner.

Consequence-to-life Category	Required Minimum Factor of Safety
1 (e.g. affecting buildings)	1.4
2 (e.g. affecting sitting-out areas)	1.2
3 (e.g. affecting country parks)	> 1.0

Table 2 Design standards for man-made slopes in Hong Kong

(3) Holistic landslide risk management since mid-1990s: In the past 20 years, the GEO has pioneered the development and adoption of an explicit risk-based strategy and approach, in addition to the deterministic approach, for slope assessment and landslide risk management. The risk-based methodology embraces a holistic consideration of the likelihood of landslide and its adverse consequences. It can be applied in a qualitative or quantitative framework, with the combined use of both engineering and non-engineering risk management measures, which is now referred to as the Hong Kong Slope Safety System (Chan, 2000). The quantitative applications, in particular, have been instrumental in formulating the overall slope safety strategy for Hong Kong, as well as managing the landslide risk at individual vulnerable sites (Wong, 2005). This approach aligns slope engineering and landslide mitigation with other engineering fields that practise state-of-the-art risk management in an explicit manner.

Fig. 4 The 1972 Po Shan landslide (67 fatalities)

4. HOLISTIC LANDSLIDE RISK MANAGEMENT

4.1 *Landslide risk trend and achievements of the slope safety system*

The roles and contributions of the different components of holistic landslide risk management can be illustrated by reference to the landslide risk trend. As noted by Wong (2013), two types of landslide risk trend have been assessed in Hong Kong:
(a) historical landslide risk trend, and (b) theoretical landslide risk trend.

The annual landslide fatality figures based on documentary records are shown in Fig. 5. The rolling 15-year average values of the annual fatalities, which better depict the historical risk trend, are also given in Fig. 5.

While historical landslide fatalities reflect the risk that has actually been realized, they do not necessarily represent the 'true' (or theoretical) level of landslide risk, because the historical fatality figures can be affected by the actual rainfall conditions including their spatial distribution, near-miss events, etc. To address this limitation, Quantitative Risk Assessment (QRA) has been applied in Hong Kong to quantify the levels of theoretical landslide risk (Ho & Ko, 2009). As far as the overall landslide risk is concerned, it was found that: (a) implementation of the LPM Programme has reduced the theoretical landslide risk at year 2000 to about 50% of that which existed in year 1977 (Cheung & Shiu 2000), and (b) by year 2010, based on projection of the progress of the LPM Programme, the overall landslide risk will be reduced to about 25% of that in year 1977 (Lo & Cheung 2004). These give two data points (X and E in Fig. 6) on the theoretical landslide risk.

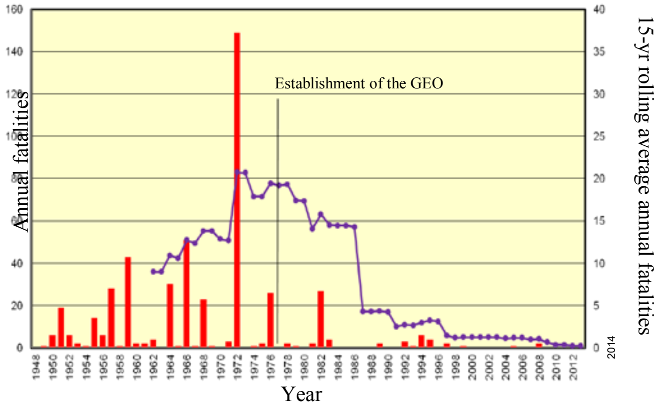


Fig. 5 Landslide fatalities in Hong Kong (1948-2014)

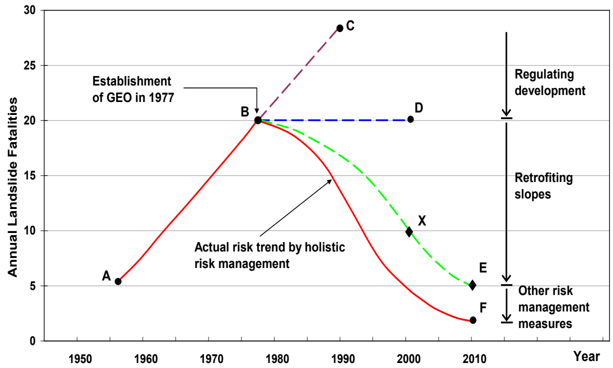


Fig. 6 Landslide risk trends in Hong Kong

Fig. 6 is a diagrammatic representation of the overall landslide risk trend, encompassing the historical and theoretical landslide risk data. Different components of the holistic landslide risk management have contributed to the reducing risk trend.

4.2 *Increasing landslide risk from geotechnically unregulated urban development*

Line AB in Fig. 6 shows an increasing trend of landslide risk in the early years, during the era of lack of territory-wide geotechnical control. Rapid urban development after the Second World War with little geotechnical input resulted in the formation of a considerable number of substandard man-made slopes. This led to the escalation of landslide risk, as reflected by the large number of landslide fatalities at the time.

4.3 *Containing risk increase by regulating and policing new developments*

Since the establishment of the GEO in 1977, territory-wide geotechnical control has been exercised to ensure that newly formed slopes in

Hong Kong are designed and constructed to the required safety standards. This serves to prevent further increase in landslide risk and thereby freeze the size of the problem. As a result, the increasing risk trend was leveled off (i.e. turned from line BC to line BD in Fig. 6), despite an additional 20,000 sizeable man-made slopes having been formed as a result of urban development in Hong Kong since 1977.

The GEO has implemented a comprehensive geotechnical control regime to audit the adequacy of the design and construction of all new geotechnical works including slope works, site formation, earth-retaining structures, deep excavations and tunnels. The geotechnical control covers both the Government and private sectors. To empower this regulatory function, legislative amendments and improvements to administrative instructions have been made (Chan, 1997).

The geotechnical works of private developments are controlled under the ambit of the Buildings Ordinance (BO) (Chapter 123, Laws of Hong Kong) and its subsidiary Regulations. GEO is vested with the responsibility of vetting the geotechnical aspects of works in the private sector. Since 2004, it is a statutory requirement that only qualified geotechnical engineers are eligible for the design of the geotechnical aspects of private building works (which include slope works), in the interest of enhancing the quality of geotechnical input.

The mandate for the geotechnical control of public works is derived from administrative instructions issued by the Government. Under these instructions, any Government departments responsible for public works projects are required to submit the design of their proposed permanent geotechnical works to the GEO for vetting, where this is warranted because of public safety considerations. Tenders shall not be invited for any part of the geotechnical works that have not been agreed by the GEO. The GEO issues a Checking Certificate for slopes that are checked to have been designed and constructed to the required standards.

GEO also carries out site audits of the standards of supervision of construction of all new geotechnical works, including slope works.

To facilitate the effective execution of geotechnical control and landslip preventive works functions, the GEO sets slope safety standards and promulgates good geotechnical practice. The GEO publishes and updates technical guidance documents from time to time, based on the findings of the applied research and development work carried out by the GEO and its agents or partners. These are available for viewing and downloading from the official website (http://www.cedd.gov.hk).

Much of the enhanced slope engineering practice in recent years has originated from an improved understanding of landslides in Hong Kong. The systematic landslide investigation programme of the GEO, which was launched in 1997, has played a key role in advancing the state of knowledge on slope performance and better understanding of the causes and mechanisms of slope failures. This programme also serves as a safety net by identifying slopes that are in need of early attention, as well as providing a basis for auditing the performance of the Slope Safety System and diagnosing areas for improvement (Ho & Lau, 2010).

4.4 Reducing landslide risk by engineering measures

4.4.1 Retrofitting substandard slopes and mitigating the risk of vulnerable natural hillside catchments

As the prevailing risk posed by the legacy of the old man-made slopes affecting existing developments was at a high level, risk mitigation actions were called for in order to reduce the risk to a more tolerable level.

Since the late 1970s, the GEO has embarked on the LPM Programme as a systematic, Government-funded slope retrofitting initiative, to deal with substandard sizeable man-made slopes registered in the Catalogue of Slopes. Under the LPM Programme, man-made slopes formed before the establishment of the GEO are selected for study, in accordance with a risk-based priority ranking system. This system takes account of the relative landslide risk posed to the community. Where high-ranking Government slopes are found to be substandard, they would be upgraded to modern safety standards. Where prima facie evidence is established that a private slope is liable to become dangerous, a statutory repair order (known as Dangerous Hillside Order) would be served under the Buildings Ordinance to the private slope owners requiring them to investigate and upgrade their slopes as appropriate within a designated time period.

Before 1994/95, the annual funding provision for the LPM Programme was within HK$100 million. In response to increased public demand for slope safety, the funding has increased to about

HK$900 million per year in the 10-year period between 2000 and 2010, with the annual output targets of the Programme set at retrofitting 250 Government man-made slopes and carrying out safety-screening studies on another 300 private man-made slopes.

It was projected that by 2010, all existing high-risk man-made slopes (i.e. substandard pre-1977 slopes affecting buildings and busy roads, which amount to a total of about 7,000 slopes), would have been retrofitted. The cumulative expenditure under the LPM Programme will reach about HK$12 billion by then. However, there will still be about 33,000 old man-made slopes, which are of lower risk, in the Catalogue of Slopes awaiting assessment and retrofitting.

The outcome of the retrofitting effort is progressive risk reduction along Line BE, as illustrated in Fig. 6. QRA calculations confirm that the LPM Programme has been cost effective in reducing the potential number of landslide fatalities (Wong, 2005).

The LPM Programme is a successful long-term retrofitting project. Two supporting initiatives are instrumental in the effective planning and implementation of the LPM Programme. They are:

(a) Compilation of a comprehensive Catalogue of Slopes, under which all sizeable man-made slopes in Hong Kong (about 60,000 in total) identified from interpretation of historical aerial photographs and field inspections are registered (Lam et al. 1998). The Catalogue of Slopes provides the essential information for assessment of the scale of the problem, risk quantification, determination of slope ownership, planning of the retrofitting studies and works, demarcation of maintenance responsibility and slope safety management. The Catalogue is freely accessible to the Public via a web-based Geographic Information System (http://hkss.cedd.gov.hk/hkss).

(b) Development and application of a risk-based priority ranking system (Wong, 2005), for selection of slopes according to their ranked order of priority for study and retrofitting under the LPM Programme. This maximizes the rate of risk reduction achieved by the LPM Programme. In addition, it provides a rational basis for determining the priority for spending public funds in slope retrofitting, given the relatively small number of man-made slopes that can be dealt with each year under the Programme.

Continuous improvements to the slope retrofitting process have been sought over the years (Tang et al, 2007). These include measures to enhance productivity, partnership with practitioners and other stakeholders involved in the delivery process, slope assessment and stabilization techniques, quality of works, slope appearance and integration of slope upgrading and landscaping design (Fig. 7), environmental performance during construction, etc.

QRA calculations (Wong et al, 2006) suggest that the overall risk posed by natural hillside catchments will be similar to the overall risk associated with the remaining registered man-made slopes upon the completion of the LPM Programme in 2010. The majority of the remaining landslide risk posed to existing developments by the year 2010 comes from some 15,000 man-made slopes of moderate risk and about 2,700 vulnerable natural hillside catchments with known hazards and that are close to existing buildings and important transport corridors (known as Historical Landslide Catchments).

Fig. 7 Slopes retrofitted under the LPM Programme with landscape treatment to enhance the built environment

Through sustained efforts to improve slope safety, the prevailing landslide risk in Hong Kong has been reduced to a reasonably low level. However, if investment in slope safety is not maintained, landslide risk will progressively increase with time due to slope degradation, population increase, encroachment of more urban development on steep hillsides and potential impact of extreme weather conditions, which could become more frequent and more severe due to climate change.

4.4.2 Promoting regular slope maintenance by slope owners

Regular slope maintenance helps to reduce the chance of shallow landslides caused by increased surface infiltration and wash-out failures caused by concentrated surface water flows, which are common in an urban setting and are aggravated by blockage of surface drainage channels and defective slope surface protection associated with lack of maintenance. As part of the recommended good practice for slope maintenance inspections and works (GEO, 2003), man-made slopes should be inspected by a suitably qualified geotechnical professional at least once every five years. This provides a mechanism for detecting signs of distress and deterioration, as well as changes in site setting that may adversely affect slope safety, in order to facilitate taking timely follow-up action. A clear demarcation of the responsibility for slope maintenance is essential to facilitate slope owners to take responsible action. For this purpose, the maintenance responsibility of the 60,000 man-made slopes registered in the Catalogue of Slopes have been established by the Hong Kong Government in the late 1990s. Slopes of Government responsibility are assigned to various maintenance departments based on the "owner maintains" and the "beneficiary maintains" principles. Privately-owned slopes are identified based on the terms of the lease or other land title documents. The information is made available to the public through the Internet.

Apart from regular maintenance, the concept of preventive maintenance, incorporating the use of prescriptive measures (which are pre-determined, experienced based and suitably conservative), is promoted (GEO, 2009).

4.5 Reducing landslide risk by non-engineering measures

It is evident that the sole reliance on the use of engineering measures to retrofit existing slopes has the following limitations in addressing the landslide problems:

(a) Slope retrofitting works are time and resources demanding to implement, and even after many years of effort, there are still a large number of slopes that have not yet reached their turn for upgrading. The risk of these slopes therefore needs to be managed by other means.

(b) Some slopes are particularly difficult to retrofit due to acute access and site constraints, and occasionally due to adverse geological conditions. This renders the use of engineering measures either not practical or not being the preferred risk management strategy.

(c) Landslide problems cannot be solved by the Government's action alone. Partnership with the general public and other stakeholders is of the essence in risk management. Partnership in this context has two elements. Firstly, the Government's risk management initiatives should meet the needs and expectations of the community. Secondly, the stakeholders, especially the public who are at risk, should play their part in enhancing slope safety and minimizing their own exposure to landslide risk.

In view of the above considerations, a suite of non-engineering initiatives has been implemented as part of the holistic landslide risk management in Hong Kong. These include the following initiatives:

(a) Operation of a Landslip Warning system by the GEO to forewarn the public of landslide danger during periods of heavy rainfalls (Yu et al, 2004).

(b) A 24-hour landslide emergency service operated by the GEO to advise on emergency and follow-up actions, such as emergency or urgent repair works, building evacuation or road closure, with a view to addressing the immediate landslide danger.

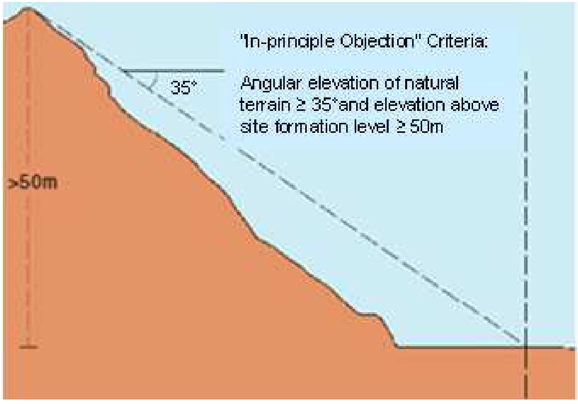
(c) GEO advises government town planners, land administrators and project departments on land development proposals and land use planning. The purpose is to mitigate landslide risk and facilitate safe and economic development at the earliest possible stage. Special geotechnical conditions may be imposed by the GEO in lease documents for controlling potential landslide hazards. In especially difficult terrain, the GEO may advise against development or make alternative proposals. Administrative measures were introduced in the early 2000s to control new developments close to natural hillsides. Various criteria (viz. "in-principle objection criterion" and "screening criterion", see Fig. 8) were adopted to control, as far as possible, the land-use for new developments in areas with significant natural terrain hazards. These also require the study and mitigation of natural terrain hazards as part of the new developments where necessary.

(d) Provision of slope- and landslide-related information services to the general public and the geotechnical profession, including data on slopes and past landslides, geotechnical and ground investigation reports, rainfall records, groundwater information, etc. The GEO also operates a Slope Safety Telephone Hotline to provide general information and advice, and mans a Community Advisory Unit to answer queries and give site-specific advice to the public on slope maintenance and rectification of dangerous slopes of private ownership.
(e) Implementation of public education and publicity initiatives, to enhance the public's understanding of the nature and reality of landslide risk, and to promote awareness of taking personal precautionary measures to minimize their exposure to landslide hazard, especially during Landslip Warning periods (Chan et al, 2007).
(f) Posting of warning signages at selected vulnerable locations.
(g) Providing advice on clearance of vulnerable squatters on slope safety grounds (Fig. 9).

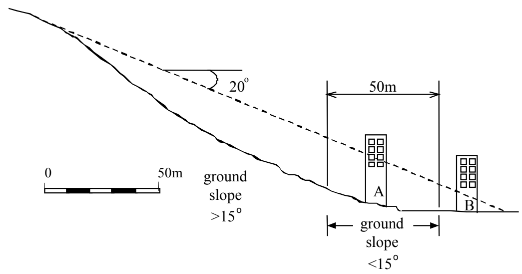
The implementation of the above non-engineering initiatives calls for partnering with the community and stakeholders. This is fostered by openness, transparency and proactive sharing of information and knowledge, as well as through education. Risk communication is greatly enhanced in the process. This promotes building of trust by the general public in the Government's effort in combating landslide problems and managing landslide risk, and thereby helps to promote tolerability of landslide risk by the community at a more rational and realistic level.

The non-engineering initiatives form an integral part of holistic landslide risk management. Their contributions are shown diagrammatically as line BF in Fig. 6, reflecting a further reduction in the landslide risk from the theoretical level (Line BE) that accounts only for the effect of slope retrofitting works.

Over the past 20 years, the actual annual landslide fatalities in Hong Kong have been consistently less than the theoretical risk level by at least 50%. While the risk figures should only be taken as an indication of the likely order of landslide risk, the overall risk trend suggests that the contribution of the non-engineering initiatives to reduction of landslide risk in Hong Kong could be fairly significant.



(a) In-principle objection criteria for new developments



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

(b) Screening criteria for assessing the requirement for natural terrain hazard study in new developments

Fig. 8 Criteria for control of new developments

Fig. 9 Vulnerable squatter huts on sloping ground

Over the past 20 years, the actual annual landslide fatalities in Hong Kong have been consistently less than the theoretical risk level by at least 50%. While the risk figures should only be taken as an indication of the likely order of landslide risk, the overall risk trend suggests that the contribution of the non-engineering initiatives to reduction of landslide risk in Hong Kong could be fairly significant.

5. TECHNICAL ADVANCES IN SLOPE ENGINEERING

5.1 Man-made slopes

The technological approaches adopted and advances made in urban slope engineering and landslide mitigation in Hong Kong are described at different time periods by various authors, e.g. Brand (1985), Wong (2001), Ho (2004), and Pun & Urciuoli (2008).

Stabilization works on man-made slopes embrace engineering works based on the principle of removal (e.g. cutting back the slope to reduce its gradient), reinforcement (e.g. installation of soil nails), retention (i.e. provide retaining structures to support the slope), and replacement (e.g. excavating and reforming slopes with a denser soil). A combination of different types of works may also be used as appropriate.

5.2 Fill Slopes

Many of the old (i.e. pre-1977) fill slopes comprise loosely dumped or end-tipped fill materials without compaction. These are susceptible to static liquefaction when they become saturated and are subjected to shearing during rainfall infiltration. A proven 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 the maximum dry density (HKG, 1977). Most of the fill slopes under LPM Programme were upgraded by means of this method because of its effectiveness and reliable performance (Fig. 10). For certain sites with specific constraints (e.g. working space is limited), the replacement of loose fill has been done via the 'pit by pit' approach.

Fig. 10 Re-compaction of an existing fill slope

Practical difficulties can be 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 necessitate the removal of the prevailing trees on the slopes, which may not be acceptable by the public. To minimize the disturbance to the environment and minimize the earthworks, an alternative method of upgrading loose fill slopes using the technique of soil nailing was recently developed by the GEO in conjunction with the Hong Kong Institution of Engineers (CEDD & HKIE, 2011; Cheuk et al, 2013). This entails the use of soil nails together with 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. A novel design methodology was developed to take full account of the liquefaction potential of the loose fill. Because of the construction advantages offered through the use of soil nailing, the method is now commonly used for upgrading fill slopes (Fig. 11).

Fig. 11 Upgrading of loose fill slopes by means of soil nails and concrete grillage beams

5.3 Soil Cuts

Before the late 1980s, the usual method of improving the stability of a substandard soil cut slope was by trimming back the slope to a gentler profile. 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 slope stability (Powell et al, 1990).

Discussions on the reliability of the design of soil cut slopes were initiated in the 1980s (Malone, 1985). The profession recognized that there were uncertainties inherent in some of the important elements of slope design such as the geological model, selection of slip surfaces, design groundwater conditions and operational shear strength of the heterogeneous groundmass. Massive landslides involving unsupported cuts have taken place, e.g. the Fei Tsui Road landslide in 1995 (Fig. 12) and the Ching Cheung Road landslide in 1997 (Fig. 13). Unsupported cuts are demonstrably not sufficient robust, as they are highly sensitive to deviations from the design assumption (e.g. adverse groundwater conditions and adverse geological features).

Fig. 12 Landslide at Fei Tsui Road in 1995

Fig. 13 Landslide at Ching Cheung Road in 1997

The use of soil nailing, which comprises drilling, installation of a high yield steel reinforcing bar and grouting, since the early 1990s, has proved to be not only a simple and versatile, but also a very robust technique. The design methodology is given in GEO (2008). As the 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. The design and performance of soil-nailed cut slopes are much less sensitive to adverse ground and groundwater conditions. The improved ductility of a soil nailed slope near the failure state, as compared to that of an unsupported cut, is a further advantage.

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.

As soil nails are passive elements and are not prestressed to a sustained high load, long-term monitoring is therefore not needed.

For some sizeable cut slopes, alternative slope stabilization schemes have been adopted. For example, up to 3 m diameter hand-dug caissons were used as stabilizing piles to upgrade an 100 m high cutting (Fig. 14).

Fig. 14 Upgrading of cut slope by hand-dug caissons

5.4 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 are similar to works typically adopted elsewhere (e.g. scaling, buttresses, dentition, dowels and rock bolts, drainage provisions and mesh netting). It is noteworthy that anchors are not favoured in Hong Kong because of the stringent requirements in respect of durability (i.e. corrosion protection) and long-term monitoring (GCO, 1989).

Based on the 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).

5.5 Masonry retaining walls

The assessment of stability of old masonry retaining walls is not straight-forward because of their variable and non-monolithic construction. Suggestions on the approach to investigate stability of masonry walls were made by Chan (1996). Further guidelines on the assessment of old masonry walls are given by GEO (2004) for thin masonry walls (defined as those with an aspect ratio of 5 or more).

A special feature of many old masonry walls in Hong Kong consists of "wall trees", which refer to trees (mostly Chinese Banyan) growing from the open joints or crevices between the stone blocks. These "wall trees" constitute an important landscape element in the community and should be preserved, together with the masonry wall fabric, wherever possible in view of their amenity and heritage values. Soil nails have been used successfully to preserve both the existing wall trees and the original masonry fabric (Fig. 15).

Fig. 15 Upgrading of an old masonry wall by soil nails

5.6 Drainage

5.6.1 Surface Drainage

Slope surface drainage is an integral part of an engineered slope and is essential in ensuring slope stability. Early design guidelines have been given in the Geotechnical Manual for Slopes (GCO, 1984). Review and enhancement of the guidelines have been carried out to incorporate the actual performance of drainage provisions and lessons learnt from notable landslides (Hui et al, 2006). The GEO carried out a study in mid-2000s with a view to improving the hydraulic design of stepped drainage channels. In the improved design method, skimming flow condition is assumed since skimming flows would dissipate energy more efficiently. The field tests showed good agreement between the observed and design capacity using the improved design method (Fig. 16). The improved design method was promulgated through GEO Technical Guidance Note No. 27 (GEO, 2006). Recently, the GEO has completed a review of the methods for estimating surface runoff for slope surface drainage systems. These include the Rational Method, time-area method, unit-hydrograph method, reservoir routing methods, flow gauging methods and statistical methods. The improved design guidelines were promulgated through GEO Technical Guidance Note No. 43 (GEO, 2014).

5.6.2 Subsurface drainage

The stability of a slope can be improved by reducing groundwater levels through subsurface drainage, e.g. horizontal drains (Martin et al, 1995). In case where slope stability relies on the continued functioning of the provisions, long-term monitoring is important. Experience and field observations indicate that the performance of subsurface drainage systems is liable to be subject to progressive deterioration and may not be robust enough, and substantial efforts are needed for the long term monitoring and maintenance. For example, more than 70 horizontal drains (up to 90 m long) were installed in the Po Shan area in the mid-1980s Monitoring data show that the groundwater levels could be high during period of heavy rainfall and some of the horizontal drains, which are more than 20 years old, exhibit a decreasing trend of outflow with time. As a result, subsurface drainage system is now generally taken to be contingency measures, i.e. they are installed in a prescriptive manner (GEO, 2009).

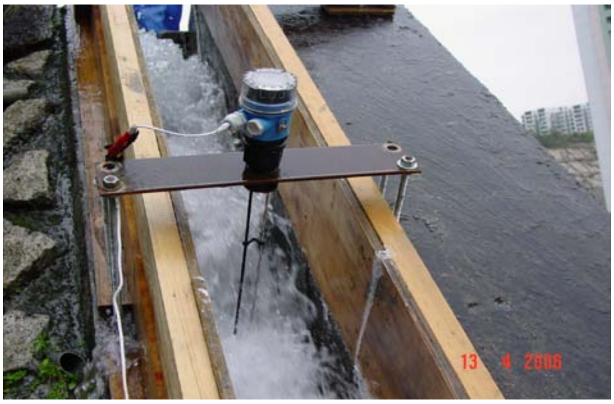


Fig. 16 Field test of stepped drainage channel

5.7 Use of novel technology for quality control of soil nails

To enhance the quality control of soil nails, the GEO has developed non-destructive testing methods for assessing both the length of installed steel bar and the integrity of the grout annulus. Among the potential testing methods considered, time domain reflectometry (TDR) was found from field trials to be a simple, sufficiently reliable, relatively quick and least expensive tool for the above purpose (Cheung & Lo, 2011). The GEO pioneered the use of TDR to audit soil nailing works since 2004 and a quality assurance framework has been promulgated (GEO, 2008). To date, more than 53,000 soil nails have been successfully tested to date using TDR.

5.8 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 under the Slope Safety System, vegetation is used as slope surface cover in the upgrading of existing man-made slopes that are not steeper than 55^{o} (Fig. 17). A hard surface cover such as chunam or shotcrete may be used for steeper slopes as a last resort, 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 the visual impact (Fig. 18).

Fig. 17 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 (Fig. 19) would be provided to minimise the visual impact of the mitigation works and blend them with the surrounding environment.

(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

Fig. 18 Landscaping to man-made slopes with hard cover

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). GEO promotes input by professional landscape architects during the early stage of the design process working along geotechnical engineers to ensure that the landscaping considerations are integrated with the geotechnical input.

(a) Vertical greening on a concrete barrier

(b) Screening planting in front of a flexible barrier

Fig. 19 Landscaping to natural terrain mitigation measures

5.9 *Advances in Natural Terrain Landslide Risk Management and Hazard Mitigation*

Considerable advances have been made in respect of natural terrain landslide risk management in Hong Kong (Ng et al, 2014).

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 often 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 (see Fig. 20).

(a) Rigid debris-resisting barrier

(b) Flexible debris-resisting barrier

Fig. 20 Debris-resisting barriers

5.9.1 Natural Terrain Landslide Inventory

As part of the hazard identification process, the GEO has compiled the Enhanced Natural Terrain Landslide Inventory (ENTLI), 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. In conjunction with this, mapping of historical natural terrain landslides using available low-flight (taken at less than 2,400 m) and high-flight aerial photographs was also carried out. The ENTLI contains the locations and attributes of >100,000 natural terrain landslides.

5.9.2 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 landslide hazards involved. The natural terrain hazards have been grouped into six 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, topographic depression 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 et al, 2003). Further technical development work has been carried out based on a consolidation of the more recent experience, which resulted in the development of an enhanced approach for NTHS (GEO, 2013a). The enhancements aim to pitch at a level of hazard mitigation that is appropriate and practically achievable, commensurate with the current state of knowledge and technology, and they serve to provide a more cost-effective and practical approach in dealing with natural terrain landslide hazards.

5.9.3 Technical development

(a) *Application of digital and remote sensing technology*

Significant advances have been made in the application of digital and remote sensing technologies to meet the new challenges primarily associated with natural terrain (Wong, 2004). 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 (InSAR) to enhance the capability and efficiency of NTHS (Wong, 2007).

The conventional aerial photographic interpretation (API) and photogrammetric analysis using stereoscope and stereo-plotter can now be undertaken by digital means via digital photogrammetry, with improved efficiency, resolution and analytical capability.

Notable advancement in respect of GIS system and capability made by the GEO includes advanced GIS search, browsing, editing and publications, GIS-based geotechnical analyses (e.g. landslide susceptibility analyses, rainfall-landslide correlations, etc.), GIS modelling such as modelling of runout of landslide debris and QRA of natural terrain landslides and 3-D visualization.

Since 2003, the GEO has been using a land-based LiDAR for topographic surveys where access is difficult or dangerous (e.g. 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 natural terrain hazard studies. The bare-earth models facilitate the identification of ground features, such as relict landslides and subtle terrain morphology. In 2012, the GEO conducted a territory-wide airborne LiDAR survey in Hong Kong to produce fine-scale topographical maps and DEM typically with grid size of about 1 m. This has enabled delineation of geomorphological and geotechnical features, detection of changes in landform, enhancing visualization of landslides in 3D, as well as identification of anthropogenic features.

Recently, the GEO has successfully applied the mobile laser scanning technology to conduct topographic survey at some man-made slopes and natural terrain.

(b) *Advances in debris mobility modelling*

One of the key factors that can affect the design of defense works is debris mobility. This requires the use of dynamic analysis to assess the probable distance of debris runout, debris velocity and debris thickness of natural terrain landslides. Computer codes based on continuum models are commonly used and they 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. Past studies suggest that the frictional rheology can be used to estimate the mobility of open hillside landslides and the Voellmy rheology can be used for assessing channelized debris flows. A set of suitably 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.

Based on the findings of further back analyses of the more recent mobile landslides, supplementary guidelines on the assessment of mobility of channelized debris flows are promulgated by GEO (2011a, 2013b, see Table 3).

The GEO developed two in-house numerical models, 2dDMM and 3dDMM, for landslide debris mobility analysis. Both models consider debris as a continuum material and the dynamic characteristics are assumed to be governed by the modified shallow water equations. The major modifications involve (i) inclusion of the base friction as determined using either a frictional rheology or Voellmy rheology, and (ii) incorporation of the Savage-Hutter theory to calculate the internal pressure within the debris mass.

Table 3. Recommended rheological parameters for debris mobility analysis

Hazard type	Rheological model	Recommended rheological parameters	
		Apparent friction angle	**Turbulence coefficient**
Channelized debris flow	Voellmy	10°	500 m/s^2
		8° (Note 1)	500 m/s^2 (Note 1)
Topographic depression debris flow (Note 2)	Voellmy	18°	1,000 m/s^2
Open hillslope failure	Frictional	25°	-
		20° (Note 3)	-

Note: 1. For channelized debris flow catchments that are prone to watery Debris.
2. See GEO (2013a) for definition.
3. For landslide debris volume greater than 500m^3.

2dDMM (Kwan & Sun, 2006) is an enhanced version of the 2-dimensional DAN model proposed by Hungr (1995). It solves the shallow water equation using a Lagrangian framework and is capable of simulating debris movement along a pre-set runout path with trapezoid cross-sections.

3dDMM (Kwan & Sun, 2007) is developed using a numerical strategy called Particle-in-cell, which can evaluate the dynamics of debris travelling over a three-dimensional terrain. In the algorithm, the debris mass is represented by a number of imaginary mass points and the terrain is divided into arrays of cells. The debris mass and debris height at a particular cell are determined based on the number of mass points located within the cell. It was used to back-analyse the dynamics of landslides and debris flows that occurred in Hong Kong and other countries including Italy and Canada.

The effects of debris entrainment can be simulated by both 2dDMM and 3dDMM. The calculation procedure proposed by McDougall & Hungr (2005) has been incorporated in 3dDMM. The procedure assumes that the amount of entrainment is directly proportional to the debris velocity and the overburden pressure of the debris acting on the ground. 2dDMM calculates the amount of entrainment based on a different algorithm which assumes that the total volume of debris increases in accordance with a specified rate when entrainment occurs. Fig. 21a shows the 2008 Yu Tung Road debris flow, which had been back-analysed using both 2dDMM and 3dDMM (see Fig. 21b & c).

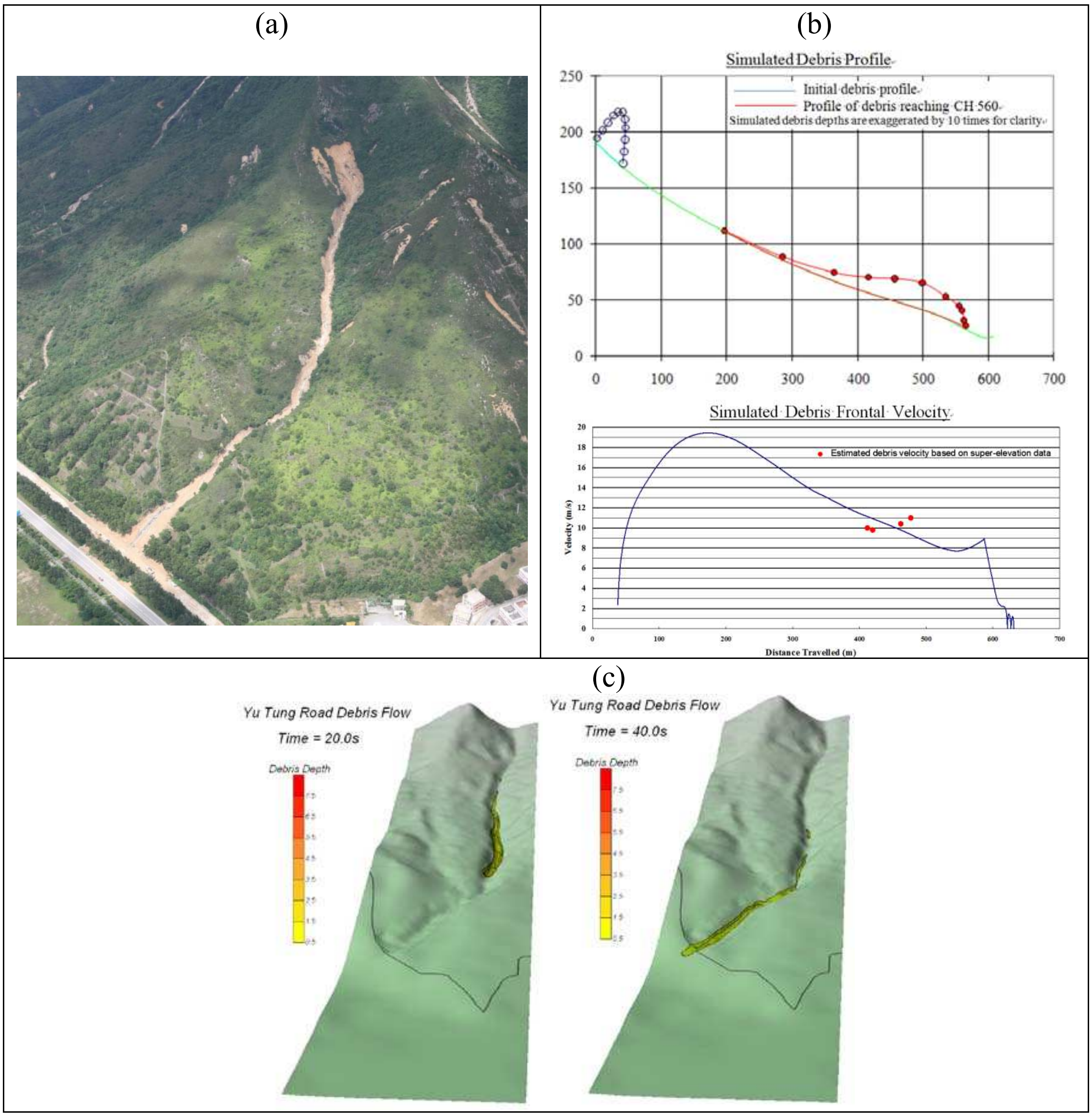


Fig. 21 (a) Aerial view of the landslide trial of Yu Tung Road Debris Flow
(b) Results of Yu Tung Road Debris Flow by 2dDMM
(c) Simulations of Yu Tung Road Debris Flow by 3dDMM

(c) *Use of cutting-edge techniques for age dating of old landslide debris*

The relevance or otherwise of large relict landslides plays an important role in QRA or the assessment of the design event, i.e. the likely volume that could occur. Based on a pilot study on dating of natural terrain landslides at 19 sites, the GEO concluded that direct age determination of carefully selected debris in Hong Kong was viable using dating techniques of Radiocarbon (C14), Optically Stimulated Luminescence (OSL), and Cosmogenic Nuclide surface exposure (Sewell & Campbell, 2005).

For example, the large coastal landslide on Lamma Island had an estimated volume of about 30,000 m^3 and probably occurred within the last few hundred years based on OSL dating technique. The massive debris lobe at Sham Wat in Lantau covers a plan area of about 0.3 km^2. Age dating revealed that the main body of the hillside probably failed some 30,000 years ago, but further sizeable detachments continued to take place and the youngest one was dated at about 2,000 years old. These landslide ages could have implications on their relevancy to the assessment of landslide risk in the present day terrain conditions.

A systematic age dating programme of natural terrain landslides is now in progress, both from shallow landslides as well as from boreholes and trial trenches in thick colluvial lobes, in order to establish a better framework for assessing design events.

(d) *Bio-engineering*

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 associated with the difficult access to most of the scars and the adverse effect on the environment. In situations where the long-term repair of natural terrain landslide scars are called for, soil bioengineering offers an effective, low cost, light reflective, maintenance free, sustainable and environmentally acceptable alternative to conventional slope works, which can help to minimise deterioration of natural terrain in areas affected by recent, shallow landsliding or related gully erosion. Following some field trials that were initiated in the early 2000s, the GEO promulgated “Guidelines for Soil Bioengineering Application on Natural Terrain Landslide Scars” (Campbell et al, 2008).

(e) *Rainfall-based landslide susceptibility analyses*

Recently, a rainfall-based landslide susceptibility analysis has been carried out by the GEO that correlates rainfall to landslide occurrence, with consideration of terrain slope angle and solid geology (Fig. 22). This was possible because of the availability of abundant high-resolution rainfall data (automatic raingauges are installed for every 10 km^2 and real time data are transmitted at 5-minute interval round the clock) and a inventory of historical natural terrain landslides (which contains information on about 100,000 landslides). A storm-based model was developed taking into consideration of geology and terrain slope angle. This model can be applied to predict the number of natural terrain landslides that would occur in a rainstorm (Lo et al, 2015).

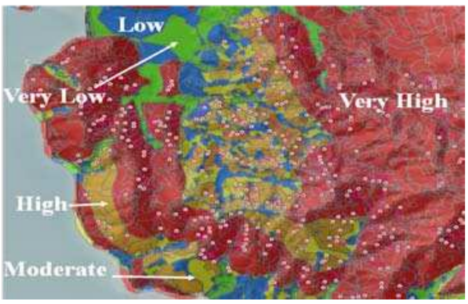


Fig. 22 An extract of the first territory-wide landslide susceptibility map in Hong Kong

5.9.4 Hazard mitigation using rigid barriers

Rigid barriers are typically constructed using reinforced concrete and deployed mostly to intercept CDF. They are designed to resist the impact force of the debris and occasional boulders in the debris front. Lo (2000) recommends the use of the hydrodynamic pressure equation (i.e. $p = \alpha \rho v^2$ where p = debris impact pressure, α = dynamic pressure coefficient, ρ = debris density and v = debris impact velocity) to estimate the debris impact load. He also suggests using the Hertz Equation (with an appropriate load reduction factor of 10) to estimate the boulder impact load.

Kwan (2012) has updated the above recommendation in respect of the value of dynamic pressure coefficient, with the coefficient being revised down from 3 to 2.5. The latest standard and guidance on the design of rigid debris-resisting barriers is given in GEO (2012a). The above recommends the consideration of multiple phases of landslide debris impacting on the barrier (see Fig. 23), and the use of the maximum calculated debris impact velocity for design.

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

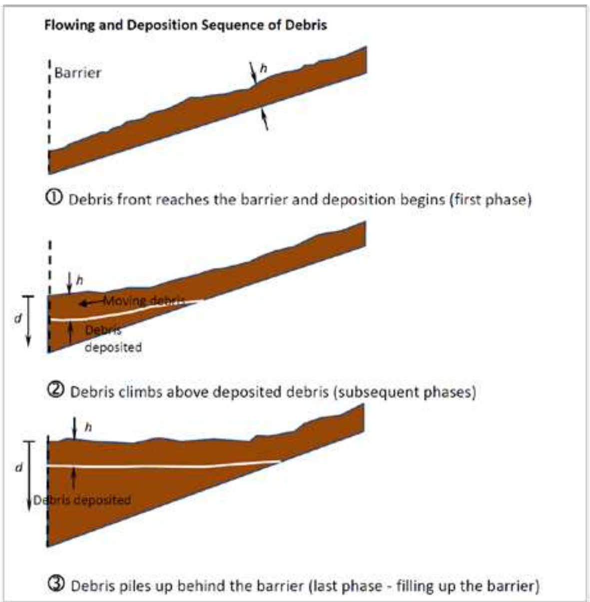


Fig. 23 Consideration of multiple phases of landslide debris impacting on barrier for design purposes

5.9.5 Hazard mitigation using flexible barriers

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 (Fig. 20b). 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.

Proprietary rockfall barriers are available from various suppliers. They are mostly applied based on empirical design and verification by full-scale testing. Rockfall barriers are rated by the energy that a set of panels can absorb without being breached, and their design is verified using full-scale test and the product is certified against various national or European standards (EOTA, 2008). Over the years, flexible rockfall barriers have occasionally been hit by debris flows and landslide debris, which demonstrated that flexible barriers could be capable of arresting a certain amount of debris (Roth et al. 2004; Duffy 1998). However, there still lacks a well-established and internationally accepted design methodology for flexible debris-resisting barriers.

Sun & Law (2012) proposed analytical solutions for calculating the energy loading of debris, with due consideration given to the energy loss (e.g. caused by basal resistance) experienced by the landslide debris, for two principal modes of debris impact mechanisms (see Fig. 24).

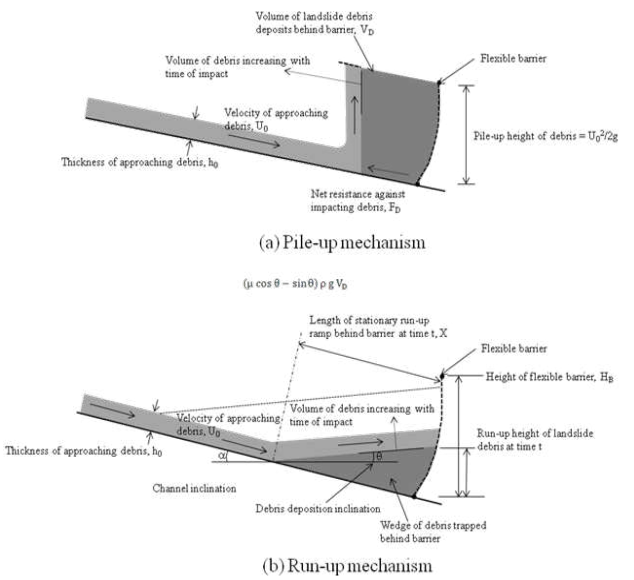


Fig. 24 The pile-up and run-up mechanisms considered by Sun & Law (2012) in establishing the energy loading for design of flexible barriers

As part of the empirical design methodology of flexible barriers for open hillslope failures, GEO put forward an approach based on a probabilistic consideration of the scale and mobility of landslides with reference to the landslide inventory (GEO, 2013c) in order to justify the use of flexible rockfall barriers, which may be prescribed using their energy ratings (incorporating a suitable reduction factor to account for the distributed debris loading together with a 'debris train' as opposed to point load impact by a boulder) in accordance with the proposed framework (GEO, 2013c).

For the design of flexible barriers that do not meet the qualification criteria for the adoption of the above prescribed flexible barriers, interim design guidelines on the use of the force approach were proposed by Kwan & Cheung (2012). Conservative assumptions have been made in these guidelines due to a lack of comprehensive understanding of debris-barrier interaction and the dynamic response of flexible barriers subject to debris impact. A number of R&D initiatives are in progress with a view to improving our technical understanding and optimizing the design.

5.9.6 Other natural terrain hazard mitigation measures

An example of other natural terrain risk mitigation measures that have been adopted is given by the Po Shan natural terrain catchments, which are known to have high transient groundwater tables in a thick layer of bouldery colluvium and a history of past failures. In the 1980s, a large number of designed horizontal drains were installed to control the groundwater regime. Monitoring of the horizontal drain performance, groundwater condition, and ground movement was carried out on a long-term basis.

The monitoring indicated evidence of deterioration in the performance of the horizontal drains with time (decreasing trend of outflows). In the early 2000s, a QRA was carried out which concluded that the hillside is susceptible to shallow landslides and that further risk mitigation works should be carried out to bring the prevailing risk level down to the ALARP level.

The works comprised an underground drainage tunnel system with sub-vertical drains to improve the long-term stability of the Po Shan hillside (Fig. 25). A retractable (thereby avoiding the need for a receiving shaft) Tunnel Boring Machine (TBM) was deployed for the excavation of the two 3 m diameter drainage tunnels. Over 100 m long sub-vertical drains were installed from within the tunnels, and an automatic pressure relief system was provided to regulate the flow rate of selected sub-vertical drains within a pre-defined range. The sub-vertical drains are self-cleansing by gravity, which avoids clogging and minimises future maintenance. Details of the studies and works carried out are described by Chau et al (2011).

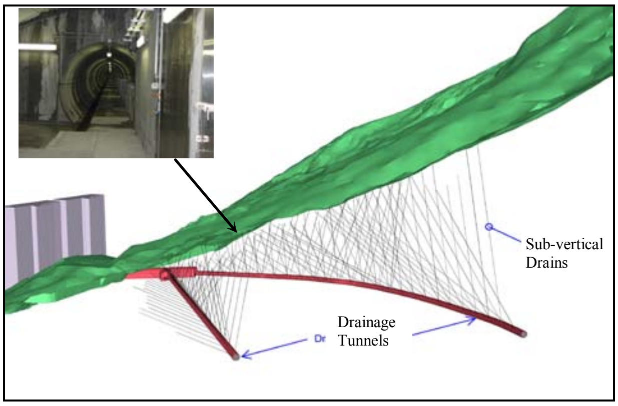


Fig. 25 Construction of two drainage tunnels at Po Shan natural hillside, Hong Kong

5.9.7 Slope instrumentation as a risk management tool

Wong et al (2006) summarized the experience in Hong Kong with regard to the role of slope instrumentation in landslide risk management.

Slope instrumentation entails the use of instruments or remote sensing for slope monitoring. Monitoring of existing and potential landslide sites is reported to have played an important role in landslide loss mitigation and landslide research (NRC, 2004).

Slope instrumentation can be used for different purposes. There is a need to differentiate the different applications and their capability and limitations in order to make appropriate use of the available technology. Typical applications include:

- Instrumentation for slope assessment and design
- Instrumentation for enhancing technical knowledge
- Health monitoring of slope stabilization measures
- Monitoring of landslide development at individual sites
- Instrumentation for regional landslide warning
- Monitoring to provide an alert of possible occurrence of landslide

Much advance has been made in respect of instrumentation, data capture and data transmission systems. GEO has studied the performance of various instruments and conducted pilot instrumentation schemes incorporating real-time monitoring of landslide sites. A wide range of conventional and state-of-the-art geotechnical sensors (e.g. multi-antenna GPS, ground movement Time Domain Reflectometry, in-place inclinometers, real-time data communication and geotechnical data processing system were installed (Ng et al, 2014).

The systems can be applied to other sites where potentially hazardous condition may exist as a landslide risk management tool or strategy. The implementation of an effective slope instrumentation programme is not only a matter of procuring the necessary instruments and related hardware and software. More importantly, it calls for a good understanding of the ground model, likely failure mechanisms, proper engineering analysis as well as the corresponding emergency preparedness and risk management system. Appropriate installation and maintenance and protection of the instruments (e.g. against lightning) are also critical in getting reliable data, particularly during the critical period of severe weather conditions.

5.9.8 Ongoing R&D initiatives

Some of GEO's ongoing R&D initiatives relating to natural terrain landslide risk management and hazard mitigation are summarized below:

(a) *Flume tests to investigate performance of baffles*

Arrays of baffles are a type of flow-impeding structure installed along natural drainage lines to impede debris flows. Baffles are usually installed prescriptively. Understanding on the interaction mechanism and the influence of baffle configuration on flow impedance is limited. Recently, the GEO commissioned a series of flume tests to investigate flows characterizing landslide debris using a dry uniform sand impacting on an array of baffles.

Choi et al (2014) reported the experimental results and analyzed the influence of baffle geometry on the energy loss of the landslide debris.

(b) *Tests on cushioning materials to reduce boulder impact load on rigid barrier*

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 have been carried out (Fig. 26).

The acceleration of the impacting block and impact load on wall at some positions were measured. The collected data are being used to calibrate numerical models and further parametric study using the numerical models will be carried out.

Fig. 26 A large-scale physical impact test on a concrete barrier with a gabion cushioning layer

(c) *Debris mobility analysis for design of multiple barriers*

Multiple debris-resisting barriers may be used to mitigate landslide hazards. In general, multiple barriers comprise rows of single barrier installed at different strategic positions along the runout path of a debris flow (e.g. along a streamcourse). Each of these rows of single barrier is designed to retain a certain landslide volume. However, there are so far no well-established design guidelines for assessing the landslide mobility with consideration of the presence of multiple barriers.

Debris mobility assessment for design of multiple barriers calls for consideration of (a) filling-up of barriers, (b) overflowing from the barrier crest and (c) energy dissipation at the debris landing position. A staged analysis is suggested by Kwan et al (2015). The analysis has been benchmarked against the computation results of numerical codes (e.g. LS-DYNA).

(d) *Review of computer codes for analysis of flexible barrier subject to debris impact*

(i) NIDA-MNN

Various computer codes have been explored with a view to using them for analyzing the behavior of a flexible barrier upon debris impact.

NIDA-MNN, developed by Chan et al. (2012), is a structural program. The program was developed by modifying a non-linear finite element structural package, NIDA. NIDA-MNN has been demonstrated to be capable of analyzing large deformations of structural elements, such as ring nets and energy dissipation devices. In a flexible barrier, netting is attached to cable ropes spanning across steel posts. The netting can slide along the cable ropes. Special 'sliding cable elements' have been built into NIDA-MNN to simulate the sliding action of the netting. To realistically capture the behaviour of the netting, frictional forces between the contact points of the nets are considered in the calculations. Zhou et al. (2011) verified this program against the published results of the Illgarben field test of a flexible barrier impacted by landslide debris, as reported by Wendeler et al (2006).

Kwan et al (2014) back-analyzed the pseudo-static impact load acting on the flexible barrier using a case study from Hong Kong. The range of pseudo-static impact load which can replicate numerically the observed behaviour of the barriers was identified, and it was noted that dynamic pressure coefficient (α) in this case corresponded to 1.6 to 2.1.

(ii) LS-DYNA

NIDA-MNN analysis considers pseudo-static load. Numerical model which is capable of undertaking coupled analysis to simulate both the landslide debris dynamics and the structural response of flexible barriers during impacts could reveal better the barrier-debris interaction.

The use of the Finite element package LS-DYNA has been explored for this purpose. A structural model of flexible barrier has been set up. Calibrations against the rockfall tests by Volkwein (2004) and Maccaferri (2011) have been carried out which verified that the model is capable of reproducing correctly the dynamic response of flexible barriers subject to rockfall impacts. Koo & Kwan (2014) reported the details of the calibration (see Fig. 27). Development work pertaining to the use of LS-DYNA for landslide mobility assessment has also been carried out. In the analysis, landslide debris is assumed to be elasto-plastic which follows Drucker-Prager yield criteria. The computational domain is discretized into an array of hexahedral elements. The elements record the variables, e.g. velocity, strain, etc. of landslide debris mass at various positions within the computational domain. Coulomb frictional rule is assumed at the interface between the landslide debris and the shell surface. The LS-DYNA model is benchmarked against several well-documented laboratory and field studies. Results are documented by Kwan et al (2015). More recently, couple analysis has been carried out to replicate the Illgarben field test by Wendeler et al (2006), and satisfactory results have been obtained.

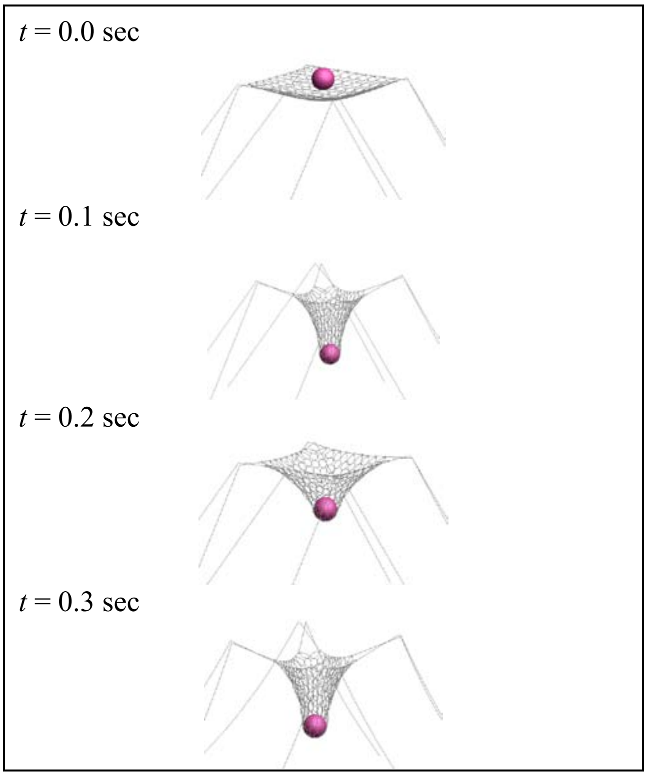


Fig. 27 Numerical simulation of Volkwein's rockfall test

(iii) CFD-DEM

GEO is also teaming up with local university partners to explore the potential of doing more advanced numerical modeling, including the use of coupled Computational Fluid Dynamics and Discrete Element Method (CFD-DEM) scheme to investigate wet debris flow dynamics. The scheme explicitly considers the mechanical interaction of granular materials in fluid and examines the mechanisms of behavior at soil grain scale.

In contrast to rock fall, the impact of landslide debris on a flexible barrier is delivered in the form of consecutive pulses and the loading on the barrier (either in terms of force or energy) is affected by the compressibility and mobility of the debris. Therefore, the design methodology for rock fall barrier is not directly 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 serves as a useful reference for practitioners. Fig. 28 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.

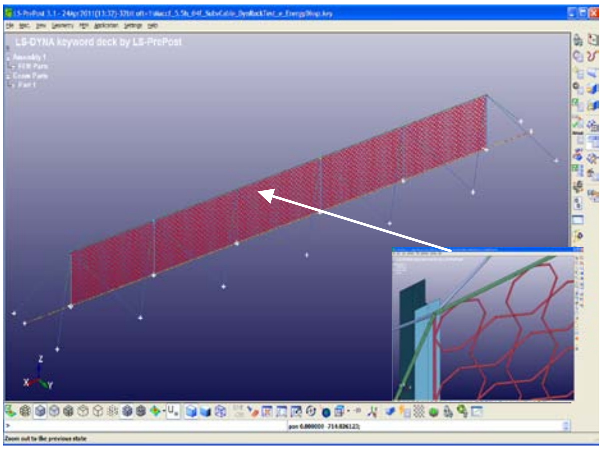


Fig. 28 Establishment of numerical model for a flexible barrier using LS-DYNA

(e) *Centrifuge testing*

GEO has commissioned the Hong Kong University of Science and Technology to conduct centrifuge tests of landslide debris impacting on flexible barriers. A specially designed spring system, which exhibits a bilinear stiffness profile, was developed to replicate the load-deformation characteristics of energy dissipation devices in flexible barriers. Fig. 29 shows the test set-up. The test results are intended to be used for further calibration of the coupled analyses.

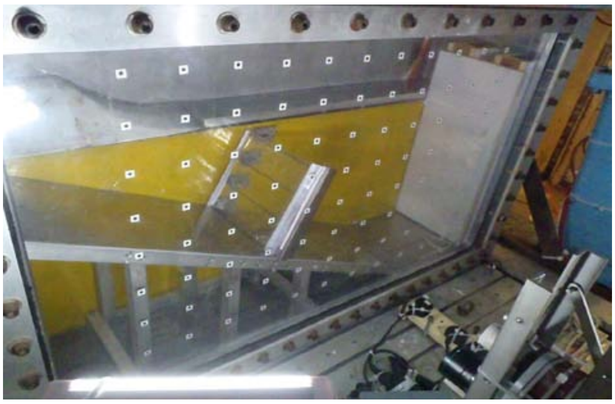


Fig. 29 Set-up of the centrifuge test

6. NEW CHALLENGES

Holistic landslide risk management calls for insightful preparation for possible changes in the risk pattern and development of refined strategy to address new challenges in the future.

In Hong Kong, with the completion of the current phase of the LPM Programme by 2010, all existing high-risk man-made slopes affecting buildings and major roads were retrofitted. GEO has continued to undertake technical and strategy development work to evaluate the changing risk pattern and prepare for the future landslide challenges beyond 2010. This has culminated in policy endorsement of the post-2010 Landslip Prevention and Mitigation Programme (LPMit Programme) by the Administration in 2007, as part of Hong Kong's long-term strategy in managing landslide risk (Development Bureau, 2007).

The future landslide challenges come from two key areas:

(a) A large number of moderate-risk (about 15,000) and low-risk (about 18,000) man-made slopes, including non-engineered slopes and some 9,000 post-1977 slopes engineered over 20 years ago with less robust technology and affected by progressive slope deterioration.
(b) About 2,700 vulnerable natural hillside catchments that have a known landslide hazard and are located close to existing buildings and important transport corridors (Fig. 30). Other vulnerable catchments may be identified in future as a result of improved knowledge and technology and occurrence of natural terrain landslides (Wong, 2009).

The post-2010 landslide risk management strategy recognizes that the overall landslide risk in Hong Kong reached an ALARP level, but that continuing efforts are required in order to contain the landslide risk within a low level. If Hong Kong's investment in slope safety is not maintained, landslide risk will progressively increase with time (line FG in Fig. 31). Factors contributing to progressive risk increase include: (a) population growth, (b) encroachment of more urban development on vulnerable natural terrain, (c) progressive slope degradation, and (d) projected increase in the frequency and severity of extreme rainfall events due to climate change.

While the key components of the Hong Kong Slope Safety System and the resources for risk management will be sustained after 2010, a shift in the focus of the retrofitting programme is necessary to meet the future challenges. The previous LPM Programme was aimed at retrofitting pre-1977 high-risk man-made slopes. The post-2010 LPMit Programme will, apart from carrying out landslide prevention works on man-made slopes, allocate about half of its resources to mitigation of landslide risk from vulnerable hillside catchments, based on the findings of QRA calculations (Wong, 2005). Moderate-risk man-made slopes that are at a more advanced state of deterioration will be selected for prompt follow-up action, on a rolling basis, as opposed to the 'Total Retrofit' approach currently adopted for the high-risk man-made slopes. Expanded efforts will be made under the LPMitP to systematically combat the natural terrain landslide risk pursuant to the 'react-to-known-hazard' approach, i.e. where significant risk becomes evident. The primary aim of the LPMit Programme is to reduce the probability of occurrence of multiple-fatality landslides as far as possible.

Fig. 30 A natural hillside with historical landslides occurring close to existing development

The annual output of LPMitP comprises stabilization of 150 government man-made slopes, conduction of safety-screening studies on 100 privately owned man-made slopes, and implementation of risk mitigation works for 30 hillside catchments. To meet these objectives, the priority ranking system for man-made slopes has been revised, and a new ranking system has also been developed for prioritizing hillside catchments for action under the LPMit Programme.

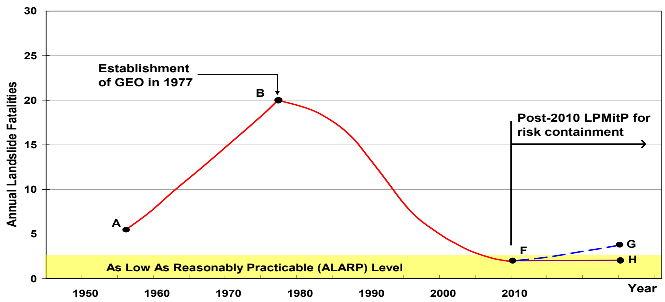


Fig. 31 A proactive strategy to contain future landslide risk within ALARP zone

The strategy of the post-2010 landslide risk management in Hong Kong is to prevent risk increase and thereby contain the landslide risk within a low level in the ALARP zone, to facilitate sustainable development in Hong Kong and discharge Government's due diligence in managing landslide risk. In terms of risk trend, this is indicated by keeping the risk along line FH as shown in Fig. 31.

The proactive expansion of the long-term retrofitting programme for slopes affecting existing development, which was approved by the Administration in 2007, was corroborated by the rainstorm in June 2008, which was probably the most severe storm in Hong Kong since rainfall records began in 1884. The number, scale and mobility of the corresponding natural terrain landslides during this severe rainstorm were far in excess of that predicted based on the knowledge and technical-knowhow at the time. The technical insights derived from studies of landslides that occurred during this rainstorm were summarized by Wong (2009). In addition, it highlighted the new challenges posed by the potential impact of extreme rainfall, which may be exacerbated by climate change. This needs to be addressed from a strategy, policy and technical perspective, as the number, scale and mobility of the corresponding landslides could be unprecedented and their assessments are fraught with considerable uncertainties.

A series of technical and strategy development work has been launched by the GEO to address these new challenges. The work to date was described by Wong (2013) and Ho et al (2015).

7. DISCUSSIONS AND CONCLUSIONS

Although serious landslides can still occur from time to time, the overall scale and severity of the landslide problem have been reduced considerably as a result of the implementation of a comprehensive Slope Safety System by the GEO to manage landslide risk. Urban slope engineering has progressed to a stage whereby the landslide risk should be managed in totality, with holistic risk management entailing the use of hard (i.e. engineering) and soft (i.e. non-engineering) measures.

Despite the achievements made to date with regard to landslide risk reduction, there is no room for complacency by the Government and the community. It is important that all stakeholders should continue to remain vigilant about landslide risk.

Reflecting on the experience over the last few decades in Hong Kong, some of the key ingredients for successful landslide risk management include the following:

(a) adoption of a system approach;
(b) investment in applied technical development work;
(c) embracing the application of new technology and innovations;
(d) development of slope safety strategies and policies and public safety goals;
(e) a sound geotechnical control regime via legislation or administrative instructions;
(f) maintaining risk communication and partnership with all stakeholders, especially during periods of dry weather, and listening to feedback; and
(g) continuous improvement culture and willingness to learn from serious failures and near-misses;

All systems need competent personnel to man and steer them. GEO gives high priority to human resources development and promotes personal development. The GEO has also been practising formal strategic planning for more than 20 years to engage our staff and involve them in cross-divisional teams on various improvement initiatives. Due attention is given to enhancing knowledge management and promoting knowledge sharing. The target is to nurture a talented team that is not only technically strong but also has the capability of communicating with the public with creative ideas to win their trust and support, talents with insights for new challenges and novel solutions, talents to devise new strategies and embrace evolving technology.

ACKNOWLEDGEMENTS

This paper is published with the permission of the Head of the Geotechnical Engineering Office and the Director of Civil Engineering and Development, Government of the Hong Kong Special Administrative Region.

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