Natural Terrain Management Criteria – Hong Kong Practice and Experience

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Abstract: Different approaches are being applied for assessment of natural terrain landslide hazards in Hong Kong. The use of Quantitative Risk Assessment in risk management and Design Event methodology in hazard mitigation is notable. Susceptibility analysis and zoning have been carried out at 1:20,000 scale for the whole of Hong Kong, and at 1:5,000 or larger scales in selected regions. However, their resolution, despite the use of good quality data and techniques, are generally not adequate for direct application to landslide risk management. As an alternative, suitably conservative, principally consequence-based hazard screening criteria are adopted on a case-by-case basis in the land and development management process. In area-based and site-specific applications, typically at 1:2,000 scale or larger scales where evaluation of potential landslide events, runout modeling and consequence assessment can be practically and reliably carried out, hazard analysis and quantified risk zoning would give useful results. These results have been adopted in landslide risk management at a site-specific level.

Keywords: landslide risk, natural terrain landslide, debris flow, susceptibility analysis, hazard zoning, GIS

1 NATURAL TERRAIN LANDSLIDES IN HONG KONG

Hong Kong has a population of about 7 million and a land area of 1,100 km^2. About 75% of the terrain is steeper than 15º, and over 30% steeper than 30º. Intense urban development has taken place in flat terrain and foothill areas, and is encroaching on the rugged hillside where natural terrain landslides could pose a significant hazard (Figure 1).

Hong Kong's natural terrain is susceptible to shallow, small to medium-sized landslides (Figure 2), which could develop into debris flows if entering drainage lines (Wong & Lam, 1998; Wong & Ho, 2000). Should the debris reaches densely developed areas, serious consequences may occur, even if the volume of landslide is relatively small (Figure 3). The Geotechnical Engineering Office (GEO) has compiled a comprehensive Geographic Information System (GIS) inventory of about 30,000 nos. of recent landslides on natural hillsides in Hong Kong (e.g. see Figure 4), based on interpretation of 10,000 feet aerial photographs taken since 1943 (King, 1999). About 1,900 large relict natural terrain failures have also been identified from interpretation of aerial photographs and hillside geomorphology (Scott Wilson 1999a, b).

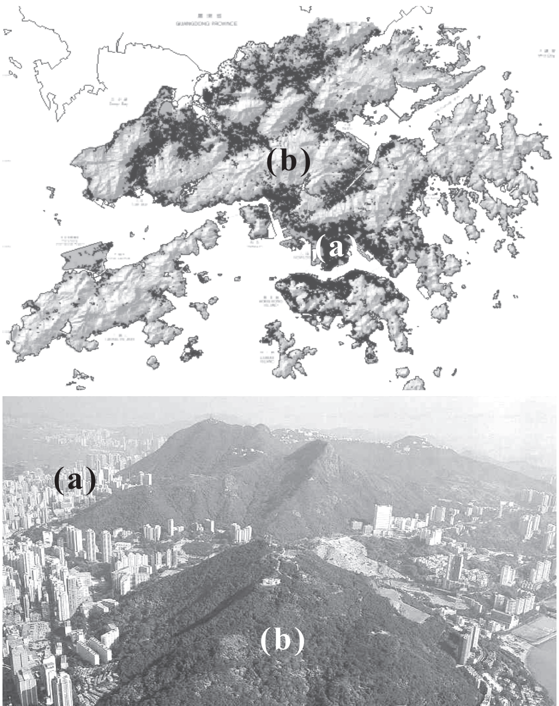


Figure 1. Hong Kong, with (a) urban development fringing (b) steep natural hillsides

2 TECHNICAL CRITERIA FOR MANAGEMENT OF NATURAL TERRAIN LANDSLIDE RISK

2.1 *Technical Guidelines and Professional Practice*

The strategy for dealing with natural terrain landslide hazards in Hong Kong has been to avoid, as far as possible, new developments in vulnerable areas. Where this is not practicable, assessment of hazards and design of necessary mitigation measures are

Figure 2. Landslide-prone natural terrain in Hong Kong

Figure 3. A 50 m^3 landslide in 1998 resulted in damage to property

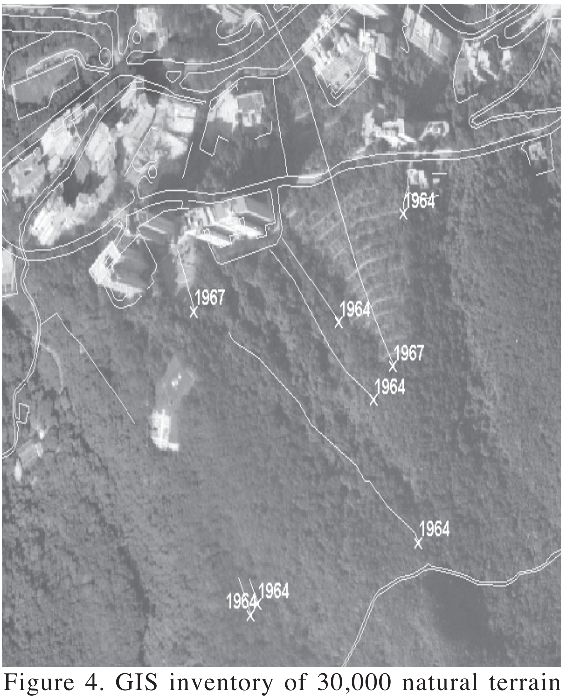


Figure 4. GIS inventory of 30,000 natural terrain landslides - landslide source, trail and year shown on a geo-referenced, othorectified infrared image

required. Technical criteria and guidelines for study and mitigation of natural terrain landslides risk in Hong Kong are given in the following GEO publications:

- Special Project Report No. SPR 1/2002 'Guidelines for Natural Terrain Hazard Studies' (Ng et al, 2002), which provides guidelines on study and mitigation of natural terrain hazards. The guidelines include recommended design standards and good practice in hazard mapping and in risk assessment and mitigation.
- GEO Report No. 75 'Landslides and Boulder Falls from Natural Terrain - Interim Risk Guidelines' (ERM, 1998), which provides guidelines on the tolerable individual and societal risk criteria for application in quantitative risk assessment (QRA).
- GEO Report No. 104 'Review of Natural Terrain Landslide Debris-resisting Barrier Design' (Lo, 2000), which provides guidelines on assessment of impact force and velocity of natural terrain landslide debris and design of debris-resisting barriers.

Three different approaches for assessment of natural terrain hazards and design of mitigation measures are being adopted in Hong Kong (Wong, 2002), as illustrated in Figure 5 and summarized in Sections 2.2 to 2.4.

2.2 *Factor of Safety Approach*

The conventional engineering approach, commonly applied to man-made slopes, has been to design the slope of concern to the required factors of safety. In Hong Kong, the design requirements (Figure 5) are stipulated in the Geotechnical Manual for Slopes (GCO 1984). These can also be applied to natural terrain should the designer chooses to adopt the Factor of Safety approach in dealing with natural terrain landslide hazards.

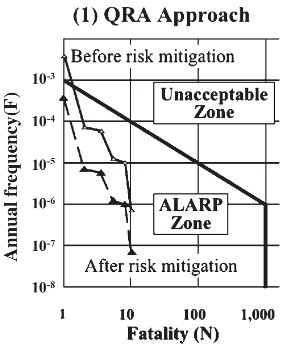
As in the case of designing man-made slopes, this Factor of Safety Approach aims to avert landslides by ensuring a prescribed margin of safety. The approach is applicable if the design objective is to reduce the likelihood of natural terrain failure. A typical circumstance of such application is in the study of natural terrain below a development site to check that natural terrain landslides that may adversely affect the site will not occur.

However, in many other circumstances, this approach is fraught with inherent difficulties and its use in natural terrain is not practical in that:

(a) As natural hillside is often only marginally stable over a large area, stabilization of the hillside would be expensive and may not be justified. Also, widespread stabilization works on natural hillside could result in considerable impact on the environment, and are usually difficult to carry out safely, particularly in an urban setting like Hong Kong.

(b) Averting failure is not necessarily the most cost-effective engineering solution. Provision of hazard mitigation measures (e.g. debris-resisting barriers) could be the preferred option in reducing the risk of natural terrain landslides.

For these reasons, two alternative approaches, viz the QRA and Design Event Approaches, have been introduced for use in assessment and mitigation of natural terrain landslide hazards in Hong Kong.



(2) Design Event

Required design event	Notional return period
Worst credible	1000 yrs
Conservative	100 yrs
Nil	N/A

(3) FOS Requirements

Consequence category	FOS
1 (e.g. building)	1.4
2 (e.g. road)	1.2
3 (e.g. parks)	N/A

Figure 5. Different approaches adopted in assessment and mitigation of natural terrain landslide hazards in Hong Kong

2.3 *QRA Approach*

The QRA Approach is applicable when designers opt for quantification and management of natural terrain landslide risk instead of prevention of failures. Based on this approach, the designer carries out QRA to quantify the risk of natural terrain landslides (Figure 5). The need for any necessary risk mitigation measures is assessed by reference to the risk guidelines given in GEO Report No. 75. This approach would entail a detailed assessment of the probability and consequence of natural terrain landslides with account taken of the uncertainties in an explicit and systematic manner, and consideration of the tolerability of the assessed risk level. It may be considered as the most rigorous and comprehensive assessment. The assessment often requires expert input and may be fairly involved and costly.

2.4 *Design Event Approach*

The Design Event Approach adopts a risk-based design framework and is applicable when designers opt for mitigation of natural terrain landslide risk without carrying out a formal QRA. Under this approach, the required mitigation measures (e.g. check dams) to protect a development from natural terrain landslides are determined by reference to an assessment of the design landslide event that may occur on the hillside affecting the development. Uncertainties are generally considered in an implicit manner through the assessment of the design event (e.g. a landslide of a certain size with a given degree of mobility).

The framework for the design event approach takes account of the failure consequence and the susceptibility of the hillside to landsliding in a semi-quantitative manner. Under the framework, the susceptibility of the hillside to failure is categorized based on historical landslide data and assessment of geomorphological features and other relevant information. The consequence of failure is categorized based on the types of facilities affected and their proximity to the hillside, as adapted from the generalized landslide consequence model developed by Wong et al. (1997).

Further studies will not be required if the consequence of failure and the landslide susceptibility of the hillside are insignificant. Otherwise, further studies should be carried out to establish the need for any mitigation measures to deal with the estimated design events. Depending on the consequence and susceptibility of the site, the required design event may be either a 'worst credible' event or 'conservative' event, which correspond to a notional return period of 1,000 years and 100 years, respectively (Figure 5).

The design event approach is relatively easy to apply as it does not demand formal and rigorous quantification of risk, and is favoured by many practitioners in Hong Kong. However, it gives no provision for consideration of the practicality and cost-effectiveness of risk mitigation. Such consideration is inherent in the QRA approach if the risk level is found to be within the 'As Low As Reasonably Practicable (ALARP)' region.

2.5 *Hazard Screening for Land Management and Development Planning*

Not all development sites are affected by natural terrain landslides. Whether a site may be affected depends on how close the site is to the hillside and how susceptible the hillside is to landsliding. To facilitate land management and early identification of potential geotechnical constraints in development planning, an initial hazard screening is implemented in Hong Kong to examine whether a site may be subject to natural terrain landslide hazards and thereby require further hazard studies. Such screening needs to be undertaken as early as possible in the land management and project planning process. The screening should be efficient to carry out, and should give reasonably conservative results based on use of readily available data.

For these purposes, the GEO has established a set of simple screening criteria (Figure 6) based on analysis of debris runout data from historical natural terrain landslides in Hong Kong (Ng et al. 2000; Choi et al. 2001). These criteria are adopted by the GEO on a case-by-case basis in screening new developments and land-disposal sites to determine whether a natural terrain hazard study is needed or not.

3 SUSCEPTIBILITY AND HAZARD ZONING

3.1 *Terrain Classification, Physical Constraints and Geotechnical Land Use Maps*

Since the early 1980s, the GEO has been compiling regional terrain data and thematic maps that provide geotechnical information for use in land and project planning. A series of eleven 1:20,000 terrain classification maps covering the whole of Hong Kong were produced by the GEO in the 1980s. Each map covers an irregular region based on catchment boundaries. Derivative maps and accompanying reports have been published for each region as the Geotechnical Area Studies Programme (GASP) series. The series contains 12 volumes of GASP reports, of which Volume XII (Styles & Hansen, 1989) is a summary report for the whole of Hong Kong.

The terrain classification system recorded three attributes: slope angle, landform, and instability and erosion. The information was derived from interpretation of topographical maps and pre-1980 aerial photographs. A total of 56,920 terrain classification units, each with an average map size of 1.9 ha, were delineated. The terrain classification maps were used to create 1:20,000 thematic maps, e.g. Physical Constraints Maps and Geotechnical Land Use Maps (GLUM).

Physical Constraints Maps present the major geotechnical constraints that may affect development at the corresponding terrain unit. The major constraints shown in the maps include zone of general instability, colluvium, flood plain, disturbed terrain, waterbodies, erosion areas, etc. In GLUM, terrain units are categorized into four classes in respect of their suitability for development based on geotechnical considerations. An oblique aerial photograph on which the GLUM classes are shown is given in Figure 7.

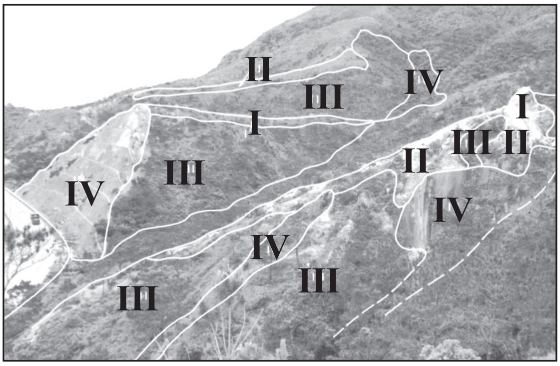


Figure 7. GLUM classes on suitability for development - I) High; II) Moderate; III) Low; IV) Probably Unsuitable

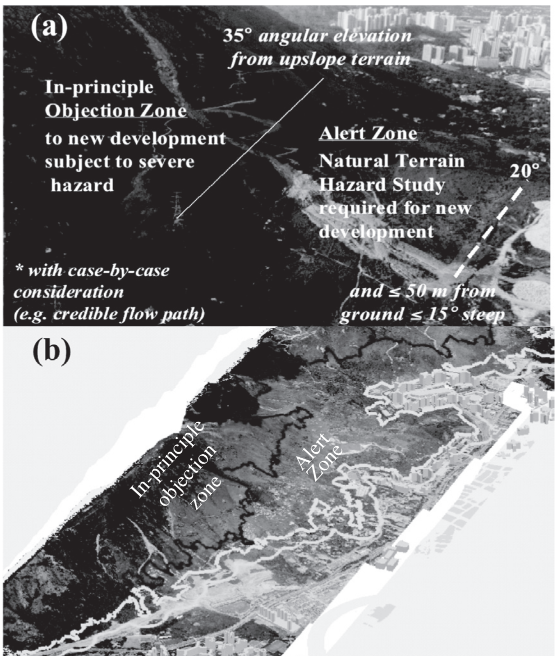


Figure 6. Screening criteria - (a) technical criteria for case-by-case consideration; (b) applied on a regional GIS model

More detailed terrain classification and thematic mapping work was undertaken for selected areas. Maps at 1:2,500 scale were produced for nine catchments that contain extensive colluvial deposits in developed areas. These maps also provide details of interpreted old landslide scars. Mapping was also completed for eleven 1:5,000 map sheets in the North Lantau Area, where major infrastructure development was planned. These data have been incorporated into three engineering geology reports on the North Lantau Area (Franks, 1991, 1992; Woods, 1992).

These thematic mapping products provide regional terrain classification and related geotechnical data. They are consulted for general land planning and resources evaluation purposes, and form part of the information for review in desk study for development projects. As a general rule, the GEO recommends that they should not be used to interpret parcels of land smaller than 3 ha in size. They are not of sufficient detail and accuracy for direct assessment of natural terrain landslide hazards.

3.2 *Historical Landslide-prone Sites*

The comprehensive inventory of historical natural terrain landslide data provide valuable information on locations where natural terrain landslides have been active in Hong Kong in the past 50 to 100 years. These locations, if close to existing or planned developments, deserve attention for potential landslide hazards (Figure 8). Identification of sites that are affected by or geographically linked to these historical landslides can be efficiently carried out with the use of GIS.

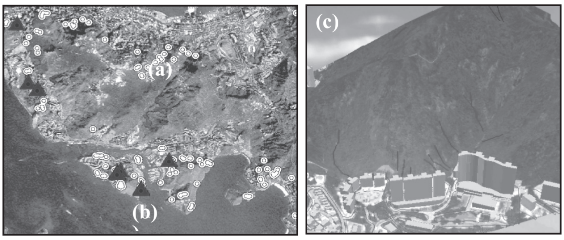


Figure 8. Identification of development sites with a history of natural terrain landslides - (a) landslide close to development; (b) landslide trail reaching development; (c) GIS virtual reality model

3.3 *Susceptibility Analysis and Zoning*

Other landslide-susceptible areas may exist even though they may not be readily evident from the available historical landslide data. Susceptibility analyses, to different scales and levels of details, have been carried out in Hong Kong over the past ten years, to examine the practicality and reliability of susceptibility and hazard zoning. Notable work completed to date include:

(a) 1:20,000 Susceptibility Analysis for Hong Kong – debris avalanche susceptibility analysis at 1:20,000 scale was completed for the whole of the natural terrain in Hong Kong (Evans & King, 1998). The analysis made use of GEO's inventory of historical natural terrain landslides. GIS-based landslide correlation was established with the available geotechnical and terrain parameters, such as slope gradient and lithology. Based on the results of the susceptibility analysis, terrain units are categorized into five susceptibility classes, with an average annual landslide frequency ranging from < 1 per km^2 to > 10 per km^2 (Figure 9).

(b) 1:5,000 Regional Susceptibility Analysis Using Logistic Regression – a regional susceptibility analysis was carried out at 1:5,000 scale on Lantau Island of Hong Kong, covering an area of about 140 km^2 (Dai & Lee, 2002). Lantau Island was the largest outlying island in Hong Kong, with a history of natural terrain landslides. Previous field study and diagnostic analysis of landslides on Lantau Island have identified landslide correlation with slope gradient, lithology and landform (Wong et al, 1998). In this regional susceptibility analysis, landslide susceptibility was assessed with terrain attributes, including elevation, land cover and distance to drainage line in additional to slope gradient, lithology and landform. A GIS-based logistic regression model was adopted to relate combinations of terrain variables to landslide susceptibility, and to study the spatial distribution of landslide susceptibility (Figure 10). The model was found to have achieved a concordance rate of about 80% of the actual landslides being correctly classified with the use of a 50% probabilistic cut-off value. Recently, the methodology has been applied to a 13 km^2 zone in the Tung Chung area on Lantau Island. With the use of improved data quality (e.g. 1:5,000 geological data and 1:1,000 topographic data) and consideration of additional attributes including slope aspect, profile curvature and upslope catchment area, the concordance rate was improved to 87% (Dai, 2002). Landslide susceptibility was zoned into classes, based on landslide probability predicted from the logistic regression model.

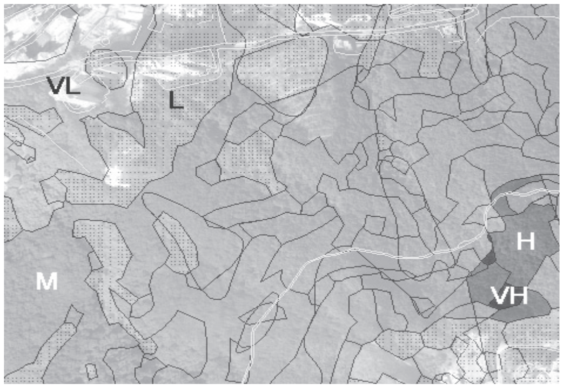


Figure 9. 1:20,000 susceptibility zoning. VH = Very High landslide frequency (> 10 no./km^2); H = High frequency (4 - 10 no./km^2); M = Moderate frequency (2 - 4 no./km^2); L = Low frequency (1 - 2 no./km^2); VL = Very Low frequency (< 1 no./km^2)

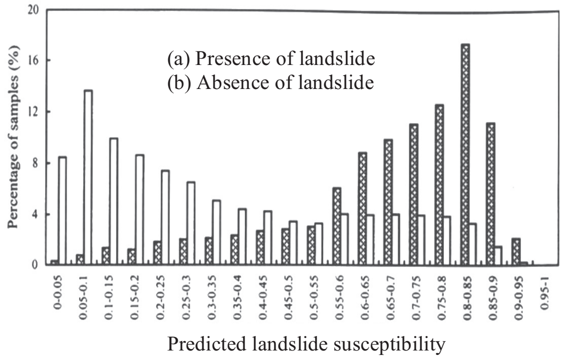


Figure 10. Comparison of predicted landslide susceptibility with actual landsliding (after Dai & Lee, 2002)

(c) 1:5,000 Regional Susceptibility Analysis Using Artificial Neural Network (ANN) Techniques – ANN techniques were adopted in another regional susceptibility analysis carried out at 1:5,000 scale for the central part of Lantau Island, covering an area of about 45 km^2. The back-propagation (BP) network method of ANN was applied in the work, on a GIS platform. A total of 1,220 landslides were used as training samples, to develop the trained network for landslide susceptibility classification. The model was reported to have been able to predict 85% of the recent landslides (Lee et al, 2002).

(d) 1:2,000 Area-based Susceptibility Analysis Using Additional Field Mapping Data – it was undertaken by the GEO as part of an area-based study of the natural terrain hazards in the Tsing Shan Foothills of Hong Kong. A susceptibility analysis supported by additional field mapping data at 1:2,000 scale was completed, covering an area of about 10 km^2. Positive correlation was established with three additional terrain attributes, viz. regolith type, lithological boundaries and proximity to head of drainage lines, obtained from the field mapping (Maunsell Fugro Joint Venture, 2003). As a result, improved resolution was achieved in susceptibility zoning, which gives an average annual landslide frequency of > 80 per km^2 at the most susceptible zone (Figure 11).

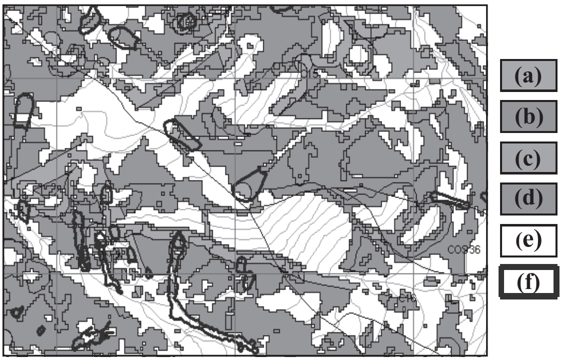


Figure 11. 1:2,000 susceptibility zoning from Tsing Shan Study. Landslide frequency (a) > 80 no./km^2 ; (b) 40 - 80 no./km^2; (c) 20 - 40 no./km^2; (d) 2 - 20 no./km^2; (e) < 2 no./km^2. Actual landslide area (f).

Hong Kong's experience brings out the following observations:

- Where data are available, it is practical to carry out susceptibility analysis to obtain insight on correlation of landslide susceptibility with different terrain attributes, and to give broad categorization of landslide frequency and susceptibility zoning of terrain.
- Use of GIS technology greatly improves the capability and efficiency of susceptibility analysis and reduces human error. Statistical, probabilistic and ANN methodologies provide useful tools to analyze the data and develop susceptibility models.
- Hong Kong is rich in data at 1:20,000 to 5,000 scale. Regional analyses carried out at this scale gave reasonable statistical correlation and reasonable susceptibility categorization. However, the resolution achieved in terms of landslide frequency, which spans about one order of magnitude between the least and most susceptible zones, is limited. These susceptibility analyses form an important part of the continued technical development work. But in practice, given the overall low resolution, the zoning derived has not been directly applied in management of natural terrain landslide risk under Hong Kong's slope safety system.
- The resolution and reliability of the susceptibility zoning can be improved in area-based studies at 1:2,000 to 1:1,000 scale, together with collation of supplementary data. This requires considerable additional resources, which are costly particularly if a large area is covered. The work completed in Hong Kong to date shows that the resolution may be improved to covering about two orders of magnitude in respect of landslide frequency. This improvement enhances hazard zoning and quantitative risk assessment work. However, susceptibility zoning at this resolution is still of limited use for direct application. As a comparison, it is not difficult to achieve resolution better than three to four orders of magnitude in consequence assessment with the use of a generic consequence model (e.g. Wong et al, 1997).

Figure 12. Hazard map delineating (a) areas potentially affected by debris flows; (b) zoning of catchment based on risk of debris flows on downstream development, i.e. with consideration of susceptibility and consequence of debris flows

3.4 *Hazard and Risk Zoning*

In view of the limitations of the susceptibility analyses completed to date, the GEO has not adopted regional hazard zoning derived directly from 1:20,000 to 1:5,000 susceptibility analyses. Instead, primarily consequence-based hazard screening as described in Section 2.5 above is adopted in the land and development management process.

However, where an area-based natural terrain hazard study is undertaken, such as that at 1:2,000 scale described in Item (d) of Section 3.2 above, it is practical to supplement the findings of susceptibility analysis with assessment of credible landslide events and runout modeling for different landslide scenarios. Hazard maps produced by this means (e.g. Figure 12) are suitable for application to land management and project planning.

Formal QRA has been applied in Hong Kong for years in management of natural terrain landslide risk at site-specific level, typically at 1:1,000 scale and covering within 1 km^2. At such level of study, quantified consequence assessment is carried out in addition to hazard assessment, and thereby producing quantified risk figures and zoning (e.g. Figure 13). The findings are adopted in assessment of risk tolerability and evaluation of risk mitigation strategy and requirements, following established risk criteria and quantified risk management principles.

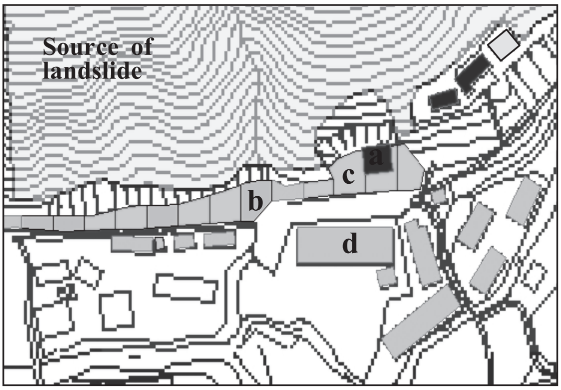


Figure 13. Risk zoning map from QRA showing annual risk in terms of potential loss of life x 10,000 - (a) 2 - 5; (b) 0.2 - 0.5; (c) 0.02 - 0.05; (d) < 0.02 (based on OAP, 2003)

4 CONCLUSION

The work completed to date in Hong Kong has illustrated the practicality of undertaking susceptibility, hazard and risk zoning at different scales given the availability of relevant data and use of suitable techniques. Hong Kong's experience also highlights the need to be mindful of the limited resolution and accuracy of the zoning, which affect the usefulness and reliability of their application to risk management.

5 ACKNOWLEDGEMENT

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