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Abstract

This paper presents a case study of the application of quantitative risk assessment techniques to a site-specific natural terrain hazard study in Hong Kong. The development of the landslide hazard and susceptibility models is described and salient details of the consequence model are given, including the assessment of debris flowpaths and runout using state-of-the-art Geographic Information System (GIS) tools and debris runout computer models. A synthesis of the risk quantification process and schematic design of risk mitigation works is presented.

Introduction

The geotechnical profession in Hong Kong has pioneered the use of formal quantitative risk assessment (QRA) techniques to assist in the management of natural terrain landslide hazards posed to the dense urban developments on steep hillsides. QRA has proved to be a practical and useful tool for landslide risk management, and it provides a rational and structured framework for assessing the key attributes relating to the probability and consequence of landslides.

This paper presents a case study of the use of QRA in a site-specific hazard study of a natural hillside catchment overlooking two existing high-rise residential blocks in the Mid-levels area of Hong Kong. Signs of deterioration and recent minor movements were identified on the hillside. As a result, a natural terrain hazard study was undertaken to evaluate the landslide risk and assess the need for risk mitigation.

The Site

Topography. The 50-hectare catchment is located on a steep, north-facing hillside overlooking the urbanized Mid-levels area on Hong Kong Island. The fall in elevation from the upper reaches (at around 500 mPD) is more than 300 m. The catchment is defined laterally by spur ridges on the eastern and western flanks that are convergent in the upper reaches with a maximum width of some 180 m, about 60 m above the northern boundary where the high-rise apartment blocks and a road traverse the hillside at approximately 180 mPD. A section through the site is shown in Figure 1.

The catchment is inclined at angles of about 40^o to 45^o in the upper reaches, flattening to between 25^o and 35^o in the lower portions, with the transition at a line of rock cliffs (about 10 m height) that area located at about 340 mPD.

A digital elevation model (DEM) was developed for the catchment using the published 1:1,000 scale digital topographic maps. This was supplemented by site-specific terrestrial survey, which was found to be imperative in achieving the necessary level of detail for the geometry of drainage lines and hillside depressions, together with localised, sharp changes in topography, which could significantly affect debris flowpaths and runout.

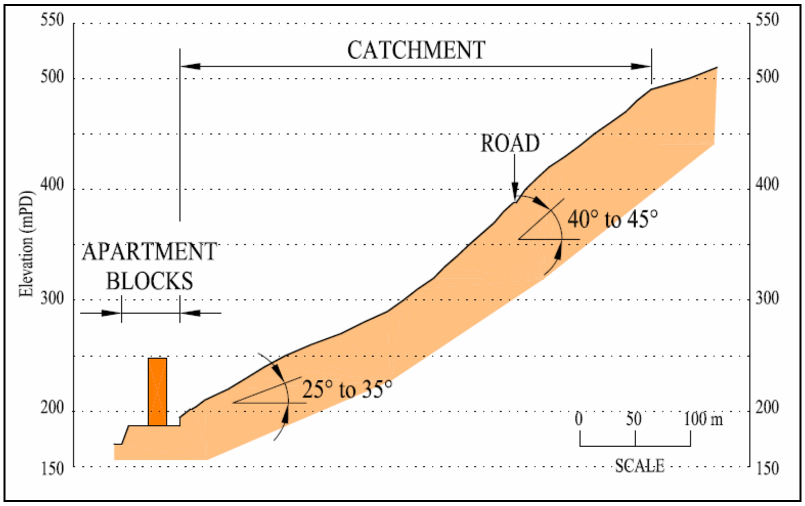

Figure 1. Section through catchment.

Geology and Geomorphology. The local geology, as confirmed by a ground investigation, comprises superficial deposits of colluvium (about 20 m maximum thickness) that cover the majority of the site, overlying an insitu weathering profile of fine ash vitric tuff (about 30 m maximum thickness). The saprolite (about 5 m to 10 m maximum thickness), together with occasional rock outcrops, predominates in the area above the rock cliffs.

Two classes of colluvium were identified, comprising an older deposit which consists of more weathered materials with clasts that have weathered following deposition, and a younger colluvium that is less weathered and contains a higher proportion of coarse clasts and boulders. The younger unit typically forms elongate lobate features within the central portion of the catchment. Rockfall debris, typically comprising >80% of large angular boulders probably sourced from the rock cliffs, is located in the central western and lower eastern portions of the catchment.

The geomorphology of the subject catchment is different to that of the adjacent hillsides in that it is flanked by divergent spur ridges containing poorly defined drainage lines, as contrasted with the well-defined, convergent drainage lines in the adjacent catchments.

Hydrology & Hydrogeology. The hydrology and hydrogeology of the catchment reflect complex geology and geomorphology. In broad terms, the hydrological/ hydrogeological model comprises a transient surface flow over and shallow subsurface flow through the colluvium, together with a base groundwater level generally located at depth but with piezometric responses indicating a potential to rise sharply (by some 4 to 5 m) following heavy rainfall.

Historical Landslides. A number of historical landslides were identified within the catchment (Figure 2), the most notable of which comprised two large landslides that occurred in 1966, with estimated source volumes of 1,500 m^3 (upper scar) and 500 m^3 respectively. The debris from the upper landslide travelled about 120 m before depositing on relatively flatter ground, with further outwash travelling a further 120 m downslope along drainage lines. Debris from the lower landslide travelled about 190 m and reached the building platform now occupied by the high-rise residential blocks.

Vulnerable Facilities. The facilities at risk from natural terrain landslide hazards comprised the two high-rise residential blocks and the associated carpark and driveway, together with a section of the road and pedestrian footpaths in front of the northern catchment boundary (Figure 2).

Hazard Identification and Hazard Model

The engineering geological and geomorphological assessments, based on detailed aerial photograph interpretation, field mapping and ground investigation, identified four principal landslide hazards (Table 1).

Table 1 – Types of Landslide Hazards

I	Shallow retrogressive failures of old colluvium on eastern and western flanks
II	Shallow debris slides from the upper portion of the catchment
III	Rock slides on the rock cliffs in the mid- to upper-portions of the catchment
IV	Deep-seated failures in old colluvium/saprolite

Landslide hazard Types I and III were considered to be more dominant at the site, with Type I posing the highest level of hazard to the toe facilities due to the possibility of channelisation of landslide debris and potential increase in debris mobility.

The inventory of recent and relict natural terrain landslides identified within the catchment suggested an upper bound volume of around 4000 m^3 for the past landslides. Assessment of landslide frequencies for future events was based on four debris volume classes covering the historical range, namely H1a (10 m^3 to 200 m^3), H2a (200 m^3 to 800 m^3), H2b (800 m^3 to 2000 m^3) and H3a (2000 m^3 to 8000 m^3).

An assessment was made of the natural terrain hazards posed by the individual portions of the catchment in order to generate the landslide hazard model. On the basis of this, the site was divided into five hazard 'zones' (see Table 2 and Figure 3), with each of the zones considered to have within it a similar potential to generate similar magnitude landslides with a similar frequency of occurrence.

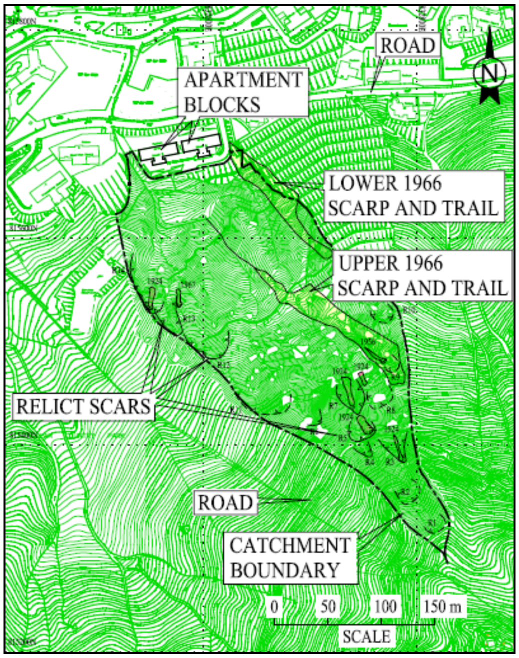

Figure 2. Historical landslide events.

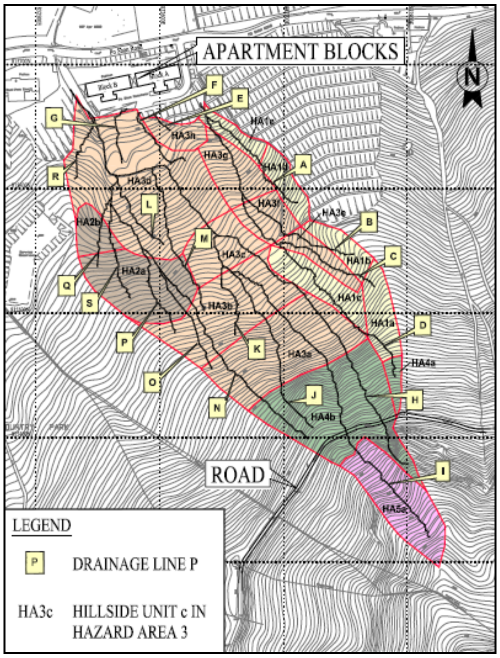

Figure 3. Hazard zones and hillside units.

Table 2 – Landslide Hazard Zones

Hazard Zone HA1	The 1966 landslide scars and associated debris lobe
Hazard Zone HA2	The relict scars situated in the northwest of the catchment
Hazard Zone HA3	The remaining terrain situated below the rock cliffs
Hazard Zone HA4	The rock dominated terrain from 338 mPD to 400 mPD
Hazard Zone HA5	Terrain exposing saprolite from 400 mPD to 500 mPD

These hazard zones were further divided into a total of eighteen smaller 'hillside units' (Figure 4), which are of similar topography, with a similar potential to generate landslides and from which debris originating from any location within the unit probably travelling along a similar runout path.

Assessment of Debris Runout

An assessment was made of the probable runout distances of debris from potential landslides for use in the evaluation of landslide consequence. The objective was to determine the distance by which debris from a given landslide may travel past a given facility and the associated probability. Debris runout paths comprised major drainage lines and hillside depressions as identified from the DEM, and these were matched to the individual hillside units and related to the affected facilities at the toe of the catchment.

Debris mobility modelling was performed using the Debris Mobility Model (DMM) software developed by the Geotechnical Engineering Office (Kwan & Sun, 2006), which is an extension of Hungr's (1995) DAN model. The Voellmy mode was adopted, incorporating a range of rheological parameters derived from the back analyses of natural terrain landslides in Hong Kong. Separate runs were made for different assumed source volumes and the seven sets of rheological parameters as shown in Table 3.

Table 3 – Parameter Sets and Probability Function for Debris Mobility

Set	Apparent Friction Angle ϕ (^{o})	Turbulence Coefficient ξ (m/s^2)	Probability Distribution of Debris Mobility for Landslide Volume Class			
			H1	H2a	H2b	H3a
1	8	500	0%	0%	0%	2%
2	11	500	0%	0%	2%	5%
3	15	1000	0%	3%	5%	13%
4	20	1000	3%	7%	13%	30%
5	25	5000	7%	20%	35%	30%
6	30	5000	45%	35%	35%	10%
7	35	∞	45%	35%	10%	10%

The probability distributions (Table 3) were derived from the analyses of some 60 mobile natural terrain landslides in Hong Kong. These were applied to the runout distances for each of the landslide volume classes in order to determine the relative likelihood of debris with different runout distances.

Risk Quantification

The QRA comprised the integration of the landslide hazard model and the outcome of the susceptibility assessments and consequence assessments in evaluating the risk posed to the population at the vulnerable facilities. The assessments are done on a GIS platform. The results are expressed in terms of individual risk and societal risk.

Landslide Susceptibility Assessment. The approach used in the derivation of the magnitude-frequency models for the hazard zones involved distributing the baseline landslide frequency (established on the basis of whether the hazard zone contained recent or relict landslide scars) across the adopted landslide volume classes using a probabilistic approach (with due account taken of whether the previous landslides occurred as a singular event or multiple events). In the case of Hazard Zone HA3 which contained a single major relict scar but comprised about 53% of the overall surface area of the catchment, the magnitude-frequency relationship was conservatively based on the global natural terrain landslide data for the whole of Hong Kong.

The natural terrain landslide magnitude-frequency model for each of the hazard zones was spatially distributed to the individual hillside units on the basis of surface area and an assigned relative landslide susceptibility factor, which accounts for local topography, geology and geomorphology. The range of the estimated landslide annual frequency across the landslide volume classes considered for the individual hillside units was 10^{-2} to 10^{-6}.

The calculated frequencies of natural terrain landslides from the various hillside units were updated to take account of cases where there was more than one viable runout path (e.g. bifurcation of a drainage line), and more than one viable boundary segment (e.g. broadening of drainage line above the interface between boundary segments at the toe of the hillside). To take account the above, an event tree was constructed in such instances in order to assess the relative likelihood of scenarios following the initiation of a landslide up to the point where landslide debris would cross a particular boundary segment and impact on the facilities at risk.

The various vulnerable facilities were matched to the relevant boundary segments as described earlier for determining the likelihood of a facility being affected in the event of debris from a given hazard crossing a particular boundary segment.

Consequence Assessment. The general form of the adopted consequence model comprised the product of an 'Overall Vulnerability Factor' (OVF) and the average number of vulnerable population in a given facility directly hit by a landslide. The OVF is the probability of fatality when subjected to a given landslide. For the assessment of Individual Risk (see below), the most vulnerable person in a given facility with the longest exposure time was considered.

Vulnerability. The OVF was derived considering specific attributes including landslide volume, location of the facility relative to the range of debris runout distances, and the degree of protection afforded to individuals by the nature of the facilities.

Average Population. The average populations at the vulnerable facilities, expressed as the probability of individuals being present at the facility at any given time (viz. temporal probability), were determined using a combination of site surveys and census data projected using the building plans of the high-rise blocks. Additionally, the exposure of the most vulnerable individual occupying each facility, expressed as the percentage of time this individual would occupy the facility, was assessed.

Building Collapse Scenario. An assessment was made of landslide scenarios that could result in differing degrees of structural collapse of the apartment blocks. The frequency of occurrence of structural collapse was assessed using an event tree approach. The likelihood of collapse of key structural elements was assessed on the basis of the structural capacity of the elements and the estimated loading applied by various debris volumes and impact velocities obtained from probabilistic debris runout modelling.

Risk Quantification.

Individual Risk. The individual Risk (IR) was calculated as the summation of the product of the frequency of a landslide affecting the facility and the vulnerability of the most vulnerable individual occupying the facility for each of the landslide scenarios from the hillside units (i.e. Personal Individual Risk (PIR)). The calculated results indicated that the PIR was generally of the order of 10^{-7} for the road and footpaths fronting the high-rise apartments and also the upper floors of the apartments, and about 10^{-6} for the driveway and carpark. The ground floor of the apartments had the highest PIR of 2.1×10^{-4}, which was due to the high degree of exposure of security guards.

Societal Risk. Societal Risk depicts the overall risk to the affected community and is typically presented in the form of cumulative frequency, F, of N or more fatalities per year on a double logarithmic graph known as an F-N curve. The societal risk can also be presented in terms of Potential Loss of Life (PLL) per year for the facilities, which is calculated by summing up the product of the frequency of a landslide affecting the facility, the vulnerability of the affected population and the average population at the facility, for all landslide events from each of the hillside units.

The calculated total PLL for all facilities was 3.9×10^{-3}. The breakdown of the PLL with respect to the five natural terrain hazard zones (Table 2) indicated that the landslide risk is unevenly distributed and is heavily weighted towards hazard zone HA1, which contributed about 90% of the total PLL. A breakdown of the PLL with respect to landslide volume indicated that about 60% of the PLL is contributed by the H2a volume class (viz. 200 m^3 to 800 m^3), which indicates that the hazard is derived mainly from fairly sizeable events for this catchment. A notable share of the PLL (about 35%) is derived from the ground floor of the high-rise apartment block.

The F-N curve derived following a methodology similar to that outlined by Wong et al (1997) is shown in Figure 4.

Sensitivity Analyses. Sensitivity analyses were carried out by varying the major input parameters according to the level of confidence in the individual assigned values, as well as considering other facilities situated further downslope. The overall effects were found not to impact significantly the above outcome.

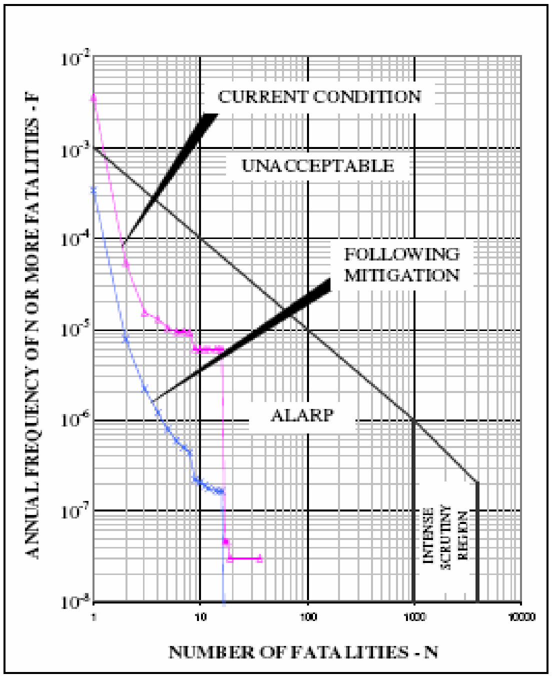

Figure 4. Societal risk expressed as F-N curves.

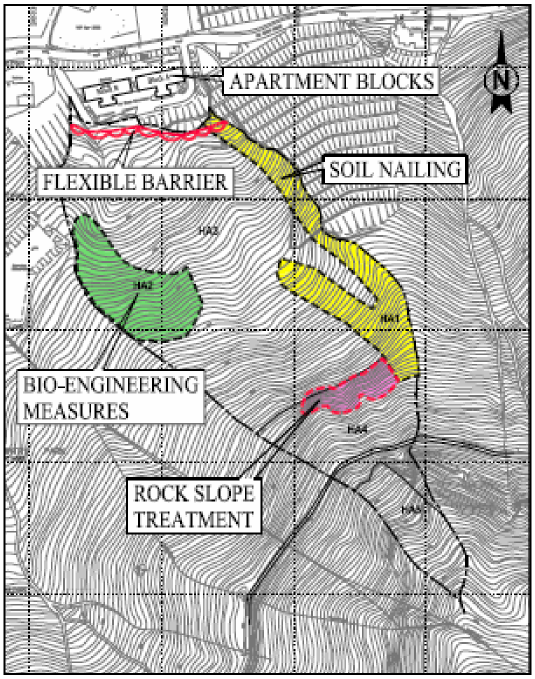

Figure 5. Proposed risk mitigation strategy.

Risk Management Strategy

A comparison of the calculated IR and societal risk with the interim risk acceptance criteria (ERM, 1998) promulgated by the Hong Kong Government for natural terrain landslides indicated that the risk levels exceed the tolerability limits, with the IR exceeding the PIR risk criterion of 10^{-4} per year for existing developments, and the societal risk falling into the 'unacceptable' zone of the F-N curve. Hence, risk mitigation is called for in the interest of public safety.

A hybrid solution comprising preventive and protective measures was adopted. This involved installing soil nails in hazard area HA1, rock slope treatment to the rock cliffs, bio-engineering measures within hazard area HA2, and provision of a prescriptive flexible debris barrier along the toe of the catchment (Figure 5).

The proposed mitigation strategy would reduce the IR to about 2×10^{-5} (i.e. less than the 10^{-4} tolerable limit), and reduce the societal risk such that the entire F-N curve lie within the as low as reasonably practicable (ALARP) region (Figure 4). Cost-benefit analyses accounting for public aversion to multiple fatalities resulting from landslides were carried out to confirm that the proposed scheme was economically justifiable.

Conclusions

It is noteworthy that quantification of landslide risk in itself may not necessarily improve the accuracy and resolution of the assessment. In practice, the reliability of QRA comes with the rigour of the assessment and the use of data, techniques and procedures that are appropriate to the problem at hand. State-of-the-art QRA and GIS tools, together with rigorous geotechnical input and the use of quality data, have been adopted in the study. The QRA results provided sufficiently reliable estimates of landslide risk to support cost-benefit analyses and risk management decisions.

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