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EMBRACING INNOVATION AND TECHNOLOGY IN LANDSLIDE PREVENTION AND MITIGATION

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ABSTRACT

Landslides are a ubiquitous natural hazard in mountainous terrain and often lead to human casualties in urban settlements and along transportation corridors. Given the adverse topographical and climatic setting, both Malaysia and Hong Kong are vulnerable to rain-induced landslides. For example, the 1996 Keningau debris flow in Sabah recorded the highest level of fatality (>300 deaths) for a single landslide in Malaysia.

Upon the loss of more than 150 lives in three disastrous landslides in the 1970s, the Hong Kong Government established the Geotechnical Engineering Office (GEO). In striving to achieve its missions of saving lives and facilitating sustainable development, the GEO has made notable advances over the years in the understanding of initiation and propagation of landslides, masterminded the implementation of a systems approach to manage landslide risk holistically, championed the development of novel methodologies for landslide risk assessment, and pioneered new design approaches for landslide prevention and mitigation works.

This paper highlights the successful application of innovation and technology in advancing slope engineering practice and managing landslide risk. The prospects of the geotechnical profession entering into a new era of making further transformational advances through a wider use of innovation and emerging technology are discussed.

1.0 INTRODUCTION

Hong Kong is confronted with frequent landslides caused by intense rainfall. The casualty toll escalated in the 1960s and 1970s due to rapid urban development and population growth. The professional practice at that time was primitive and empirical. The establishment of the GEO in 1977 as the geotechnical authority was a turning point for improved slope safety in Hong Kong.

Sustained efforts by the GEO in combating landslides have suppressed the prevailing landslide risk to a reasonably low level that is commensurate with the international best practice in risk management. The significant reduction in landslide risk is reflected by the decreasing annual landslide fatalities over the period, together with the indicative landslide risk trend based on the 15-year rolling average landslide fatalities (Wong, 2017).

The progressive evolution of slope engineering practice in Hong Kong entails an enhanced technical understanding of landslides and the adoption of a holistic, risk-based approach embracing innovation and technology. It also involves continuous improvement in the slope safety system under which multi-pronged risk management strategies are implemented with the combined use of 'hard' engineering measures and 'soft' resilience measures to minimize the consequence of landslides.

As Hong Kong continues to develop closer to the natural hillsides as part of its continued urban and population growth, the overall risk of natural terrain landslides has been increasing with time. In contrast, the risk of man-made slope failures has significantly reduced due to improved slope engineering and safety management. With the novel QRA tool, the GEO demonstrated that the risk of landslides due to natural terrain failures would become comparable to that of man-made slope failures. This led to an important change in GEO's slope safety strategy in 2010 to devote expanded efforts to systematically deal with natural terrain landslides in Hong Kong.

Consequently, the geotechnical profession is tasked with the new challenge of tackling natural terrain landslides, in addition to engineering man-made slopes. This extended responsibility called for development of new areas of competence and resulted in further cutting-edge advances in professional practice.

In this paper, examples are given under the following three themes to illustrate the range of advances that have been made in landslide risk management through the implementation of innovation and technology:

(i) Hazard identification;
(ii) Risk mitigation;
(iii) Management of residual risk

The prospects of the geotechnical profession entering into a new era of further transformational advances through a wider application of innovation and emerging technology are discussed.

2.0 STRATEGIES FOR MANAGING LANDSLIDE RISK

Risk is a measure of the chance of occurrence of an adverse event (e.g. landslide) causing a certain amount of harm (e.g. fatality). This is given by the product of probability of failure and consequence of failure, and may be expressed as follows:

$$\text{Risk} = \sum_{i}^{N} P_{(i)} E_{(i)} V_{(i)} \qquad [1]$$

where P is the probability (or likelihood) of landslide. E refers to the elements at risk (i.e. number of people affected taking into account temporal presence of population, or the total economic value of the elements). V is the vulnerability (i.e. expected degree of loss given the landslide impact). N refers to all credible landslide hazards

Risk can be mitigated by reducing P(i), E(i) or V(i), or their various combinations. Under a risk management framework, possible strategies to deal with landslide hazards comprise the following:

a. Avoidance (i.e. reducing or eliminating E(i));
b. Stabilisation (i.e. reducing P(i));
c. Mitigation (i.e. reducing V(i)).

The avoidance strategy is best implemented during the land-use planning stage in citing proposed high-consequence development away from hazardous slopes. It may also involve relocation of existing facilities, if feasible (e.g. re-routing of an access road or clearance of squatters). Some landslide hazards may be avoided by alternative means of transportation across the threatened area, e.g. use of tunnels, viaducts or elevated roads on embankments. Other examples of hazard avoidance include the use of landslide warning system, use of warning fence (e.g. trip-wire system for a railway) or erection of warning signs.

The stabilization strategy involves the implementation of landslide preventive works (such as trimming an over-steep slope to a gentler gradient or installing soil nails) to reduce the probability of slope failure.

The mitigation strategy involves the construction of defensive works to protect the affected facility from damage by landslide debris impact. For example, barriers may be used to arrest the debris (i.e. containment system), or training walls may be used to divert the debris (i.e. deflection system).

3.0 RANGE OF LANDSLIDE PREVENTIVE AND MITIGATION WORKS

Ho (2004) presented the state-of-the-art geotechnology in landslide preventive and mitigation works with particular reference to a densely urbanised city with significant site constraints and high public expectation of slope safety. Recent advances in the design and construction of landslide mitigation works for natural terrain hazards were presented by Ho et al (2015 & 2016).

The range of different techniques may be categorized as follows (Figure 1):

a. Surface protection and drainage,
b. Subsurface drainage,
c. Slope regrading,
d. Retaining structures,
e. Structural reinforcement,
f. Strengthening of slope-forming material,
g. Vegetation and bioengineering,
h. Defensive measures,
i. Removal of hazards, and
j. Use of special materials or techniques.

A compendium of about 70 structural and non-structural landslide prevention and mitigation measures for different landslide types has been developed, with input by GEO, as part of the SafeLand research project, which forms a web-based 'toolbox' (https://www.larimit.com/mitigation_measures/). The toolbox presents technical specifications, experience and effectiveness of the approaches, estimated costs, benefits and uncertainties, together with a framework for evaluating the relative merits of the different measures.

Landslide risk mitigation measures can be divided into three principal functions, namely flow control, erosion control and deposition control (see Table 1 and Figure 2).

Table 1: Classification of landslide mitigation measures (Shum & Lam, 2011)

Function	Objective	Mitigation Measure
Flow control	Flow path diversion	Deflection structure
		Transport channel
		Debris flow shed
	Energy dissipation	Drop structure
		Debris flow impediment
		Debris-straining structure
Erosion control	Reduce erosion potential of channel bed	Check dam
Deposition control	Arrest / contain debris	Debris-resisting barrier
		Debris retention basin
		Boulder fence

3.1 Insights on Landslide Preventive and Mitigation Works

Man-made slopes

The risk of a substandard man-made slope is typically managed by means of landslide preventive works which are designed to the required geotechnical standards. A key finding of the GEO's systematic landslide investigation programme was that man-made cut slopes that have been engineered to the required design standards still have a finite chance of failure (Ho & Lau, 2010). Many of these failures are small-scale landslides, either wash-out failures caused by concentrated surface water flow or slope instability controlled by localised, geological weaknesses. Sizeable failures of engineered slopes have also occurred from time to time, typically associated with adverse geological and hydrogeological setting that was not recognised and properly addressed at the design stage.

The systematic landslide investigation programme has provided comprehensive data on the failure rates of different types of man-made slopes, and important findings on the causes of failure.

Due attention was given to enhancing the robustness of engineered slopes through the use of design schemes that are less sensitive to uncertainties in the geological and hydrogeological

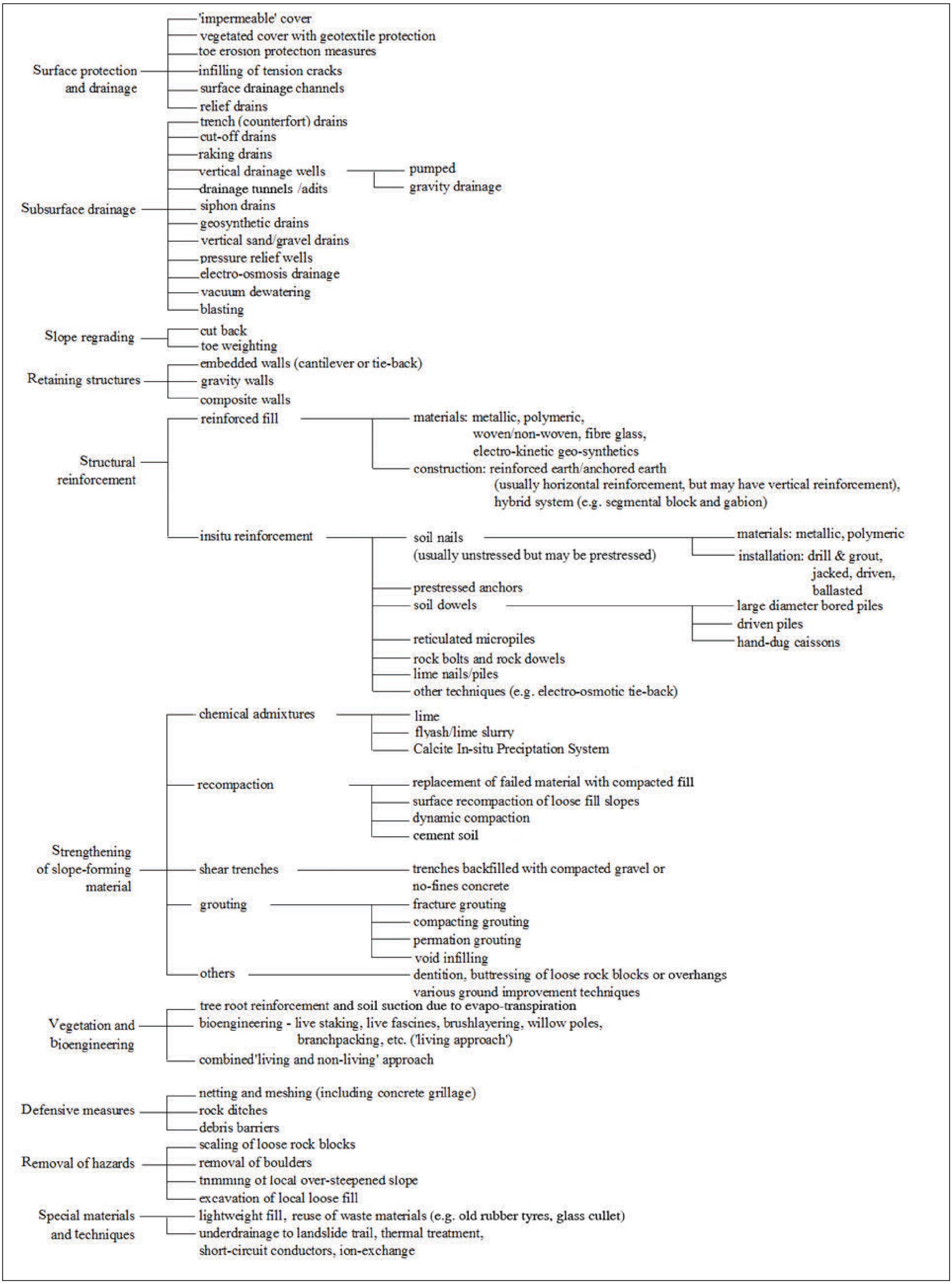

Figure 1. Range of landslide preventive and mitigation measures

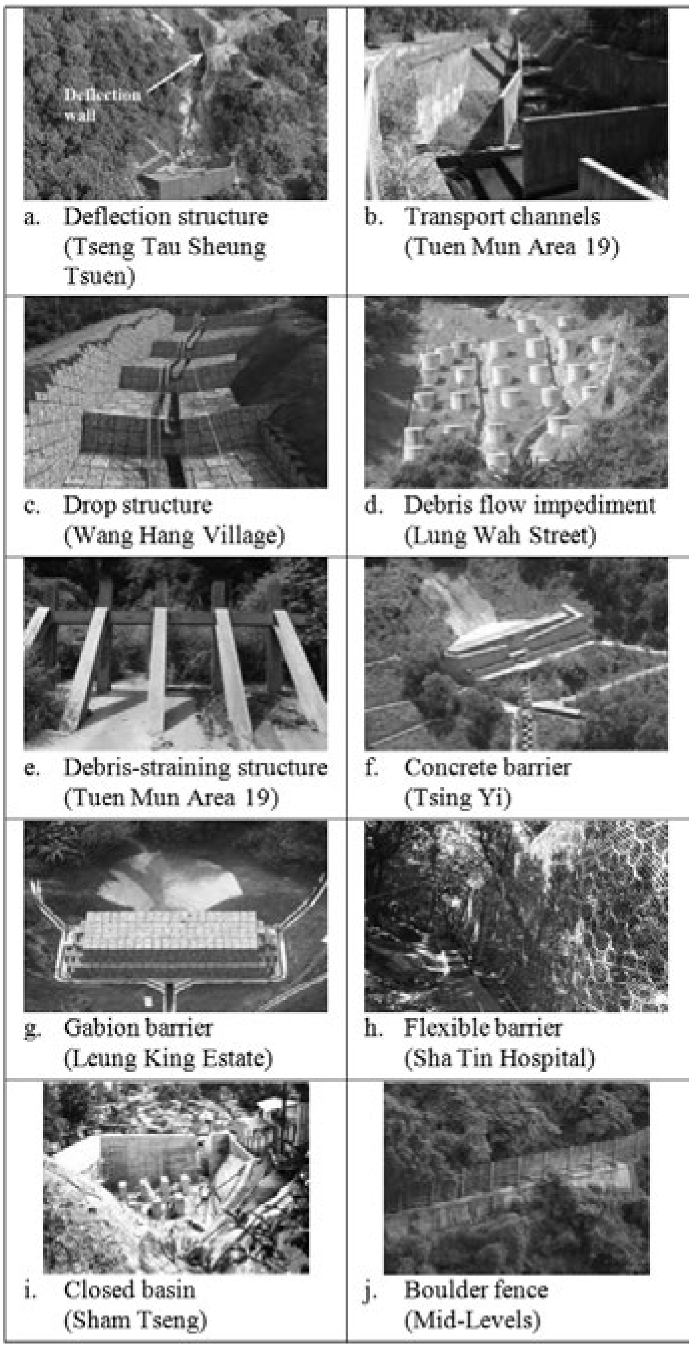

Figure 2: Examples of mitigation measures used in Hong Kong

conditions (such as soil nailing and retaining wall) and improved detailing. There was also a need to improve slope drainage and surface protection, thereby making the slopes less vulnerable to adverse effects from concentrated surface water flow and subsurface seepages. The strong emphasis on the use of more robust measures and improved detailing took Hong Kong's slope engineering to a higher level of reliability and safety (Wong, 2017).

Natural Terrain

Unlike man-made slopes, natural hillsides extend over large areas and involve highly variable ground and hydrogeological conditions. Conventional geotechnical approaches of detailed ground investigation and slope stability analysis are not practicable. Also, extensive stabilization works on natural hillsides would be costly, impractical and environmentally undesirable. In light of these, the landslide risk of vulnerable natural terrain is typically dealt with by means of mitigation measures, such as debris-resisting barriers or boulder fences. Reduction of natural terrain landslide risk is usually achieved through protecting the facilities at the foothill from impact by the landslide hazard.

In some cases, the optimal approach may comprise a hybrid approach by implementing a combination of landslide preventive works (such as soil nailing on a particularly active portion of the hillside) and landslide mitigation works. The former measures could result in a smaller design event that needs to be catered for by the mitigation measures.

Given the typical scales of historical landslides and design events established from natural terrain hazard studies in Hong Kong, most of the debris-resisting barriers in practice are in the form of a terminal barrier. Such barrier is comparatively more amenable to long-term maintenance and/or debris clearance works when needed. However, for cases involving the need to design for more sizeable debris flows, other forms of mitigation measures, such as multiple barriers along a drainage line, may be considered.

4.0 INNOVATION AND TECHNOLOGY IN HAZARD IDENTIFICATION

Hazard is defined as a condition that expresses the probability of a particular threat occurring within a certain time period and area (*Corominas et al., 2014*). The severity of the hazard is characterized by the intensity of the hazard event. Landslide hazard is a function of the failure mechanism and mode of failure (e.g. whether it fails in a ductile or brittle manner), failure volume, debris runout characteristics (e.g. runout distance, thickness, degree of entrainment, etc.).

4.1 Exploring an Efficient Means for Identifying New Natural Terrain Landslides from Images

The compilation of a comprehensive landslide inventory is a crucial element for landslide risk management. Typically, this is done by visual interpretation of stereoscopic imagery (either aerial photographs or satellite images) by engineering geologists. However, the process is resources demanding and calls for the development of automated methods.

Traditional image processing techniques can be used to identify recent natural terrain landslides by observing changes to spectral values or other characteristics within the images. These can be divided into two approaches, namely feature extraction and change detection.

A pilot study is being carried out by GEO to examine the use of deep learning algorithm for image recognition as compared to traditional image processing techniques. The Convolution Neural network (CNN) methodology was adopted to develop a fully automated computer model that can facilitate systematic landslide identification from digital aerial photographs. CNN is a technique for multi-layer artificial neural network designed for highly non-linear problems. In this trial, CNN is being combined with image analysis methodology to automatically acquire accurate locations and geometric information on new natural terrain landslides using a deep learning model, which involves a modified Residual Neural Network (*Kwan et al., 2019*).

Ortho-rectified aerial photographs were input into the computerised algorithm after data pre-processing. A training model was developed. 60%, 30% and 10% of the data was used for training, testing and validation purposes respectively. The boundary of individual identified landslide features was delineated automatically as polygons in a GIS platform.

The deep learning algorithm has been applied to a site at Tai O with widespread landslides in 2008. The extracted landslide boundaries were compared with the manually mapped landslides based on the inspection of ortho-rectified aerial photographs. The accuracy was assessed using a confusion matrix (Figure 3). The precision rate represents the percentage of extracted landslides that are true landslides, while the recall rate gives an indication of the omission of landslides by the algorithm. The achieved precision rate and recall rate of the deep learning algorithm are 88% and 93% respectively, which performs much better than traditional image processing approaches (Table 2).

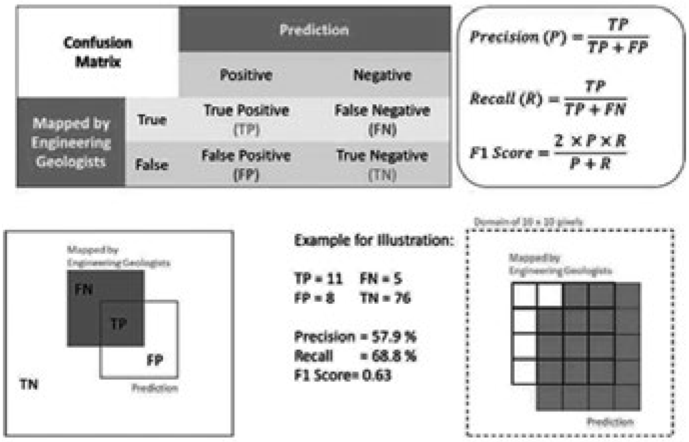

Figure 3: Methodology for accuracy assessment for automated landslide extraction using deep learning

Table 2: Preliminary quantitative assessment results of the pilot study at Tai O, West Lantau (Shi, 2019)

Image Processing	Precision Rate	Recall Rate	F1 Score
1) Traditional image feature extraction	63%	58%	0.60
2) Traditional image change detection	52%	89%	0.66
3) Deep learning	88%	93%	0.90

4.2 Identifying Potentially Hazardous Hillsides Posing a Notable Landslide Risk

Spatial susceptibility analyses are commonly used to establish the correlation of past landslides with terrain attributes in order to identify the locations of potentially hazardous hillsides. Given abundant landslide data, there has been ample experience in Hong Kong with territory-wide (1:20,000 scale) and regional landslide susceptibility analyses (1:5,000 scale) based on various probabilistic or statistical models. However, the key insight is that the resolution that can be achieved in terms of relative landslide probability is rather limited and is considered insufficient for the differentiation of vulnerable hillsides, especially given the potentially high consequence of landslides in a densely urbanised city. In light of this, the results of susceptibility analyses have not been applied to the management of natural terrain landslide risk in Hong Kong. Instead, a more pragmatic approach was developed.

The policy directive for taking follow-up actions on natural hillsides affecting existing development comprises the *react to known hazard principle*. An important observation from systematic landslide studies in Hong Kong is that many recent landslides (i.e. since 1924 when the first set of aerial photographs became available) occur in close proximity to terrain with past failures (both recent and relict landslides). This may reflect areas with steep gradient and/or adverse local geology/hydrogeology.

Based on the comprehensive natural terrain landslide inventory compiled using low-level aerial photographs, a database of hillside catchments with historical natural terrain landslides that occurred in close proximity to existing buildings and important transport corridors (denoted as Historical Landslide Catchments, HLC) was compiled by Geographic Information System (GIS) analysis based on the defined proximity criteria (Figure 4). The HLC is taken to pose known significant hazard and the follow-up actions (hazard study and implementation of the necessary mitigation works) are deemed to comply with the policy of *react to known hazard* for existing development.

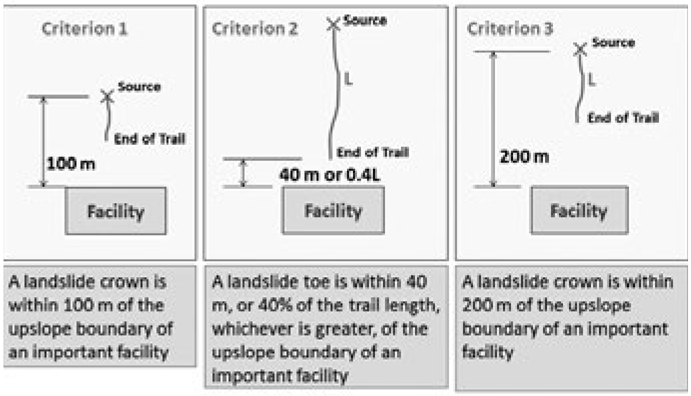

Figure 4: Criterion for historical hillside catchment

A portfolio QRA was completed by GEO to assess the risk level of the 2,700 HLC, diagnose their risk characteristics and project the overall risk of natural terrain landslides in Hong Kong. Using the QRA results, a risk-based ranking system was devised for establishing the relative priority of the 2,700 HLC for systematic follow-up under the long-term Landslip Prevention and Mitigation LPMit Programme.

The preliminary findings suggest that the deep learning technique can achieve satisfactory results for the study area at Tai O and highlight the potential for adopting deep learning in the identification of new landslides using ortho-rectified aerial photographs in an efficient manner. Further trials using additional training data in other study areas with aerial photographs of different quality are in progress. In addition, the automatic generation of selected landslide attributes (e.g. landslide source width, source area and travel angle) will be developed.

4.3 Rational Methods for Evaluating Natural Terrain Landslide Hazards

4.3.1 Novel QRA Approach

Once a potentially vulnerable natural hillside is identified, the landslide hazards need to be evaluated. This is fraught with uncertainties in practice. Previously there was no detailed technical guidance available. Hence, the studies were done in a qualitative and rather haphazard manner, and lacked a unified approach.

Quantified Risk Assessment (QRA) is a novel technical development pioneered by the GEO. This comprehensive approach can be used to evaluate the landslide hazards and risks of a natural hillside (*Ho et al., 2000*). The need for risk mitigation works is assessed by reference to the risk guidelines promulgated by GEO, which stipulate the tolerable risk criteria in respect of Individual Risk as well as Societal Risk. QRA entails a detailed assessment of the probability and consequence of natural terrain landslides, with account taken of the uncertainties in an explicit and systematic manner. It also considers the tolerability of the assessed risk level as well as the cost-benefit of the risk mitigation measures. This represents the most rigorous methodology, which requires expert input and may be fairly involved in terms of time and cost. Wong (2005) presented several case studies to illustrate their application to slope safety management.

4.3.2 Enhanced Design Event Approach

As an alternative approach for routine problems, the GEO has developed the Design Event Approach (DEA), which adopts a simplified hazard assessment framework without the need to carry out a formal QRA. The uncertainties are considered in an implicit manner through the assessment of the design event (e.g. a landslide of a certain size from a vulnerable location with an assessed degree of debris mobility). The design event approach is relatively easy to apply and is favoured by many practitioners.

Taking cognizance of the experience and feedback, the DEA framework has recently been refined and rationalised. The systematic methodology incorporates the application of engineering geological mapping and geomorphological mapping, together with debris dating techniques, in assessing the potential landslide hazards. Analytical approaches are used to quantify the debris runout characteristics in order to assess the landslide impact on the element at risk.

As compared with the first-generation DEA framework, the enhanced framework places the hazard mitigation measures at a level that is more appropriate and practically achievable, hence providing a more cost-effective and pragmatic approach to address natural terrain landslide hazards. The Design Event is taken to correspond to a 1 in 100-year event which, in combination with a cautious estimate of the debris mobility, is considered to be sufficiently robust for the purposes of mitigating 1 in 1,000-year natural terrain hazards based on analytical design. The mitigation measures to be provided are aimed at dealing with a realistic estimate of the credible failure volume (e.g. based on recent landslides as well as relict landslides with a high degree of certainty) combined with the entrained volume along the landslide runout path where appropriate.

Technical guidance on the DEA methodology is given by Ho & Roberts (2016). The approach involves desk study, aerial photograph interpretation (API) of the morphology and past instability, ground investigation and detailed field mapping as a basis for developing an engineering geological and geomorphological model of the study area. Based on the above, the nature and magnitude of the Design Event is assessed. The typical modes of natural terrain failure (or landslide hazards) considered comprise channelized debris flows along incised drainage lines, landslides in a catchment setting with topographic depressions, and open hillslope landslides on relatively planar slopes, as well as rock falls, boulder falls and deep-seated failures. The judicious application of DEA to evaluate landslide hazards is illustrated through the case studies presented in Appendix A.

It is noteworthy that the formal QRA framework has been used to benchmark the results of the enhanced DEA for some typical natural terrain sites in Hong Kong. The degree of uncertainty in various key elements of the QRA was considered using Monte Carlo analyses. The calculated risk levels took into account the propagation of the various uncertainties and the results are delineated with confidence intervals shown in order to facilitate decision-making.

In essence, the above benchmarking exercises established that the results of enhanced DEA are broadly consistent with the ALARP framework of QRA in respect of the practicality and cost effectiveness of the risk mitigation measures. Although the DEA methodology does not consider risk tolerability explicitly, if judiciously applied by experienced professionals it can nonetheless yield results that are in line with the conclusions from QRA.

4.4 Advances in Debris Mobility Analyses

Debris mobility analysis is an important tool for assessing landslide impact on the element at risk. As a result of technical advances made by GEO, landslide runout analysis is now routinely carried out in Hong Kong as part of the natural terrain hazard study.

Common numerical analyses for simulation of the dynamics of landslide debris runout adopt a continuum model based on the depth-averaged, shallow flow equations. These have been shown to be pragmatic tools that are sufficiently robust for forward prediction purposes provided they have been calibrated against local case histories with good quality field data (*Hungr et al., 2007; Pastor et al., 2018*). A pre-defined volume of detached material follows a path of a pre-defined direction and width. The computer program DMM, developed by the GEO, allows input of channel section geometry in a trapezoidal shape.

Recent advances made are two-fold. Firstly, there are improvements in numerical tools for both two- and three-dimensional debris mobility analysis. Two-dimensional debris mobility modelling (2D-DMM) has changed its computing engine from Microsoft Excel using the programming language Visual Basic to a stand-alone calculation module using the multi-paradigm programming language C# that is coupled with a GIS software (i.e. ArcGIS). Three-dimensional debris mobility modelling (3D-DMM) has gained the benefits of advances in computer technology to couple Smoothed Particle Hydrodynamics (SPH), a numerical method used for simulating the dynamics of continuum media, with ArcGIS. Secondly, there have been technical developments in the choice of basal rheological models and the use of appropriate mobility parameters for assessing the runout characteristics of different landslide hazards. The computer programs were validated and the input parameters calibrated against field observations of historical natural terrain landslides in Hong Kong.

For certain site settings and for detailed assessment of landslides, 3D debris mobility modelling can be an important tool to supplement the results of 2D debris mobility modelling. This offers a technical means of objective assessment of the likely debris runout path as debris runout may not entirely follow the topographically steepest slope, given that debris has a certain momentum and may overshoot the channel at the bends.

Overall, the advances have resulted in numerical models with much improved analytical capability, streamlined the workflow for natural terrain hazard studies, and enhanced the visualization of the output. These have collectively led to more accurate results and improved efficiency in the study and mitigation of natural terrain landslide risk.

4.5 Recognising the Hazard Mode Associated with Slender Masonry Walls

Based on past experience and field observations, conventional wisdom in Hong Kong in respect of the collapse behavior of a 'well-proportioned' old masonry wall (typically with a slenderness ratio, defined as the overall height divided by the base width, of 3 or less) was that it would fail in a ductile manner. This means that distress in the form of cracking will be manifested for some time before the wall collapses. This important empirical observation has been taken into account in the technical guidance for assessing the stability condition of old masonry walls.

The forensic study of the fatal collapse of a 100-year old masonry wall, which practically did not display any notable signs of distress before sudden collapse, revealed the important lesson that a slender masonry wall (i.e. slenderness ratio of 5 or more) is liable to fail in a brittle manner. The corresponding failure mechanism is different to that assumed in conventional retaining wall analysis. The behavior is evidently highly sensitive to the strength (i.e. cohesion, c') of the mortar joints between the masonry blocks. The failure mechanism was investigated by numerical analyses using the distinct element method. Large displacement and rotation of the blocks were permitted in the program. The assumed constitutive model simulated the effect of damage to the mortar joints due to tensile or shear failure, with the c' of the failed portion of the joints being set to zero.

The analyses predicted that the masonry wall would fail in a complex mode. The masonry wall was found to bulge initially at about mid-height, accompanied by overturning of the portion of the wall below this level. These deformation modes combined to lead to tensile and shear failure of the mortar joints and consequential reduction of the shear strength of the mortar joints. Bulging and overturning continued, resulting in abrupt fractures of the masonry wall at about mid-height. The ground behind the masonry wall lost support and slid forward. The analyses suggested that the upper part of the masonry wall would rotate backward as a result of the displacement of the sliding mass and was predicted to come to rest on the surface of the landslide debris, with the front surface facing upward. The lower portion of the masonry wall was predicted to disintegrate and become buried by the debris.

An important finding was that once failure of the mortar joints was initiated, the masonry wall would deform rapidly and instability would develop in a brittle and uncontrolled manner.

The above complex failure mechanism of a slender masonry wall cannot be readily discerned from a simple retaining wall analysis. For a slender masonry wall, the factors of safety calculated from conventional retaining wall analysis are neither realistic nor reliable. In light of this insight about the hazard associated with the brittle collapse behavior of a slender masonry wall, the technical guidelines in Hong Kong were duly amended to regard a slender masonry wall as substandard without the need to undertake any stability calculations.

4.6 Accounting for Different Modes of Liquefaction in a Novel Method to Upgrade Loose Fill Slopes

Existing loose fill slopes (typically with a relative compaction ranging from about 75% to 85%) are liable to fail suddenly involving the mechanism of static liquefaction following water ingress during heavy rainfall. When a sufficient shear stress ratio is mobilised due to saturation and build-up of water pressure, the metastable structure of the loose fill collapses abruptly and that the fill material effectively behaves in an undrained manner, with significant increase in excess pore water pressure and a corresponding sharp reduction of the undrained shear strength (i.e. exhibits strain-softening behavior).

The conventional approach for upgrading a loose fill slope is to recompact the upper 3 m of the material (to at least 95% relative compaction), together with the provision of a basal drainage layer below the recompacted cap. The relatively low permeability of the recompacted capping layer and the basal drainage combine to protect the deeper loose fill from significant water ingress through surface infiltration. The dense state of the capping layer will behave in a dilatant manner instead of contractive manner. This approach has worked well for many years and remains a feasible technical option.

However, the recompaction option frequently requires removal of mature trees and vegetation, which is often objected to by the stakeholders in recent years. Hence an alternative method was sought. Soil nails provided an innovative solution for the treatment of a loose fill slope that is vulnerable to undrained brittle collapse in the form of liquefaction. A novel analytical design framework to guard against mass liquefaction was developed by the GEO and the Hong Kong Institution of Engineers (Pappin, 2003). A key component of the design is the structural facing which connects all the soil nail heads together on the slope surface. When the loose fill liquefies, the earth pressure generated from the liquefied fill is resisted by the facing structure and is transferred to the insitu ground underneath the fill through the soil nails. The continuous slope facing or grillage beams, anchored by soil nails at regular spacing, is similar to an anchored structure resisting the earth pressure acting normal, or nearly normal, to the slope face. As a result, soil nails are constructed almost perpendicular to the slope surface and hence are relatively steeply inclined.

A review was subsequently carried out by the GEO with special emphasis on further enhancing the robustness of the above novel soil nailing scheme. It was recognised that the steep orientation of the nails may reduce their effectiveness if the stabilising forces need to be mobilised from relative movement between the nail and the surrounding soil. Numerical and experimental studies revealed that an increase in nail inclination would decrease the tensile forces mobilised in the nails, which in turn would reduce the stabilising effect. The steep nail orientation leads to the concern as to whether sufficient stabilising forces could be mobilised if static liquefaction were confined to a thin layer with a failure mechanism resembling a sliding failure (i.e. 'interface liquefaction').

A series of numerical analyses was carried out to investigate the effect of different failure modes. It is noteworthy that although interface liquefaction may represent a less critical loading scenario, the slope deformation required to mobilise sufficient stabilizing force would be excessive due to the inefficiency of generating tensile forces in steeply inclined soil nails.

A hybrid nail arrangement comprising soil nails at two different inclinations was found to be a more robust solution (Figure 5). The presence of sub-horizontal nails in the upper part of the fill slope facilitates early development of stabilising nail forces at small deformation and enhances the rigidity of the system along the potential failure direction (HKIE & GEO, 2011). This approach is now widely used in Hong Kong.

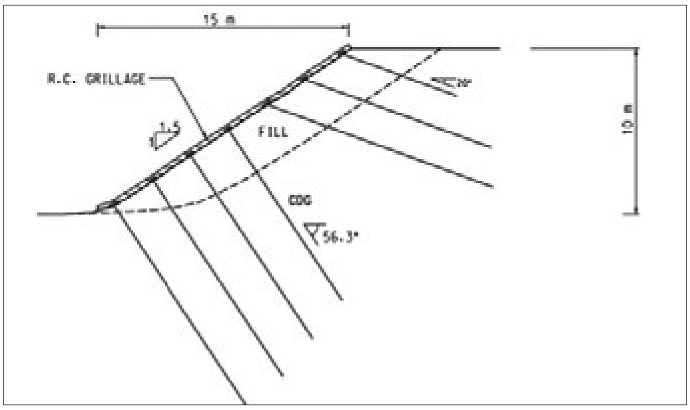

Figure 5: Typical hybrid soil nail arrangements for loose fill slopes

5.0 INNOVATION AND TECHNOLOGY IN RISK MITIGATION

5.1 Improved Design Methodologies for Debris-Resisting Barriers

The high risk scenarios associated with a densely developed city like Hong Kong warrant the use of more robust structural counter measures to manage natural terrain landslide risk. Properly designed and detailed debris-resisting barriers can be an effective solution. However, there were no unified design standards for such barriers.

Concerted efforts have been made by the GEO to improve the understanding of the performance of both rigid and flexible barriers. Physical modelling tests in the laboratory and in the field have been conducted to investigate the interaction of landslide debris and boulder impact and barrier. Advanced numerical modelling tools (i.e. LS-DYNA) are used to back analyse the laboratory and field observations. The work has culminated in the formulation of rational methodologies for the design of rigid and flexible debris-resisting barriers (*Ho et al., 2018 & 2019*). A key consideration is to build in sufficient robustness to cater for the uncertainties in the field associated with the complex characteristics and highly variable composition of debris flows.

a. Energy approach – a design methodology for debris impact on flexible barriers using an energy approach was developed based on insights from Discrete Element Model (DEM) analyses (Sun & Law, 2012). The framework takes into account the energy loss associated with the pile-up and run-up mechanisms of debris impact on a flexible barrier respectively (Figure 6).

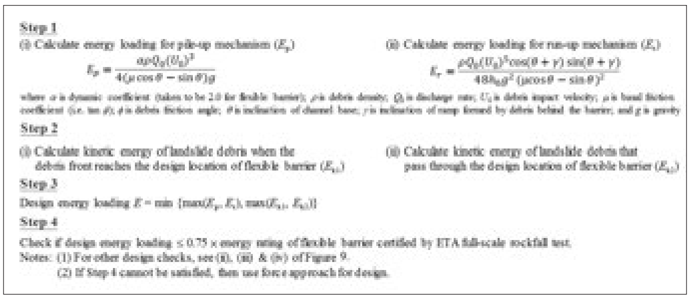

Figure 6: Summary of energy approach for design of flexible barriers

b. Force approach – a new design methodology was developed to assess the impact of debris and boulders on rigid and flexible barriers using a force approach (Kwan & Cheung, 2012). This approach adopts a multiple-phase debris impact model which considers both the dynamic impact pressure and the static earth pressure of the deposited debris (Figure 7).

Due consideration is given to the variation in debris velocities at different phases of debris impact as computed from debris mobility analysis (Figure 8).

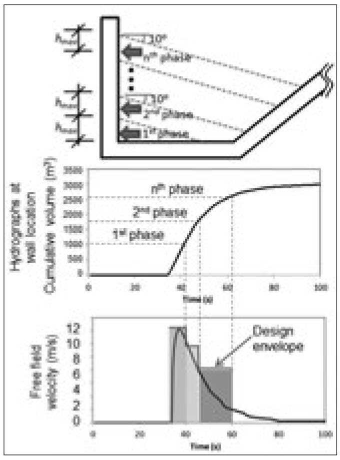

Figure 7: Multi-phase debris impact scenarios

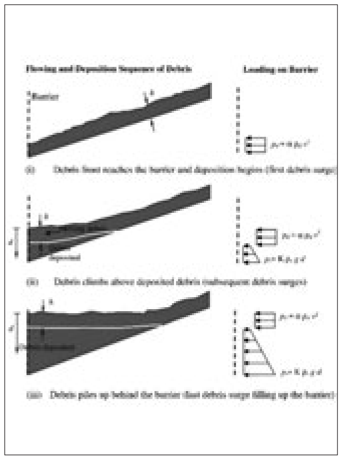

Figure 8: Allowance for attenuation of debris impact velocity

Allowance is made for the additional drag force in the event the debris overtops the barrier. The formulation of the force approach and the key design checks for a flexible barrier and a rigid barrier respectively are summarized in Figure 9.

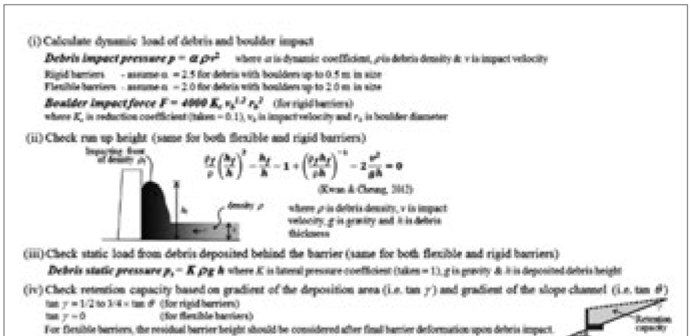

Figure 9: Summary of force approach and key design checks for flexible and rigid barriers

5.2 Insights from Coupled Analysis of Debris Impact on Flexible Barriers

In the conventional approach, landslide mobility analyses and structural analyses of the barrier are undertaken separately. The landslide mobility is first simulated under a free-field condition to obtain the design parameters (e.g. debris velocity and depth), which are then converted into a pseudo-static impact force using the hydrodynamic model as inputs to a separate structural model (e.g. NIDA-MNN). Such an approach neglects the dynamics of the debris-barrier interaction.

The advanced computer program LS-DYNA, which is a 3D finite element model based on the Arbitrary Lagrangian-Eulerian (ALE) formulation, has been enhanced and is capable of modelling debris flow runout and carrying out realistic coupled numerical analysis of debris-barrier interaction.

Coupled analyses can be carried out using LS-DYNA with the landslide mass modelled as a continuum in the finite element formulation in order to evaluate the deformations and forces in various structural components (Figure 10). The coupled analyses have successfully reproduced the field monitoring results in several instrumented case studies.

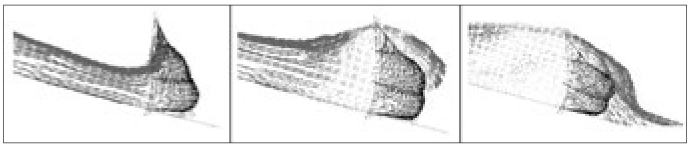

Figure 10: Coupled analysis of debris flow impacting on a flexible barrier using LS-DYNA

Coupled analyses have provided invaluable insight on the energy dissipation of landslide debris in the debris-barrier interaction process. Parametric studies revealed that the overall strain energy absorbed by the flexible barrier upon debris impact only amounted to a fairly small portion (generally less than 35%) of the total debris impact energy, due to internal distortion of the debris and changes in the momentum flux direction under the debris impact mechanism.

Recent advances in numerical modelling enable the coupling of Computational Fluid Dynamcis (CFD) with the discrete element method (DEM), which can capture the behavior of solid and fluid phases in debris flow problems. Currently, these approaches are extremely demanding in terms of computational resources, whereas LS-DYNA is computationally efficient and can simulate large-scale problems using a conventional desktop computer.

5.3 Novel Approaches for Assessment of Boulder Impact on Rigid Barriers

The conventional force-based design approach using limit equilibrium analyses often results in over-design of rigid barriers subject to boulder impact, which is highly impulsive and transient in nature as confirmed in centrifuge tests. The newly developed displacement-based approach provides a more realistic evaluation of the performance of rigid barriers subject to boulder impact. Based on the fundamental principles of dynamic analysis as applied in earthquake engineering, Lam & Kwan (2016) developed closed-form formulae for estimating the translational and rotational movements, as well as the flexural deflection and tensile reinforcement strain due to boulder impact on a rigid barrier in accordance with the enhanced flexural stiffness method.

A series of small-scale impact tests were carried out to verify the predictions using this displacement-based approach and good agreement was obtained. Large-scale flume tests were also carried out to investigate the structural response of a rigid barrier subject to impact by solid steel impactors. The geotechnical stability of the rigid barrier would be robust by limiting the estimated barrier displacements. By allowing energy dissipation through barrier movement, it would obviate the need to provide extensive structural restraints for maintaining the barrier in a static equilibrium condition.

All the tests successfully validated the novel displacement-based method and the newly proposed enhanced flexural stiffness method. Substantial cost savings can be achieved in the design by accounting for the inertia effect of rigid barrier, as the predicted translational and rotational movements of the barrier in typical impact scenarios were found to be insignificant based on the displacement-based approach.

5.4 Novel Design Framework for Multiple Barriers

Kwan et al., (2015) developed an innovative analytical framework for the design of multiple 'closed' barriers acting as rigid check dams based on a rational staged debris mobility analysis. This framework incorporates a set of velocity attenuation impact equations that capture the dissipation of kinetic energy as the debris is deposited in layers up to the crest of a barrier. The dynamics of the ballistic flight during debris overtopping the barrier are accounted for, with the overflow following an inviscid jet and allowance made for the momentum loss upon landing of the debris (Figure 11).

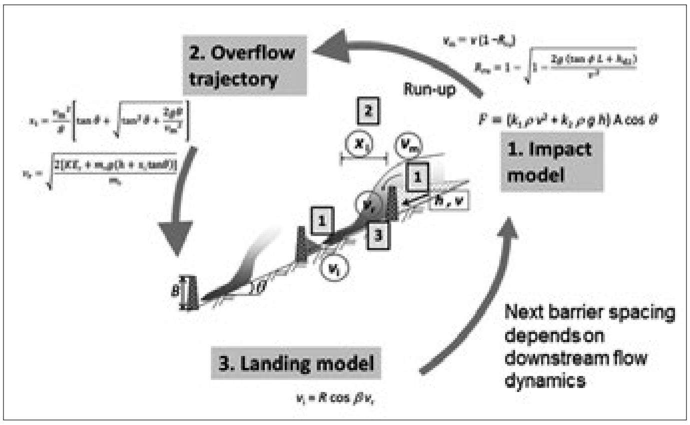

Figure 11: New design framework for multiple barrier system

The design framework was calibrated against laboratory flume tests with the use of photo-sensors and high speed cameras to quantify the debris dynamics behavior based on the Particle Image Velocimetry (PIV) technique. The results of the staged mobility analysis were benchmarked against the advanced finite element program LS-DYNA.

5.5 Innovative Drainage Tunnels to Combat Deep-Seated Natural Terrain Landslides

The Mid-levels area in the vicinity of the Po Shan hillside is underlain by thick bouldery colluvium which comprises old landslide debris. The colluvium is susceptible to the development of high groundwater levels and has a history of past failures.

The Po Shan hillside was found to be of marginal stability because of the high base and transient groundwater levels. Horizontal drains of up to 90 m in length were previously installed to lower the groundwater table with a view to improving the stability of the hillside against deep-seated, large-scale landslides.

After a service life of some 20 years, monitoring results showed that some of the horizontal drains exhibited a decreasing trend of outflow. A QRA established that in addition to the risk of potential deep-seated landslide, the hillside is also susceptible to shallow failures that may transition into mobile channelised debris flows when debris enters a drainage line. In this event, the horizontal drains, which are already showing deteriorating performance, could be ruptured. A more robust and sustainable groundwater drainage scheme is warranted. The adopted novel solution comprised an underground drainage tunnel system together with very long sub-vertical drains to improve the long-term stability of the hillside. The project involved the following pioneering elements and technological advances:

(i) Horizontal Directional Coring was used for the first time in Hong Kong as a ground investigation tool to obtain continuous rock core samples along the proposed tunnel alignments including the curved sections.
(ii) A retractable Tunnel Boring Machine was deployed for the

excavation of the two 3 m diameter drainage tunnels.

(iii) Over 100 m long sub-vertical drains were drilled and installed from within the tunnels.

(iv) An automated pressure relief system for regulating the flow rate of selected sub-vertical drains to stay within a pre-defined range was implemented. The aim was to achieve the necessary pressure relief but avoid any excessive drawdown and possible ground settlement that might affect the adjoining buildings.

(v) An automatic real-time groundwater instrumentation system was established for long-term health monitoring.

The performance of this innovative groundwater control system has proved to be very effective and require little maintenance efforts.

5.6 Nature Based Solutions Using Soil Bioengineering

After natural terrain failures, bare soil is exposed at the landslide scars and loose debris may accumulate downslope. In situations where long-term repair works of natural terrain landslide scars are called for, nature based solutions using soil bioengineering techniques may offer a low cost, sustainable and eco-friendly alternative to conventional 'grey' construction works.

Soil bioengineering comprises the combined application of engineering practices and ecological principles with the use of the 'living' or 'combined living and non-living approach' to control soil erosion and enhance the stability of the shallow soil profile and improve the surface and sub-surface drainage. A key element of such a nature based solution to landslide mitigation is the selection of suitable plant species based on an ecological survey.

A comprehensive field trial involving the use of a variety of soil bioengineering measures was carried out to minimise the deterioration of natural terrain in areas affected by recent, shallow landslides. The objectives were (i) to identify measures that are capable of reinforcing the soil mass, and (ii) to identify means of accelerating the natural re-vegetation of deteriorating slopes, which would enhance the local ecosystems. This led to the promulgation of the 'Guidelines for Soil Bioengineering Application on Natural Terrain Landslide Scars' (*Campbell et al., 2006*). Soil bioengineering was also used to rehabilitate shotcreted landslide scars in Hong Kong.

Field trials are in progress with the use of drones to test the relative effectiveness of promoting vegetation succession through direct seeding of native tree and shrub species as compared with mulch collected from the vicinity and sown manually on the landslide trails.

5.7 Application of Emerging Technology

The geotechnical profession in Hong Kong has been proactive in applying technology and enhanced construction tools to improve the capability and efficiency of slope engineering practice.

5.7.1 Unmanned Aerial Vehicles (UAV)

UAV or drones equipped with sensors (such as laser scanners) to capture the existing ground data (including landslides) for producing a 3-dimensional model of the site are now in common use. UAV with RTK positioning module is suitable for aerial survey in remote areas and requires fewer ground control points. The embedded RTK module provides real-time fully georeferenced data for improved absolute accuracy on image metadata. This is designed to optimize flight safety while ensuring the most precise data are captured for complex surveying and mapping workflows.

UAV with advanced image processing system is also capable of delivering images and videos in fine resolution. Reliability has been enhanced through dual redundancy of some key modules of UAV, such as the battery system. These functions provide the UAV with enhanced reliability, stability and safety.

High-precision surveying by UAV can be mobilized rapidly after major natural terrain landslides to help assess the residual risk of any remaining landslide hazards (e.g. distress or precarious conditions with potential for further landslide, boulder fall, or washout failure of deposited debris on the landslide trail) to supplement emergency visual inspections on site by professional staff. Such signs of residual hazards may be located at a significant distance away from the affected facility, and safe and easy access is usually not available for some time after a natural terrain landslide.

UAV technology can now provide a wide range of survey deliverables, including aerial photographs (oblique, vertical or ortho-rectified photos), point cloud model, 3D mesh model and high-definition texture realistic models. The use of geometrically corrected ortho-rectified photos allows the user to take digital distance measurement easily and coloured point clouds can facilitate spatial analysis of the terrain. Off-the-shelf hardware and software packages can be used for digital photogrammetric analysis and presentation. Applications to geotechnical work include stereo visualisation (including walk-through or fly-through animation video), and aerial photograph interpretation, site surveying and measurement, compilation of digital terrain models which have important 3D GIS and virtual reality applications, rock joint assessment, etc.

5.7.2 Light Detection and Ranging (LiDAR)

As a remote sensing tool for scanning surface topography, airborne, land-based, mobile and hand-held LiDAR systems have been applied extensively in local geotechnical practice for the following applications:

a. Construction of high-resolution digital terrain models;

b. Compilation of 3D digital models of slopes, barriers, etc. for construction monitoring or as digital as-built records for future maintenance and asset management;

c. Rock slope mapping and rock joint survey.

d. The use of multi-return LiDAR tools can capture the ground profile of vegetated terrain. This has proved to be very useful in producing fine-scale topographic maps and digital terrain models with grid size of about 1 m, which in turn allow landslide geomorphology to be interpreted and facilitate debris mobility analysis.

5.7.3 Geotechnical Information Hub

Over the years, the GEO has compiled a large number of geospatial datasets. The centralized system is being upgraded to provide a one-stop integrated web-based information hub and application platform embedded with state-of-the-art technologies including 3D GIS, Building Information Modelling (BIM), remote sensing, digital photogrammetry and various analytics to allow users to access and visualize geotechnical and slope related data in a 2D or 3D environment and perform analytical functions. Applications include the management of point cloud data, sharing of landslide information and doing

3D measurements. The opening up and sharing of the available geotechnical data promotes collaboration and enables thematic applications, thus enhancing the capability of geotechnical work as well as the operational efficiency.

Apart from managing spatial data, GIS has been used extensively for spatial modelling and analysis (such as debris runout analysis, rainfall landslide correlation, landslide susceptibility analysis, QRA, etc.), as well as 3D visualisation and virtual reality applications. Apart from web application, a GIS-GPS mobile mapping system has been developed to guide navigation in the field and allow the retrieval of the relevant spatial data (e.g. past landslides) for location-based applications. The system is equipped with wireless telecommunication via the Internet with the server in the GEO for data transfer in order to support the geotechnical fieldwork.

GIS-BIM data integration system is being developed for the management of different forms of data, displaying field monitoring results and site progress analysis, as well as design optimisation for enhanced efficiency and minimising human errors.

5.7.4 Cautious Use of Interferometric Synthetic Aperture Radar (InSAR)

In principle, InSAR using the available satellite imagery is a potentially useful remote sensing technique for measuring ground displacement with millimeter-level accuracy. The application of InSAR for detection of slope movement in Hong Kong is, however, beset with challenges as the results can be seriously affected by 'noises' due to (i) temporal decorrelation associated with cloudy and rainy weather, (ii) geometric distortion with steep terrain, and (iii) atmospheric effects and temporal decorrelation associated with humid environment and vegetation.

Further development work including the trial use of multi-dimensional SAR tomography technique and other proposed novel enhancement measures, before the potential of applying InSAR to monitor steeply-sloping, heavily vegetated slopes can be realised.

5.7.5 Digital Slope Design

Geohazard assessment for slope design has traditionally been a labour-intensive process that requires expert input in the interpretation of data from desk study, field mapping, ground investigation, etc. The GEO has stepped up the application of BIM technology in the planning and design of slope works. BIM is not just a 3-dimensional tool but a platform to be used by the project team to holistically manage digital information relating to construction projects from the planning stage, through the design and construction stages, to the operational stage. Through the use of BIM, complex topography, geological conditions, foliage, utility matrices and underground facilities are considered in slope design and coordination of the works during construction. Some examples of BIM applications to digital design of slope works in Hong Kong are presented below:

i. GEO's 3D geological database – obtaining subsurface data through the available ground investigation information is of critical importance for engineering projects. Currently, about 200,000 GI data in AGS format have been stored in a centralised computer kept in GEO. In order to facilitate the sharing of the GI data in digital format, the GEO has enhanced the AGS data such that they are now compatible with other GIS and 3D modelling tools including BIM software. Such valuable subsurface information, including geological sections, can be used to create large-scale 3D geological models and will be useful for planning future ground investigation works and preliminary geotechnical designs.
ii. Field mapping assisted by digital tools – the quality of field data (e.g. landslide scar) can be significantly enhanced by the deployment of a hand-held mobile laser scanning device. This latest technology is a fusion of LiDAR, colour imagery and inertia measurement unit (IMU) data, which can collect a large quantity of 3D measurements and allow real-time scanning feedback to facilitate BIM modelling (e.g. for rock slope stability assessment).
iii. Simulation of 3D debris mobility and runout path – the mobility of landslide debris and its runout path can be incorporated into BIM models for optimal positioning of flexible barriers. The debris impact velocity profile can also be delineated along the 3D runout path to facilitate barrier design. The buildability of the barrier can also be enhanced by locating barriers judiciously at strategic hillside areas.
iv. Minimising earthworks for rigid barrier construction – BIM can be used to optimise the barrier layout by minimizing the cut and fill balance for site formation works. The configuration of the rigid barriers may be altered in the design very efficiently in order to minimise the earthworks cost, as well as reduce the environmental and visual impact.
v. Automatic clash detection – by defining the soil nail lengths, orientations and inclinations in 3D space, the BIM model can help to coordinate the alignments of soil nails so as to avoid the clashing of different elements.

5.7.6 Improved Construction Technology

In the consideration of improvement in construction plant, the focus has generally been on enhancing productivity, safety, quality, environmental performance, as well as versatility and miniaturization. Elegant solutions in practice often lie in the use of simple tools that are fit for purpose given the typical site constraints associated with difficult access and tight working space. The relatively minor nature of slope works as compared with heavy civil engineering works normally do not justify major investments in sophisticated construction equipment. Some recent examples of successful application of enhanced tools to improve the construction process are described below.

Mobile aerial platforms can be used for the installation of soil nails on slopes adjacent to busy and narrow roads that cannot be closed for a long period of time from a traffic management point of view. Appropriate customization of construction techniques to overcome the site constraints is called for. For example, an improved excavator-mounted mobile drilling rig, together with a separate mobile scissors and aerial platform, were custom-made to reduce the risk of workers working at height and facilitate quick mobilisation for the soil nailing works without the need to erect and dismantle the temporary working platform.

Another example is given by the development of a water-cooled coring machine (as opposed to traditional air-cooled machine) with a tailor-made noise enclosure on a mobile working platform for use during night-time work with restricted working hours within an urban area. This obviates the need to adopt an elaborated noise enclosure for the mobile platform, which will require the workers to operate in a confined space. Also, overheating of the water-cooled coring machine is unlikely. The improved machinery reduced the noise level from 83 dB with a traditional coring machine to 65 dB with a water-cooled coring machine.

To enhance the data traceability and efficiency of site supervision, mobile Apps are increasingly being used for easy and efficient recording of site data and capturing images, which can be transmitted to a central server. Record forms can then be generated automatically and the results can be plotted and interrogated easily.

5.7.7 Novel Quality Control Tool for Grouted Steel Soil Nails

Once a soil nail has been installed, it is difficult to check its quality, such as the length of the reinforcement bar and the integrity of the cement grout annulus. To enhance the quality control of soil nailing works, GEO developed a simple and cost effective non-destructive test based on the Time Domain Reflectometry (TDR) principle in order to check the quality of the installed soil nails (Cheung & Lo, 2011). This technique has been applied successfully as a screening tool to assess the quality of a considerable amount of grouted steel soil nails with a pair of pre-installed steel wires.

6.0 INNOVATION AND TECHNOLOGY IN MANAGEMENT OF RESIDUAL RISK

6.1 Insights on Potential Impact of Climate Change on Landslide Risk

Extensive scientific research has been conducted to study the probable impact of climate change in Hong Kong. The studies indicate that extreme rainfall events will likely become more frequent and more intense.

A major uncertainty associated with the evaluation of climate change impact is that past experience may no longer be a reliable basis for predicting the characteristics and frequency of future events, especially extreme weather events. This has major implications on risk assessment and risk management, as the risk of low-probability, high consequence extreme events (or 'black swans') that occur exceedingly rarely can become significant. However, there are often not enough data to make a statistical estimate of the probabilities of occurrence of all the contributing factors.

The record-breaking rainfall that struck Hong Kong in 2008 brought about widespread natural terrain landslides with escalated frequency, scale and mobility. An important insight in relation to the risk profile is that natural terrain landslides and debris flows would overtake man-made slope failures and become the principal slope safety concern during extreme rainfall events. The GEO has developed a novel stress testing technique to assess the potential impact of extreme rainfall event associated with climate change on landslide risk (*Ho et al., 2017*).

To quantitatively assess the impact of climate change, the GEO conducted scenario-based assessments utilising the Probable Maximum Precipitation (PMP) concept and established two plausible extreme rainfall scenarios. The probable response of slopes was evaluated based on projections from the updated rainfall-landslide correlation models.

The first scenario considered the actual 1,000-year rainfall event which hit Lantau Island (an outlying island with a population density of only about 800 persons/km^2) in June 2008 and triggered about 2,600 natural terrain landslides. This rainstorm was transposed spatially to Hong Kong Island (an urban area with a population density of about 1,600 persons/km2). It was estimated that this could result in some 300 serious landslides, which would stretch the existing landslide emergency system to the limit.

The second scenario assumed that the more severe rainstorm associated with Typhoon Morakot that struck Taiwan in 2009 is transposed to Hong Kong Island (with corresponding corrections made to the rainfall intensity to account for the orographic effects). This was found to result in a range of 4,000 to 9,000 serious landslides. This would completely overwhelm the capacity of the prevailing landslide emergency system of the GEO.

These findings have major implications on emergency preparedness and response, and the strategy for managing the landslide risk associated with climate change. A new strategy for crisis preparedness and enhancement of emergency response, crisis communication and community resilience is called for.

The above work provided much insight on the need to improve our preparedness for meeting the unprecedented challenges of extreme weather events. This includes the formulation of an appropriate adaptation strategy, enhancement of our emergency preparedness and response, and strengthening of the resilience of the community and the slope safety system in coping with the scenarios of widespread serious landslides.

6.2 Hillside Catchments Vulnerable to Low-Frequency, Large-Magnitude Landslides

The increase in the severity and frequency of extreme rainfall calls for attention to the potential impact of low-frequency, large-magnitude landslides. As demonstrated by the record-breaking rainstorm in 2008 in Hong Kong, the frequency, source volume, entrained volume and mobility of channelised debris flows could increase drastically with rainfall intensity.

Hillside catchments with a long drainage line (>750m) have been identified as an adverse site setting that is prone to the development of low-frequency, large-magnitude channelised debris flows with debris of high mobility under the impact of extreme rainfall events (Figure 12).

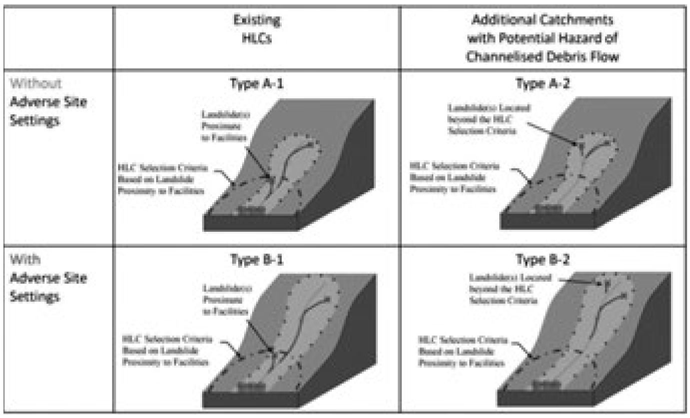

Figure 12: Historical hillside catchment selection criteria

The GEO has undertaken a portfolio QRA, which indicates that some of these potentially vulnerable catchments deserve prioritised attention under the systematic Landslip Prevention and Mitigation Programme. A GIS methodology has been developed for the systematic delineation of major drainage lines and the corresponding catchment boundaries on a territory-wide basis. Site-specific QRA has been carried out on selected catchments with long drainage lines to assess the individual risk and societal risk and help assess the appropriate risk mitigation strategy.

6.3 Innovative Resilience Measures

Whilst the overall landslide risk in Hong Kong has been much reduced and is largely contained by engineering works and land-use planning, it cannot be totally eliminated. The GEO has stepped up its early warning system and emergency information management and response to further control the residual risk.

6.3.1 New Early Warning System for Debris Flows

Risk can be managed by alerting the public or the affected stakeholders of the level of landslide risk during periods of heavy rainfall in order to promote them to take precautionary or self-protection actions (e.g. evacuation or avoiding the use of hilly roads). Hong Kong has been operating a Landslip Warning System based on real-time rainfall and radar monitoring, together with a short-term rainfall nowcasting model and a probabilistic framework for the correlation between rainfall intensity and landslide probability, taking into account the spatial and temporal distribution of the rainfall as well as the spatial distribution of the different slope types. The model allows a realistic projection of the landslide pattern in real time as the rainfall pattern develops.

Given that extreme rainfall events can lead to much more serious hazard scenarios and landslide patterns as compared to those under a moderately heavy rainstorm, a new and additional set of natural terrain landslip alert criteria was established. The criteria are based on the correlation of storm-based rainfall and natural terrain landslides. The correlation model has incorporated the new territory-wide rainfall-based landslide susceptibility model (Ko & Lo, 2016), and can be used to predict the expected total number of landslides for the operation of the new 3-tier natural terrain landslip alert.

6.3.2 Smart Barrier System for Enhanced Emergency Response

(i) Design Consideration

Barriers are capable of retaining a designated volume of landslide debris. In case of exceptionally massive or recurrent landslides triggered by extreme rainfall which exceed the designated retention volume, the barriers may be overwhelmed and overflow of debris to the downstream area may occur. In addition, there have been cases whereby barriers had intercepted landslide debris in the field without being noticed for quite some time after the landslide had occurred, due to their inaccessibility and obstructed visibility.

To facilitate timely emergency response, the GEO has developed a smart barrier system to provide alerts to the government agencies and relevant stakeholders when debris impact on the barrier is detected. This system has been customised to suit the local conditions of natural hillsides.

There are three key challenges for the smart barrier system:

a. The system is exposed to hot, humid and vegetated outdoor environment without any power supply. Its design needs to be robust against rough outdoor environment and adverse weather, nominal power consumption requirement and sustainable by harvesting solar energy alone.

b. The wireless communication among the Internet of Things (IoT) devices and the cloud platform is not stable at remote and heavily vegetated sites, especially during rainy weather. The communication module of the smart barrier system has to be optimised for exceptional efficiency and redundancy.

c. The system should be of a low cost for set-up and maintenance so that it can be scalable and applied to many sites.

(ii) System Architecture

The smart barrier system has been developed with a simple system architecture to provide timely detection of debris impact. There are four modules, namely (a) debris impact detection system (b) signal transmission system (c) monitoring instrumentation system (d) power supply system. Real-time landslide detection is realised through the deployment of an array of wireless impact switches mounted on a rigid barrier. Real-time data or images recorded by the monitoring instrumentation, including customised laser depth laser gauges (for landslide debris thickness measurement) and digital cameras (for capturing photographic images) can be viewed through the mobile application to take cognizance of the situation in the field. These inter-connected IoT instruments are linked to a cloud-based information technology platform with native mobile application, which facilitates real-time surveillance and timely and informed emergency response.

(iii) Alert Trigger Mechanism and Operation

The debris impact switch is housed in a 300mm by 450mm box, which is installed at the back of a rigid barrier wall stem (Figure 13). When the front face of the box is subject to a physical hit, two wired metal plates in the impact switch originally set apart will be pressed together, hence completing an electric circuit to give a signal of landslide debris impact.

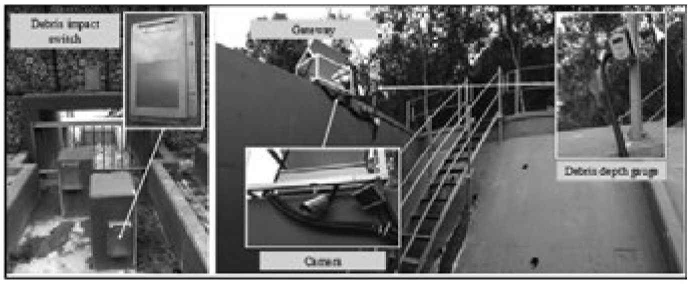

Figure 13: Field installation of smart barrier system

In addition to the impact switches, the debris depth gauges installed at the crest of the rigid barrier monitor the debris depth behind the barrier. These are programmed to take a measurement every five hours. If the depth gauge measures a depth exceeding the pre-set threshold, it will trigger an alert signal. When there is an alert signal either sent by the debris impact switch or the debris depth gauge sensor, the system will command the digital camera to capture a photographic image of the barrier retention zone, and that the frequency of the depth measurement will increase. All the data are transmitted to desktop and mobile devices via a 4G mobile network. Officers can remote control the digital camera to take additional images via the desktop or mobile application.

To facilitate the monitoring of the continued performance of the prototype smart barrier system, the system is configured to transmit its battery power level to the mobile and desktop devices at regular intervals. Such ‘heartbeat’ signals together with the continued feedback from the monitoring devices (e.g. debris depth gauges) allow the officers to monitor the condition of the system and the need for maintenance.

The performance of the smart barrier system was tested via debris impact in a large 28m long flume model in the field. A series of flume tests successfully demonstrated the capability of the smart barrier system.

For flexible barriers, a wireless pull switch is adopted for debris impact detection. The pull switch is connected by a steel wire attached across the barrier net. When the barrier is impacted by landslide debris, the barrier net will deform causing extension of the steel wire and in turn triggering the pull switch to give a warning signal. The GEO officers can receive the alert and the tilt angle data via the desktop and mobile application.

6.3.3 Enhanced Emergency Information Management

In addition to landslides, other types of natural hazards (e.g. flooding, tree falls, storm surge, damage by wind, etc.) are liable to occur concurrently during extreme weather events. Situation awareness and efficient crisis communication are instrumental to good emergency management. The GEO has recently developed the Common Operation Picture (COP), which is a new IT platform with GIS functions for sharing real-time emergency information among various government departments (Figure 14). The system can provide a timely overall picture of the emergency situations for multiple-hazard scenarios and facilitate decision-making and coordination of emergency response by different departments.

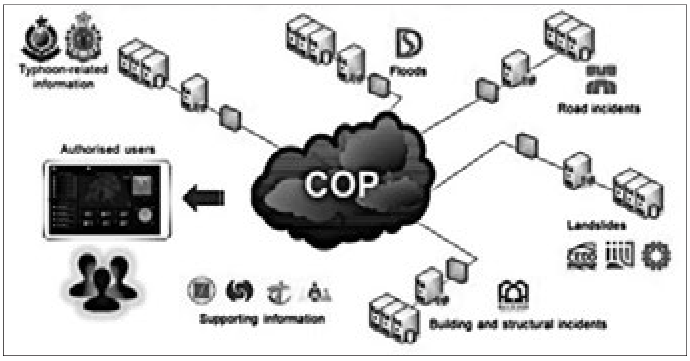

Figure 14: Common operational picture for emergency management

7.0 DISCUSSION

The success of the Hong Kong's slope safety system in becoming a role model hinges on the application of formal risk management principles using a systems approach and risk-informed decision-making and communication, together with the liberal application of innovation and technology.

In practice, innovation does not necessarily equate to invention and it is not confined to technical advances alone. Innovation can involve new ideas, analysis tools, technologies, approaches or processes, or a combination of these.

The GEO has the vision and courage to drive the extensive application of innovation and technology. In some cases, this may involve some calculated risks. Prior to implementing the innovative technical ideas, they would be subject to rigorous internal technical and management reviews before consulting the industry widely. In addition, the novel technical ideas will be deliberated by the three international experts of GEO's Slope Safety Technical Review Board.

In geotechnical engineering, the application of fundamental knowledge and judicious modelling plays a central role in understanding and solving practical problems. Burland (1987) emphasised the importance of four key distinct and yet interlinked activities in soil mechanics by reference to the "geotechnical triangle". Knill (2003) presented the "engineering geological triangle" that defines the key aspects of the engineering geology discipline. For practical purposes, the engineering geological triangle may be taken to be embedded within the geotechnical triangle, which collectively encapsulate our domain expertise.

This paper focuses more on the practically orientated, cutting-edge innovations that have been applied to landslide risk management. In recent years, notable advances have also been made in the geotechnical engineering discipline which entail the following:

(i) Pervasive field sensing technologies linked to real-time feedback [enhanced data capture capability]
(ii) 3-D analysis capability that represents soil behavior more realistically and can consider large deformation problems by Finite Element Method, Discrete Element Method or Material Point Method [enhanced analysis capability]
(iii) Emerging constitutive modelling abilities supported by high quality experimental data in addressing previously neglected factors, such as time effects, cyclic loading, anisotropy, thermal and multi-phase interactions, etc. [enhanced understanding and modelling capability of complex soil behaviour]

It is considered that the geotechnical engineering profession now faces several mega-trends that can be described by means of an overarching, mainstream triangle which would effectively subsume and embrace the geotechnical and engineering geological triangles (Figure 15). This mainstream triangle encompasses three major activities, namely 'innovation', 'technology' and 'data'. In the present context, 'data' refers to real-time data capture using modern sensor and wireless transmission technologies, with the data being turned into insights through the use of data analytics with a view to enhancing our understanding of the actual field performance and facilitating data-driven risk management decisions.

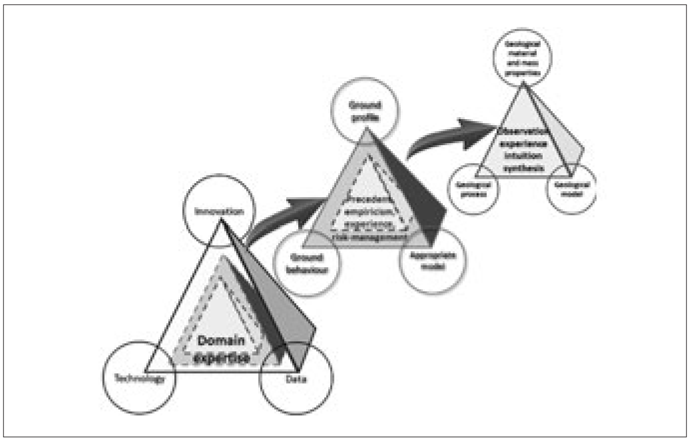

Figure 15: Nested nature of the mainstream triangle embedding the geotechnical triangle and the geological triangle

The key point to bear in mind is that the geotechnical triangle and in turn the engineering geological triangle should remain embedded within this overarching triangle that defines the mega-trends. Fundamentally, we must ensure that the anticipated trend of expanded implementation of innovation, technology and data science in geotechnical engineering must be rooted in our domain knowledge and experience.

Emerging technology can facilitate automated analyses and design processes leading to streamlining and optimisation of our work. However, we must not lose sight of the importance of becoming sufficiently familiar with the available data and achieving a good 'feel' for the problem and the likely mechanisms so that we can be sensitive to potential risks. Taking cognizance of the nature and uncertainties of geotechnical engineering, the intuition and judgement built up by competent geotechnical professionals through well-winnowed experiences cannot be totally replaced by technological tools such as Artificial Intelligence and machine learning.

Any time saved through the use of automated processes by means of technological tools should be directed to achieve a better understanding of the available data and thinking through the problem. In many cases, we need to be more professional and open-minded in seeking the optimal approach and solution. There is a danger that some designers may unwittingly opt for a sub-optimal solution that is then subjected to an automated process for optimisation, which can give rise to the erroneous appearance of an elegant solution!

Modern emerging technologies are evolving at a very fast pace. These include Artificial Intelligence (AI) in the form of machine learning and deep learning, robotics, Internet of Things (IoT), big data analytics, 3D printing, blockchain, drones, LiDAR technology, VR & AR, unmanned vehicles or machineries, quantum computing, edge computing, serverless computing, 5G technology, automation, advanced materials, numerical tools, smart sensors, etc. Some of these may appear more promising than others and given time, they could well disrupt and transform industry practice. We should step up our efforts to examine the applicability of various emerging technologies and leverage their use in enhancing our capability and practice in a cost effective manner.

What are the prospects of the geotechnical profession entering into a new era of making transformational advances through wider application of innovation and technology? Given the notable breakthroughs in technology, we are already at the cusp of this big wave and mega-trend with innovation and technology being mainstreamed in many industries. It is likely that we will be entering into a new era of digital design and collaboration, together with smart construction, before long. The geotechnical profession must gear up to meet this challenge.

We should endeavor to customise the available technologies and implement more innovations that will enhance our work in such a way that our domain expertise will not be compromised. In essence, we must ensure that all the aspects covered by the three triangles as shown in Figure 15 are kept in a fine balance. It is incumbent upon us to bear in mind the old adage "rubbish in, rubbish out' in the context of application of data analytics. We must also ensure that we use the right tools for the right problems.

Over the years, a risk-averse culture has become pervasive in the construction industry. Given this, how do we ensure or sustain successful innovations? In reality, this can be tricky and is largely dependent on competence, policy and cultural change. By its very nature, innovations may not necessarily work out given the possibility of unintended or unanticipated consequences. There is no 'silver bullet' when it comes to nurturing an innovative culture and promoting a paradigm shift. Reflecting on GEO's experience in the past four decades, the following considerations, which are by no means exhaustive, are pertinent:

a. Enhance the university curriculum and staff training to come up with more tech-savvy people and empower and encourage them to think laterally and out of the box;

b. Promote the sharing of expert knowledge and creative ideas with a view to broadening the perspectives and facilitating the build-up of a mindset of being receptive to co-create ideas;

c. Advance domain expertise and professional practice by pursuing collaborative and applied technical development work together with the academia and/or practitioners in addressing priority problems faced by the industry;

d. Strive to form diverse teams with cross-disciplinary input, where appropriate, so as to promote cross-fertilization of ideas from other disciplines;

e. Undertake critical reviews, conduct rigorous trials and embrace promising new technologies in a progressive manner;

f. Build up an organisational culture in embracing innovation and technology and celebrating success;

g. Motivate staff and cultivate an atmosphere that is conducive to maintaining curiosity, inspiration and passion to learn and pursue continuous improvement on a lifelong basis;

h. Encourage those who have the authority to vet and approve innovations to exercise discretion based on professional knowledge and judgement, and provide high-level institutional support to these people.

8.0 CONCLUDING REMARKS

Landslides pose an acute threat to life and property in an urban environment. Tackling urban landslide problems calls for the application of a holistic risk management strategy and system. It entails the use of engineering and non-engineering approaches, involving policy, legislative, vadministrative, technical, educational, community-based and emergency preparedness and response provisions. Such a systems approach has paid dividends in Hong Kong in reducing the landslide fatalities and damage.

Recent advances in slope engineering have been knowledge-based as well as technology-driven. These have enabled the application of innovations to transform industry practice. This paper has presented some examples of practical application of innovations and technologies that have enhanced landslide risk management.

Hong Kong is now faced with acute slope safety challenges associated with the potential impact by extreme rainfall, which may be exacerbated by climate change and can lead to widespread debris flows with escalated frequency, scale and mobility. Concurrent occurrence of multiple hazards, such as landslides, flooding and storm surge, could lead to cascading effects and further aggravate the consequence. This is compounded by a dwindling risk awareness and general complacency about landslide risk by the public.

We must maintain an innovative mindset in formulating smart and practical solutions by advancing the frontiers of our domain knowledge, leveraging emerging technologies and developing novel, cross-disciplinary approaches through better collaborations.

The geotechnical profession should strive to take a lead in defining innovative approaches and smart solutions to address the pertinent problems whilst ensuring that the innovations will be rooted in our domain expertise in geotechnical engineering and engineering geology.

Given the many uncertainties and the potential grave consequences that we face in urban landslide risk management in tackling climate change impact, we must remain humble and keep learning, improving and innovating. It is imperative that we do not allow ignorance or complacency to trap geotechnical professionals into doing less than they ought to, as the price to pay by the society can be tremendous.

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APPENDIX A – CASE STUDIES OF DEA

A1 Hillside A

This case study illustrates the application of the geomorphological mapping technique and detailed field mapping in assessing the Design Event for a typical hillside catchment.

Terrain Units

The determination of the Design Event requires the development of an appropriate geological and geomorphological model to aid making professional judgement. Figure A1 shows the hillside which rises approximately from +220 mPD to +600 mPD and comprises a catchment with an area of about 114,000 m2. On the basis of aerial photograph interpretation and field reconnaissance, the study area was subdivided into five Terrain Units (TU) based on the morphology, geomorphological processes, and solid and superficial geology.

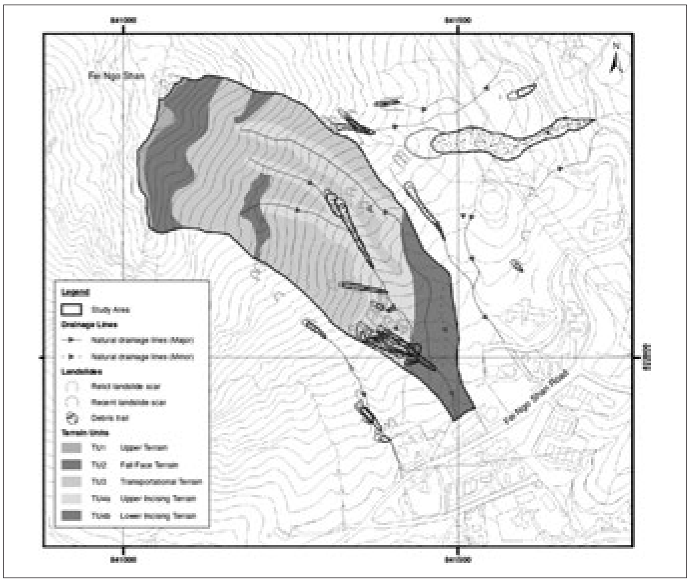

Figure A1: Terrain unit map

In this study area, the Upper Terrain (TU1) consists of a rounded topography, comprises mainly saprolite. This terrain unit may represent the oldest landform in the study area and appears to be inactive. A series of rock cliffs form the Fall Face Terrain (TU2) below TU1. The rock cliffs range from about 10m to 60m high. The potential hazard associated with TU2 is considered to be rockfall. Localised talus and taluvium present immediately below TU2 (i.e. within TU3 and TU4a). The largest block size is estimated to be around 100m3, which is comparable with the maximum fallen rock fragment of 90m3 observed within the Study Area. The existing rock faces are generally stable, risk of large scale rock fall initiated from TU2 is considered to be very low while re-mobilization of the fallen rock fragments in TU4a during debris flow events could not be discarded. Below TU2 is the Transportational Terrain (TU3), which covers most of middle portion of the study area.

TU3 is generally covered by a thin layer of colluvium underlain by saprolite. The main active process with this terrain unit is mass wasting and subsequent transportation. Few open hillslope landslides were recorded within this terrain unit. The debris from one of these landslides entered the drainage line, suggesting that open hillslope landslide occurred within TU3 could enter drainage lines within the study area and develop into debris flow. A few drainage lines are present within the catchment. The upper drainage sections are relatively broad while the lower sections are more incised.

The slope of the Upper Incising Terrain (TU4a) generally varies from 25 to 40 degrees. The main active processes associated with this terrain unit are mass wasting, fluvial erosion and transportation along drainage lines. TU4a is predominately covered by colluvium and landslide debris. This terrain unit is rather active, with over 70% of past failures occurring within it. The failures are initiated as open hillslope landslides while some of them entered drainage lines and developed into debris flows. The Lower Incising Terrain (TU4b) is generally confined with channel gradient varying from 15 to 25 degrees and is predominately associated with valley colluvium. The main active process associated within this terrain unit is considered to be fluvial undercutting and reworking of mass wasting deposits. Drainage lines within TU4a and TU4b are considered to be susceptible to debris flows and the loose materials (e.g. valley colluvium and taluvium) perched along the drainage lines is liable to be entrained during the landslide events.

Mapping Past Landslides

The failure volume to be adopted in the mitigation measures design aligns with a notional return period of 100 years, which is usually determined based on the scale of recent landslides as well as relevant relict landslides with a high degree of certainty as observed in the available aerial photographs. In general, it is considered that past events in the hillside catchment and its relevant vicinity will give a reasonable indication of the potential scale of future events.

Records from the landslide inventory contain 12 recent landslides and 14 relict landslides within the Study Area (Figure A2). They were all confirmed during site-specific aerial photograph interpretation and field mapping (Figure A3). The largest landslide has an estimated source volume of 300 m^3. This will be adopted as the Design Event source volume.

Mapping of Drainage Line

Landslides occurred within TU3 and TU4a could enter into drainage lines and become debris flows. For drainage lines that are considered susceptible to debris flows, the debris yield

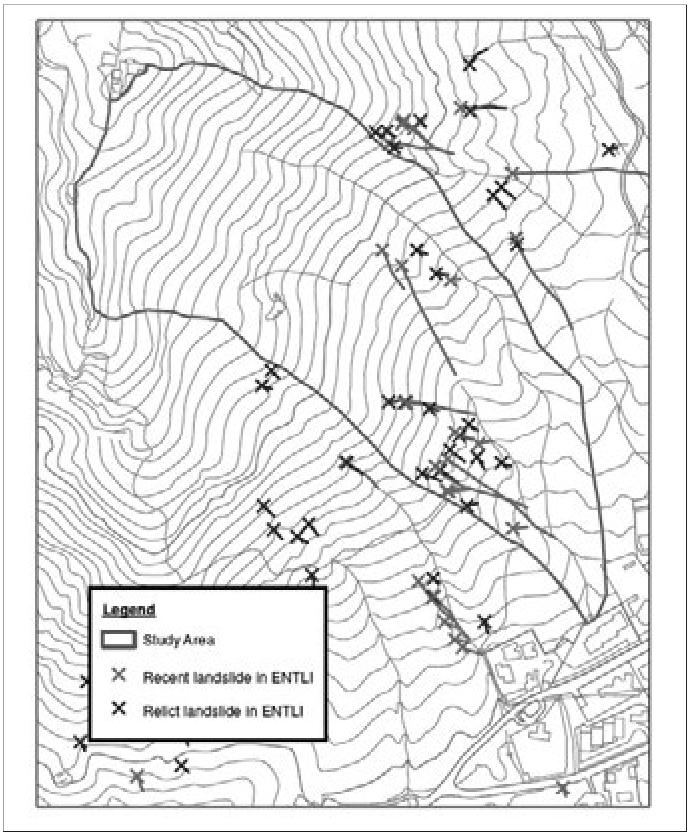

Figure A2: Past landslides within the study area

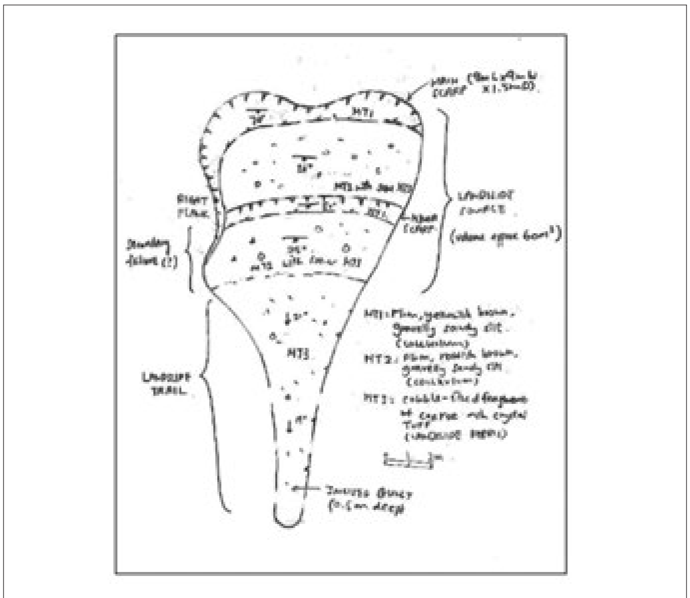

Figure A3: An example of landslide mapping

rate (volume of eroded material per linear metre, expressed in m3/m) for each section of the drainage line should be determined (Figure A4). This will be carried out typically by reference to the thickness, characteristics and distribution of the materials present within the sections of the drainage line susceptible to erosion and entrainment of debris. Detailed field mapping of drainage lines is critical to the evaluation of potentially entrainable materials during debris flows. An example of drainage line mapping is shown in Figure A5. The entrainment volume along individual drainage line is estimated to range from 500 m^3 to 700 m^3.

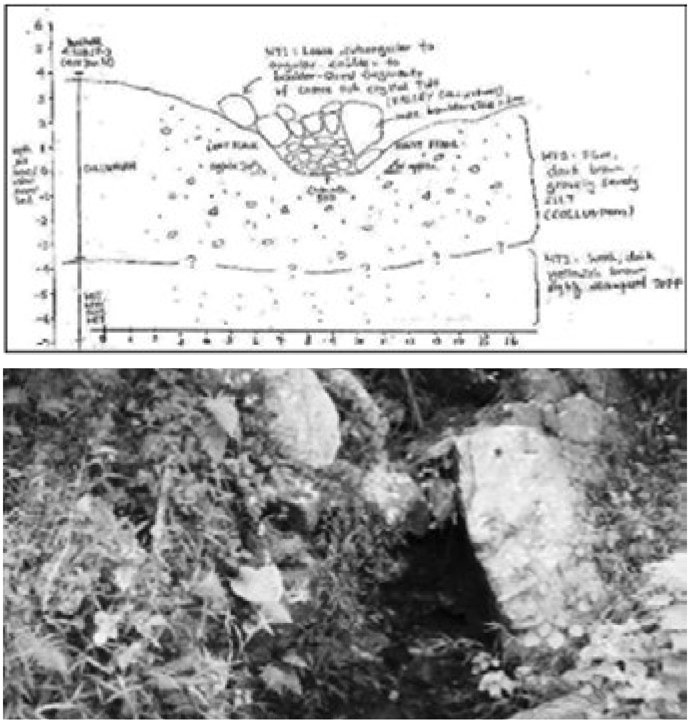

Figure A4: Derivative entrainment potential

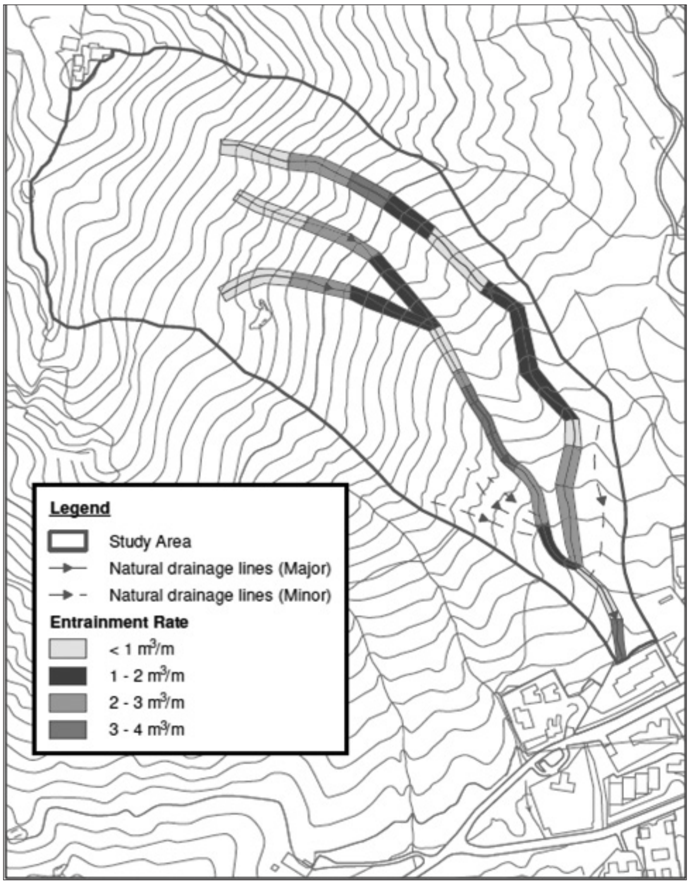

Figure A5: Mapping of drainage lines

Design Event Assessment

Based on detailed field mapping, the Design Event for a hillside catchment could be determined to facilitate the design of necessary mitigation works. For open hillslope catchments (generally planar slope with insignificant drainage concentration), the Design Event usually refers to the source volume of the largest recent landslides or relict landslides with sharp scarp observed within or adjacent to the hillside catchment overlooking the facility under study. For channelised catchments (with the presence of an incised drainage line) where debris flow could occur, specific entrainment values in drainage lines were assessed in order to estimate the maximum credible volume for each individual drainage line. The Design Event would be taken as the summation of the landslide source volume and the total entrainment volume along the drainage line. For the present case study, the Design Event of debris flow for mitigation design purposes is approximately 1,000 m^3 (i.e. 300 m^3 source volume + 700 m^3 entrainment volume).

A2 Hillside B with Large Debris Lobes

This case study highlights the assessment and interpretation of a large debris fan based on detailed field mapping and targeted ground investigation, including age dating, to allow the assessment of landslide magnitude and frequency.

Large debris fans have been identified near the toe of a natural hillside. Mapping of morphology and materials allowed the sub-division of each debris fan into separate lobes (Figure A6). Given the restricted size and relatively well defined morphology of the debris fans, drillholes were located in these debris fans. Large diameter, triple tube core barrel with air foam flush drilling was adopted within the boulder-rich landslide debris in order to obtain good core recovery for detailed inspection. Based on the field mapping and ground investigation, a schematic cross section illustrates that each debris fan complex contains multiple separate debris flow events (Figure A7).

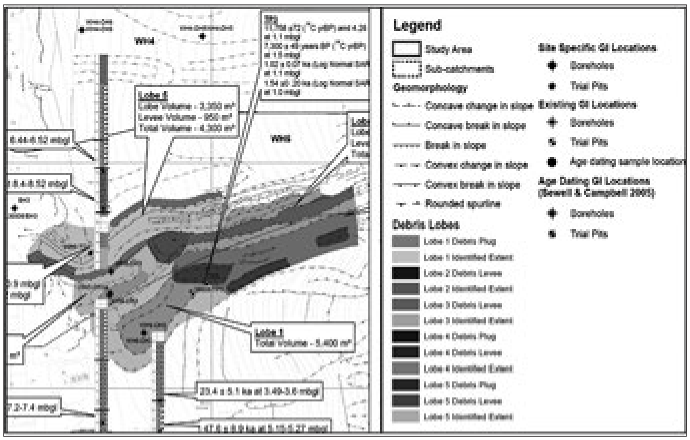

Figure A6: Map of debris lobes (extract)

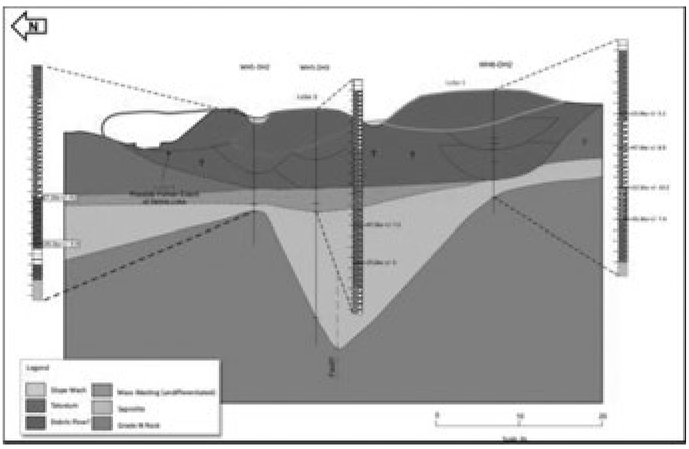

Figure A7: Cross section through debris lobes

An evaluation of the debris lobes and potential source areas was undertaken and tentative relationships between the two were assessed. With the results of the age dating, an estimation of the possible ages of the events was generated. This suggested that there have been three events in the last 1,000 years (lobe volumes of 1,000m^3, 2,000m^3 and an unknown volume), four events in 3,000 years (an additional lobe volume 3,000 m^3) and seven events in 4,000 years (additional lobe volumes of 2,500m^3, 10,000m3 and an unknown lobe volume).

There are four channeliszed catchments within the Study Area. Design event source volumes for the individual catchments ranged from 400m^3 to 900 m^3. Following the current guidelines, the above sizeable debris lobe volumes were not considered in the Design Event assessment.

A3 Hillside C with Extensive Distress

This case study shows the staged approach adopted during the ground investigation of an area with slope distress including significant tension cracks near the crest of a natural hillside.

The first phase Ground Investigation (GI) included 2 trial pits and 2 drillholes in the upper terrain as well as vegetation clearance. Once the access for GI works was available, field mapping was undertaken and a large area of hillside distress was identified and mapped. However, given the limitations with the scope of the GI, together with the large extent of distress and uncertainties regarding the depth of failure, a second phase GI was undertaken which included 9 drillholes (up to 40m in depth), installation of slope inclinometers as well as piezometers. The additional expenditure of the second phase GI was well justified given the need to evaluate the potential of a much larger scale of failure in the upper terrain.

The large area of slope distress consists of two distinct areas of slope deformation (i.e. Areas 1 and 2 as shown in Figure A8), which are located on either side of a pre-existing, large erosion scar. Area 1 measures 3,600m^2 and Area 2 measures 2,800m^2.

Figure A8: Mapped extent of distress following vegetation clearance in the Upper Terrain

The slope distress includes open tension cracks and scarps up to 30 m long (Figures A9 and A10).

The surface distress appears to be associated with the continuous surfaces of rupture which have developed at the colluvium/saprolite boundary (typically less than 2m deep). Below this, localized shear surfaces, clay infill and disturbance of uncertain origin were identified from detailed examinations of split Mazier samples (Figures A11 and A12) at depth within the saprolite (>20m). Kaolin is often associated with surfaces of rupture and buff kaolin clay probably develops progressively and over long periods of time as kaolin-infilled discontinuities are subject to intermittent shear, dilation and infilling as a result of and during intermittent slope movements. Such infilling probably requires a considerable amount of time, perhaps over time scales of the order of hundreds to thousands of years.

No continuous surface of rupture was identified from the detailed examination of split Mazier samples. As such, based on all the available information, there is no clear evidence to support the hypothesis of incipient large-scale deep-seated detachment. The features identified at depth within the saprolite are likely to be of a weathering origin and unrelated to the distress identified at the ground surface. Moreover, it is noted that the signs of surface distress on either side of the large erosion scar could be identified in the 1963 aerial photographs, which suggests that only localized, small-scale slope movements have occurred within the last 50 years or so. The current surface distress is probably associated with surfaces of rupture within the colluvium and near at the colluvium-saprolite interface (i.e. about 2m deep).

Apart from the surface distress, debris flow and open hillslope landslide hazards were also identified within the Study Area which pose significant threats to the facilities at the hillslope toe.The Design Event source volumes for the Study Area is 450m^3.

Concrete debris-resisting barrier and soil nails were adopted to mitigate these hazards. For the area of slope distress, prescriptive soil nails and raking drains were installed at the distressed area in order to render the mitigation works more robust.

This case study illustrates that very detailed logging of the GI stations and a sound understanding of the weathering processes as well as the structural geology are needed to assess the likely type, extent and age of the slope movement. It emphasises the importance of extensive engineering geological knowledge required of those who are undertaking natural terrain hazard studies. The injection of a significant amount of additional GI during a hazard study had major financial and time implications, but such geological uncertainties, if not properly addressed, could well have resulted in significant errors in the recommended Design Event and a major over-design.

Figure A9: New tension cracks in Area 1 (with 100 mm vertical displacement)

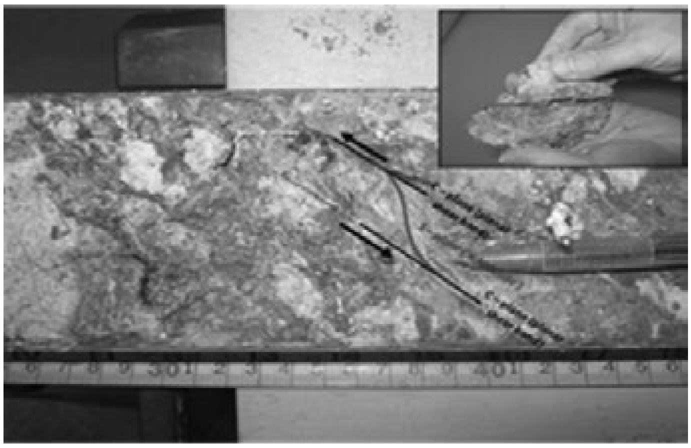

Figure A11: Slip surfaces and soil deformation (S-C fabrics) within a shear zone

Figure A10: Scarp and tension crack in Area 2

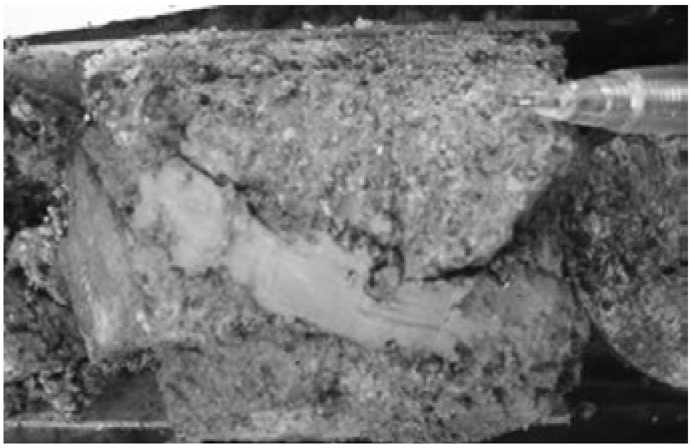

Figure A12: Intensely sheared and deformed kaolin infilling a relict joint