An approach for area and site-specific natural terrain hazard and risk assessment, Hong Kong

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ABSTRACT: As development in Hong Kong progressively expands into natural terrain, there have been increasing concerns about the risks posed by natural terrain landslides. The aim of the Natural Terrain Hazard and Risk Area Study described in this paper was to evaluate whether Quantitative Risk Assessment (QRA) methods can be developed for the cost-effective management of risks posed by natural terrain hazards. The study examined the hazards of natural terrain landslides including rock and boulder falls, in two contrasting study areas. Hazard models were developed and the uncertainties documented and quantified where possible. These were combined with hypothetical population and vulnerability models to derive Individual and Societal Risk results for various development scenarios, which were then compared with the Interim Risk Guidelines for natural terrain landslides in Hong Kong. A number of important conclusions are made regarding the use of QRA techniques for evaluating natural terrain hazards and risk.

1 INTRODUCTION

The Natural Terrain Hazard and Risk Area Study was commissioned in 1998 and forms part of an ongoing programme of research into natural terrain landslides by the Geotechnical Engineering Office, Hong Kong SAR Government (Evans et al. 1997). The study was one of the first to attempt Quantitative Risk Assessment (QRA) of hazards from extensive areas of natural terrain in Hong Kong. The areas, at Tung Chung East (TCE), Lantau, and Mount Johnston North (MJN), Ap Lei Chau, were selected for their apparently higher than average incidence of past landslide activity. The two study areas are very different with respect to size and morphology. TCE has over 75 ha of deeply incised natural terrain (Figure 1), while MJN comprises 18 ha of natural terrain with poorly defined catchments (Figure 2).

Stage 1 of the study comprised broad, rapid assessments of the natural terrain hazards within each study area using desk study, aerial photograph interpretation and site reconnaissance techniques. Approaches were developed for QRA at this broad scale and evaluated using hypothetical development and population scenarios to see whether realistic levels of hazard and risk could be determined (Halcrow 1999a).

Stage 2 comprised detailed 'site-specific' assessment of natural terrain hazards affecting three hypothetical development scenarios located within the two study areas, using site mapping and ground investigation techniques. The hypothetical developments considered included a 3-storey house, a multi-block mass housing development and a major road. Building on the Stage 1 "area" methodology, an approach was developed for site-specific QRA and evaluated to determine appropriate levels of mitigation for each development scenario (Halcrow 1999b). During Stage 2 the cost-effectiveness of increasing levels of site investigation in reducing uncertainties was evaluated together with the cost benefit of various mitigation options using QRA techniques.

2 APPROACH

Given the current state of knowledge and available techniques, it is not possible to predict precisely where and when future landslide events may occur. Hazard prediction for this study of natural terrain therefore involved the classification of the different types of landside hazard that might be expected, together with an assessment of their probable future frequency and magnitude. In doing so it was assumed that the level of natural terrain hazard activities over the last 50 years or so (for which there are photographic records) will be indicative of activities in the near future. This was considered a reasonable assumption for relatively large areas of natural terrain with few human influences. Hutchinson (1995) suggests such predictions should be limited to about 30 years, as beyond this time changes in ground conditions or climate could result in different levels of activity.

QRA for this study was based on various levels of information defining the location, type, frequency, magnitude and run-out potential of past natural terrain landslides. The different stages of the study focused on identifying appropriate levels of information and parameters for QRA and the reliability or uncertainties with the available data.

Figure 1. Tung Chung East, Lantau.

Figure 2. Mount Johnston North, Ap Lei Chau.

An appropriate geomorphological framework is needed for the collation and evaluation of spatial and temporal data for regional, area and site-specific QRA. Recognition of the controlling landforms at the various scales of assessment provides such a framework. At the regional scale, the Natural Terrain Landslide Inventory for Hong Kong (King 1997 and Evans & King 1998) permits an assessment to be made of the probable future frequency of landsliding for terrain units defined by slope angle and bedrock geology. At an area scale, definition of individual catchments was used to assess existing and future natural terrain hazards and risk given their variable susceptibility to landslide activity and potential for channelisation of debris. At a site-specific scale, recognition of landform terrain units of similar slope angle, geology and landslide susceptibility was found to be most appropriate.

3 DATA COLLECTION

In Stage 1, a distribution map and inventory of natural terrain hazard features was compiled for discrete catchments based primarily on aerial photograph interpretation, supplementary desk study data and field observations. The inventory of natural terrain landslides records parameters such as landslide type, date of occurrence, dimensions and volume (Table 1). Low-level aerial photograph coverage of both study areas for the period 1949 to 1997 was used.

Landslide reference	1
Landslide type	Debris flow
Estimated date of occurrence	1934
Source width, length, depth (m)	35, 67, 1.5
Track width, length, depth (m)	8, 210, 1
Volume = (width x slope length x depth)/2	1,980 m^3
Distance to planning/development zone	330 m
Certainty of observation (i.e. presence/age)	Certain - 100%

Note: different certainty factors were applied to each parameter

Table 1. Sample record from inventory.

The uncertainties in recording information of this nature were documented and quantified wherever possible (Table 2) and a programme of additional investigation for Stage 2 was recommended in an attempt to reduce these uncertainties.

At MJN, 62 features were identified in Stage 1 and 80% of these were found to pre-date the 1949 aerial photographs. The majority of the features were classified as open hillside landslides although coastal landslides and potential rock and boulder falls were also observed. At TCE, 298 features were recorded in Stage 1 and 88% of these were found to have occurred since 1963. The majority of the features were classified as open hillside landslides although evidence of channelised debris flows and possible large-scale landslides were also observed. Franks (1999) attributed the high frequency of landslide events in this area to recent extreme rainstorms.

Source data:
Age of vegetated landslide scars and debris
Identification of channelised debris flows
Identification of incipient large-scale landslides
Identification of rock and boulder falls
Spatial accuracy of aerial photograph and map data
Landslide width variability along source, track and lobe
Landslide length, particularly where channelised
Landslide depth variability along source, track and lobe
Derived landslide hazard data:
Frequency of occurrence
Width probability
Volume probability
Run-out probability

Table 2. Key uncertainties with data.

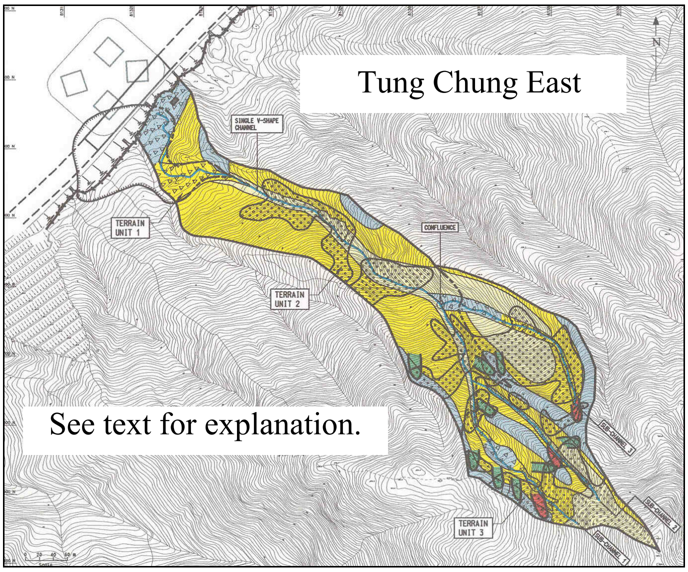

Figure 3. Stage 2 geomorphology and geology map.

In Stage 2, detailed engineering geomorphological and geological mapping was carried out for selected catchments from within the two study areas. Maps were prepared delineating terrain units defined according to grouped characteristics including slope angle, soil depth, underlying geology and interpreted landslide susceptibility (Figure 3). The detailed site mapping was used to locate sites for sub-surface investigation including drillholes, trial pits and trenches, dynamic probing and window sampling and seismic surveys to provide information on ground conditions and the nature, causes and mechanisms of landslides. Of the methods used in Stage 2, site mapping proved most cost-effective at reducing the uncertainties with the Stage 1 data derived from aerial photograph interpretation. In particular, uncertainties were greatly reduced for measurements of landslide dimensions and volume.

4 HAZARD MODELS

The Stage 1 and 2 studies identified and recognised the potential for various types of natural terrain hazards, including:

- Open hillside landslides (typically shallow debris slides and flows on open slopes – Figure 4)
- Coastal landslides (associated with oversteepend coastal slopes)
- Channelised debris flows (associated with stream valleys)
- Large scale (deep-seated) landslides
- Rock and boulder falls (associated with rock escarpments and boulder fields)

Quantified Hazard Models were developed for each of the natural terrain hazard types specified above to define key parameters and uncertainties such as frequency of occurrence, volume and debris run-out probability.

Figure 4. Example of open hillside landslide, TCE.

A number of different approaches for deriving the natural terrain hazard models were evaluated during Stage 1. The various possible options were judged on the grounds of logical consistency, simplicity and repeatability. It was also decided that all numerical estimates should be expressed in terms of confidence levels, using an upper and lower bound value, in order to allow quantification of uncertainties. Several key assumptions were made in the analysis: observational errors are unbiased and are normally distributed, and the percentage level of certainty assigned to an estimate is the probability that the estimate is within ±15% of the true value.

The area and site-specific hazard model probabilities were compared with regional data to define the error bands or uncertainty. The procedures finally adopted were considered to make the best possible use of available data at the appropriate scales, and to realistically express uncertainty given sparse or zero data.

5 POPULATION AND VULNERABILITY MODELS

Combination of the hazard models with Population and Vulnerability Models allows risk to be calculated. The hypothetical population models used in Stage 1 were derived from the current Outline Zoning Plans (OZP) for the two study areas with average population densities being assumed for differently zoned areas (Table 3). Population clusters appropriate to buildings were considered at both sites, while population levels appropriate to a major road were also considered at TCE. In Stage 2, specific population and vulnerability models were derived for the three hypothetical development scenarios and applied at both study sites (Table 3).

Type of Development	Population
Residential (Group A)	3,000/ha
Industrial	500/ha
Comprehensive Development Area	500/ha
Other specific uses	200/ha
Open space/playground	50/ha
Green belt	0/ha
Standard 3-storey NT exempted house	15/house
Multi-block mass housing	1,000/block
Major road (average daily traffic)	50,000 vehicles

Table 3. Population scenarios

Vulnerability factors for certain types and magnitudes of natural terrain hazards were applied to the hypothetical population at risk (Table 4). A vulnerability factor reflects the probability of death of a person located in the area impacted by potential landslide debris that accounts for indoor/outdoor population. The vulnerability factors were derived after DNV (1996) based on a 30-35° shadow angle, reach of landslides, and time of day.

Volume (m^3)	Indoor population	Outdoor population
50	0.0002	0.03
100	0.006	0.054
500	0.011	0.078
1,000	0.026	0.11
2,500	0.04	0.15
5,000	0.17	0.48

Table 4. Vulnerability factors for open hillside landslides (after DNV Technica, 1996)

6 QUANTITATIVE RISK ASSESSMENT

QRA was carried out to determine Individual and Societal Risk from the various natural terrain hazards. Calculation methods were developed specific to each hazard model taking account of the different population and vulnerability models. The approach for estimating potential fatalities from the various hazards and population affected generally followed the equation:

$$\text{Individual Risk (IR)} = f \times P_{run\text{-}out} \times P_{width} \times V \qquad (1)$$

where f is the frequency of occurrence of the hazard, $P_{run\text{-}out}$ is the probability of run-out of certain distance, P_{width} is the width probability of the landslide, and V is the vulnerability of outdoor and indoor population accounting for the time of day.

Societal risk results were presented as Potential Loss of Life (PLL) and fN curves. The potential loss of life was calculated for each study area OZP as follows:

$$PLL = IR \times N \qquad (2)$$

where, N is the population affected by the landslide.

For most types of development in the OZP, including building clusters, the affected population was estimated as follows:

$$N = \text{Population} \times \text{OZP area affected} \qquad (3)$$

7 RISK RESULTS

The risk to individuals at any location is the summation of Individual Risk (IR) derived for all hazard models and outcomes affecting that location. The simplest measure of societal risk is the Potential Loss of Life (PLL) arising from the various hazard models.

For illustration, the upper bound IR and PLL from the various natural terrain hazards at each study area are listed in Table 5, expressed as annual probabilities (based on the hypothetical development and population scenarios). Figures 5a and 5b show examples of IR contours for parts of each study area which illustrate the concentration of risk at the toe of steep natural terrain and at the outlets of stream valleys. The high risk levels for channelised debris flows and large-scale landslides reflect the potential for high numbers of fatalities arising from high magnitude events, albeit the historical record indicates that these are very rare.

The uncertainty or width of the error band for open hillside landslides was about 1 or 2 orders of magnitude whilst for channelised debris flows and large-scale landslides the error band was about 3 orders of magnitude, reflecting the greater uncertainty with low frequency high magnitude events.

Comparison of the area and site-specific risk results indicated generally lower IR estimates from detailed site-specific QRA. However, uncertainty increased at the site-specific scale due to the comparison of site-specific data with regional estimates, which typically differed more from the site-specific estimates than they did from the area estimates. This is a problem of scale, as statistical predictions of future landslide frequencies for small areas are generally more uncertain than predictions for large areas.

Hazard Type	Individual Risk	Societal Risk
Mount Johnston North		
Open hillside landslides[1]	3.61×10^{-4}	4.84×10^{-2}
Large-scale landslides[2]	2.75×10^{-5}	0.145
Rock and boulder falls[1]	7.5×10^{-5}	5×10^{-4}
Tung Chung East		
Open hillside landslides[1]	1.72×10^{-4}	2.68×10^{-3}
Channelised debris flows[3]	3.03×10^{-2}	3.39
Large-scale landslides[2]	8.1×10^{-6}	2.88×10^{-3}

Note: risk exposure within set distance of the toe of steep natural terrain defined as the 15° break in slope angle: 1=20m; 2=150m; 3=30m

Table 5. Stage 1 upper bound risk results.

The risk results in this study are purely theoretical, being based on hypothetical development scenarios. However, the conclusions reached on hazard model development and uncertainties are of general application. It appears that risk estimates in such situations might not be suitable for making absolute development decisions, although the QRA methodology can be very useful for assessing relative risk, which can be used to assess alternative site layouts and the effectiveness of mitigation measures.

8 RISK ACCEPTANCE CRITERIA

The risk results obtained for the combined and individual hazards were compared with the Interim Risk Guidelines (IRG) for landslides and boulder falls on natural terrain in Hong Kong (ERM-HK Ltd. 1998; Reeves et al. 1999). The IRG indicate an 'acceptable' individual risk level of 1×10^{-5} for new development and 1×10^{-4} for existing development. Individual Risk criteria were found to be most useful in this study, although ways of assessing societal risks based on PLL (potential loss of life) were also examined.

In Stage 1 the application of risk criteria did not present any major problems for the assessment of acceptability on an area-wide basis. However, in Stage 2 the use of criteria to assess risk levels determined for specific hypothetical developments raised various questions regarding the application of the interim risk guidelines for new developments.

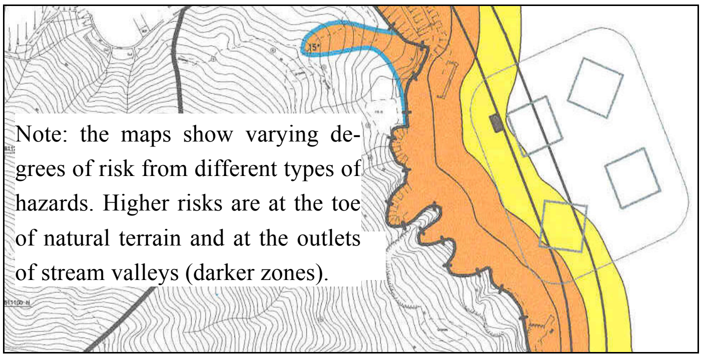

Figure 5a. Individual risk contours – Mount Johnston North.

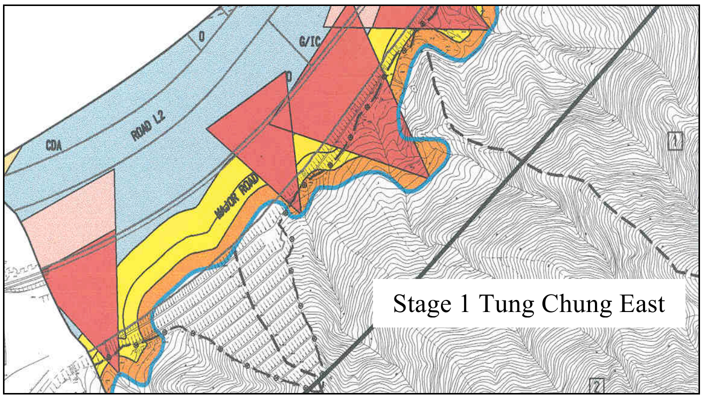

Figure 5b. Individual risk contours – Tung Chung East.

9 DISCUSSION AND CONCLUSIONS

Quantitative hazard modelling of natural landslides is very difficult. The derivation of the numerical probability of debris reaching a given location is not straightforward, and requires the application of some fairly complex statistical methods to the available data on landslide initiation and debris behaviour. Even when careful statistical analysis of the available data is carried out, there are still fundamental uncertainties relating to the frequency, magnitude and location of landslide events and resulting debris impacts. The scale of the assessment can affect the process - at one extreme regional predictions may have to be based on purely statistical data, while at the other extreme the risk from a single slope will be analysed deterministically. Difficulties arise when the site is too extensive for a deterministic analysis but not large enough to use regional data with confidence. Due to the complexity of these procedures it has to be accepted that full quantitative risk analysis will probably never be routine in area studies given the limitations of historical records of events and the uncertainties over future behaviour. Geomorphological and geological studies might provide further insight.

The application of the area hazard models, however, does not necessarily require full quantification. Even in the absence of full quantification such models can broadly indicate where hazards can be expected and their probable nature and magnitude. When assessing an area for planning or initial site layout purposes, such an assessment may be entirely adequate. It will permit planning or initial site layout decisions to be made with knowledge of where hazards can be expected. If hazard avoidance is not an option, due to site or other constraints, the hazard models will indicate where further, site-specific studies may be required.

The main conclusions of the study were:

a) The major uncertainties in the quantification of the Hazard Models are the prediction of event frequency and location. Attempts at quantifying these parameters were found, in most cases, to result in levels of uncertainty that render the results of limited practical use for land-use planning. This is a reflection of the historical record (spanning the last 60 years or so), which is biased towards recording high frequency, low magnitude events with only limited information on low-frequency, high-magnitude events. There is also uncertainty in the predicted location of future events, although recognition of landforms susceptible to various natural terrain hazards helps to reduce this.
b) Site-specific QRA studies assisted by detailed site mapping and ground investigation did not necessarily reduce uncertainties with the Hazard Models. Of the techniques evaluated, detailed mapping was found to be the most cost-effective at providing more accurate field data for QRA purposes.
c) The study has demonstrated a reasonable degree of confidence in predicting the frequency of open hillside landslides. It has been shown that the hazard and risk is concentrated within a short distance of the toe of the natural terrain. A relatively simple QRA approach was developed based on regional run-out data from the Natural Terrain Landslide Inventory for open hillside landslides.
d) For those Hazard Models with high levels of uncertainty (large deep-seated landslides and large channelised debris flows), a consequence based approach is probably more practicable than a full QRA. The approach should be based on the concept of a 'design event' or 'maximum credible event' that can account for the extent of the affected area.
e) The use of *f*N curves to describe and assess societal risk may have limitations given the uncertainties involved and the predicted low fatalities for some Hazard Models. Potential Loss of Life (PLL) may be a better measure of societal risk for many natural terrain landslide risk assessments.

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