Assessment of natural terrain landslide risk in Hong Kong: An engineering geological perspective

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Abstract: The Geotechnical Control Office, now the Geotechnical Engineering Office, was established in 1977 following a series of fatal landslides. Since its establishment, the Office has made major improvements to the safety of man-made slopes in Hong Kong. By 2010, the overall landslide risk associated with man-made slopes will be less than 25% of the level that existed in 1977 (Wong *et al*., 2004). However, given Hong Kong's rugged topography and limited land for development, an increasing number of projects are now encroaching into areas of steep natural terrain which, combined with high seasonal rainfall, has resulted in increased risk from natural terrain landslides.

This paper outlines the engineering geological input to the assessment of natural terrain landslide risk in Hong Kong, including the use of landslide inventories, landslide susceptibility analysis, consideration of entrainment and depositional rates, and landslide magnitude and frequency assessment. The paper emphasises the establishment of applicable engineering geological and geomorphological models, in particular hazard models, as the basic framework in which landslide hazard and subsequent risk assessment is undertaken.

Résumé: Le Bureau de Contrôle Géotechnique, désormais nommé le Bureau de Génie Géotechnique, fut établi en 1977 suite à une séries de glissements de terrains mortels. Depuis son ouverture, le Bureau a contribué à améliorer la sécurité des pentes anthropiques à Hong Kong. D'ici 2010, il est prévu que le risque général associé aux pentes anthropiques devraient être de 25% inférieur à celui de 1977 (Wong *et al*., 2004). Cependant, vue la topographie accidentée ainsi que l'espace limité pour le développement de nouveaux terrains à Hong Kong, un nombre croissant de projets envahissent désormais des territories à pentes naturelles abruptes. Conjugué à de fortes précipitations saisonnières, ceci entraîne une hausse des risques d'incidence de glissement de terrain.

Cet article rend compte des contributions en génie géologique en vue de l'évaluation des risques de glissement de terrain dans le contexte de Hong Kong, incluant: un inventaire des incidences de glissements de terrains, une analyse de susceptibilité des pentes, une prise en compte de l'embarquement et des taux d'accumulation, ainsi qu'une évaluation de la fréquence et de la magnitude des glissements. L'article met l'accent sur l'application des modèles de génie géologique et de géomorphologie, et en particulier des modèles de risque, comme cadre conceptuel permettant l'évaluation subséquente des risques d'incidence de glissements.

Keywords: engineering geological maps, geological hazards, geomorphology, landslides, risk assessments.

INTRODUCTION

Natural terrain, as defined in Hong Kong, is terrain that has not been substantially modified by human activities but includes areas where grazing, hill fires and deforestation may have occurred (Ng *et al*., 2003). Natural terrain landslides have caused fatalities, injuries and economic losses in Hong Kong (Wong, Ko & Hui, 2004), primarily because of the close proximity of dense urban development and steep hillslopes. A comprehensive review and evaluation of natural terrain risk is currently being planned for Hong Kong. As a result, Natural Terrain Hazard Studies (NTHS) are an increasing component of the work of geotechnical assessments in Hong Kong.

Unlike many regions in the world where landslide assessments are carried out on regional scales, the majority of Hong Kong's NTHS are often catchment or facility specific. Whilst guidelines exist for the range of data to be documented during a NTHS study in Hong Kong (Ng *et al*., 2003), there is only limited guidance (GEO, 2004) on the framework for obtaining and analysing these data. This paper outlines possible approaches to the assessment of natural terrain landslide hazard as the foundation on which any risk assessment in Hong Kong must be based from an engineering geological perspective.

INITIAL GEOLOGICAL HAZARD MODELS

One of the most common problems with natural terrain hazard studies in Hong Kong is a lack of focus in the early stages of the study. Studies commonly generate a wide variety of data that are presented with little or no analysis, partly because the volume of data, which can be considerable, makes analysis problematic unless it is organised within a framework. One way to generate such a framework is to use geological models that reflect both the landforms being studied and the location and types of landsliding. These enable targeted investigation to test and refine the models, which is especially important given the often-restricted access over much of Hong Kong's natural landscape as a result of the dense sub-tropical vegetation.

Although natural terrain hazards arise through complex geomorphological processes, they can be identified and assessed using engineering geological methods and knowledge. For a natural terrain hazard study, a geological hazard model should be developed that identifies likely geomorphological and geological controls on the location, type, magnitude, frequency and runout characteristics of the hazards concerned. This information then allows a rational and focused assessment of the potential hazard.

The geological hazard models for natural terrain hazard assessments in Hong Kong are typically based on two distinct components:

- mapping terrain characteristics and interpreting how the landscape at a site has evolved; and
- evaluating the natural terrain hazards that have occurred in the past.

These two components are undertaken in Hong Kong through engineering geological/geomorphological mapping and the compilation of a landslide database for the site.

Mapping

Geomorphological and engineering geological maps are complementary to each other and natural terrain hazard assessments require a combination of both approaches in order to assess the nature, magnitude and frequency of the various hazard types. Some practitioners consider that while engineering geological mapping is concerned with the properties of materials and their immediate or short-term engineering implication, geomorphological mapping takes in a greater sweep of time, combining the recent geological past with the present geomorphology and its foreseeable future (Hearn, 2002). Integration of the two approaches combines the short-term static with the longer dynamism of the landscape (Hearn, 2002) allowing the development of a comprehensive geological model with respect to natural terrain hazards.

Information about spatial variations in morphology and material allows the interpretation of past and present processes and relative ages of the landscape. Consequently, geomorphological mapping is the key to understanding the evolution of the landscape and the likely hazards associated with its present day form. In Hong Kong, this is undertaken by detailed aerial photograph interpretation (API), followed by field mapping, to place the site in the context of its regional geological and geomorphological setting. By placing the site and its surroundings in a framework that integrates form, materials, process and age, geomorphological maps help the practitioner assess the influence of such factors as lithology, structure, materials and processes on past landform development, and hence facilitate the analysis of future behaviour. To encourage its application in Hong Kong, general guidance has been provided on the range of geomorphological mapping that has been shown to be beneficial to NTHS (GEO, 2004). These are broadly based on Anon (1982) and comprise morphological, morphographical, morphogenetic and morphochronological approaches.

Morphological (form) mapping has been applied to various natural terrain sites in Hong Kong regardless of lithology, elevation and geomorphological history. It serves as a basic framework for subdividing terrain into appropriate catchments, units, and land-elements at breaks in slope. The more subtle level of morphological mapping is the core component in an interpretation of hillslope materials, past processes and relative ages. It can help identify areas susceptible to landslide, types of landslide hazard, and the possible extent of debris run-out. Particular attention should be given to identifying breaks in slope associated with active or potential erosion. An example of this is shown in Figure 1 where a major break in slope was associated with ongoing erosion, including landsliding (HCL, 2003).

Morphographical (materials) mapping has mainly been used in Hong Kong in terms of regolith mapping. A regolith map provides a comprehensive body of information that can include formative processes, topographical location and material properties Regolith mapping has been most successful where there are lithological variations and significant elevation differences within the study area, resulting in a range of processes, and hence regolith types. Site-specific regolith classes and guidance notes have been developed for some individual studies (Parry, Massey & Williamson, 2002). Regolith units are typically based on a combination of topographical position, morphology, material type, vegetation cover and relative age. Figure 2 shows the identification of the regolith unit "Rock Fall Debris" (Talus) (MFJV, 2002). Morphographical mapping has been found to be of maximum benefit when used in conjunction with morphological mapping. However, regolith has proved insufficiently diverse at some sites to be of key importance in the subsequent analysis.

Morphogenetic (process) mapping is of most use where the landscape has been affected by different processes of erosion and deposition, e.g. active regression of a drainage line, river undercutting, etc. The advantage of this approach is that it can be applied early on in an assessment as a reconnaissance tool to help focus the investigation. Figure 3 shows a morphogenetic map for Luk Keng (OAP, 2004). As with morphographical mapping, this approach is best used in combination with morphological mapping.

Morphochronological (age) mapping is useful if a relative age relationship between landforms is discernible through aerial photograph interpretation, or if the absolute age of various surface features can be determined. Significant climatic variations during the Quaternary have influenced the rates of hillslope processes such as weathering, erosion and landsliding. Of particular importance in Hong Kong were episodic changes in sea level promoting fluvial downcutting during low sea level stands. These resulted in pulses of landscape change, or "waves of aggression" (Brunsden, 2002), that started in the lower reaches of a drainage line and proceeded upslope over time. As these changes acted on varied hillslope material, including both bedrock and regolith, responses have commonly been complex and site specific. This has resulted in spatial variations in slope gradients, depth of weathering, morphological features, etc., which can be interpreted with knowledge of landscape evolution and geomorphology.

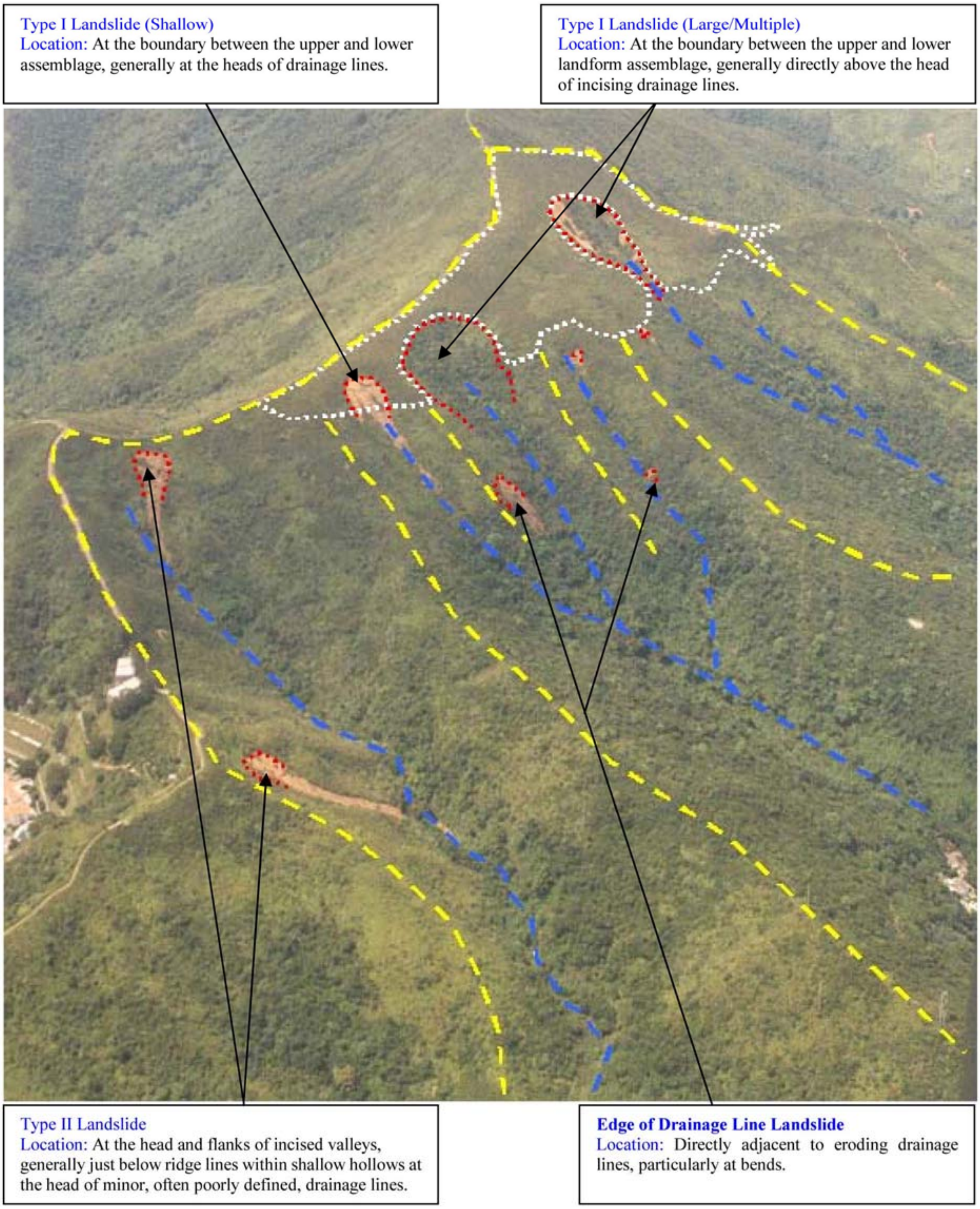
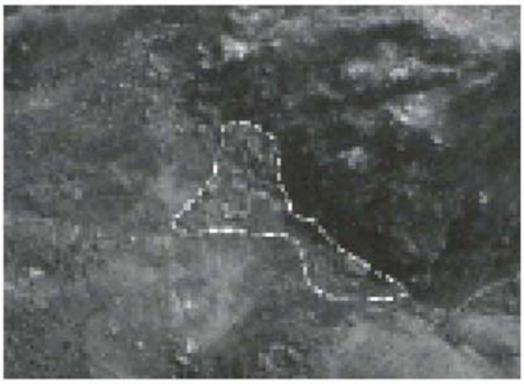


Figure 1. Major Break in Slope Associated with Landsliding (HCL, 2003)

Where hillslopes and main drainage lines are directly adjacent, their coupling promotes undercutting and onward transmission of the change. Where there is a barrier between the stream and the hillslope, such as a cliff or floodplain, the change is delayed. An understanding of such time-dependent variations in landscape can help to interpret zones of relative hazard activity. A useful example is the evolutionary model of the Hong Kong landscape developed by Hansen (1984). He used relative ages to divide the Hong Kong landscape broadly into two-component landform assemblages with differing associated process activity. It has been useful for some studies, but will not be directly applicable on a site-specific scale for every location.

Dating techniques can provide more precise age information than geomorphological interpretation. Sewell and Campbell (2005) have demonstrated the value of a suite of techniques for dating natural terrain landslides and rock surfaces in Hong Kong, where suitable material is available and care is taken in sample selection. Their results suggest some large relict landslides are a thousand to tens of thousands of years old, and therefore may have occurred under different environmental conditions than Hong Kong presently experiences. However, the time-constraints of most engineering programmes limits the use of dating techniques.

In summary, a combination of approaches to geomorphological mapping should be considered when assessing natural terrain hazards. These combinations will vary depending upon the lithology, variation in elevation, size of the study area and its geomorphological history. The practical result of considering form, material, age and process is often threefold (Figure 4). Firstly, desk study information is used to generate a preliminary geological model. This is upgraded into a detailed geological model by incorporating field evidence and ground investigation results etc. Finally, the results are summarised for decision-making purposes into a natural terrain hazard map that expresses the nature, frequency and location of potentially hazardous hillslope processes.



1963 Aerial Photograph

2000 Aerial Photograph

Oblique Aerial Photograph

Regolith Type	Crf (Rock Fall Debris - Talus)
General description	Forms below rock slopes/escarpments either as a result of individual rock block failures or rock avalanches. The size of the rock blocks generally depends upon joint characteristics (e.g. spacing and orientation).
Topographical position	**Must occur down-slope of rock outcrops.** Commonly can form on planar (unconfined) slopes. Rock fall deposits can commonly be confined by topographic depressions e.g. gullies/ ephemeral drainage lines.
Morphology	Concave break in slope usually occurs at the toe of the deposit. Can commonly be fan-shaped, becoming more linear on steeper slope angles. Can form a planar surface, which locally appears hummocky/irregular. Individual boulders commonly apparent. Occasionally incised/truncated by recent landslides or drainage lines.
Material Properties	**Must be clastic debris comprising angular boulders and cobbles with fine material either not present or present in minor amounts**. The size of the blocks is dependent upon both joint spacing and the degree of comminution that the blocks suffer in transport.
Vegetation	Can be bare on steep slopes, but commonly vegetated by both ferns and grasses if topographically confined.
Relative Age	Relatively recent (Category A).
Aerial Photograph Characteristics	
1963	Appears as a hummocky/irregular surface with boulders commonly apparent.
2000	Commonly vegetated with tall grasses; larger boulders can be apparent protruding above the vegetation.

Figure 2. An Example of Regolith Mapping Guide (MFJV, 2002)

Landslide Inventory Assessment

The second major component of a geological model for NTHS is the collection and subsequent assessment of site-specific data for the evaluation of magnitude and frequency of the hazards being assessed. The data, derived from API with field checking, should consider hazard location, possible mechanisms, source dimensions and debris path morphology. This allows the examination of the influence of terrain characteristics on the generation of natural hazards and aids the selection of locations for field inspection and ground investigation.

In Hong Kong, landslides are classified as "recent" if the landslide is bare of vegetation in the relevant aerial photograph, or "relict", where the landslide is vegetated in the relevant aerial photograph. Aerial photographs of Hong Kong date back to 1924, but the first virtually territory-wide coverage dates from 1963, and this dataset is often used as a baseline given its clarity, scale (1:5 400 to 1:7 800) and the low vegetation cover at that time. In addition, annual high-level aerial photograph coverage has been available since 1978 (1:20 000–1:25 000).

A territory-wide inventory of landslides already exists for Hong Kong (Evans, Huang & King, 1997). This database was compiled using high-level aerial photographs. However, in a recent pilot study, a comparison of the territory-wide dataset with detailed site specific API using both low level and high-level photographs noted that approximately 30% of recent landslides and 55% of relict landslides in the area examined had been misclassified. The study also identified relict landslides and recent landslide incidents not in the inventory, resulting in an increase of 150% in relict landslide and 300% in recent landslides. These results confirm the findings of other studies that compared the territory-wide inventory with those developed from site specific API (Pinches, Smallwood & Hardingham, 2002, Parry & Wong 2002) and which concluded that the use of low-level photographs is crucial for site-specific evaluations.

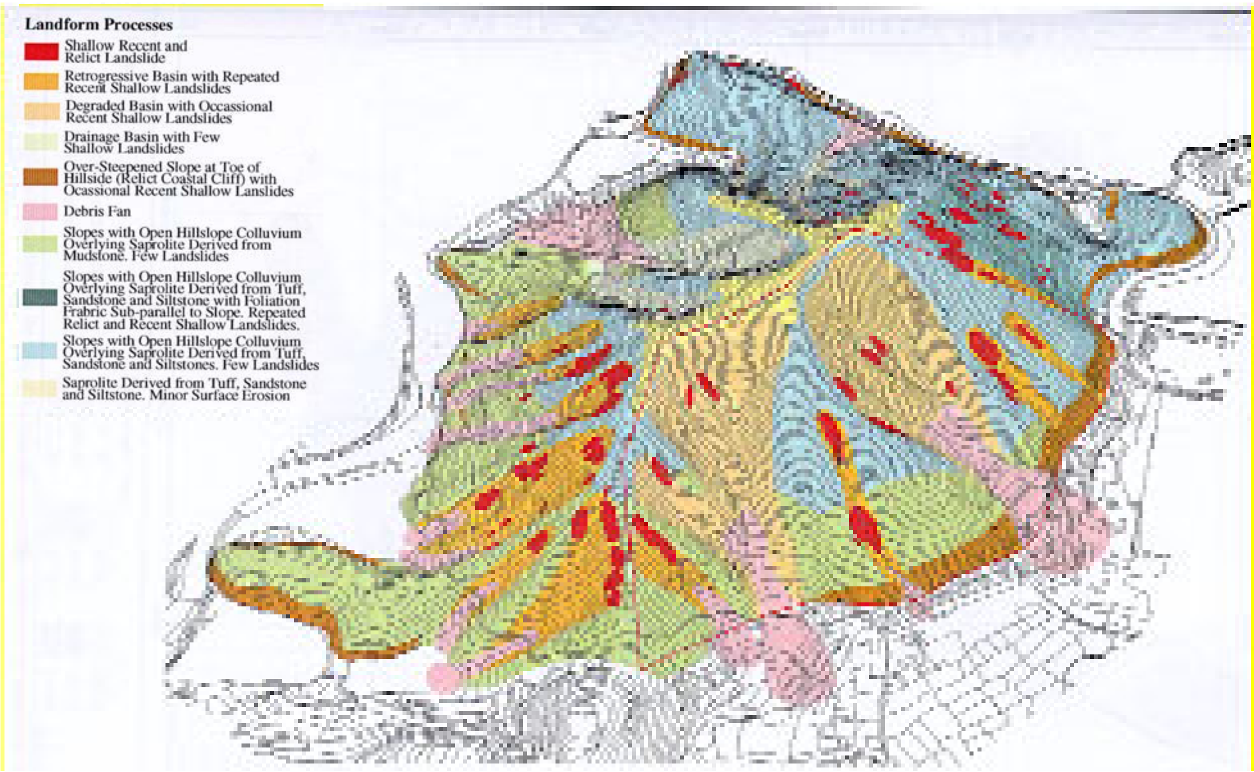
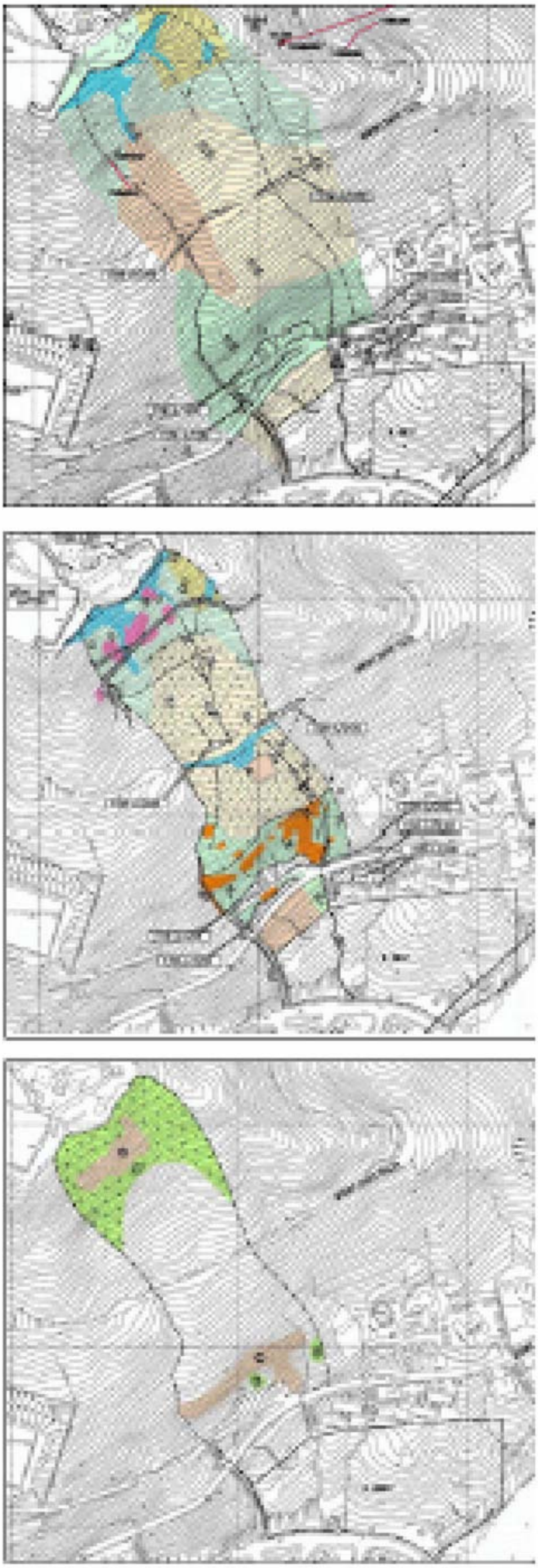


Figure 3. Morphogenetic map for Luk Keng (OAP, 2004)

Whilst the source areas of recent landslides are relatively easy to identify from API, a notable difficulty is determining the length of recent debris trails, especially channelised debris flows, as subsequent fluvial processes commonly result in areas of high reflectance extending well beyond the toe of the landslide debris. In addition, the appearance of the trail can change rapidly through vegetation regrowth. Relict landslides are more problematic and require careful judgement as landslide scars progressively lose their morphological definition, at rates depending on factors such as vegetation, landslide size, material and location, and debris is rarely evident due to erosion or vegetation growth.

The certainty with which each individual feature can be interpreted and identified as a landslide will vary depending upon on a number of factors including:

- Original source volumes: Larger failure scars tend to be preserved longer in the landscape. Sewell and Campbell (2004) reported that the upper bound age for the relict landslides they examined was approximately 46,000 years BP. With respect to a lower bound age, Evans *et al*. (1997) suggested that a landslide source would typically be 90% re-vegetated after 20 years.
- The presence of debris below a scarp: This is the clearest evidence that a landslide has occurred. However, unless the landslide is relatively large, or the debris is deposited as levees outside the drainage line, fluvial erosion commonly results in the removal/reworking of the debris with time.
- The sharpness of the scarp: Landslide scarps tend to degrade with time although this may be affected by subsequent minor failures of the over-steepened scarp area.
- The position of the depression within the landscape: Landslides are commonly interpreted as such when a depression is inconsistent with the adjacent landform.



Preliminary Geological Model

- Desk study information, particularly a detailed API, permits a preliminary classification of the site in terms of morphology, material (lithology and regolith), human activity, previous evidence of hazard, etc.
- This includes looking beyond the site boundary to ensure the setting of the site has been adequately considered.
- The preliminary ideas of terrain characteristics and hazard are used to direct the field work and indicate useful ground investigation locations.

Detailed Engineering Geological Model

- An amended and more detailed model of materials, morphology, history and process is generated after fieldwork and ground investigation.
- In the presented case, increased details included amended distribution and classification of regolith and lithology, slope gradients, seepage zones and human activity.
- The information in the detailed engineering geological model permits identification of areas with different potential hazard models.

Potential Natural Terrain Hazards

- Areas susceptible to potential hazard are identified. The areas and potential hazards can be rationally evaluated using desk study, field and ground investigation information.
- The detailed nature of each hazard becomes the input information for any subsequent hazard assessment if a risk has been identified.
- In the presented case, the upper slope offered no risk given its distance from the facility. Detailed analysis of the lower slope also indicated no risk to the facility.

Figure 4: Progressive Development of Geological Models of Natural Terrain Hazard (Fugro, 2002)

In a recent study, relict landslides were subdivided into three classes based on API alone. The classification was based on the presence or absence of specific morphological characteristics of the features in addition to their locations within the landscape. These comprise:

- Class A relict features have identifiable characteristics that provide a high degree of confidence for interpreting the feature as a landslide. These include identifiable debris lobes or levees that can be clearly related to the source area and/or a source area scarp that is predominantly sharp.
- Class B relict features have characteristics that allow interpretation of the features as a landslide with a reasonable rather than high degree of confidence. If debris is present, it is obscured by vegetation or is difficult to interpret positively from API due to degradation of the feature's morphology. The presence of a predominantly rounded main scarp, surrounding a depression that is inconsistent with the adjacent slope morphology would be readily classified as a Class B relict feature.
- Class C relict features are those that have a degree of uncertainty that the feature is a landslide. These typically comprise two types of features:
    a) Depressions located close to, or at heads of, drainage lines. Such features could have formed from the prolonged degradation of a landslide source, but are presently occupied by a drainage line. A supportive reason for inclusion is the relative high susceptibility associated with these features (Ruse, *et al*., 2002, Parry *et al*, 2002, HCL, 2003); even if there is lower confidence that the feature was a landslide rather than simply the expansion of a drainage line source, this class provides useful susceptibility indicators.
    b) Broad depressions outside drainage lines. While no landslide scarp is evident, the depression is typically relatively flat and is demarcated by a change in slope gradient. The absence of fluvial activity permits interpretation as possible degraded landslides.

Once the initial data have been generated, they should be improved where possible during field inspections. Such work is essential to clarify the nature and extent of reported features and to include features not visible from the API. For example, in a recent large-scale study, observations during fieldwork resulted in an additional 93 relict landslides (for an original dataset of 320 identified by API (Parry *et al*., 2002)). This is particularly important where complete detachment of the landslide does not occur, as these landslides exhibit only relatively small main scarps that are difficult to distinguish from API. However, "walk-over" site inspections in Hong Kong vary from difficult to impossible, depending on the terrain and vegetation cover, and hence there remains considerable reliance on API to identify targets for specific site observations.

Initial Geological Hazard Model

Geological hazard models can be developed from the initial assessment of the landslide data, providing a framework that locates site-specific hazards within their geological and geomorphological setting. Such a model:

- simplifies the often-complex information and patterns that may be evident at a site;
- encourages the crucial step of predicting areas of potential hazards; and
- allows the classification of the site by terrain units based on both geomorphology and the level and type of hazard it contains.

HAZARD ASSESSMENT

The hazard model approach requires detailed field observation to test and improve on the initial hazard models derived from desk study. It focuses effort on the hazards that are of greater concern and that require detailed assessment. It also encourages the application of site-specific geomorphological information to the hazard analysis.

The simplest approach to gathering this information is by mapping previous failures. Site-specific examples of hazard are extremely valuable in providing evidence of past initiation and debris runout behaviour. These examples can be used to establish specific models for the location, size, failure type and mobility mechanisms of potential failures, based on the terrain units determined in the geological model. These hazard models are the input to the subsequent stage, i.e. establishing appropriate design models for mitigation design.

A longitudinal section of the landslide scar, with suitable cross sections, is also useful for recording morphological details of the debris trail. Knowledge from a large number of events that have been mapped in detail of the active volume, velocity, channel morphology, substrate and degree of entrainment/deposition, can facilitate the development of runout and entrainability models that can assist in the assessment of future debris flow hazards.

By detailed field mapping of landslide sources, factors that control landslide initiation can be identified (e.g. Ruse *et al*., 2002), which in turn help in predicting potential landslides and provide data for the subsequent design models.

Key initiation factors for natural terrain landslides in Hong Kong include:

- hydrogeological boundaries – material differences that promote elevation of transient pore water pressures;
- geological influences – these are important for many types of hazard, but particularly for rock falls/avalanches and deep-seated landslides;
- topographical factors - concentration of water at hillslope concavities, heads of drainage lines, immediately below rock outcrop, and at or close to convex breaks in slope;

- slope deterioration - tension cracks, dilated and infilled joints, and development of slickensides within discontinuities can be diagnostic of slope deterioration (although they may also be related to general weathering); and
- human influences - water discharge from developments, leakage of water-carrying services and possibly the promotion of infiltration and rapid runoff by vegetation changes.

Careful mapping of landslide debris also helps to identify different phases of landsliding and therefore the estimation of realistic design volumes for mitigation works. Such mapping needs to take into account factors such as subsequent retrogression at the landslide scarp or undercutting in the trail which may cause secondary pulses of debris during the triggering rainstorm or a later rainstorm. The temporary formation and subsequent break of a dam of landslide debris can increase debris mobility and hence runout distance (HCL, 2001). However, the hazard may be dominated by fluvial processes. The apparent trail length may be exaggerated if post-failure washout debris is not correctly identified by field mapping.

Debris runout broadly increases with landslide source volume, giving greater travel distances and lower angles of reach (Corominas, 1996; Wong, Chen & Lam, 1996). A fundamental control is whether the debris enters a confining drainage line, where increased fluidity encourages debris transportation. Furthermore, large channelised debris flows in Hong Kong (Figure 5) have developed upon entrainment of additional material within the debris trail (e.g. King, 2001; MGS, 2004). Entrainment may be a critical issue in the assessment of hazard where:

- the source volume is large;
- topography is steep enough to increase debris velocity and hence erosive power; and
- readily entrainable material is present within the travel path.

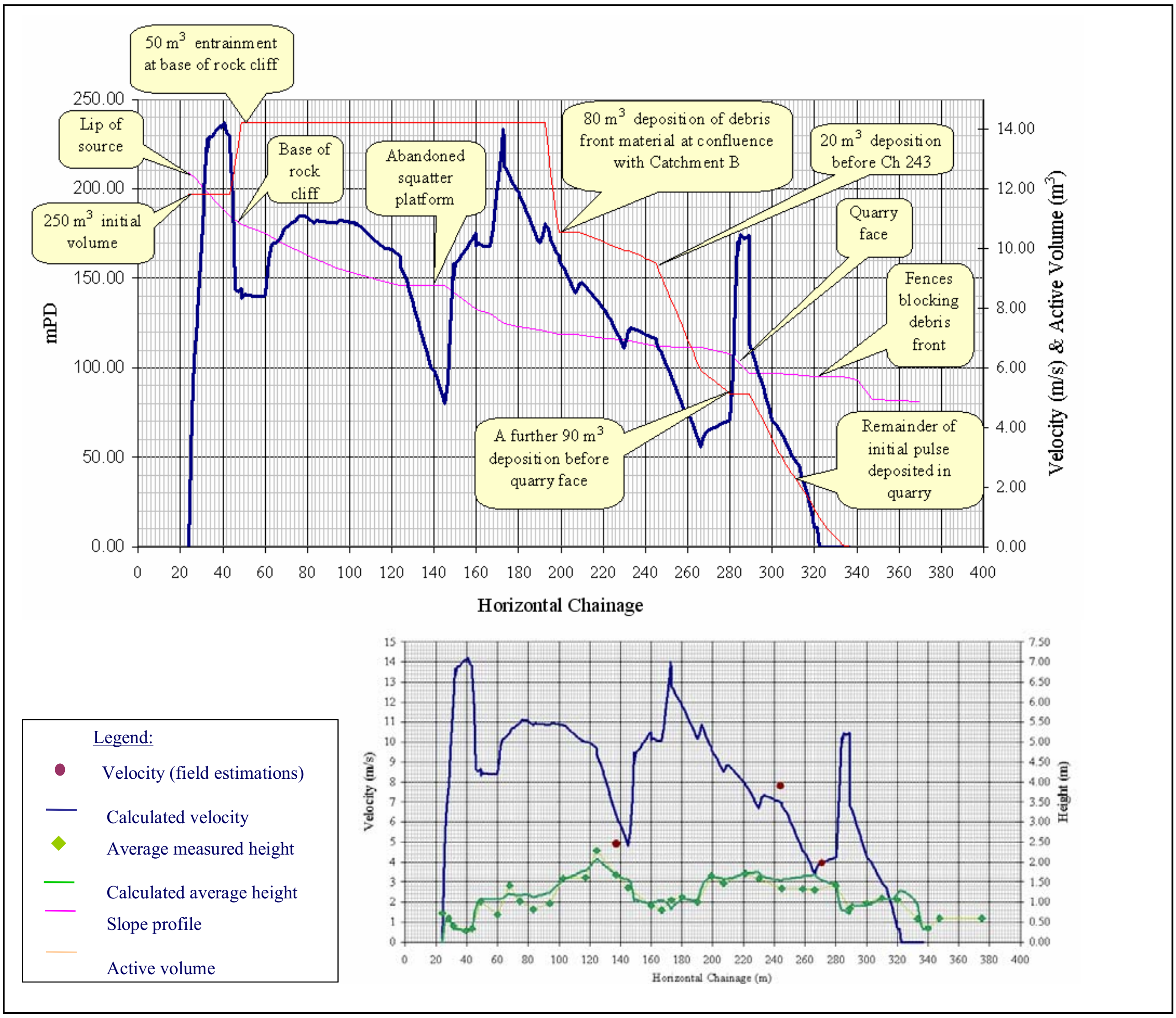


Figure 5. Modelling of a large channelised debris flow with significant entrainment (MGS, 2004)

A major purpose of engineering geological mapping of drainage line morphology and superficial deposits is to identify the potential for entrainment. Colluvium can be entrained in large volumes from thick lobes and extensive fans, if a channelised debris flow impacts the material with enough energy, such as when a landslide occurs in saprolite above a steep cliff at the base of which colluvial debris is present (King, 2001, MGS, 2004). Consequently, the geomorphological setting is a key consideration. However, for small, more typical Hong Kong landslides entrainment is limited.

Where recent examples of each hazard type are not available for a site, it might be possible to apply empirical evidence from adjacent sites or generalised parameters from further afield. However, this requires careful judgement and consideration as to how appropriate the data will be to the specific site, and in particular to its geological and geomorphological characteristics.

DETERMINATION OF THE DESIGN EVENT

The main outcomes of a natural terrain hazard assessment for a given facility are:

- establishment of reliable design events for each identified hazard model;
- an indication of the frequency of such hazards;
- the likelihood of such hazards affecting the facilities in question; and
- determination, and where appropriate, cost/benefit analysis, of mitigation options.

The identification of a suitable design event requires sound engineering geological judgement. The results of hazard assessments can be very sensitive to change in the selected variables (potential volume, distance between source and facility, rates of deposition and entrainment, etc.). The key value of utilising an engineering geological approach at this stage is to ensure the design event is consistent with the information derived from the geological models. Allowing ongoing feedback between the gathering and analysis of geological data promotes the development of rational hazard analysis, possibly allowing a reduction in the design events with associated savings in cost. The following sections describe the main steps taken in the process of determining the design event. This describes where and what the potential hazard is (susceptibility), how often it will occur and how large it is at the source (magnitude/frequency analysis), and what quality and quantity of material can be expected to reach the facility (mobility analysis).

Susceptibility Analysis

Susceptibility is the propensity of a site to produce hazards at locations of interest. Some analyses compare susceptibility against an amalgam of simple factors on a purely statistical approach, comparing regional landslide information with generic spatial data such as slope gradient and rock type (e.g. Evans and King, 1998; Dai and Lee, 2001). Whilst such factors can be useful indicators of potential hazard for planning purposes, they may be of insufficient resolution for application to site-specific risk management (Ho, 2004).

A significant improvement arises in the prediction of hazard behaviour, at area-study scale (ca. 1:5 000) or greater, when susceptibility factors are chosen for their causative relationship with geological and ground models. For example, in a recent susceptibility analysis in Hong Kong, detailed mapping provided information on landslide initiation factors, regolith and rock outcrop distribution, locations of heads of drainage lines, and lithological boundaries (Parry *et al*, 2002).

However, not all hazard initiation factors can be applied to susceptibility analyses; for example, hydrogeological boundaries, which are often key controls on failure, cannot be readily mapped. Of 47 initiation factors identified by mapping landslide scars in the Tsing Shan Foothills, only three (i.e. lithological boundaries, regolith downslope of rock outcrop and regolith at the head of a drainage line) were found to be relevant for susceptibility analysis, in addition to regolith types and slope gradient (Parry *et al*., 2002).

Magnitude/Frequency Analysis

A hazard assessment needs to determine the size of the potential hazard sources and how frequently hazardous events are likely to occur. To estimate frequency, a simple age relationship of the hazards is commonly assumed, such as the 100-year period for all relict and recent landslides used by Evans and King (1998). However, given the difficulties of assigning ages to a landslide database and the great range of landslide ages (Sewell and Campbell, 2004), this process requires considerable care.

Engineering geological input to the construction of magnitude/cumulative frequency (MCF) relationships should ensure that the MCF relationships reflect the findings of the ground model. The approach can provide a false sense of precision if the period selected to represent the hazard data is inappropriate, if the data are insufficient, or if they are taken from a significantly different location (Wong, Lam & Ho, 1998; MFJV, 2003; OAP, 2005). Furthermore, the hazard inventory can have significant problems in over-representing younger and larger landslides compared with the smaller and older features that are less readily observed (Hungr, 2002). Given the uncertainty in ages of relict landslides evident in the landscape, a range of ages can be applied to the MCF graphs, or composite graphs by assuming differing ages for differing volumes of landslide scars (MFJV, 2003).

Mobility Analysis

Having determined the location of various sources of design events within the landscape, mobility analysis aims to derive estimations of the volume and velocity of the potential debris reaching the facility in question. This can be either empirical or analytical. The main contributions of engineering geology to both approaches are:

- in providing useful raw data about landslide debris runout and drainage line characteristics; and
- ensuring appropriate application of such data.

Crucial information required for analytical models of channelised debris flows includes entrainability, size of catchment/stream course, channelisation ratio, debris volume, debris path longitudinal profile, debris height and super-elevation. The failure to distinguish between runout distances of remoulded debris and washout could result in significant errors in the back analysis of the landslide event.

Figure 5, illustrates the importance of field data on debris distribution and drainage line characteristics in an analytical model. This was used to gain insight into the likely sequence of events and mobility of the debris flow for mitigation design.

Determination of Mitigation Options

The nature of the potential hazard should be integrated with the selection of mitigation options beyond the facts of its size and velocity. Knowledge of the terrain is essential in the selection of a practical, cost-effective and environmentally acceptable design. For example, the location of a debris-resisting barrier should take advantage of the topographical characteristics of the terrain and an area of entrainable material may warrant in-situ stabilisation where more-general application across an extensive portion of hillslope might be costly and hard to implement. Debris floods are better accommodated by simple drainage provision rather than a costly active mitigation facility.

CONCLUSIONS

The derivation and application of geological information and models is critical to the development of a cost effective, efficient and environmentally acceptable methodology of assessing and mitigating landslide risk in Hong Kong. Whilst Hong Kong has made clear advances in the use of QRA in the assessment of landslide risk, its application is reliant on a careful assessment of:

- the likely type of hazard,
- the likely location of such hazards,
- the volume of the hazards (both the initial volume and the potential for entrainment) and,
- the likely frequency of such events.

All of these assessments require an intimate understanding of the geology and geomorphology of the site within the Hong Kong context, i.e. considerable engineering geological skills.

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