ASSESSMENT OF LANDSLIDE RISK OF NATURAL HILLSIDES IN HONG KONG

GEO REPORT No. 191

H.N. Wong, F.W.Y. Ko & T.H.H. Hui

GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING AND DEVELOPMENT DEPARTMENT

THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

ASSESSMENT OF LANDSLIDE RISK OF NATURAL HILLSIDES IN HONG KONG

GEO REPORT No. 191

H.N. Wong, F.W.Y. Ko & T.H.H. Hui

This report was originally produced in July 2004 as GEO Special Project Report No. SPR 5/2004

Table of Contents
Table of Contents
Table of Contents
Table of Contents

First published, September 2006

Prepared by:

Geotechnical Engineering Office,
Civil Engineering and Development Department,
Civil Engineering and Development Building,
101 Princess Margaret Road,
Homantin, Kowloon,
Hong Kong.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

PREFACE

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. The GEO Reports can be downloaded from the website of the Civil Engineering and Development Department (http://www.cedd.gov.hk) on the Internet. Printed copies are also available for some GEO Reports. For printed copies, a charge is made to cover the cost of printing.

The Geotechnical Engineering Office also produces documents specifically for publication. These include guidance documents and results of comprehensive reviews. These publications and the printed GEO Reports may be obtained from the Government's Information Services Department. Information on how to purchase these documents is given on the last page of this report.

R.K.S. Chan
Head, Geotechnical Engineering Office
September 2006

Table of Contents
Table of Contents
Table of Contents
Table of Contents

FOREWORD

This report presents the findings of an assessment of the overall landslide risk to the community posed by natural hillsides in Hong Kong. Quantitative risk assessment (QRA) methodology was adopted in the assessment, which included review of natural terrain landslide hazards, quantification of the risk to life, and diagnosis of the risk distribution and characteristics. As part of the work, QRA models were developed and an inventory of catchments with known historical natural terrain landslides occurred close to existing developments was compiled.

The work was led by H.N. Wong. Florence W.Y. Ko and Thomas H.H. Hui undertook the risk quantification work, and they also assisted in the development of the QRA models and diagnosis of the risk distribution and characteristics. Samuel K.C. Ng assisted in the review of natural terrain landslide hazards. Vitus M.C. Chan and Willie W.L. Shum managed the compilation of the catchment inventory and carried out the relevant Geographic Information System (GIS) analysis. GEO's landslide investigation consultants, Fugro (Hong Kong) Limited and Maunsell Geotechnical Services Limited assisted in collecting data on the catchments and performing GIS analysis. Ken K.S. Ho and other colleagues of the Landslip Preventive Measures Division 1 assisted in collating data on historical landslide fatalities.

H.N. Wong
Chief Geotechnical Engineer/Planning

Table of Contents
Table of Contents
Table of Contents
Table of Contents

EXECUTIVE SUMMARY

The overall risk of natural terrain landslides in Hong Kong, as at 2004, has been assessed by the Geotechnical Engineering Office (GEO) using state-of-the-art quantitative risk assessment (QRA) methodology and Geographic Information System (GIS) techniques. The findings provide useful information for examining the nature and scale of natural terrain landslide problems in Hong Kong and formulating risk management strategy.

The work that has been carried out includes:

(a) Review of natural terrain landslide risk in Hong Kong;

(b) Compilation of an inventory of catchments where historical natural terrain landslides have occurred close to existing developments (denoted as Historical NTLI Catchments), where NTLI stands for Natural Terrain Landslide Inventory;

(c) Compilation of an inventory of catchments that are bordering development areas but have not been recorded as Historical NTLI Catchments (denoted as Inventory of Supplementary Catchments). The Inventory covers Supplementary Catchments in five selected regions and six selected areas;

(d) Formulation of QRA models;

(e) Quantification of the overall risk to life of natural terrain landslides to the community, expressed in terms of the annual potential loss of life (PLL); and

(f) Diagnosis of the risk distribution and characteristics.

The key results are:

(a) A GIS Inventory of 453 Historical NTLI Catchments has been compiled, which comprises 291 catchments affecting existing building structures, 56 catchments affecting dilapidated or demolished structures, and 75 catchments affecting sensitive routes and mass transportation facilities.

(b) The best estimated risk to life of natural terrain landslides arising from the catchments is 1.4 PLL per year. The 56 catchments that affect dilapidated or demolished structures were taken as of negligible risk (PLL = 0) in the QRA, i.e. assuming that the structures would neither be re-occupied nor re-built. Another 10 catchments were found to have negligible risk (PLL = 0) by the QRA.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(c) The average risk-per-catchment for the 387 risk-bearing Historical NTLI Catchments is about 3.6 x 10^{-3} PLL per year. This is comparable to that of the catchments found to have required follow-up actions in recent years based on the ‘react-to-known-hazard’ principle. Landslide risk is unevenly distributed among the catchments, and it is likely that a large number (e.g. the top-ranking catchments in terms of the calculated risk) of the Historical NTLI Catchments would require risk mitigation, based on experience from the ‘react-to-known-hazard’ cases and alignment with the risk mitigation strategy adopted for dealing with Potentially Hazardous Installations in Hong Kong.

(d) Projection of risk from the Historical NTLI Catchments based on assessment of the Supplementary Catchments indicates that the Historical NTLI Catchments constitute about 25% to 50% of the overall risk of natural terrain landslides on existing developments in Hong Kong. The balance of 50% to 75% of the overall risk comes from Supplementary Catchments, i.e. other vulnerable catchments affecting existing developments but not included in the Inventory of Historical NTLI Catchments.

(e) The best-estimated overall risk of natural terrain landslides on existing developments in Hong Kong is 5 PLL per year. This calculated risk to life is of comparable order as that of registered man-made slopes by the year 2010.

(f) Sensitivity analyses of the optimistic and pessimistic scenarios show that the overall calculated risk of natural terrain landslides may range from 1 to 10 PLL per year. The range of calculated risk reflects uncertainties in the assessment. The range is within an order of magnitude, and is considered among the best that can be practically achieved by state-of-the-art QRA.

(g) The number of Historical NTLI Catchments would increase with time, as new natural terrain landslides occur. The average growth rate would be in the order of 10 nos. per year.

(h) The risk of natural terrain landslides in Hong Kong will continue to increase as developments take place close to steep hillside.

(i) Identification of the other vulnerable catchments, particularly those with few historical landslide records, is a technically difficult task. Some areas requiring further work have been identified.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(j) The global QRA covers only risk to life as expressed in PLL. Other consequences of natural terrain landslides, such as economic loss, disruption to the community and the public aversion to multiple fatalities are not reflected in the calculated risk figures. Professional evaluation based on qualitative assessment of the available landslide data, landslide characteristics, rainfall-landslide correlation, etc, indicate that consequences other than risk to life are also of concern in natural terrain landslides.

(k) Hillside failures within and in the vicinity of the Year 2000 Development Lines, which are not included in this global QRA, deserve attention. Further work to assess the potential scale of the problem is being undertaken by the GEO.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

CONTENTS

Table of Contents
Table of Contents
Table of Contents

Page No.

Table of Contents
Table of Contents
Table of Contents

1. INTRODUCTION

This report presents the findings of an assessment, using quantitative risk assessment (QRA) methodology, of the landslide risk of natural hillsides in Hong Kong. The assessment includes review of natural terrain landslide hazards in Hong Kong, quantification of the risk to life posed by the hazards, and diagnosis of the risk distribution and characteristics. The findings provide useful information for examining the scale of natural terrain landslide problems in Hong Kong and formulating risk management strategy.

In Hong Kong, sizeable man-made slopes, including cut slopes, fill slopes and retaining walls, are registered by the Geotechnical Engineering Office (GEO) in the comprehensive Catalogue of Slopes (GEO, 2004). ‘Natural hillside’ is commonly used in Hong Kong to denote hillsides that are not significantly modified by human activities, whereas ‘hillside’ refers in general to sloping terrain that is outside the boundaries of registerable man-made slopes.

In this report, for the purpose of the QRA, the term ‘natural terrain’ is adopted to denote specifically natural hillsides that are outside the Year 2000 Development Lines (Figure 1). In compiling and updating the Natural Terrain Landslide Inventory (NTLI, see Box 1), Development Lines that broadly define the boundaries between natural hillsides and developed areas were delineated. The Year 2000 Development Lines are those that broadly bound the developed areas as in the year 2000.

Box 1 - Natural Terrain Landslide Inventory (NTLI)

The Natural Terrain Landslide Inventory (NTLI) was compiled by the GEO from interpretation of high level aerial photographs. Plate (a) shows some typical natural terrain landslides in Hong Kong. The location of each identified natural terrain landslide crown was recorded and the centre-line of the debris trail was marked with a line (Plate (b)). Up to the year 2000, the NTLI has catalogued some 30,000 landslides, about 19,000 and 11,000 of which are considered recent and relict landslides respectively. Recent landslides in the NTLI refer to those that occurred within the aerial photograph coverage. On aerial photographs, recent landslides appear in light tone and are bare of vegetation. Relict landslides in the NTLI refer to scars which still have a well-defined main scarp and on which vegetation has re-established.

Factors such as photograph coverage, cloud cover, ground shadows, vegetation cover, and scale and resolution of the high-level aerial photographs impose certain limitations on the dataset. Consequently, some landslides may not have been identified and some landslides shown may be other features mis-identified as landslides. The inventory is updated about every three years.

Plate (a) - Natural terrain landslides

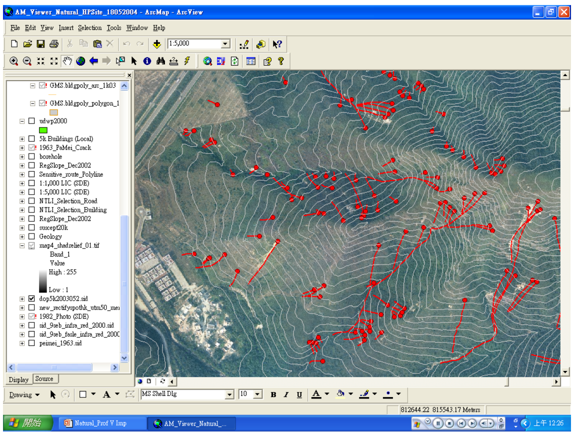


Plate (b) - Natural Terrain Landslide Inventory in GIS Format

Table of Contents
Table of Contents
Table of Contents
Table of Contents

2. NATURAL HILLSIDE LANDSLIDES IN HONG KONG

2.1 Nature of Natural Terrain Landslides in Hong Kong

Hong Kong has a substantial portion of its dense urban development located on or near steep hillsides (Figure 2). Natural terrain, as defined by the Year 2000 Development Lines, covers over 60% of the total land area (about 1,080 km^2) of Hong Kong. Nearly 50% of the natural terrain is sloping at 25° or more. As the present-day morphology reflects on-going geological and geomorphological processes, much of the natural terrain is only marginally stable over large areas.

Natural terrain landslides in Hong Kong arise typically from rain-induced shallow failures of the surface mantle of the hillside (Figure 3). The materials that fail at the source areas of the landslides may include top-soil, colluvium and weathered rock (Figure 4). Most of the landslides are of several hundred cubic meters in volume, but some have developed into massive, mobile debris flows with devastating destructive power. Falls of individual boulders from natural terrain into developed areas are also reported from time to time (Figure 5).

Given the steep topography, debris from a natural terrain landslide could travel a considerable distance downslope. Mechanisms of debris movement are broadly classified into three types: debris slide, debris avalanche and debris flow (Figure 6). Some typical scenarios of debris movement are as follows:

- Where the hillside is relatively planar, the debris may slide down the hillside as an intact slab and result in an open slope debris slide (Figure 6(a)). If disintegration occurs during debris movement, the landslide becomes an open slope debris avalanche (Figure 6(b)).

- A channelized debris flow would occur if the debris enters into an incised drainage line that governs the alignment of the debris flow path (Figures 6(c) & (d)). Where loose materials are present in the drainage line, entrainment of the loose materials may occur and this could significantly escalate the debris volume and mobility (Box 2).

- Where the drainage line or depression in topography is more subtle, the mechanism becomes a mixed debris avalanche-and-flow, which is intermediate between an open slope landslide and a channelized debris flow.

Natural hillside landslides are not confined to shallow failures. Deep-seated landslides also occur from time to time in Hong Kong, and some of these could involve a massive volume of debris. Some examples of large natural terrain landslides are given in Box 3.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Box 2 - The 1990 Tsing Shan Debris Flow

The east-facing hillside of Tsing Shan (Plate (a)) has been active in debris flows for the last 15 years. In September 1990, a massive debris flow took place in a moderately heavy rainstorm. The debris flow started with a 350 m^3 landslide at the upper part of Tsing Shan. The debris volume increased when the landslide debris travelled down the drainage line, resulting in a 20,000 m^3 channelized debris flow with a runout distance of more than 1 km. The steep terrain (Plate (b)) together with presence of loose, boulderly materials (Plate (c)) that are susceptible to entrainment along the drainage line are factors contributing to the scale of the event. Before the debris flow, residential buildings were in place on the other side of Lung Mun Road, and the site between the road and the hillside was planned for building development (Plate (d)). If the site had been developed at the time as that on the other side of Lung Mun Road, the debris flow would have resulted in serious consequences. After the debris flow, development at the site was changed to a golf course to minimize the risk exposure to debris flows. In April 2000, three other sizeable debris flows occurred on the hillside, and resulted in debris deposited on the golf course (see Box 11). Developments in the area are moving closer to steeper hillsides as much of the flat ground including reclaimed land in the area has already been developed. The case is a vivid illustration of the risk of debris flows and the importance of proper land-use and development planning in controlling undue increase in the risk of natural terrain landslides.

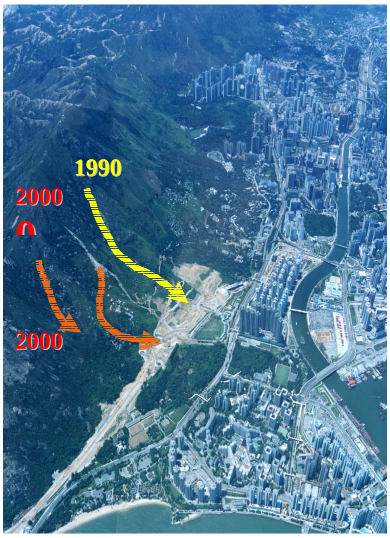


Plate (a) - The east-facing hillside of Tsing Shan

Plate (b) - Steep terrain

Plate (c) - Entrainable materials at the drainage line

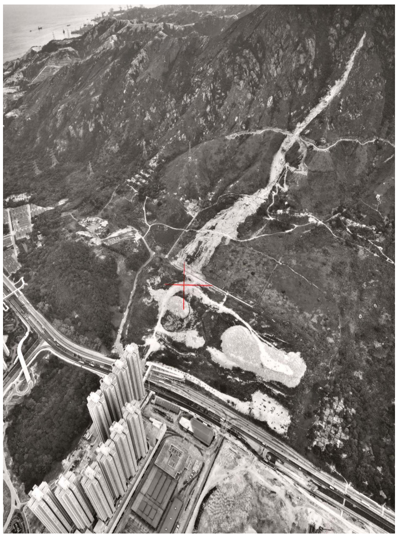


Plate (d) - Development in 1990

Box 3 - Large Natural Terrain Landslides in Hong Kong

A database of about 1900 nos. large natural terrain landslides was compiled by the GEO based on interpretation of aerial photographs. These large landslides include recent natural terrain landslides with a scar width exceeding 20 m, as well as large-scale relict morphological features that have been identified from aerial photographs. Plate (a) shows an example of a large coastal landslide on Lamma Island, with an estimated volume of about 30,000 m^3. The landslide probably occurred within the last few hundred years. Shown in Plate (b) is a massive debris lobe at Sham Wat, Lantau, covering a plan area of about 0.3 km^2. Age-dating undertaken by the GEO found that the main body of the hillside probably failed some 30,000 years ago, but further sizeable detachments continued to take place and the youngest one was dated back to only about 2,000 years. Plates (c) and (d) show a large relict landslide scar that were left in place after massive debris flow near the present Tung Chung Road. Age-dating indicated that the scar was created only about 8,000 years ago. These cases are relatively young in terms of the geological process and are relevant to assessment of the current landslide hazard.
.

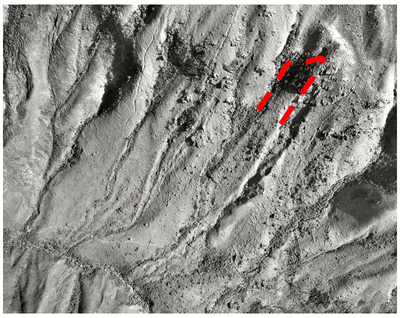


Plate (c) - 1963 aerial photograph showing a large relict landslide near the existing Tung Chung Road

Plate (a) - Large coastal landslide on Lamma Island

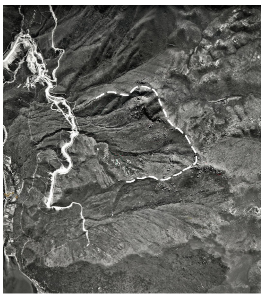


Plate (b) - Massive debris lobe at Sham Wat, Lantau

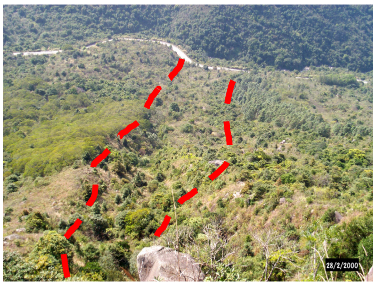


Plate (d) - Current condition of the large relict landslide near Tung Chung Road

Table of Contents
Table of Contents
Table of Contents
Table of Contents

While most of the natural hillside landslides result in mobile debris travelling downslope, some failures do not result in a complete detachment of the ground. However, the conditions of the distressed ground could continue to deteriorate, typically in the form of opening up of joints and development of tension cracks (Box 4). Hence, a hillside that has apparently withstood a severe rainstorm may fail in a subsequent rainstorm due to progressive deterioration of the ground conditions. Also, a distressed hillside without significant detachment of debris could subsequently turn into a mobile failure.

Box 4 - Hillside Deterioration

The natural hillside in Hong Kong is subject to continued erosion and degradation, which is part of the on-going geological and geomorphological process under the prevailing climatic conditions. As a result, shallow failures of the surface mantle of steep hillside are frequent. Plate (a) shows a scarp of a natural terrain landslide where sub-vertical joints in the weathered rock are infilled with topsoil. This is indicative of a relatively recent process of joint opening, which could result in increased infiltration of rain water into the hillside and thereby affect its stability. Plate (b) shows a hillside where extensive cracking is present above a recent natural terrain landslide. The ground has been distressed but not yet resulted in a mobile failure. However, with continued deterioration of the ground conditions, the distressed hillside may turn into a large mobile landslide. Identification of these features on site requires detailed field mapping by experienced professional, which is an important task in the assessment of natural terrain landslide hazards.

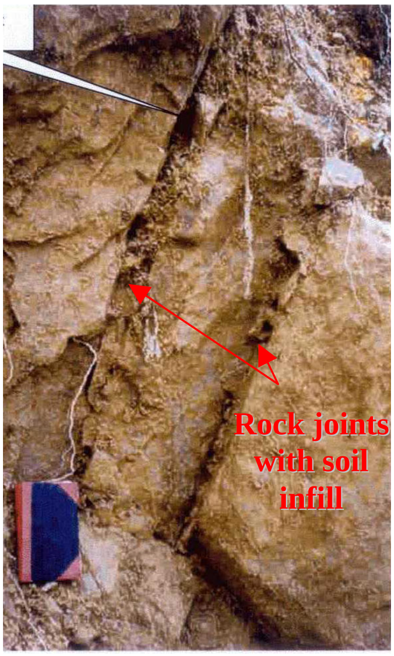


Plate (a) - Rock joints with soil infill at a landslide scarp

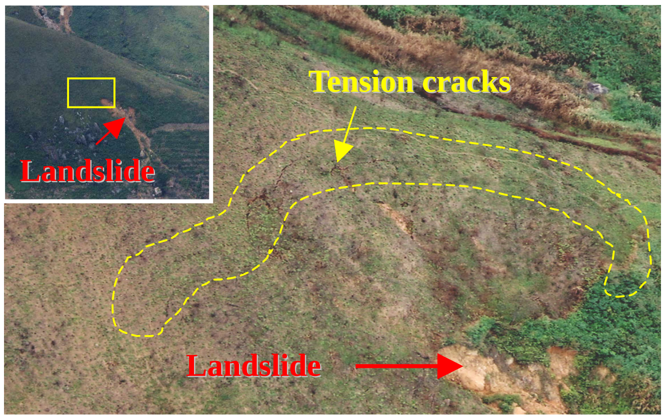


Plate (b) - An extensively cracked hillside above a recent natural terrain landslide

2.2 Historical Natural Terrain Landslides

The steep natural hillsides in Hong Kong are susceptible to landsliding when subject to heavy rain. There are indications that Hong Kong suffered from large natural hillside landslides before the early 1900s (Box 5), when extensive urban developments had not yet taken place. After the Second World War, aerial photographs covering the whole of Hong Kong were taken more frequently, and they provide a means of identifying the more recent natural terrain landslides. From interpretation of high altitude aerial photographs taken between 1945 and 2000, about 30,000 landslides on natural terrain were identified and recorded in the NTLI (see Box 1). These landslides are referred to as 'NTLI landslides' in this report. They exclude smaller size landslides and less mobile failures that are not readily noticeable from high-flight aerial photographs. They also exclude hillside failures that occur within or adjoining Development Lines. On average, about one NTLI landslide occurs each year for every 2 km^2 of natural terrain in Hong Kong. This NTLI landslide density is of a

Table of Contents
Table of Contents
Table of Contents
Table of Contents

similar order to that of major failures (landslide volume >50 m^3) occurring on pre-1977, un-engineered soil cut slopes registered in the Catalogue of Slopes.

Box 5 - Natural Terrain Landslides in the Old Days

Little information is available on natural terrain landslides in Hong Kong before the early 1900s, although landslide activities are evident from some old photographs. Long debris trails are visible in Plate (a), which shows the western part of Hong Kong Island in the 19th Century. Plate (b) shows a big fallen boulder, which killed 5 people in Pokfulam in 1924.

Plate (a) - Landslide debris trails on Hong Kong Island in the 19th Century

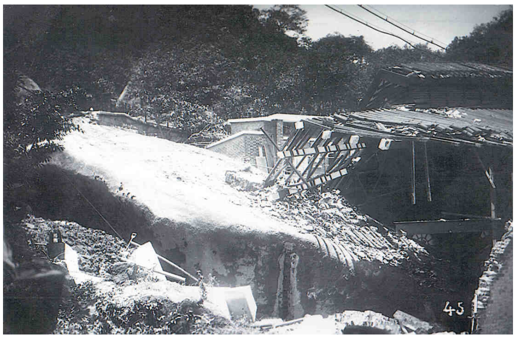


Plate (b) - Fallen boulder in Pokfulam in 1924

Most natural terrain landslides occur in relatively remote areas but some of them have affected existing developments. Between 1982 and 2003, about 900 natural terrain landslides and boulder falls affected the community were reported to the GEO, and some of these have resulted in serious consequences.

A summary of historical landslide fatality figures from 1980 to 2003 is given in Table 1. Over the period, landslides have resulted in 50 fatalities. Among these, 16 were due to landslides from natural hillsides, illustrating that natural hillside failures are a significant hazard to the community. In landslide risk management, historical landslide fatality figures over a relatively short period do not fully reflect the inherent landslide risk, because some of the natural hillside landslides were ‘near-misses’ in that major casualties were only narrowly avoided. Also, more severe rainstorm events have not affected hillsides close to developed areas over the short observation period. However, from the available data, some observations on possible causes for concern can be made:

- The majority (nine out of 16, see Table 1) of the fatalities from natural terrain landslides occurred in two heavy rainstorms in 1982 (Box 6). This illustrates on the one hand the sensitivity of the historical landslide data to occurrence of severe rainfall events. On the other hand, it illustrates the serious consequences that may bring about by natural terrain landslides, in particular occurrence of multiple fatalities when natural hillside close to developed area is hit by a severe rainstorm.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Box 6 - Natural Terrain Landslides in 1982

Hong Kong was hit by two heavy rainstorms in May and August 1982, which resulted in 1415 natural terrain landslides recorded in the NTLI. A total of 25 landslide fatalities were reported and 9 of these were due to natural terrain failures. Plate (a) shows a 200 m^3 natural terrain landslide, which killed two people in Kau Wah Keng, Lai Chi Kok. Plate (b) shows a cluster of 1982 natural terrain landslides on the hillside overlooking Sham Tseng San Tsuen, where further landslides occurred in one of the catchments in 1999 and resulted in one fatality and injury to 13 people (see Box 7). Plate (c) shows a long-runout debris flow near Route Twisk.

Plate (a) - 1982 landslide in Kau Wah Keng

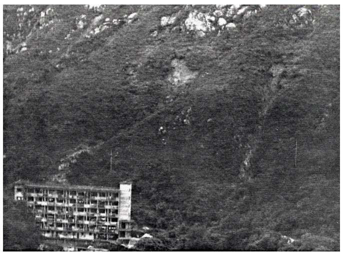


Plate (b) - 1982 landslides in Sham Tseng San Tsuen

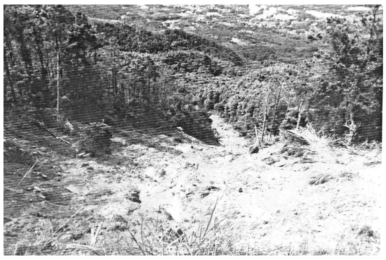


Plate (c) - Long-runout debris flow near Route Twisk

Box 7 - The 1999 Debris Flow at Sham Tseng San Tsuen

One large landslide and three smaller failures occurred on the natural hillside above Sham Tseng San Tsuen and developed into a debris flow during a heavy rainstorm in August 1999 (Plate (a)). The large landslide had a failure volume of about 600 m^3 and was the primary source of the debris flow (Plate (b)). The debris flow travelled downslope along a drainage line and hit Sham Tseng San Tsuen. A number of building structures were damaged (Plate (c)), and the incident resulted in one fatality and injury to 13 people. The drainage line did not contain a lot of loose materials, and there was not much increase in debris volume due to entrainment during the debris flow.

A check dam (Plate (d)) with a debris retention volume of 1,400 m^3 was constructed to protect the village from future debris flows.

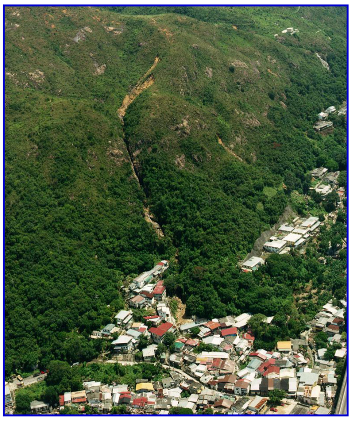


Plate (a) - The 1999 debris flow affected Sham Tseng San Tsuen

Plate (b) - The landslide source

Plate (c) - Houses demolished by the debris flow

Plate (d) - Check dam constructed to protect the village from future debris flows

- There are notable variations in the landslide fatality figures over different periods. Apart from variation in the rainfall pattern over the period, near-miss events could distort the historical landslide fatality figures. There could be multiple fatalities in the 1999 natural terrain landslide at Sham Tseng San Tsuen (Box 7) if the consequence to the 13 people injured was more serious. In addition, the 2001 Shek Lei Hill natural terrain landslide could have resulted in multiple fatalities, if the four occupants of the two structures destroyed in the debris flow had not fortuitously left the houses before the debris flow occurred (Box 8). The 1999

Table of Contents
Table of Contents
Table of Contents
Table of Contents

landslide near University Station, Shatin is another ‘near-miss’ event, which could have potentially lead to very severe consequence if the debris had not stopped just before it reached the railway track (Box 9).

Box 8 - Debris Flow at Shek Lei Hill in 2001

In September 2001, a debris flow with a volume of about 800 m^3 occurred at Shek Lei Hill above Lei Pui Street, Kwai Chung (Plate (a)). The landslide developed into a channelized debris flow down a drainage line and demolished two squatter structures (Plate (b)). The four occupants of the structures left their houses two hours before the debris flow, after being alerted by the unusual barking of their dogs and running of muddy water in the ephemeral drainage line. Part of the debris reached Lei Pui Street, which is the sole vehicular access to Shek Lei Estate. Lei Pui Street was closed for three days after the debris flow.

After the event, a check dam was constructed at the toe of the hillside as an emergency protective measure (Plate(c)). In line with the ‘react-to-known-hazard’ principle, a natural terrain hazard study was being undertaken on the hillside in 2003.

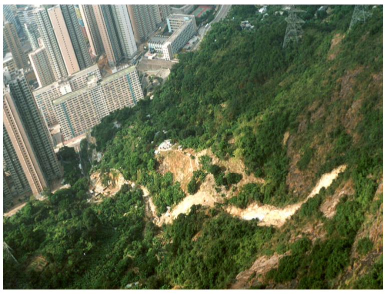


Plate (a) - Debris flow at Shek Lei Hill

Plate (b) - Location of the houses demolished by the debris flow

Plate (c) - Check dam constructed after the debris flow

Box 9 - Natural Terrain Landslide Affecting Mass Transportation Facilities

A 200 m^3 natural terrain landslide occurred in 1999 with debris deposited close to the KCRC track near University Station (Plate (a)). This ‘near-miss’ case could have resulted in serious consequence in case of more mobile debris or larger scale failure.

Plate (a) - Natural terrain landslide near KCRC University Station, Shatin

Table of Contents
Table of Contents
Table of Contents
Table of Contents

- The less frequent, large-scale natural terrain landslides, if they were to take place close to developed areas, could result in severe consequences. These large-magnitude events are under-represented by the limited historical data available. As an illustration, the 20,000 m^3 Tsing Shan debris flow in 1990 reached a foothill development platform (Box 2). Had the development proceeded as originally planned, the consequence could have been serious. The 26,000 m^3 open slope hillside landslide in 1995 at Shum Wan Road, Aberdeen, which resulted in fatalities, could have caused much more severe consequences if the area swept by the landslide debris was more densely populated (Box 10).

Box 10 - The 1995 Shum Wan Road Landslide

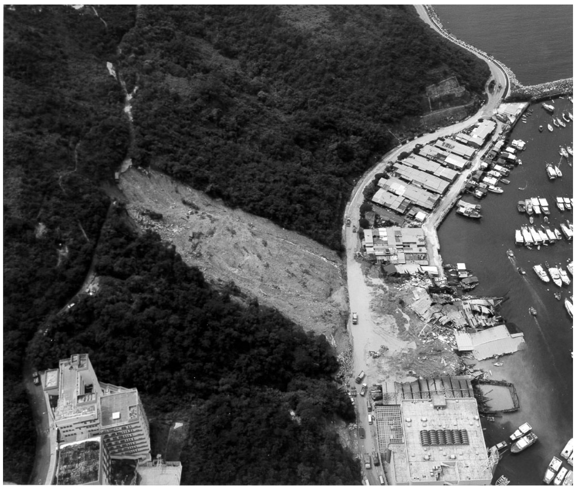


Plate (a) - Shum Wan Road landslide in 1995

In August 1995, a massive landslide occurred at the hillside above Shum Wan Road, Aberdeen (Plate (a)). The landslide was a mobile open slope failure involving a total of 26,000 m^3 of soil and rock debris, and resulted in a 70 m high landslide with a maximum width of 90 m. A 30 m section of Nam Long Shan Road in the upper part of the failure collapsed in the landslide. The landslide debris crossed Shum Wan Road at the toe of the hillside and damaged three shipyards and a factory, and resulted in two fatalities and injury to five people.

The landslide occurred in a heavy rainstorm, with about 330 mm of rain within 24 hours before the landslide. Post-landslide investigation found that uncontrolled discharge of surface water into the hillside from Nam Long Shan Road, which traversed the upper part of the hillside had significantly increased the amount of water that reached the hillside and thereby contributed to triggering the massive landslide. The landslide could have caused more severe consequences if the area swept by the landslide debris was more densely populated.

- The population of Hong Kong is increasing with time and developments are taking place in close proximity to steep natural hillsides. The increase in population at risk from natural terrain landslides is not reflected in the historical landslide fatality and damage figures, which correspond to the state of development at the time of landsliding. The risk will continue to increase given the trend of developing land close to steep natural hillsides. This trend will be accentuated as a result of public resistance to new reclamation, which will drive even more developments close to steep hillsides.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

- Apart from posing a risk to life, natural hillside failures could also bring about economic loss and severe disruption to the community (e.g. see Box 11). This is of particular concern because a very large number of natural hillside landslides could occur within a local area subject to heavy rainfall. It is also noted that for Hong Kong's highly urbanized setting, even a relatively small-size natural terrain landslide could be damaging to facilities close to the hillside (e.g. see Box 12).

Box 11 - The 2000 Tsing Shan Debris Flows

About 120 natural terrain landslides occurred in the east-facing hillside of the Tsing Shan in the April 2000 rainstorm. A 1,600 m^3 bifurcated debris flow (Plate (a)) took place in the catchment next to that of the 1990 debris flow (Box 2). The 2000 debris flows started with a 150 m^3 landslide at the source, and involved significant entrainment along the channelized debris flow path (Plate (b)). An electricity pylon (Plate (b)) was damaged in the event. The debris affected an extensive foothill area, including a construction site and the golf-course at the toe of the hillside, an access road that runs from the construction site to Lung Mun Road (Plate (c)), and the Light Rail at Lung Mun Road (Plate (d)). It is fortunate that the debris flows have not resulted in any causalities. However, the economic loss and disruption to the community were still severe.

Plate (a) - The 2000 Tsing Shan debris flows

Plate (b) - Debris flow trail at the drainage line below the pylon

Plate (c) - debris deposited on the access road

Plate (d) - Light Rail affected

Box 12 - A Small but Potentially Damaging Hillside Landslide below Bowen Road

A small landslide occurred on a hillside below Bowen Road (Plate (a)) in 1998. The debris had a volume of about 20 m^3 only, but it directly hit the building below the hillside and resulted in some damage. Given the close proximity of the building to the hillside, the consequence of the failure could have been more serious if the landslide was of larger volume. Post-landslide investigation undertaken by the GEO found that discharge of water into the hillside from a leaked water main along the edge of Bowen Road probably contributed to triggering the landslide. The case illustrates that in Hong Kong's urban setting, even a relatively small-size hillside landslide could be damaging to facilities close to the steep hillside. Also, the stability of natural hillsides may also be affected by man-made influences, such as discharge of surface water and leakage of water-carrying services.

Plate (a) - A 20 m^3 landslide below Bowen Road in 1998

Table of Contents
Table of Contents
Table of Contents
Table of Contents

2.3 Rainfall Effects

The correlation between rainfall and natural terrain landslide density, based on data from 1985 to 2000, was assessed in Ko (2003). In the assessment, the normalized 24-hour rainfall, defined as the maximum rolling 24-hour rainfall divided by the mean annual rainfall, was adopted as an indicator of rainfall intensity. Natural terrain landslide density was calculated as the number of NTLI landslides divided by the area of natural terrain subject to different ranges of normalized 24-hour rainfall. As the correlation applies only to NTLI landslides, it does not account for smaller size landslides (landslides not identified in high-flight aerial photographs), less mobile failures and incidents within or adjoining Development Lines.

The findings of the correlation are summarized in Figure 7, and plotted graphically in Figure 8. A strong correlation between density of NTLI landslides and normalized 24-hour rainfall up to 35% is evident. There are insufficient data to establish the landslide density at normalized 24-hour rainfall exceeding 35%. However, as shown in Figure 8, an exponential trend in increase of NTLI landslide density with normalized 24-hour rainfall is apparent. The Hong Kong Observatory has assessed scenarios of 24-hour Probable Maximum Precipitation (PMP) for Hong Kong (Hong Kong Observatory, 1999; Chang & Hui, 2001). Based on extrapolation of the rainfall-landslide correlation, the expected number of NTLI landslides for PMP scenarios are shown in Table 2.

In the event of a PMP rainfall hitting a 10 km^2 area of natural terrain, a very large number of NTLI landslides (in the order of 10,000 to 20,000) would occur. Some 10% to 20% of the natural terrain area could detach, which is considered credible in light of the experience from other countries.

The analysis highlights the severe landslide situation that may arise from extreme rainfall events. Such extreme rainfall events have not occurred in Hong Kong in the past thirty years or so, the period during which landslide data have been systematically collected. However, records of some heavy rainstorms that have caused a large number of natural terrain landslides are available. These rainstorms, although less severe, do illustrate the possible devastating scenarios:

- In 4-5 November 1993, Lantau Island was hit by a rainstorm with normalized 24-hour rainfall ranging from about 10% to 35%, resulting in about 860 natural terrain landslides on Lantau Island (Box 13). The NTLI landslide density was about 7 no./km^2. Since Lantau Island was largely undeveloped at the time, there were no serious consequences apart from blockage of roads and catchwaters. Had the rainstorm hit other more densely populated parts of Hong Kong, the landslides would have resulted in very significant consequences.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Box 13 - Natural Terrain Landslides on Lantau Island in November 1993

Lantau Island was hit by a heavy rainstorm in November 1993 (Plate (a)). About 860 natural terrain landslides have occurred on Lantau Island in the rainstorm (Plates (b) to (d)). The normalized 24-hour rainfall on Lantau Island in the rainstorm ranged mainly from 10% to 35%. The NTLI landslide density on Lantau Island was about 7 no./km^2. The landslides resulted in blockage of roads and catchwaters, and as Lantau Island was largely undeveloped at the time, fortunately there were no casualties. The landslide consequences could have been very severe if the rainstorm hit a more developed part of Hong Kong.

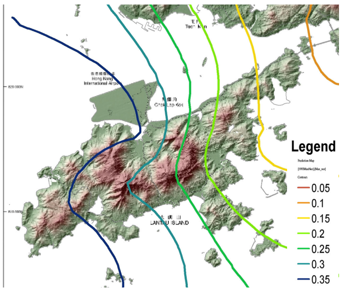


Plate (a) - Normalized 24-hr rainfall isohyets

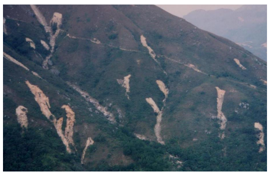


Plate (b) - Natural terrain landslides

Plate (c) - A drainage line swept by debris flow

Plate (d) - A debris flow near the present Tung Chung New Town

- In May and August 1982, Hong Kong was hit by two heavy rainstorms (Box 6). The normalized 24-hour rainfall of the two rainstorms ranged from 5% to 25%. A total of 1415 NTLI landslides were identified, and nine natural terrain landslide fatalities were reported. The average natural terrain landslide density on all the natural terrain of Hong Kong was 2.2 no./km^2. Hong Kong was less densely developed in 1982 and since then more developments have taken place closer to steep hillsides.

- In June 1966, a heavy rainstorm affected Hong Kong Island, with a normalized 24-hour rainfall ranging from about 10% to 25%. A total of 146 NTLI landslides took place over the 45 km^2 natural terrain of Hong Kong Island, i.e. NTLI landslide density on Hong Kong Island was about 3 no./km^2 (Box 14). It is noted that Hong Kong Island has a total of 358 recent NTLI landslides up to the year 2000, i.e. over 40% of these occurred in the 1966 rainstorm. Although a full picture of the landslide damage is not known, the limited available records show that the landslides had resulted in 64 fatalities, 29 people injured and admitted to hospital, 2,672 people homeless, 8,561 people temporarily evacuated and 407 houses damaged (Chen, 1969). It can be envisaged that if the rainfall is more severe, or if the area affected is more densely developed as is now than in 1966, even more serious consequences can be caused by natural terrain landslides in a severe rainstorm.

Table of Contents

Box 14 - Hong Kong Island in the June 1966 Rainstorm

Hong Kong Island was seriously disrupted by natural terrain landslides in the June 1966 rainstorm, with NTLI landslide density of about 3 no./km^2. Plate (a) shows a debris flow above Robinson Road in the Upper Glenealy Area. Plate (b) is a hillside failure that run into the junction of Magazine Road and May Road. Plate (c) shows the hillside above Victoria Road, where 18 debris flows occurred. Plate (d) shows open hillside landslides truncating Shek Pai Wan Road near Aberdeen. Breach of the Braemar reservoir resulted in large debris flow entraining soil, rock, cars, etc. along its flow path (Plate (e)). The Peak Tram track was also hit by debris and operation was reported to have stopped for 8 days (Plate (f)).

Plate (a) - Debris flow at the junction of Robinson Road with Upper Glenealy

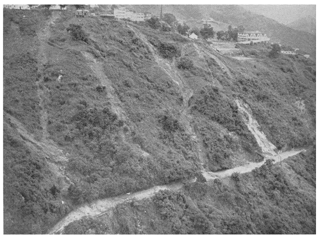


Plate (c) - Debris flows at Victoria Road

Plate (b) - Hillside failure at junction of Magazine Road and May Road

Plate (d) - Open hillside landslides at Shek Pai Wan Road

Plate (e) - Debris flow reaching North Point due to washout from Braemar Reservoir

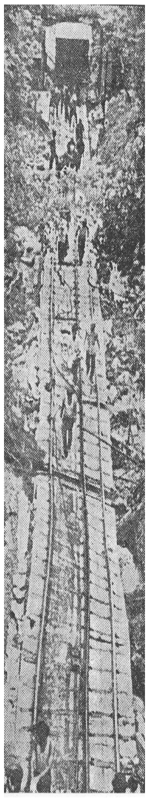


Plate (f) - Peak Tram affected by landslides

While the drastic increase in the density of natural terrain landslides at high rainfall intensities is evident, it is noteworthy from the rainfall-landslide correlation that some natural terrain landslides would occur at less intense rainfall conditions. Detailed studies undertaken by the GEO on selected natural terrain landslides in Hong Kong have confirmed that not all natural terrain landslides are triggered by heavy rainfall. Deterioration of ground conditions, which may in some cases result in development of open joints and tension cracks, is an important factor (Box 4). This is also demonstrated by the fact that a hillside that apparently has withstood a recent heavy rainstorm may fail in a subsequent less severe rainstorm. A possible circumstance where this could take place is that the ground has been distressed but not resulted in a mobile detachment of debris in the previous heavy rainstorm. With the deterioration of the ground, a landslide could be triggered by a subsequent rainstorm that has less severe rainfall intensity.

The 1990 Tsing Shan debris flow (Box 2) is an example of a large scale natural terrain landslide triggered by relatively low rainfall. Only about 110 mm of rain was recorded for the 24 hours before the debris flow. Apart from effects of ground deterioration, it is possible that the stormwater discharge conditions in the drainage line at the time of the debris flow could have affected the degree of debris entrainment and hence the magnitude of the landslide.

The 1995 Shum Wan Road landslide (Box 10), with a volume of 26,000 m^3, is another notable example. The landslide occurred in heavy rain, with about 330 mm recorded within 24 hours before the landslide. However, detailed post-landslide investigation has found that

Table of Contents
Table of Contents
Table of Contents
Table of Contents

uncontrolled discharge of surface water into the hillside from the road that traversed the upper part of the hillside had significantly increased the amount of water that reached the hillside and thereby triggered the massive landslide. The case illustrates that in Hong Kong's urban setting, environmental factors relating to surface drainage conditions and other man-made influences on the topographic setting could have significant effects on hillside stability, particular in terrain that is close to the development boundary. Hence, extreme landslide events could be the result of a combination of unfavorable environmental factors, and these would not necessarily occur in severe rainfall conditions.

2.4 Susceptibility Analysis and Hazard Zoning

Landslide susceptibility refers to the likelihood of a landslide occurring in an area. Susceptibility analysis is the process of assessing the relative landslide susceptibility of different types of hillside, usually on the basis of local terrain conditions. Landslide hazard zonation refers to division of the hillside into relatively uniform units and the categorization of these units according to their degree of actual or potential landslide susceptibility. Where landslide hazard zoning is based on potential landslide susceptibility, the reliability and resolution of the landslide hazard zoning are dependent on those of the susceptibility analysis.

A review of the work on natural terrain landslide susceptibility analysis that has previously been undertaken in Hong Kong is given in Wong (2003), in which the methodology adopted in different types of susceptibility analysis carried out at different scales are described and the key findings summarized. These include the 1:20,000-scale HK-wide susceptibility analysis on debris avalanche based on direct correlation of terrain attributes with NTLI landslide densities (Evans & King, 1998; see Box 15), the 1:5,000 regional susceptibility analyses on Lantau Island using Logistic Regression Techniques (Dai & Lee, 2002) and using Artificial Neural Network (ANN) Techniques (Lee et al, 2002), and the 1:2,000-scale area-based susceptibility analysis on the Tsing Shan Footfills using field mapping data (Maunsell Fugro Joint Venture, 2003).

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Box 15 - Susceptibility Analysis

The first territory-wide landslide susceptibility map in Hong Kong was prepared in 1998 (Evans and King, 1998), based on correlation of landslide susceptibility with slope angle and geology. Nineteen geological groups and thirteen slope angle classes were used, which resulted in some 247 different types of terrain units. The natural terrain landslides data were taken from the NTLI up to the year 1994. The analysis used a Digital Elevation Model created from the 1:20,000-scale 20 m contour topographic plans converted first into a Triangulated Irregular Network (TIN) model and then into a grid model (Plate (a)). The period of landsliding evident in the aerial photograph record was approximated to 100 years allowing a straightforward conversion from landslide density to landslide frequency. The actual susceptibility was increased by 20% to allow for landslides not recognized in the NTLI. Five susceptibility classes were defined: very low, low, moderate, high and very high with densities varying from <10 to >100 landslides per km^2 corresponding to frequencies varying from 0.1 to >1 landslide/yr/km^2 (Plate (b)).

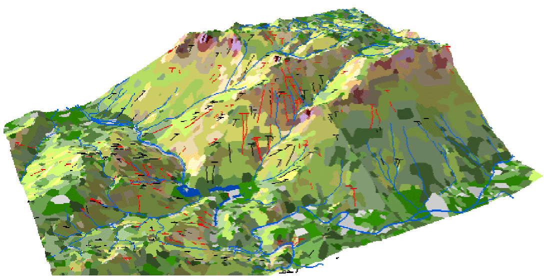


Plate (a) - Analysis of landslide susceptibility using 3-D GIS

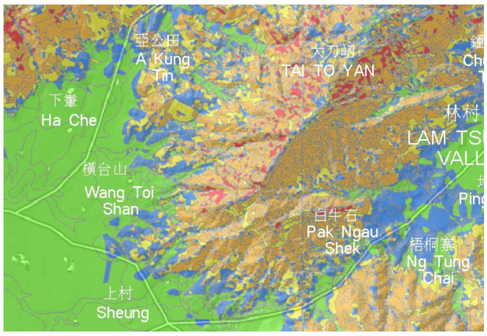


Plate (b) - Landslide susceptibility map

The following points summarize the current state of knowledge and capability:

(a) Where data are available, it is practical to carry out susceptibility analysis to obtain insight into 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.

(b) Hong Kong is rich in data at 1:20,000 to 1:5,000 scales. Regional analyses carried out at these scales gave reasonable statistical correlation for susceptibility categorization. While the analyses carried out are considered the state-of-the-art, the resolution achieved in terms of landslide frequency, which spans about one order of magnitude between the least and most susceptible zones, is still limited. These susceptibility analyses form an important part of the continued technical development work. But in practice, given the overall low resolution, hazard zoning derived from such analyses is of limited use for direct application in demarcating whether a hillside would be practically free from landslides or whether it would pose a major problem.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(c) The resolution and reliability of the susceptibility zoning can be improved in area-based studies at 1:2,000 to 1:1,000 scales, together with collation of supplementary data. This requires considerable resources, which are costly particularly if it covers a large area. The work completed in Hong Kong to date shows that the resolution may be improved to about two orders of magnitude in respect of landslide frequency. This improvement enhances hazard zoning and quantitative risk assessment. 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; Wong & Ho, 1998a).

(d) In view of the limitations of the susceptibility analyses completed to date, regional hazard zoning derived directly from 1:20,000 to 1:5,000 scales susceptibility analyses has not been adopted in Hong Kong. However, susceptibility classification and hazard zoning can be incorporated as part of risk assessment, in which other factors such as consequence assessment and sensitivity analysis are duly considered in deriving the risk level, either in a qualitative or quantitative manner, for risk management application.

(e) Where an area-based natural terrain hazard study is undertaken, such as the 1:2,000-scale study at Tsing Shan foothills, it is practical to supplement the findings of susceptibility analysis with assessment of credible landslide events and runout modelling for different landslide scenarios (Figure 9). The findings are useful for application to risk management.

(f) Formal QRA has been applied in Hong Kong for a number of 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 detailed study, quantified consequence assessment is carried out in addition to hazard assessment, for producing quantified risk figures and zoning (Figure 10). 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.

(g) The GEO is undertaking further development work to improve the understanding of landslide susceptibility of the natural hillsides in Hong Kong and the resolution of susceptibility analysis. Notable development includes integration with rainfall-landslide correlation, use of

Table of Contents
Table of Contents
Table of Contents
Table of Contents

improved methodology, and application of enhanced models and analytical approach. It is anticipated that the work would lead to improved capability in the identification of hillsides that are potentially more susceptible to landsliding. This would be useful to assessment and management of natural hillside landslide risk in Hong Kong. However, it is unlikely that the technology that is available in the foreseeable future will enable reliable prediction of where and when natural hillside landslides would occur.

2.5 Mitigation of Natural Hillside Landslide Risk

Unlike man-made slopes, it can be impractical to adopt conventional engineering methods to prevent natural hillside failures. The approach of undertaking stabilization works on man-made slopes is generally not suitable for dealing with natural hillside hazards. Given the large area of potentially unstable natural hillside involved, such works are likely to be very expensive. Also, widespread stabilization works on natural hillsides could cause considerable environmental problems, and are difficult to carry out safely. However, natural terrain landslide risk could be effectively mitigated through land-use planning and landslide mitigation measures, such as protective barriers, check dams, debris diversion, drainage provisions, and where appropriate, bioengineering methods (Figure 11). Where practical, non-engineering measures, such as permanent evacuation or relocation of the facilities, may be a cost-effective solution (Box 16). These measures have been adopted in Hong Kong, and technical guidelines on study and mitigation of natural terrain risk in Hong Kong are available (e.g. ERM, 1998, Lo, 2000 and Ng et al, 2003).

Box 16 - Distressed Hillside at Burma Lines Camp, Fanling

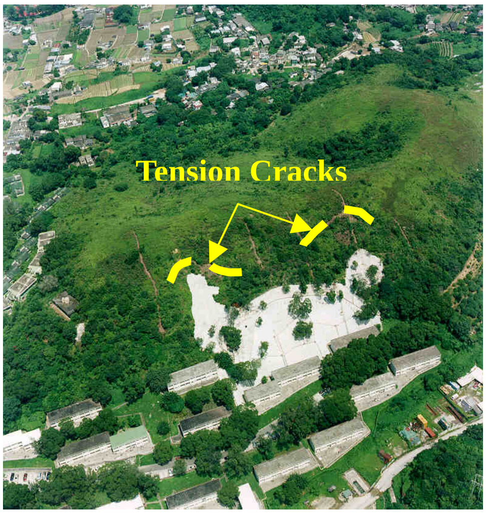


Plate (a) - Hillslide overlooking Government quarters at Burma Lines Camp

Extensive cracking at the hillside behind Burma Lines Camp at Fanling was found in 1997, and it was estimated that the distressed zone had a total volume of about 2,000 m^3 (Plates (a) and (b)). Although the registered cut slope at the toe of the hillside meets current standards, the natural terrain instability problem is found to be difficult to fix. As a result, four existing Government quarters buildings at the toe of the hillside were permanently evacuated.

Plate (b) - Tension cracks on the hillside

Table of Contents
Table of Contents
Table of Contents
Table of Contents

3. VULNERABLE CATCHMENTS CLOSE TO EXISTING DEVELOPMENTS

3.1 Recent Cases of Studies and Mitigation of Natural Terrain Landslide Risk Affecting Existing Developments

The GEO is adopting a ‘react-to-known-hazard’ approach in dealing with natural terrain landslide hazards affecting existing developments, i.e. to carry out studies and mitigation actions where significant hazards become evident (see Box 17). This approach is modelled on that adopted for dealing with boulder fall hazards from natural terrain since 1988.

Since 2000, actions have been taken on twelve sites based on this approach, following occurrence of recent landslides affecting the sites. The sites include (Figure 12):

(a) Burma Lines Camp, Fanling (Box 16)
(b) Leung King Estate, Tuen Mun (Box 18)
(c) Shek Lei Hill, Kwai Chung (Box 8)
(d) Luk Keng Wong Uk, Luk Keng
(e) Mok Law Shui Wah School, Lantau
(f) North Lantau Expressway near Tung Chung, Lantau
(g) Pak Sha Wan, Sai Kung
(h) Pat Heung, Yuen Long
(i) Sham Tseng San Tsuen, Sham Tseng (Box 7)
(j) Shatin Heights, Shatin (Box 19)
(k) Tung Wan Island Hostel, Lantau
(l) Tsing Shan Foothill, Tuen Mun
(m) Victoria Road near Cyberport, Pokfulam

Box 17 - React-To-Known-Hazard Principle

Under the ‘react-to-known-hazard’ principle, actions are taken where significant natural terrain landslide hazards become evident. This is modelled on the strategy adopted by the Government for dealing with boulder fall hazards affecting existing developments since 1988. This ‘react-to-known-hazard’ principle entails the following:

(a) Mitigation actions should be taken urgently where there exists an immediate and obvious danger.

(b) The natural terrain hazards should be studied where there is reason to believe that a dangerous situation could develop, and mitigation actions should be taken where considered necessary.

An ‘immediate and obvious danger’ situation typically refers to natural terrain that shows significant signs of distress, continuing hazardous movement or incipient instability, and which will involve a significant consequence to life or serious damage to property in the event of landsliding. A typical example in the category of ‘there is reason to believe that a dangerous situation could develop’ is where there have been in the past persistent landslides on natural terrain and where a significant consequence to life or serious damage to property may occur in the event of further landsliding. These cases are normally identified by the GEO through inspections of landslides, review of documentary records, studies for safety clearance of squatters, etc.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Box 18 - Debris Flows Affecting Leung King Estate

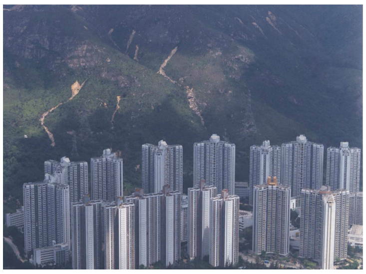


Plate (a) - Debris flows on the hillside above Leung King Estate in 2000

In April 2000 during heavy rain, a series of channelized debris flows occurred on the hillside above Leung King Estate, Tuen Mun (Plate (a)). The largest of these debris flows, with a total volume of about 600 m^3 (source and entrained volumes) deposited an estimated 400 m^3 of outwash material within the perimeter access road of the estate (Plates (b) and (c)). The remaining debris flows had total volumes ranging from 70 m^3 to 350 m^3. Four debris resisting barriers in the form of gabion structures, each of which was designed to check a 600 m^3 landslide debris, were constructed in four drainage lines to protect the estate from future channelized debris flows (Plate (d)).

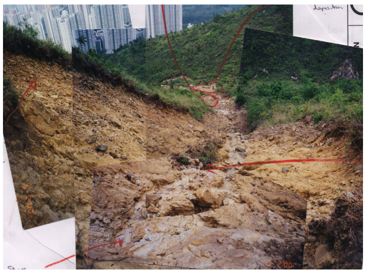


Plate (b) - The landslide source of a debris flow

Plate (c) - Debris flows reached the access road to the housing estate

Plate (d) - Debris-resisting barrier with 600 m^3 design debris retention volume

Box 19 - Hillside Landslides at Shatin Heights

Six landslides occurred on a small hillside at Shatin Heights in 1997 (Plate (a)). The debris of three of the landslides, involving a total volume of about 520 m^3 encroached onto and resulted in damage to residential developments at the toe of the hillside (Plate (b)). The natural terrain landslide risk was found to be not tolerable by QRA carried out after the landslides. Mitigation measures are designed based on QRA principles (Plate (c)), and their construction is in progress in 2004.

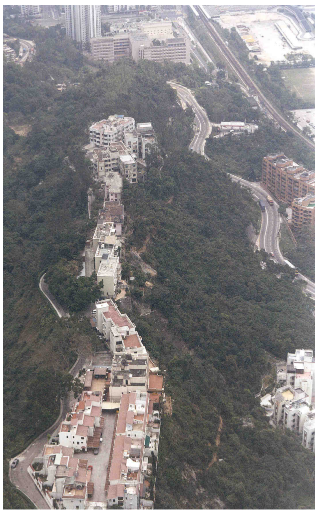


Plate (a) - Hillside at Shatin Height

Plate (b) - Debris flow in 1997

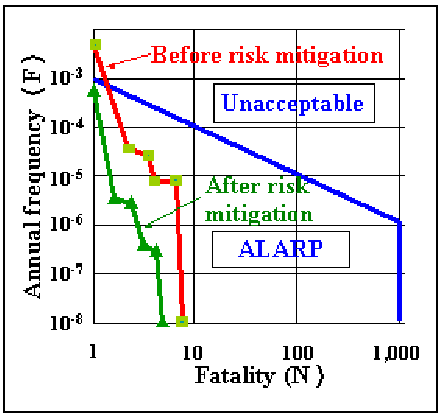


Plate (c) - Societal risk of natural terrain landslides before and after provision of risk mitigation measures

Table of Contents
Table of Contents
Table of Contents
Table of Contents

3.2 Identification of Catchments with Historical Natural Terrain Landslides Close to Existing Developments

It is evident that the sites listed in Section 3.1 present only part of the picture of natural terrain landslide hazards on existing developments, in that the sites were found to require action because the catchments have been hit by recent rainstorms resulting in landsliding. There are other vulnerable catchments that were hit by historical rainstorms with landslides occurring close to or debris reaching existing developments. These vulnerable catchments deserve special attention in risk assessment and management, as the hazards are already evident from known landslide events.

A systematic search of catchments with historical natural terrain landslides close to existing developments was not practical in the past due to the lack of information on historical natural terrain landslides and difficulty in analyzing the spatial relationship between landslides and existing facilities efficiently. With the compilation of the NTLI and application of Geographic Information System (GIS) techniques, a search has recently been carried out to identify natural terrain catchments with known NTLI landslides close to major developments (Figure 13), which comprise:

(a) Building structures, including building polygons and building lines as recorded in Land Information Centre's (LIC) 1:1,000-scale topographic maps of Hong Kong;

(b) Sensitive routes, including red routes, pink routes, routes to vulnerable areas, bus routes and bus depot routes as set out in Highways Department's strategic routes database (Highways Department, 2001); and

(c) Mass transportation facilities, including Kowloon Canton Railway (KCR), Mass Transit Railway (MTR), Light Rail Transit (LRT), Tramway and Peak Tram.

The methodology adopted and details of the work carried out in the GIS search are described in Appendix A. NTLI updated to the year 2000 was used in the search, based on the criteria shown in Figure 13. The NTLI and existing facilities that were identified from the search were checked by interpretation of aerial photographs and field inspection to validate that the relevant NTLI features are genuine landslides, the facilities are still in existence and that there is a credible path for the landslides to reach the facilities. A total of 656 NTLI landslide sources and 462 NTLI landslide debris trails were confirmed after the validation, i.e. genuine natural terrain failures close to major existing developments.

The catchments that contain the validated NTLI landslides were delineated and key data on the catchments and the facilities of concern were collated. The information is compiled into an inventory, which contains 453 catchments that cover a total plan area of about 5 km^2, i.e. within 1% of all the natural terrain in Hong Kong. The average plan area per catchment is about 0.01 km^2. The catchments are denoted as 'Historical NTLI Catchments' and the inventory is referred to as 'Inventory of Historical NTLI Catchments' in this report.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

A breakdown of the 453 Historical NTLI Catchments, based on the information available up to June 2004, is given in Figure 14. Some salient statistics on the catchments characteristics are given in Tables 3 and 4.

3.3 Delineation of Supplementary Catchments

For the purpose of the assessment of the overall risk of natural terrain landslides, information is required on catchments that are bordering development areas but have not been recorded as Historical NTLI Catchments in the exercise described in Section 3.2. These catchments could also pose natural terrain landslide risk on existing developments, and are denoted as 'Supplementary Catchments' in this report.

An Inventory of Supplementary Catchments has been compiled for five selected regions and six selected areas (Figure 15):

(a) Five selected regions (representing a broad range of geographic distribution and of catchment types), including Fan Kam, Mid-levels, Pak Sha Wan, Tsing Shan Foothills and Tsing Yi, which comprise 1018 Supplementary Catchments with a total plan area of 22.6 km^2; and

(b) Six selected areas (where detailed natural terrain hazard studies have been carried out; site-specific QRA was employed in some of the selected areas), including Shek Lei Hill, Luk Keng, Pat Heung, Shatin Heights, Tung Wan and Victoria Road, which comprise 43 Supplementary Catchments with a total plan area of 1.5 km^2.

Details of the work in delineating these Supplementary Catchments are given in Appendix A.

4. QUANTIFICATION OF NATURAL TERRAIN LANDSLIDE RISK

4.1 Background

Hong Kong is one of the leaders in the world in developing and applying QRA techniques to quantification and management of landslide risk (see Box 20). QRA has been adopted in Hong Kong at site-specific level to quantify the level of natural terrain landslide risk and establish the required risk mitigation measures for individual sites. QRA has also been applied at a global level, to assess the overall risk to life posed by the registered man-made slopes in Hong Kong and assist in the formulation of risk management strategy and targets for such slopes under the 10-year (2000 - 2010) Landslip Preventive Measures (LPM) Project.

A global QRA has been carried out in this study to quantify the overall level of risk posed by natural terrain landslides in Hong Kong, and to facilitate the assessment of the scale of the problem and development of future risk management strategy. The assessment is confined to evaluation of the risk to life, which is at par with the other formal global QRA

Table of Contents
Table of Contents
Table of Contents
Table of Contents

carried out in Hong Kong and elsewhere. In parallel with this exercise, an update of the global QRA on registered man-made slopes has been undertaken and the findings are reported in Lo and Cheung (2004).

Box 20 - Application of Landslide Quantitative Risk Assessment (QRA) in Hong Kong

QRA was developed, and is now used worldwide, to estimate risks from industrial plants, such as petrochemical facilities. Certain types of chemical plants and related facilities are designated Potentially Hazardous Installation (PHI) in Hong Kong, and the use of QRA for their risk estimation is well established. Guidance on land use planning in the vicinity of PHIs is given in the Hong Kong Planning Standards and Guidelines. Risk management is also practiced by major corporations in Hong Kong, including the HK China Gas Co., Mass Transit Railway Corporation and China Light & Power Co. Limited.

The GEO has pioneered the development of landslide QRA techniques and their application to landslide risk management in Hong Kong. QRA has been applied to two types of landslide risk assessment in Hong Kong:

(a) Global QRA - to assess the overall risk due to certain types of landslide hazard posed to the community. This provides a useful and valuable reference for landslide risk management, in particular, in the consideration of the scale of the problem, resources allocation and formulation of risk management strategies. Notable examples of global QRA carried out in Hong Kong include assessment of the overall risk from man-made slope failures (Wong & Ho, 1998a; Cheung & Shiu, 2002; and Lo & Cheung, 2004), boulder fall risk (Reeves et al, 1998) and earthquake-induced landslide risk (Wong & Ho, 1998b).

(b) Site-specific QRA - to assess the landslide risk at a given site. This is most useful for problems that may not be directly amenable to conventional slope stability analysis, or where a failure is liable to result in serious consequences. It facilitates the development of cost-effective mitigation strategy for management of the landslide risk on individual sites. It has been a professional practice in Hong Kong to use site-specific QRA in assessing the risk of natural terrain landslides and identifying the required risk mitigation actions. Notable examples include those reported in Ho et al (2000), Ho & Wong (2001), Fugro Maunsell Scott Wilson Joint Venture (2001) and OAP (2003). GEO Report No. 75 (ERM, 1998) provides interim risk guidelines that define the tolerable levels of societal and individual landslide risks from natural terrain and boulder falls (Plate (a)).

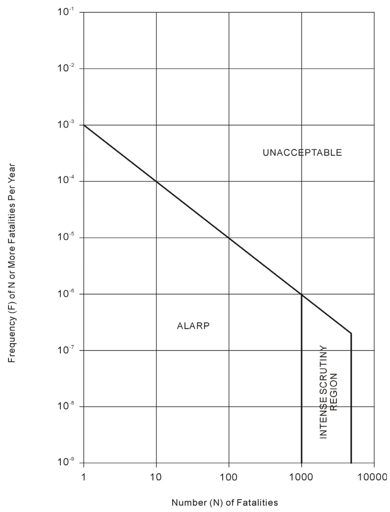


Plate (a) - Interim risk criteria for natural terrain landslides in Hong Kong

A web page (http://hkss.cedd.gov.hk/hkss/eng/studies/qra/) hyperlinked to the Hong Kong Slope Safety Website has been created to provide information on the development and application of QRA to geotechnical problems in Hong Kong.

4.2 Development of QRA Models

A comparison of the methodology adopted in this report for the global QRA on natural terrain landslides with that adopted for global QRA on man-made slopes is listed in Table 5. Given the considerations and circumstances specific to the assessment of the overall natural terrain landslide risk, considerable technical development work has been made as part of this global QRA to improve the QRA methodology and techniques. They include:

(a) Development of a natural terrain landslide frequency model, which cover the relevant natural terrain hazard scenarios, incorporate rainfall-landslide correlation and allow for Bayesian updating of the landslide probability with account taken of the historical NTLI frequency at individual catchments.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(b) Formulation of a new consequence model, which is a major update of the model developed by Wong et al (1997) for use in global QRA on man-made slopes, to cater for debris runout characteristics and consequence assessment specific to natural terrain landslides in Hong Kong.

(c) Implementation of a risk model that has been calibrated against site-specific QRA results and permits extrapolation of the risk of the Historical NTLI Catchments to the overall risk of natural terrain landslides in Hong Kong.

(d) Integration of GIS techniques with the global QRA, which enables undertaking the QRA on GEO's GIS platform with enhanced capability and improved efficiency.

In the global QRA, natural terrain landslide hazards are classified by a combination of the scale of landslide and mechanism of debris movement:

(a) Scale of landslide -

(i) H1 = 50 m^3 notional (20 m^3 to 200 m^3)
(ii) H2 = 500 m^3 notional (200 m^3 to 2,000 m^3)
(iii) H3 = 5,000 m^3 notional (2,000 m^3 to 20,000 m^3)
(iv) H4 = 20,000+ m^3 notional (>20,000 m^3)

(b) Mechanism of debris movement -

(i) C = channelized debris flow
(ii) T = mixed debris flow/avalanche along topographic depression
(iii) S = open slope debris slide/avalanche

Four Rainfall Scenarios A to D, as listed in Table 6 have been considered. In view of the significant uncertainties involved and the lack of reference data, the risk arising from extreme rainfall event with normalized 24-hour rainfall exceeding 35% has not been formally included in the risk quantification. However, an assessment of its possible contribution based on extrapolation of the QRA results has been made as part of the sensitivity analysis described in Section 5.

The frequency model, consequence model and risk model developed and adopted in the QRA are described in Appendices B, C and D respectively.

4.3 Assessment of Risk from Historical NTLI Catchments

The natural terrain landslide risk arising from the 453 Historical NTLI Catchments have been assessed, based on information on the catchments and the facilities at risk collated in the Inventory of Historical NTLI Catchments and application of the QRA models. The risk to life is quantified in terms of the annual potential loss of life (PLL).

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Use of the 'Best-estimate' model with Half-Bayesian update (Table 7) gives a calculated PLL of 1.4 per year for the 453 catchments. Breakdowns of the QRA results are given in Figure 16. The average risk per catchment is 3.1 x 10^{-3} PLL per year. The average risk of catchment affecting building structures (3.3 x 10^{-3} PLL per year) is higher than that affecting sensitive routes and mass transportation facilities (1.2 x 10^{-3} PLL per year). As each of the catchments affecting building structures has an average of 2.4 building structures at risk, the average risk on each building structure is 1.4 x 10^{-3} PLL per year.

The 453 Historical NTLI Catchments comprise 291 catchments affecting existing building structures, 56 catchments affecting dilapidated or demolished structures, and 75 catchments affecting sensitive routes and mass transportation facilities. The 56 catchments that affect dilapidated or demolished structures were taken as of negligible risk (PLL = 0) in the QRA, i.e. assuming that the structures would neither be re-occupied nor re-built. Another 10 catchments were found to have negligible risk (PLL = 0) by the QRA. Hence, by excluding these 66 catchments, the average risk-per-catchment for the 387 risk-bearing Historical NTLI Catchments is about 3.6 x 10^{-3} PLL per year.

The risk figures calculated from the global QRA have been benchmarked against those previously calculated at individual sites/areas from site-specific QRA. Shown in Figure 17 is the comparison made for Pat Heung and Shatin Heights. It illustrates that the global QRA results derived from the 'Best-estimate' model are comparable to those from the site-specific QRA, where detailed site information is available for analysis using tailor-made QRA techniques.

4.4 Assessment of Overall Natural Terrain Landslide Risk

The PLL of 1.4 per year calculated in Section 4.3 comes from the 453 Historical NTLI Catchments. This constitutes only part of the overall natural terrain landslide risk, because the Supplementary Catchments also pose some risk to the community.

In order to evaluate the relative contributions from the Historical NTLI Catchments and from the Supplementary Catchments, the global QRA has been extended to the five selected regions where data on the two types of catchments have been collated. The results are summarized in Table 8.

As discussed in Section 5.2 below, the results of the assessment are sensitive to assumptions made in QRA models, particular in respect of the degree of Bayesian Update adopted in the frequency model. As shown in Table 8, the 'Best-estimate' model indicates that the Global Risk Ratio, i.e. the ratio of the total calculated risk of all catchments (i.e. including the Historical NTLI Catchments and the Supplementary Catchments) to the risk of the Historical NTLI Catchments in the five regions, ranges from 2 to 4.

The five selected regions represent different settings in Hong Kong, and the range of the calculated Global Risk Ratios reflect variation in the contribution from the Supplementary Catchments to the overall risk on existing developments in the regions. As the Global Risk Ratio is assessed to be in the order of 2 to 4 (Table 8), this means that the 453 Historical NTLI Catchments constitute about 25% to 50% of the overall risk of natural terrain landslides on existing developments in Hong Kong. The other 50% to 75% of the risk comes from Supplementary Catchments, i.e. catchments near existing developments but without known

Table of Contents
Table of Contents
Table of Contents
Table of Contents

and/or validated NTLI landslides.

Using a mean Global Risk Ratio of 3, the overall risk of natural terrain landslides on existing developments in Hong Kong is found to be about 5 PLL per year. Adopting the 'Best-estimate' model with Half-Bayesian Update (Tables 7 and 8) together with the consideration of the additional risk increase due to extreme rainfall condition based on extrapolation (see Section 5.3(f)), the overall risk is also found to be about 5 PLL per year. Hence, the best-estimate overall risk of natural terrain landslides in Hong Kong is assessed to be 5 PLL per year.

5. EVALUATION OF HAZARD AND RISK

5.1 General

Quantified risk assessment provides a means of quantifying the risk figures, which assist in diagnosis of risk distribution and characteristics. As part of QRA, the calculated risk figures have been evaluated together with other information available to examine their sensitivity to the assumptions adopted and to assess their implications.

5.2 Sensitivity Analysis

NTLI data up to the year 2000 were used in developing the frequency model. As the data have already been analyzed via a statistically rigorous rainfall-landslide correlation, the frequency model would not be too sensitive to changes that may arise from further update of the NTLI.

The consequence model itself is independent of the spatial distribution of the existing facilities. However, in applying the consequence model to the QRA, the current development conditions as indicated in the LIC maps and validated from the field inspections (where these were carried out) have been considered. Hence, the calculated risk level refers to that of the current conditions. The future risk level, say in the year 2010, would be affected by increased developments on or close to natural hillside. The possible increase in risk due to this factor has not been accounted for in the QRA.

The sensitivity of the calculated risk of the 453 Historical NTLI Catchments to the key assumptions adopted in the frequency and consequence models has been examined. The findings are summarized in Table 7. Adopting alternative assumptions would give different calculated risks, but overall the results are not unduly sensitive to the assumptions made.

As a complete inventory of all natural terrain catchments in Hong Kong is not available, the overall risk has to be projected from the calculated risk of the Historical NTLI Catchments. This projection involves considerable uncertainties. Firstly, the number of Supplementary Catchments that have been examined in the five selected regions is relatively few and only limited data on the catchments are available. Secondly, the calculated risk ratios in different regions have considerable variations, which reflects the spatially variable nature of the problem (Table 8). Thirdly, the calculated risk ratio in a region is sensitive to the assumptions made on the degree of Bayesian updating allowed for in the frequency model (Table 8), which reflects the uncertainties involved in assessing the landslide susceptibility of

Table of Contents
Table of Contents
Table of Contents
Table of Contents

the catchments that have few NTLI records.

With account taken of the above, scenarios that bound the best-estimate calculated risk figures have been analyzed as follows (Table 7):

(a) Pessimistic Scenario: the calculated overall natural terrain landslide risk on existing developments in Hong Kong under this scenario is about 10 PLL per year.

(b) Optimistic Scenario: the calculated overall natural terrain landslide risk on existing developments in Hong Kong under this scenario is about 1 PLL per year.

Hence, it is estimated that the overall natural terrain landslide risk could range from 1 PLL per year to 10 PLL per year, with a best-estimate value of 5 PLL per year. The possible range of calculated risk reflects uncertainties in the assessment. The range is within an order of magnitude, and is considered among the best that can be practically achieved by state-of-the-art QRA.

Previous QRA on registered man-made slopes and the recent update in Lo and Cheung (2004) showed that the landslide risk from man-made slopes would reduce to about 5 PLL per year by the year 2010. The best-estimate of the overall natural terrain landslide risk is of similar order as that of registered man-made slopes upon completion of the current 10-year (2000 to 2010) LPM Project. This is reasonable and perceivable from professional consideration of the available landslide statistics and the likely scale of the problem. Hence, there is a need for increasing the attention to natural terrain landslides in formulating the future landslide risk management strategy for Hong Kong. As natural terrain landslides are more sizeable and a very large number of landslides could occur in a severe rainstorm, economic loss, major disruption to the community and the public's aversion to multiple fatalities would be of concern. These also point to the importance of dealing with natural terrain landslides in Hong Kong in a holistic and systematic manner.

5.3 Hazard and Risk Distribution

An analysis of the hazard and risk distribution was made based on examination of the QRA results on the Inventory of the Historical NTLI Catchments. The key observations are summarized below:

(a) Scale of Hazard

The distribution of risk according to different scales of hazard is presented in Figure 18. Hazard H2 (notional 500 m^3, typically ranging from 200 m^3 to 2,000 m^3) is the most significant hazard, which constitutes about 75% of the total risk. That H2 is sufficiently sizeable to cause major damage and that it has a much higher probability of occurrence than H3 and H4 are the key factors. This is consistent with the observation from the available historical natural terrain landslides with respect to the prominence of

Table of Contents
Table of Contents
Table of Contents
Table of Contents

events of such scale in causing damage. Also, mitigation works undertaken by the GEO in recent years based on the 'react-to-known-hazard' principle primarily deals with natural terrain landslide hazards at such scale.

Hazard H3 (notional 5,000 m^3, typically ranging from 2,000 m^3 to 20,000 m^3) has the largest share of risk in respect of building collapse. This illustrates the importance of more sizeable natural terrain landslide events in causing collapse of multi-storey building structures, where risk aversion to multiple fatalities would be a concern.

(b) Type of Catchment

The distribution of risk for different types of catchment is shown in Figure 19. For risk on building structures, about 80% of the risk comes from catchments where channelized debris flows could develop. This indicates the importance of the hazard scenario where a building structure is present along or close to a channelized debris flow path. The risk proportion of open slope landslides on sensitive routes and mass transportation facilities is much higher than that on building structures. This is related to the linear nature of such facilities, which renders them vulnerable to landslides that discharge at a debris flow point, as well as to open slope failures affecting a section of the linear facility at the toe of the hillside.

(c) Type of Facility

The distribution of risk according to facility types is given in Figure 20. About 60% of the risk on building structures in the Inventory of Historical NTLI Catchments comes from houses up to 3-storey, whereas the other 40% from multi-storey building structures. It should be noted that squatter structures, either registered or illegal, would not necessarily be shown in the LIC maps. Hence, they could be under-represented in the Inventory of Historical NTLI Catchments, which is based on spatial search on building structures given in the LIC maps.

The risk distribution also shows that the average risk on a multi-storey building is higher than that on a house (up to 3-storey). Furthermore, where a catchment is affecting a cluster of houses, the risk would be higher due to the presence of more population at risk. These suggest that among the Historical NTLI Catchments, those affecting multi-storey building structures and cluster of houses should in general deserve priority attention based on consideration

Table of Contents
Table of Contents
Table of Contents
Table of Contents

of the distribution of the calculated risk to life. From consideration of economic loss, disruption to the community and the public's aversion to multiple fatalities, these catchments would also deserve particular attention in risk management.

(d) Proximity of Facility to Catchment

Natural terrain landslide risk on a facility is significantly affected by the proximity of the facility to the hillside. For the 655 building structures that have been inspected and classified in the Inventory of the Historical NTLI Catchments, their proximity to the catchments concerned and the risk distribution are shown in Figure 21.

It is note-worthy that most of the building structures in the Inventory are located within Proximity Zones 3 to 5. The relatively few building structures in Zones 1 and 2 is probably indicative of the fact that developments in Hong Kong in general have not yet extended or come very close to the steepest part of the hillsides. The drop in the proportion of building structures in Zones 6 to 8 is the result of the GIS search criteria applied in compiling the Inventory, in that catchments with building structures located further away from the historical NTLI features are not included in the Inventory.

Building structures within Zones 1 to 4 have high calculated risk to life, with an average risk per building structure exceeding 10^{-3} PLL per year. Building structures within these zones are vulnerable to natural terrain landslide hazards. Sharp reduction of the calculated risk for building structures at Zone 5 and beyond is notable.

(e) Risk Ranking and Tolerability

The Historical NTLI Catchments can be ranked according to their calculated risk, as shown in Figure 22. It is evident that risk is not uniformly distributed among the catchments.

For catchments affecting building structures, the 100 highest-ranking catchments have an average risk per catchment exceeding 10^{-3} PLL per year. The risk of the catchments is comparable to, if not higher than, that of the catchments selected for follow-up action in recent years based on the 'react-to-known-hazard' principle. Site-specific QRA was carried out on some of these 'react-to-known-hazard' cases. It was established that risk mitigation measures are required based on consideration of the risk tolerability criteria and the 'As Low As Reasonably

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Practicable' (ALARP) principle, which are aligned with those adopted in mitigation of risk of Potentially Hazardous Installations (PHI) in Hong Kong. This highlights two notable issues:

(i) The global QRA indicates that a large number of the high ranking Historical NTLI Catchments in the Inventory of Historical NTLI Catchments constitutes a considerable risk. Study of the risk is necessary. It is likely that mitigation of the risk is required, based on experience from the 'react-to-known hazard' cases and alignment with risk mitigation strategy adopted in Hong Kong for PHIs.

(ii) The global QRA suggests that many high ranking Historical NTLI Catchments have a larger calculated risk than that of the catchments selected for follow-up action in recent years based on the 'react-to-known-hazard' principle. These Historical NTLI Catchments have not been previously selected for action because they have not yet been identified and their risk levels are not known. With the identification of these catchments and because it may not be practical to deal with all the catchments within a short period of time, systematic ranking of the catchments based on their priority for follow-up action would be useful to their risk management. The ranking should preferably be risk based, with account also taken of other relevant considerations, e.g. economic loss, the public's aversion to multiple fatalities and disruption to the community, etc.

(f) Projection to Extreme Event

The risk distribution according to different rainfall scenarios is given in Figure 23.

As noted in Section 2.3 above, limited data on normalized 24-hour rainfall exceeding 35% are available in Hong Kong, and projection of data to extreme events would involve considerable uncertainties. In recognition of such limitations, an attempt has been made based on linear extrapolation of the rainfall-landslide relationship to project the consequential landslide density at an extreme Rainfall Scenario E, at an annual probability of 0.002. By alignment with the QRA results for Rainfall Scenarios A to D, it is estimated that an additional 30% increase in the calculated risk (Figure 23) would arise from Rainfall Scenario E.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

5.4 Other Hillside Failures

The global QRA presented in this report covers landslides from natural terrain outside the Year 2000 Development Lines. Landslides within the Year 2000 Development Lines are not recorded in the NTLI. Hence, hillsides within the Development Lines, irrespective of whether hillside failures have occurred or not, are not considered in compiling the Historical NTLI Catchments and the Supplementary Catchments. Also, it is possible that some genuine natural hillside landslides that occurred in the vicinity of the Year 2000 Development Lines may not have been identified as NTLI features due to the limitation of resolution using high-flight aerial photographs in compiling the NTLI. Therefore, the global QRA results exclude the risk due to hillsides within or in the vicinity of the Year 2000 Development Lines.

Most of the hillsides within or in the vicinity of the Development Lines could have been disturbed or modified by man-made activities, e.g. local cutting and filling of different extent. They form a specific type of hillside problem, and landslide incidents on such hillsides are reported to the GEO from time to time. As the local cutting and filling do not result in a sizeable man-made slope features, they would not be registered in the Catalogue of Slopes and hence their potential risk is also not considered in the global QRA on registered man-made slopes (Lo & Cheung, 2004). Where the landslide is principally confined to the local cut and fill, the scale of failure is small and it would normally not result in any serious consequences unless it directly affects some vulnerable facilities, e.g. flimsy structures (Figure 24). However, where the landslide involves a significant portion of the hillside, the consequence and hence the risk of landslide would escalate as the debris volume increases (Figure 25). The landslide risk from these hillsides has not yet been quantified, and further work on assessing the potential scale of the problem is being carried out by the GEO.

The risk of boulder falls from natural hillside has been assessed to be about 0.05 PLL per year (MGSL, 2001). As the calculated risk of boulder fall is much lower than that of natural terrain landslides, it would have minimal contribution to the overall risk of hillside failures. However, as risk of boulder falls forms part of the overall risk of hillside failures, boulder fall hazards should be considered together with other types of hillside landslide hazard in risk assessment and management.

5.5 Areas for Further Work

Further works is required in the following areas on assessing and managing natural hillside landslide risk:

(a) Formulation of Risk Management Strategy for Natural Hillside Landslide Hazards Affecting Existing Developments

The Historical NTLI Catchments are known locations where recent natural terrain landslides have occurred close to existing developments. The global QRA indicates that many of these catchments may not have a tolerable risk. They deserve priority attention in the formulation of strategy for studying the risk and arrangement of any risk mitigation actions found necessary. The global QRA also

Table of Contents
Table of Contents
Table of Contents
Table of Contents

shows that other catchments are posing risk on the existing developments. It is therefore important that the strategy should include identification of the other vulnerable catchments and provision for taking integrated follow-up actions on the Historical NTLI Catchments and the other vulnerable catchments, possibly based on the use of a systematic priority ranking system. These could involve undertaking different stages of work, as illustrated in Box 21.

Box 21 - Possible Framework of Follow-up Action for Systematic Mitigation of Natural Terrain Landslide Risk on Existing Developments

Follow-up action (Plate (a)) on systematic study and mitigation of natural terrain landslide risk on existing developments in Hong Kong may include two parts:

(1) Regional Natural Terrain Hazard Review (NTHR) - Regional reviews of natural terrain landslide hazards, which are aimed at collation and validation of data, identification of vulnerable Supplementary Catchments, preliminary risk assessment, and grouping and ranking of sites for further action.

(2) Natural Terrain Risk Assessment and Mitigation (NTRAM) - Based on the findings of the regional reviews, catchments found to require attention may be ranked systematically for detailed natural terrain risk assessment and mitigation.

Boulder fields that are present in the catchments can be included in ranking and arrangement of follow-up action.

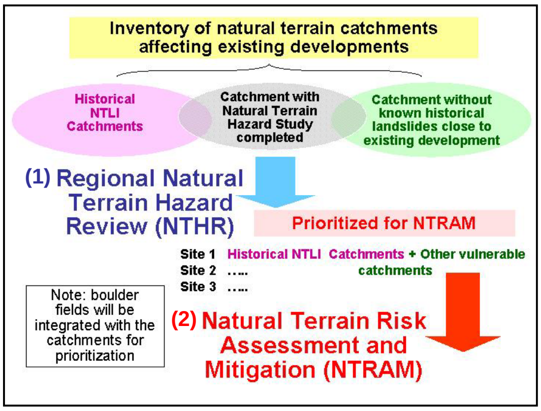


Plate (a) - Possible scope of follow-up work

(b) Identification of Other Vulnerable Catchments

Identification of the other vulnerable catchments is a technically difficult task. The work requires interpretation of low-flight aerial photographs, detailed review of the records of reported landslide incidents and landslide susceptibility analysis, and regional review of natural terrain hazards. Collation of data on Supplementary Catchments, hillsides within or in the vicinity of the Year 2000 Development Lines and vulnerable facilities including squatter structures is necessary. It is anticipated that the work would lead to identification of some vulnerable catchments.

(c) Priority Ranking

The risk to life calculated by the global QRA could be used as a catchment-based preliminary risk-ranking criterion. However, some other factors, which may not have been adequately reflected in the calculated risk to life, would deserve consideration in the formulation of the priority ranking methodology. These include economic loss, disruption to the community, the public's aversion to

Table of Contents
Table of Contents
Table of Contents
Table of Contents

multiple fatalities, and the possibility of taking area-based, integrated follow-up actions.

(d) Refinement of Global QRA

The global QRA model would warrant further refinement to enhance its use in assessing the global risk of Supplementary Catchments and hillsides within or in the vicinity of the Development Lines, and to improve its resolution in applying to special circumstances, such as dealing with squatter structures. Possible future refinements include alternative means of allowance for recognition factors and Bayesian updating for historical landslides, consideration of landslide susceptibility in frequency assessment, and use of more detailed debris runout model, etc.

(e) Maintenance of Inventory of Historical NTLI Catchments

It is perceivable that the number of Historical NTLI Catchments would grow with time, as new natural terrain landslides occur. Based on the 453 Historical NTLI Catchments from recent natural terrain landslides that occurred close to existing developments over the past 50 years or so, the average growth rate of the number of Historical NTLI Catchments would be in the order of 10 nos. per year. While some of the new NTLI landslides may occur on catchments that have already been identified as Historical NTLI Catchments, there are now more existing developments close to steep hillside than in the past. The above estimated order of rate of increase in the number of Historical NTLI Catchments is realistic, and is probably not conservative.

As a good practice in landslide risk management, the Inventory of Historical NTLI Catchments should be updated regularly. Where a priority ranking approach is adopted in future for systematic study and mitigation of natural terrain landslide risk, consideration should be given to expanding the Inventory to include other known vulnerable catchments.

6. CONCLUSIONS

The global QRA on the overall risk of natural terrain landslides has the following key conclusions, which are important to the formulation of future landslide risk management strategy in Hong Kong:

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(a) A GIS Inventory of 453 Historical NTLI Catchments has been compiled, which comprises 291 catchments affecting existing building structures, 56 catchments affecting dilapidated or demolished structures, and 75 catchments affecting sensitive routes and mass transportation facilities.

(b) The best estimated risk to life of natural terrain landslides arising from the Historical NTLI Catchments is 1.4 PLL per year. The 56 catchments that affect dilapidated or demolished building structures were taken as of negligible risk (PLL = 0) in the QRA, i.e. assuming that the structures would neither be re-occupied nor re-built. Another 10 catchments were found to have negligible risk (PLL = 0) by the QRA.

(c) The average risk-per-catchment for the 387 risk-bearing Historical NTLI Catchments is about 3.6×10^{-3} PLL per year. This is comparable to that of the catchments found to have required follow-up actions in recent years based on the 'react-to-known-hazard' principle. Landslide risk is unevenly distributed among the catchments, and it is likely that a large number (e.g. the top-ranking catchments in terms of the calculated risk) of the Historical NTLI Catchments would require risk mitigation, based on experience from the 'react-to-known-hazard' cases and alignment with the risk mitigation strategy adopted for dealing with PHIs in Hong Kong.

(d) Projection of risk from the Historical NTLI Catchments based on assessment of the Supplementary Catchments indicates that the Historical NTLI Catchments constitute about 25% to 50% of the overall risk of natural terrain landslides on existing developments in Hong Kong. The balance of 50% to 75% of the overall risk comes from Supplementary Catchments, i.e. other vulnerable catchments affecting existing developments but not included in the Inventory of Historical NTLI Catchments.

(e) The best-estimated overall risk of natural terrain landslides on existing developments in Hong Kong is 5 PLL per year. This calculated risk to life is of comparable order to that of registered man-made slopes by the year 2010.

(f) Sensitivity analyses of the optimistic and pessimistic scenarios show that the overall calculated risk of natural terrain landslides may range from 1 to 10 PLL per year. The range of calculated risk reflects uncertainties in the assessment. The range is within an order of magnitude, and is considered among the best that can be practically achieved by state-of-the-art QRA.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(g) The number of Historical NTLI Catchments would increase with time, as new natural terrain landslides occur. The average growth rate would be in the order of 10 nos. per year.

(h) The risk of natural terrain landslides in Hong Kong will continue to increase as more developments take place close to steep hillside.

(i) Identification of the other vulnerable catchments, particularly those with few historical landslide records, is a technically difficult task. Some areas requiring further work have been identified.

(j) The global QRA covers only risk to life as expressed in PLL. Other consequences of natural terrain landslides, such as economic loss, disruption to the community and the public's aversion to multiple fatalities, are not reflected in the calculated risk figures. Professional evaluation based on qualitative assessment of the available landslide data, landslide characteristics, rainfall-landslide correlation, etc., indicate that consequences other than risk to life are of concern in natural terrain landslides.

(k) Hillside failures within and in the vicinity of the Year 2000 Development Lines, which are not included in this global QRA, deserve attention. Further work to assess the potential scale of the problem is being undertaken by the GEO.

7. REFERENCES

Chang, W.L. & Hui, T.W. (2001). Probable maximum precipitation for Hong Kong. Proceedings of the 14th Southeast Asian Geotechnical Conference, Hong Kon*g*, vol. 3, pp 193 - 196.

Cheung, W.M. & Shiu, Y.K. (2002). Assessment of Global Landslide Risk Posed by Pre-1978 Man-made Slope Features: Risk Reduction from 1977 to 2000 Achieved by the LPM Programme. GEO Report No. 125, Geotechnical Engineering Office, Hong Kong, 63 p.

Chen, T.Y. (1969). Supplement to Meteorological Results 1966 - The Severe Rainstorms in Hong Kong during June 1966. Royal Observatory, Hong Kong, 79 p.

Dai, F.C. & Lee, C.F. (2002). Terrain-based mapping of landslide susceptibility using a geographic information system: a case study. Canadian Geotechnical Journal, vol. 38, pp 911 - 923.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

ERM-Hong Kong Limited (1998). Landslides and Boulder Falls from Natural Terrain: Interim Risk Guidelines. GEO Report No. 75, Geotechnical Engineering Office, Hong Kong, 183 p.

Evans, N.C. & King, J.P. (1998). The Natural Terrain Landslide Study - Debris Avalanche Susceptibility. Technical Note No. TN 1/98, Geotechnical Engineering Office, Hong Kong, 96 p.

Fugro (Hong Kong) Limited (2003). Natural terrain landslide hazard, mobility and risk assessment. Natural Terrain Hazard Study for Tsing Shan Foothill Area, Report to Geotechnical Engineering Office, Hong Kong, 2 volumes.

Fugro (Hong Kong) Limited (2004). Quantitative Risk Assessment of Landslides Affecting Squatters - Report for Final Study. Report to Geotechnical Engineering Office, Hong Kong.

Fugro Maunsell Scott Wilson Joint Venture (2001). Detailed Study of the Hillside Area below Sha Tin Heights Road. Landslide Study Report No. LSR 4/2001, Geotechnical Engineering Office, Hong Kong, 204 p.

Geotechnical Engineering Office (2004). Catalogue of Slopes. Information Note No. 25/2004, Geotechnical Engineering Office, Hong Kong, 4 p.

Highways Department (2001). Red and Pink Routes, Public Transport Sensitive Routes and Routes to Vulnerable Areas - Emergency Procedures. HyD Technical Circular No. 5/2001, Highways Department, Hong Kong.

Ho, K.K.S., Leroi, E. & Roberds, W. (2000). Quantitative risk assessment - application, myths and future direction. (Invited paper). Proceedings of International Conference on Geotechnical and Geological Engineering (GEOENG 2000), Melbourne, vol. 1, pp 269 - 312.

Ho, K.K.S. & Wong, H.N. (2001). The role of quantitative risk assessment in landslide risk management. Proceedings of the Fourteenth Southeast Asian Geotechnical Conference, Hong Kong, vol 1, pp 123 - 128.

Hong Kong Observatory (1999). The Probable Maximum Precipitation Updating Study for Hong Kong. Hong Kong Observatory, Hong Kong, 33 p.

Ko, F.W.Y. (2003). Correlation between Rainfall and Natural Terrain Landslide Occurrence in Hong Kong. Special Project Report No. SPR 7/2003, Geotechnical Engineering Office, Hong Kong, 74 p.

King, J.P. (1999). Natural Terrain Landslide Study - The Natural Terrain Landslide Inventory. GEO Report No. 74, Geotechnical Engineering Office, Hong Kong, 127 p.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Lee, C.F., Ye, H., Yeung, M.R., Shan, X., & Chen, G. (2002). Application of Artificial Intelligence to natural terrain landslide susceptibility mapping in Hong Kong. Proceedings of the Conference Natural Terrain - A Constraint to Development, Institution of Mining and Metallurgy - Hong Kong Branch, pp 223 - 237.

Lo, D.O.K. (2000). Review of Natural Terrain Landslide Debris-resisting Barrier Design. GEO Report No. 104, Geotechnical Engineering Office, Hong Kong, 91 p.

Lo, D.O.K. & Cheung, W.M. (2004). Assessment of Landslide Risk of Man-made Slopes in Hong Kong. Special Project Report No. 4/2004, Geotechnical Engineering Office, Hong Kong.

Maunsell Geotechnical Services Limited (2001). Territory Wide Quantitative Risk Assessment of Boulder Fall Hazards - Stage 2 Final Report. Report to Geotechnical Engineering Office, Hong Kong, 72 p. plus 9 Appendices.

Maunsell Fugro Joint Venture (2003). Natural Terrain Hazard Study for Tsing Shan Foothill Area - Landslide Susceptibility Analysis. Report to Geotechnical Engineering Office, Hong Kong, 71 p, plus 2 Appendices.

Ng, K.C., Parry, S., King, J.P., Franks, C.A.M. & Shaw, R. (2003). Guidelines for Natural Terrain Hazard Studies. GEO Report No. 138, Geotechnical Engineering Office, Hong Kong, 138 p.

Ove Arup and Partners Hong Kong Limited (2003). Natural Terrain Hazard Study at Pat Heung, Yuen Long. Advisory Report No. ADR 1/2003, Geotechnical Engineering Office, Hong Kong, 266 p.

Reeves, A., Chan, H.C. & Lam, K.C. (1998). Preliminary quantitative risk assessment of boulder falls in Hong Kong. Proceedings of Seminar on Slope Engineering in Hong Kong, Hong Kong, A.A. Balkema Publisher, pp 185 - 191.

Sun, H.W. & Evans, N.C. (1999). The Average Annual Global Risk from Natural Terrain Landslides in Hong Kong in 1994. Technical Note No. TN 5/99, Geotechnical Engineering Office, Hong Kong, 44 p.

Wong, H.N. (2001). Recent advances in slope engineering in Hong Kong. (Invited paper). Proceedings of the 14th Southeast Asian Geotechnical Conference, Hong Kong, vol. 1, pp 641 - 659.

Wong, H.N. (2003). Natural terrain management criteria - Hong Kong practice and experience. (Invited paper). Proceedings of the International Conference on Fast Slope Movements: Prediction and Prevention for Risk Mitigation, Naples, Italy, vol. 2 (in press).

Wong, H.N., Ho, K.K.S. & Chan, Y.C. (1997). Assessment of consequence of landslides. (Theme Paper). Proceedings of the International Workshop on Landslide Risk Assessment, Honolulu, pp 111 - 149.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Wong, H.N. & Ho, K.K.S. (1998a). Overview of risk of old man-made slopes and retaining walls in Hong Kong. Proceedings of Seminar on Slope Engineering in Hong Kong, Hong Kong, A.A. Balkema Publisher, pp 193 - 200.

Wong, H.N. & Ho, K.K.S. (1998b). Preliminary Quantitative Risk Assessment of Earthquake-induced Landslides at man-made Slopes in Hong Kong. GEO Report No. 98, Geotechnical Engineering Office, Hong Kong, 69 p.

Wong, H.N. & Ho, K.K.S. (2000). Learning from slope failures in Hong Kong. (Keynote paper). Proceedings of the Eighth International Symposium on Landslides, Cardiff (in CD).

Table of Contents
Table of Contents
Table of Contents
Table of Contents

LIST OF TABLES

Table of Contents
Table of Contents
Table of Contents

Table 1 - Landslide Fatalities between 1980 and 2003

Period	No. of Fatalities due to Landslides from Natural Hillsides	No. of Fatalities due to Landslides from Man-made Slopes	Total no. of Fatalities
1980 to 1989	13 [(2), (3)]	21 [(4)]	34
1990 to 1999	3	13	16
2000 to 2003	0	0	0
Sum (1980 to 2003)	16 [(2), (3), (5)]	34 [(4), (6)]	50

Notes:

(1) In this Table, landslides from natural hillsides include slope failures and boulder falls from hillsides that are predominantly natural, i.e. not significantly modified by human activities. Landslides from man-made slopes include (a) landslides on predominantly man-made slope features (e.g. the 1992 Baguio Villas and 1995 Fei Tsui Road landslides), (b) landslides on disturbed terrain involving predominantly ground disturbed by man-made activities (e.g. the 1982 Lam Tin Third Village Second Section landslide), and (c) landslides involving a registerable man-made slope feature and a significant portion of the hillside above it (e.g. the 1993 Cheung Shan landslide and the 1997 Kau Wah Keng landslide). Although Items (b) and (c) are not classified as natural hillside landslides in this Table, they fall partly within the 'hillside' category in that they involve sloping terrain that is outside the boundaries of registerable man-made slopes.

(2) Nine of the fatalities occurred in two rainstorms in 1982.

(3) Two of the natural terrain landslide fatalities are due to boulder falls. Both occurred in 1981.

(4) Sixteen of the fatalities occurred in two rainstorms in 1982.

(5) Thirteen of the fatalities were due to landslides affecting squatter structures.

(6) Sixteen of the fatalities were due to landslides affecting squatter structures.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 2 - Expected Number of NTLI Landslides at Probable Maximum Precipitation (PMP)

Area Affected by Rainfall (km^2)	PMP (mm)	Typical Normalized 24-hr Rainfall	NTLI Density (No/km^2)	Natural Terrain Area Affected by Rainfall (km^2)	Expected No. of NTLI Landslides
10	1250	56%	1,000 (1)	10	10,000 (4), (5)
100	930	41%	60 (1)	100	6,000 (5)
500	690	31%	8.3	400 (2)	3,300
1,000	580	26%	3.4	659 (3)	2,200

Notes:
(1) Based on extrapolation of the rainfall-landslide correlation and is subject to considerable uncertainties.
(2) Assuming natural terrain occupies 80% of the area hit by the rainfall.
(3) Total natural terrain area outside the Year 2000 Development Lines is 659 km^2.
(4) Assuming a landslide has an average plan source area of 10 m by 10 m, the total surface area of landslide in the 10 km^2 zone is 1 km^2, i.e. 10% of the natural terrain would have failed.
(5) The terrain affected by the rainfall is assumed to have average landslide susceptibility. If the rain falls on terrain that is more susceptible to landsliding, the expected number of NTLI landslides will be higher than that given in the Table. In the susceptibility analysis carried out by Evans & King (1998), about 33% of the natural terrain in Hong Kong was placed in the 'Very High' to 'High' groups. The rainfall-landslide correlation has found that landslide density on terrain in the two groups could be twice as that on an average terrain subject to the same rainfall. This implies that if the 10 km^2 terrain hit by PMP is within the two groups, about 20,000 NTLI landslides may occur, which can involve detachment of 20% of the natural terrain area.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 3 - Geographic Distribution of Different Types of the 453 Historical NTLI Catchments

Location		Number of Catchments			
		Channelized Debris Flow	Topographic Depression	Open Hillside	All
Hong Kong Island	Affecting Building Structures	40	8	29	77
	Affecting Sensitive Routes and Mass Transportation Facilities	8	0	7	15
Kowloon and New Territories	Affecting Building Structures	99	23	103	225
	Affecting Sensitive Routes and Mass Transportation Facilities	11	6	23	40
Other Outlying Islands	Affecting Building Structures	36	7	33	76
	Affecting Sensitive Routes and Mass Transportation Facilities	11	0	9	20
Total		205	44	204	453

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 4 - Catchment Size and Number of Validated NTLI Landslides

<table>
<tr><th rowspan="2">Size of Catchment</th><th colspan="4">Number of Catchments
(Average Number of Validated NTLI Landslides per Catchment)</th></tr>
<tr><th>Channelized Debris Flow</th><th>Topographic Depression</th><th>Open Hillside</th><th>All</th></tr>
<tr><td>Very Large</td><td rowspan="2">54
(4.2)</td><td rowspan="2">1
(2.0)</td><td rowspan="2">26
(3.0)</td><td rowspan="2">81
(3.8)</td></tr>
<tr><td>Large</td></tr>
<tr><td>Medium</td><td>86
(2.0)</td><td>19
(1.9)</td><td>89
(1.6)</td><td>194
(1.8)</td></tr>
<tr><td>Small</td><td>65
(1.2)</td><td>24
(1.3)</td><td>89
(1.2)</td><td>178
(1.2)</td></tr>
<tr><td>Total</td><td>205
(2.3)</td><td>44
(1.6)</td><td>204
(1.6)</td><td>453
(1.9)</td></tr>
</table>

Notes: The size of catchment is classified as follows:

<table>
<tr><th rowspan="2"></th><th colspan="4">Plan Area of the Portion of Catchment Steeper Than 15° (km^2)</th></tr>
<tr><th>Very Large</th><th>Large</th><th>Medium</th><th>Small</th></tr>
<tr><td>Channelized Debris Flow and Topographic Depression</td><td colspan="2">Greater than 20,000</td><td>Between 5,000 and 20,000</td><td>Smaller than 5,000</td></tr>
<tr><td>Open Hillside</td><td colspan="2">Greater than 10,000</td><td>Between 3,000 and 10,000</td><td>Smaller than 3,000</td></tr>
</table>

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 5 - Comparison of Global QRA on Man-made Slopes and Natural Terrain

	Man-made Slope QRA	Natural Hillside QRA
Data	♦ Full catalogue (≈ 57000 slopes) ♦ Comprehensive SIS information ♦ Detailed reported incidents	♦ Partial catalogue (453 Historical NTLI Catchments) ♦ Little information available on natural hillsides ♦ NTLI less detailed/complete ♦ Data collated for compilation of inventory and risk assessment
Model	♦ Refinement to existing frequency model (Wong & Ho, 1998a) ♦ Use existing consequence model (Wong et al, 1997)	♦ Existing frequency model not applicable; existing consequence model not reliable for assessment ♦ New frequency and consequence models developed
Approach	♦ Calculated PLL benchmarked with previous global QRA (Wong & Ho (1998a) and Cheung & Shiu (2002)) ♦ Different types of slopes classified and their calculated risks compared	♦ New approach of risk quantification developed and adopted, which includes use of rainfall-landslide correlation, provision for Bayesian updating, and risk projection ♦ Sensitivity analysis carried out

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 6 - Rainfall Scenarios for QRA

Rainfall Scenario	Normalized 24-hour Rainfall	NTLI Landslide Density (No./km^2)	Annual Frequency of Occurrence
A	≤10%	0.0593	0.8130
B	>10 – 20 %	0.4387	0.4785
C	>20 – 30 %	2.3354	0.0608
D	>30 – 35 %	10.6811	0.0035
Note:	An extreme Rainfall Scenario E, with normalized 24-hour rainfall >35%, has been considered in the sensitivity analysis.		

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 7 - QRA Results and Sensitivity Analysis for the 453 Historical NTLI Catchments

Model	Degree of Bayesian Update (see Table 8 for Definitions)	Risk of Inspected Building Structures (PLL/year)	Risk of Sensitive Routes and Mass Transportation Facilities (PLL/year)	PLL of 453 Historical NTLI Catchments[4]
Best-Estimate	Half Bayesian Update[3]	1.1551	0.0947	1.4
	No Bayesian Update	0.3988	0.0334	0.5[5]
	Full Bayesian Update	1.9113	0.1561	2.2[6]
Low[1]	Half Bayesian Update	1.0448	0.0924	1.2
High[2]	Half Bayesian Update	1.8606	0.2109	2.2[6]
	No Bayesian Update	0.6274	0.0672	0.7
	Full Bayesian Update	3.0938	0.3546	3.7

Notes:

(1) Adopt lower Vulnerability Factors for building collapse and lower debris mobility for catchments with mixed debris avalanche and flow along topographic depression than those adopted in the ‘Best-estimate’ model.

(2) Adopt higher Vulnerability Factors for Hazard H1 and higher population at risk than those adopted in the ‘Best-estimate’ model.

(3) This is the model adopted to give the best estimated QRA results on the 453 Historical NTLI Catchments as shown in Figure 16.

(4) Based on (1.089 x Risk of Inspected Building Structures) + Risk of Sensitive Routes and Mass Transportation Facilities (Figure 16).

(5) This was taken in combination with the Global Risk Ratio of 2.0 (No Bayesian Update and without Increased Facilities in Table 8) as the Optimistic Scenario. The corresponding overall risk in Hong Kong is: 0.5 x 2.0 = 1 PLL/year.

(6) This was taken as the Pessimistic Scenario, in combination with either (a) a Global risk Ratio of 4.1 (Conservative Bayesian Update with 100% Increased Facilities in Table 8); i.e. risk = 2.2 x 4.1, or (b) a Global Risk Ratio of 3.3 (Conservative Bayesian Update in Table 8) together with a 30% increase in risk due to the extreme Rainfall Scenario E (Figure 23); i.e. risk = 2.2 x 3.3 x 1.30. Both cases give an overall risk of about 10 PLL per year.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table 8 - Results of QRA on Supplementary Catchments in Five Selected Regions

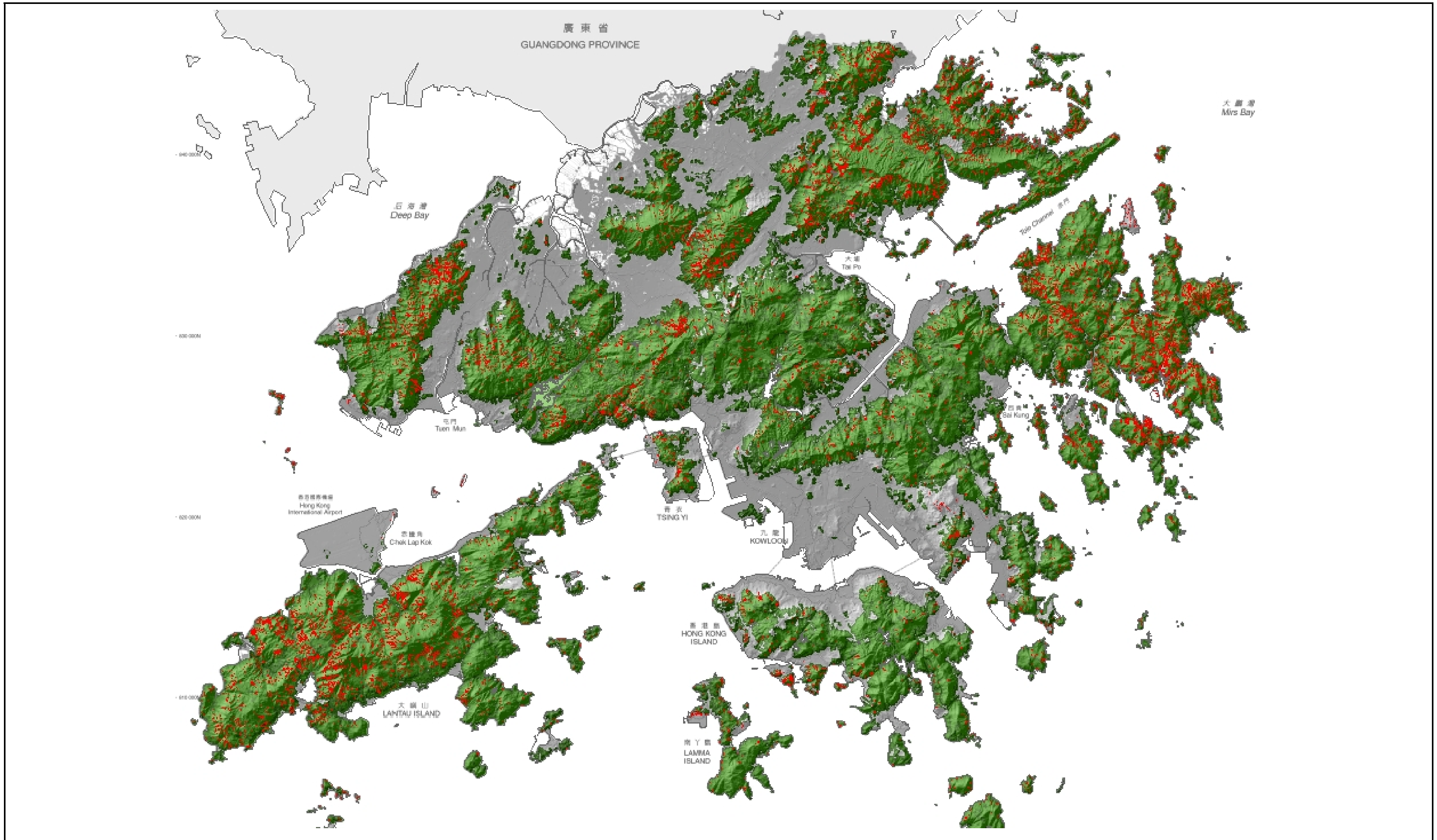
Region	Risk of Historical NTLI Catchments in the Region (PLL/year)(1)	Risk of Supplementary Catchments in the Region (PLL/year)					
		No Bayesian Update and without Increased Facilities	No Bayesian Update(3)	Half Bayesian Update(4)	Full Bayesian Update(5)	Conservative Bayesian Update(6)	Conservative Bayesian Update with 100% Increased Facilities
Fan Kam	0.015441	0.004752	0.007128	0.007182	0.007236	0.012996	0.017328
Mid-levels	0.417978	0.144959	0.217439	0.170369	0.123297	0.284039	0.378718
Pak Sha Wan	0.000243	0.001251	0.001877	0.000938	0.000000	0.001877	0.002502
Tsing Shan Foothills	0.006096	0.272546	0.408819	0.544584	0.680349	0.736169	0.981558
Tsing Yi	0.015850	0.013996	0.020994	0.014271	0.013994	0.022664	0.030218
All: Total Risk	0.455608	0.437504	0.656257	0.737343	0.824876	1.057743	1.410324
All: Global Risk Ratio(7)	-	2.0	2.4	2.6	2.8	3.3	4.1

Notes:
(1) Based on 'Best-estimate' model for Historical NTLI Catchments with Half-Bayesian Update using validated historical NTLI.
(2) Unless stated otherwise, a 50% increase in the facilities at risk is considered, to cater for the fact that no field validation has been carried out to supplement the information given in the LIC maps.
(3) Based on Theoretical NTLI Landslide Frequency (F_T).
(4) Based on mean value of F_T and Actual NTLI Landslide Frequency (F_A).
(5) Based on F_A.
(6) Based on F_T and F_A, whichever is greater.
(7) $$\text{Global Risk Ratio} = \frac{\text{Risk of Historical NTLI Catchments} + \text{Risk of Supplementary Catchments}}{\text{Risk of the Historical NTLI Catchments}}$$
(8) The best-estimate overall risk of natural terrain landslides in Hong Kong as given by the 'Best-estimate' model with Half Bayesian Update, together with the additional risk increase due to Rainfall Scenario E (Figure 23) is: $1.4 \times 2.6 \times 1.3 \approx 5$ PLL / year.

Table of Contents Table of Contents Table of Contents Table of Contents

LIST OF FIGURES

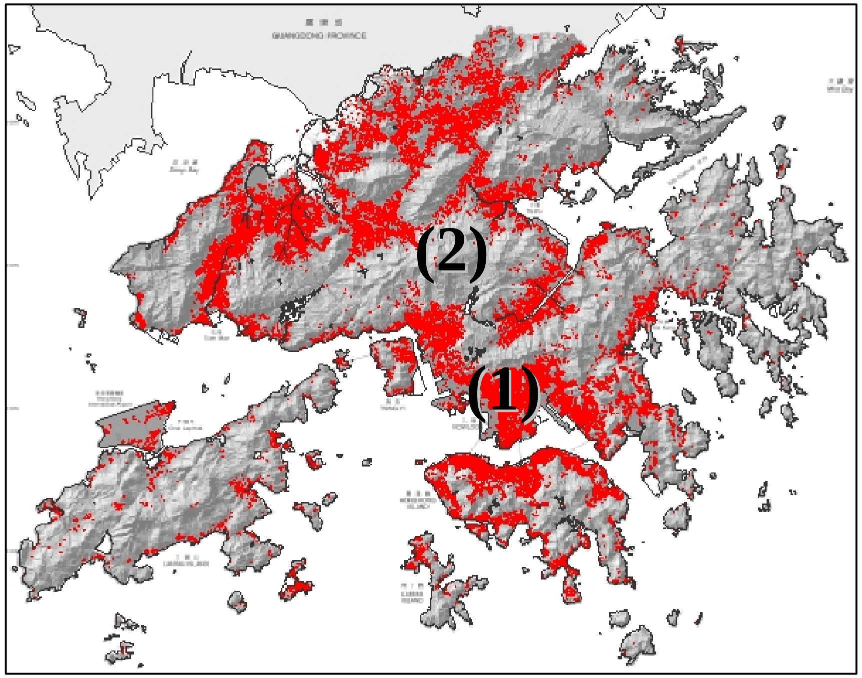
Table of Contents
Table of Contents
Table of Contents



Note: Natural terrain in green; NTLI landslides in red.

Figure 1 - Natural Terrain Outside the Year 2000 Development Line

Table of Contents
Table of Contents
Table of Contents
Table of Contents



(a) Shaded relief map of Hong Kong

(b) Western part of Hong Kong Island

Legend:

(1) Urban development
(2) Natural hillside

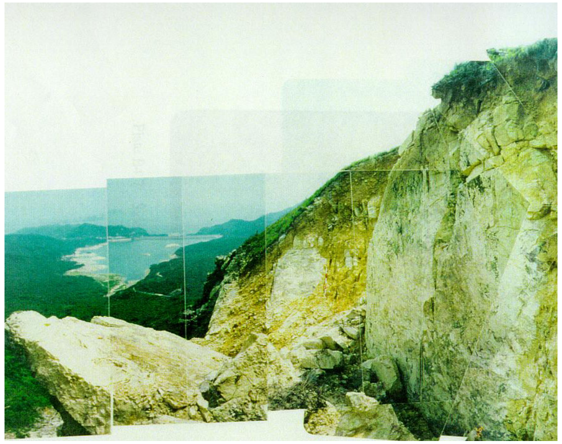
Figure 2 - Urban Development in Hong Kong Close to Natural Hillside

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Figure 3 - Rain-induced Shallow Natural Terrain Landslides

(a) Landslide in colluvium, above the interface with weathered rock

(b) Landslide in weathered rock



(c) Landslide due to rock toppling failure

(d) Landslide along joint planes in weathered rock

Figure 4 - Failure Types at the Source of Natural Terrain Landslides

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Note: Vehicles were severely damaged. Fortunately, there were no casualities.

Figure 5 - Fall of Boulders at Kennedy Town Police Quarters in 1986

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(a) Debris slide

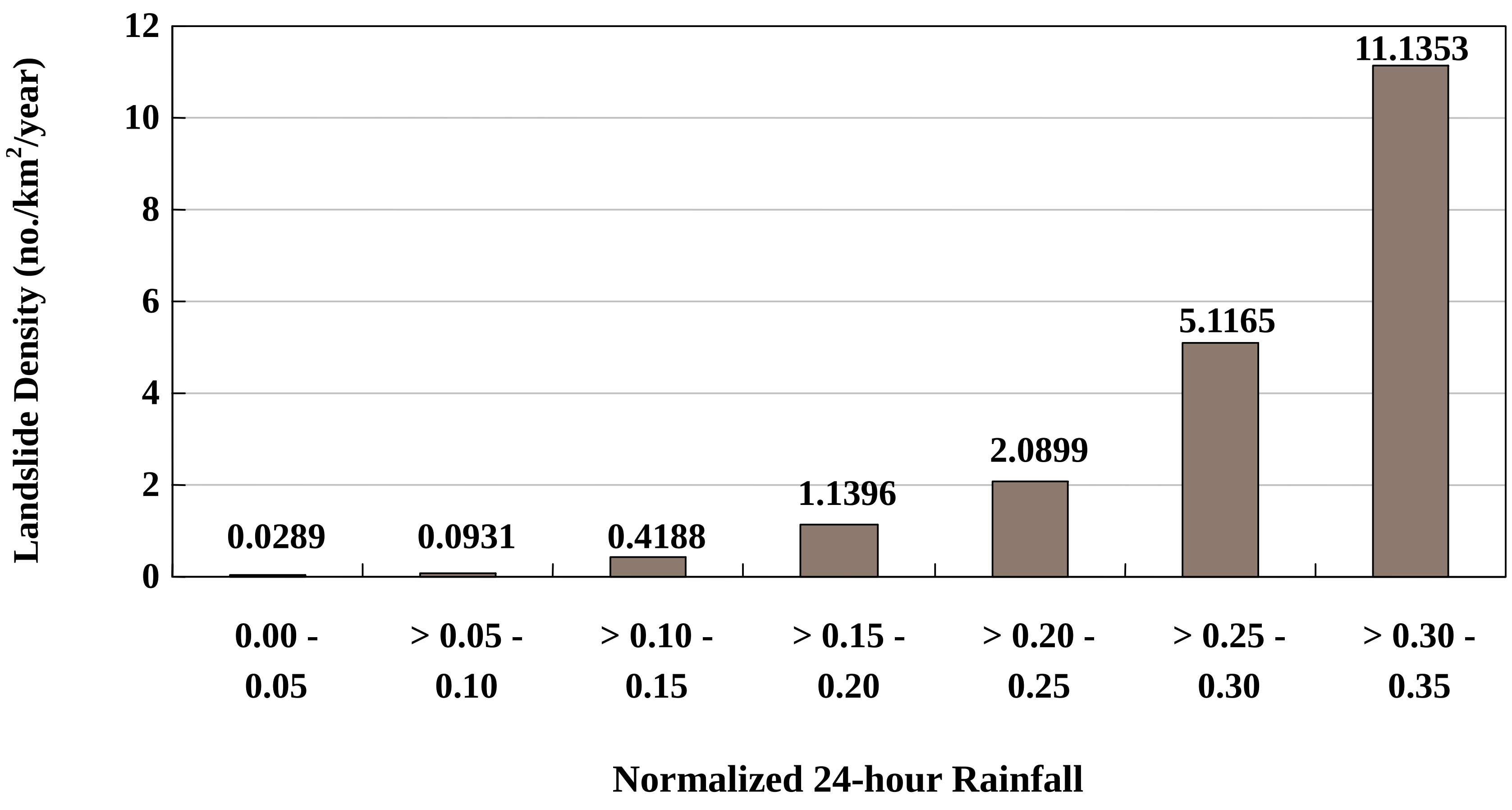
(b) Debris avalanche

(c) Change in mechanism from debris avalanche to debris flow

(d) Debris flow

Figure 6 - Different Mechanisms of Debris Movement

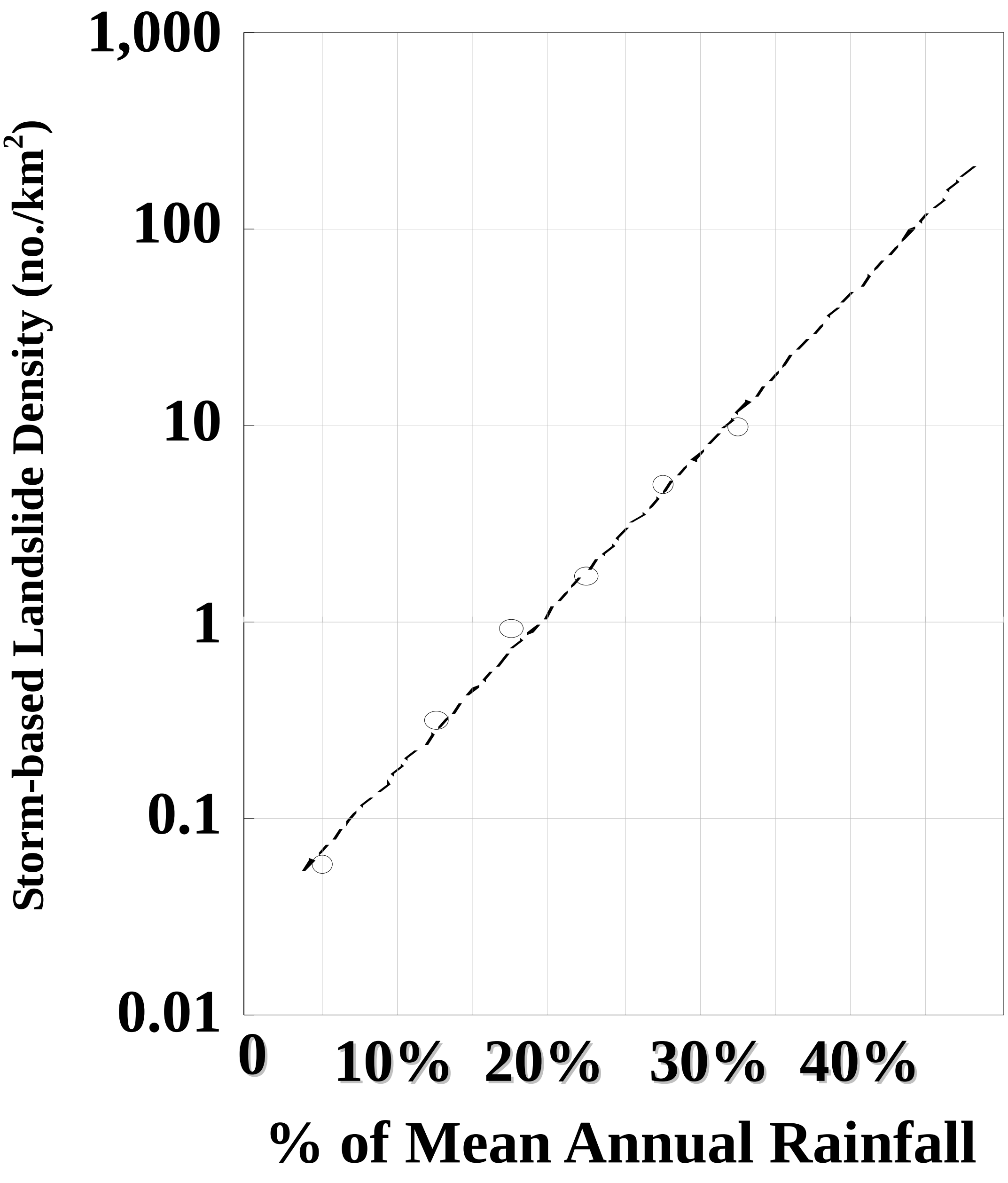
Table of Contents
Table of Contents
Table of Contents
Table of Contents



Note: This is extracted from Ko (2003) with minor changes to accommodate improvements made with the use of enhanced GIS analysis.

Figure 7 - Rainfall-Natural Terrain Landslide Density Correlation

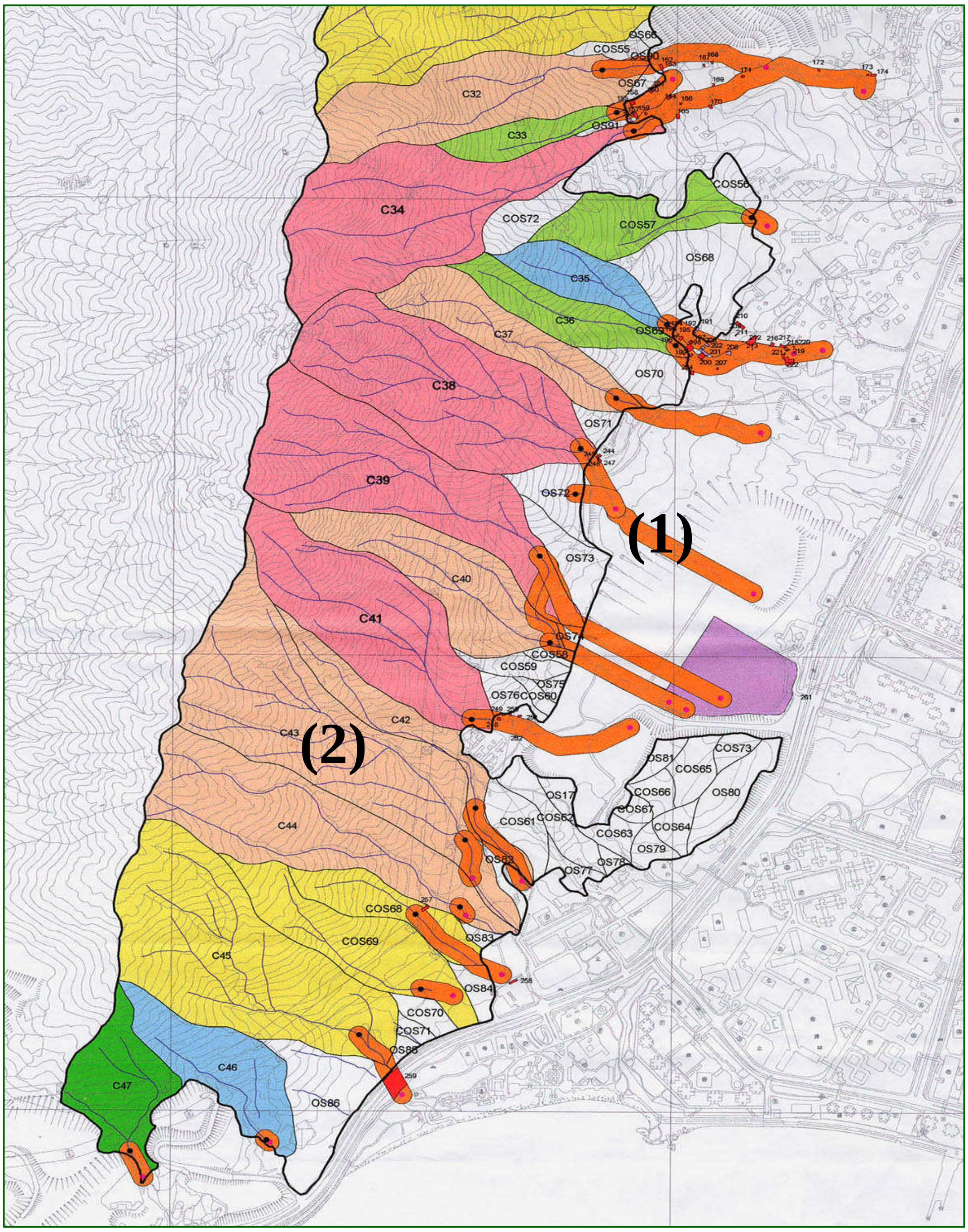
Table of Contents
Table of Contents
Table of Contents
Table of Contents



Note: Based on Ko (2003).

Figure 8 - Storm-based Landslide Density at Different Rainfall Intensities

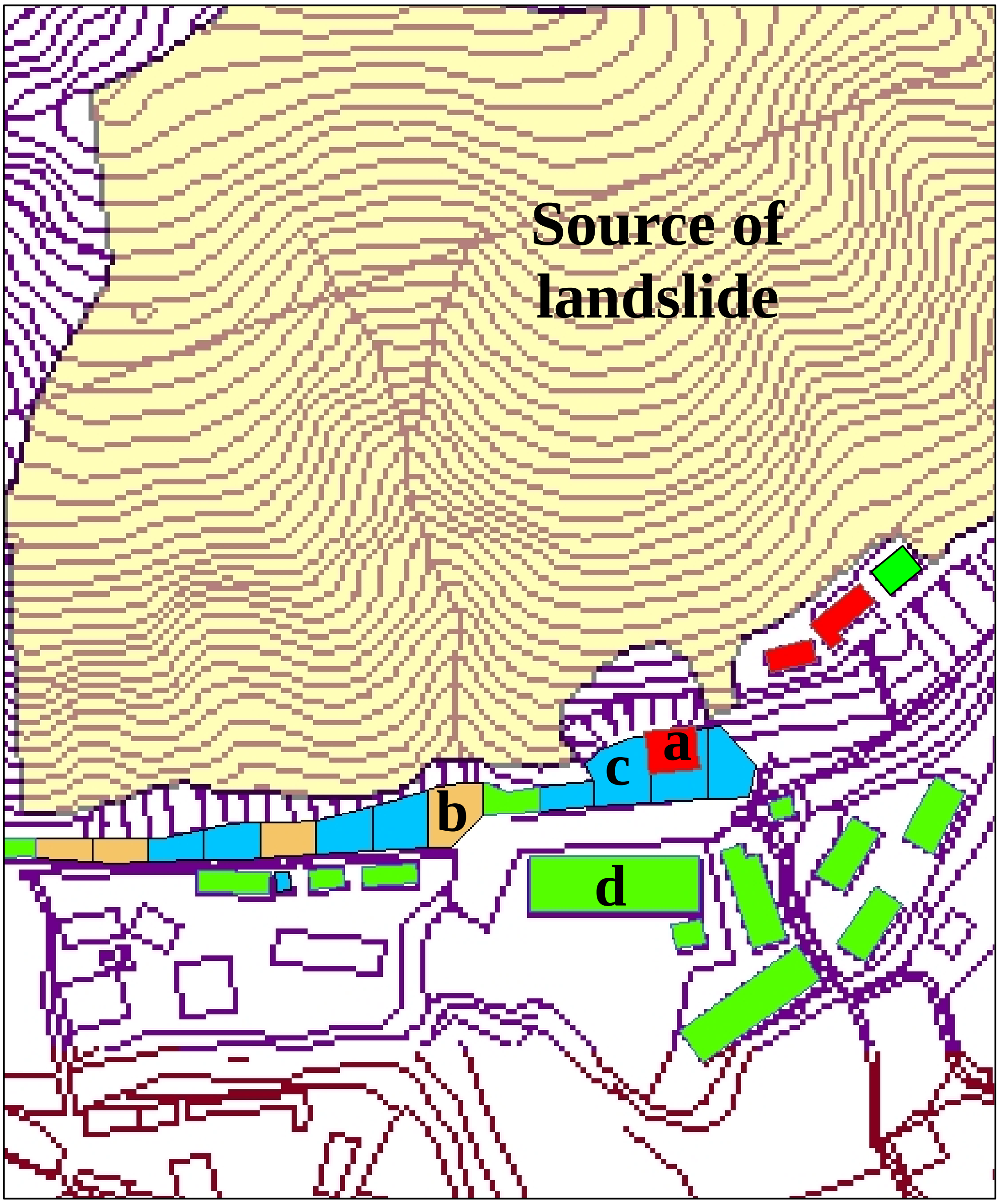
Table of Contents
Table of Contents
Table of Contents
Table of Contents



Note: Hazard map delineating (1) areas potentially affected by debris flows; (2) ranking of catchments (depicted in different colours) based on risk of debris flows on downstream development, i.e. with consideration of susceptibility and consequence of debris flows (based on FHK, 2003).

Figure 9 - An Example of 1:2,000-scale Hazard Map Developed from Regional Study of Natural Terrain Hazards

Table of Contents
Table of Contents
Table of Contents
Table of Contents



Note: Risk zoning map 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).

Figure 10 - An Example of 1:1,000-scale Risk Map Developed from Site-specific Quantitative Risk Assessment

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(a) Boulder/debris fence

(b) Protective barrier

(c) Check dam

(d) Provision of buffer zone

Figure 11 - Typical Natural Terrain Landslide Risk Mitigation Measures

Table of Contents
Table of Contents
Table of Contents
Table of Contents

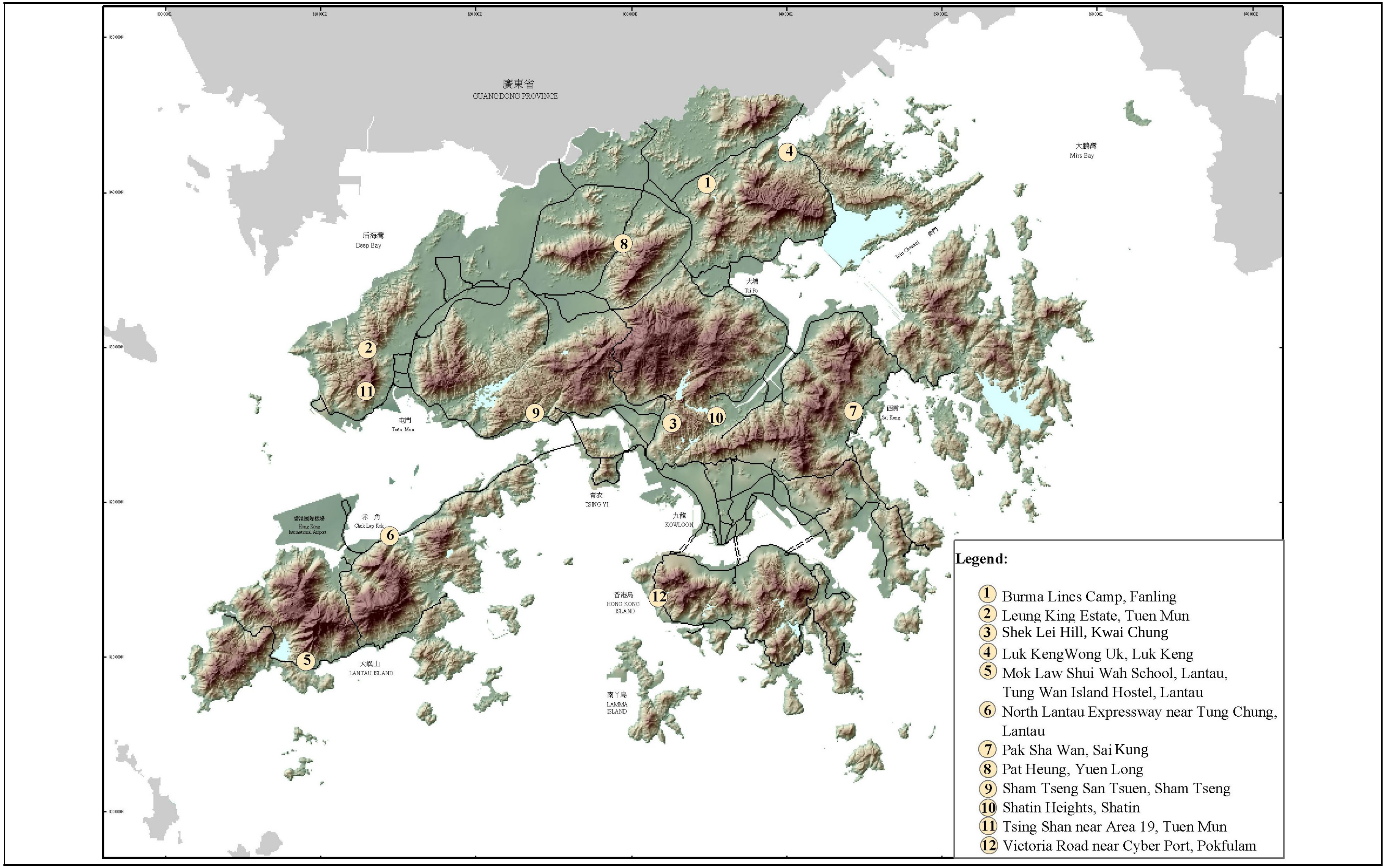
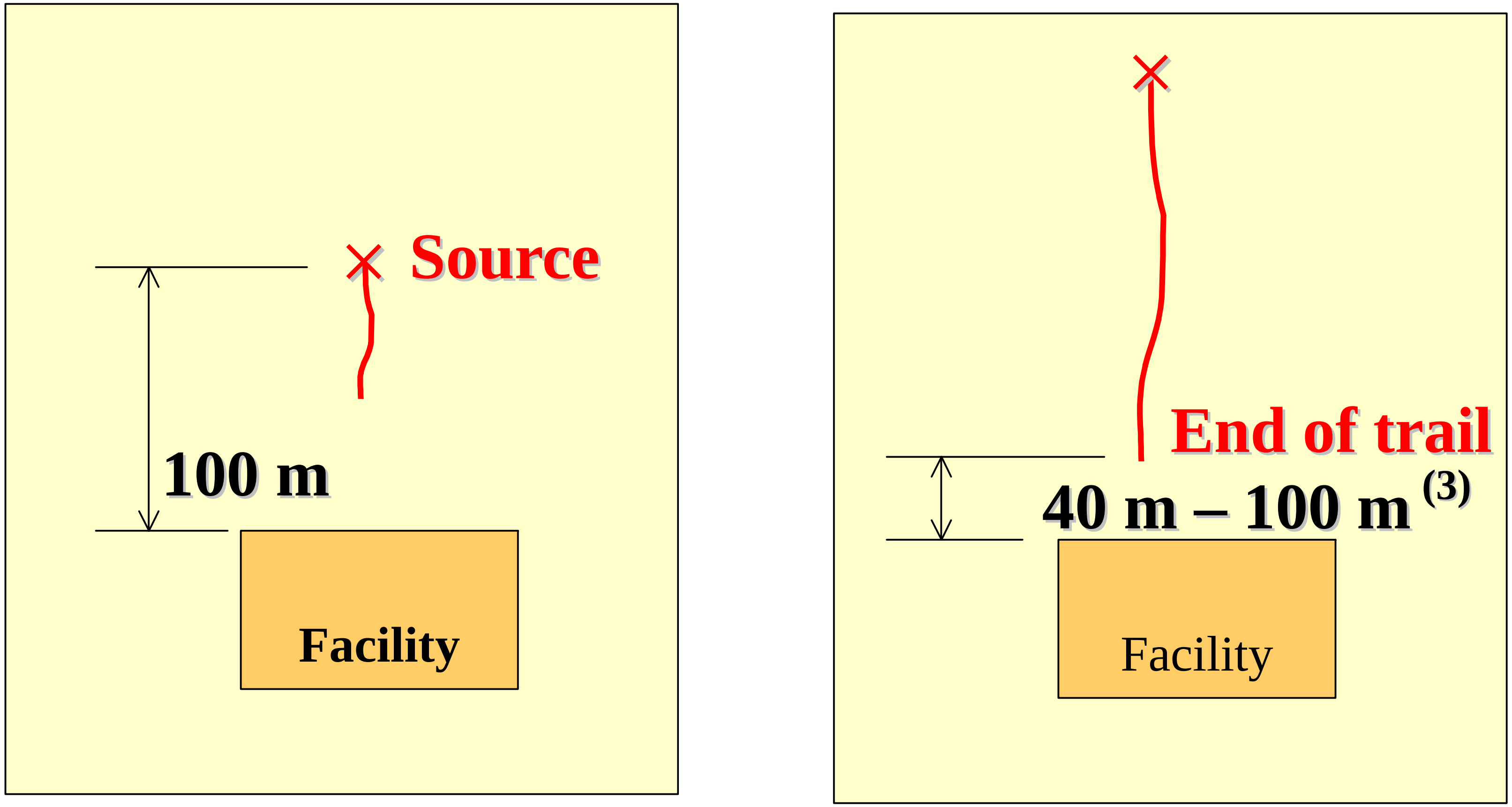


Figure 12 - Sites Recently under Action Based on the 'React-to-known-hazard' Principle

Table of Contents
Table of Contents
Table of Contents
Table of Contents



Notes: (1) Landslide records based on NTLI updated to the year 2000.
(2) Facility includes buildings, major roads and mass transportation infrastructures.
(3) Use 40% of the debris trail length or 40 m, whichever is larger.

Figure 13 - GIS Search Criteria for Identification of Catchments with Historical Natural Terrain Landslides Close to Existing Developments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

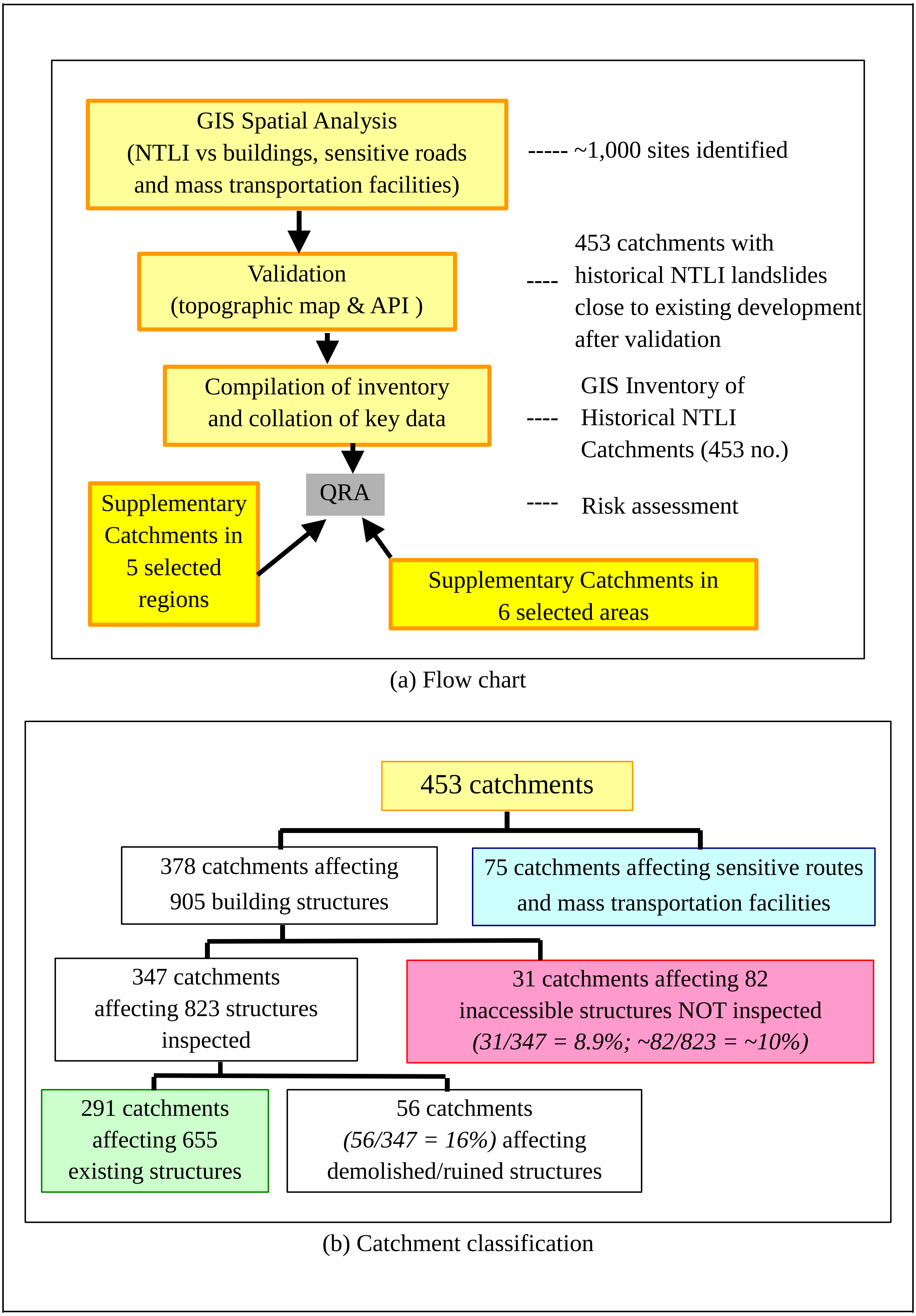


Figure 14 - Catchment Inventory and Breakdown of Historical NTLI Catchments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

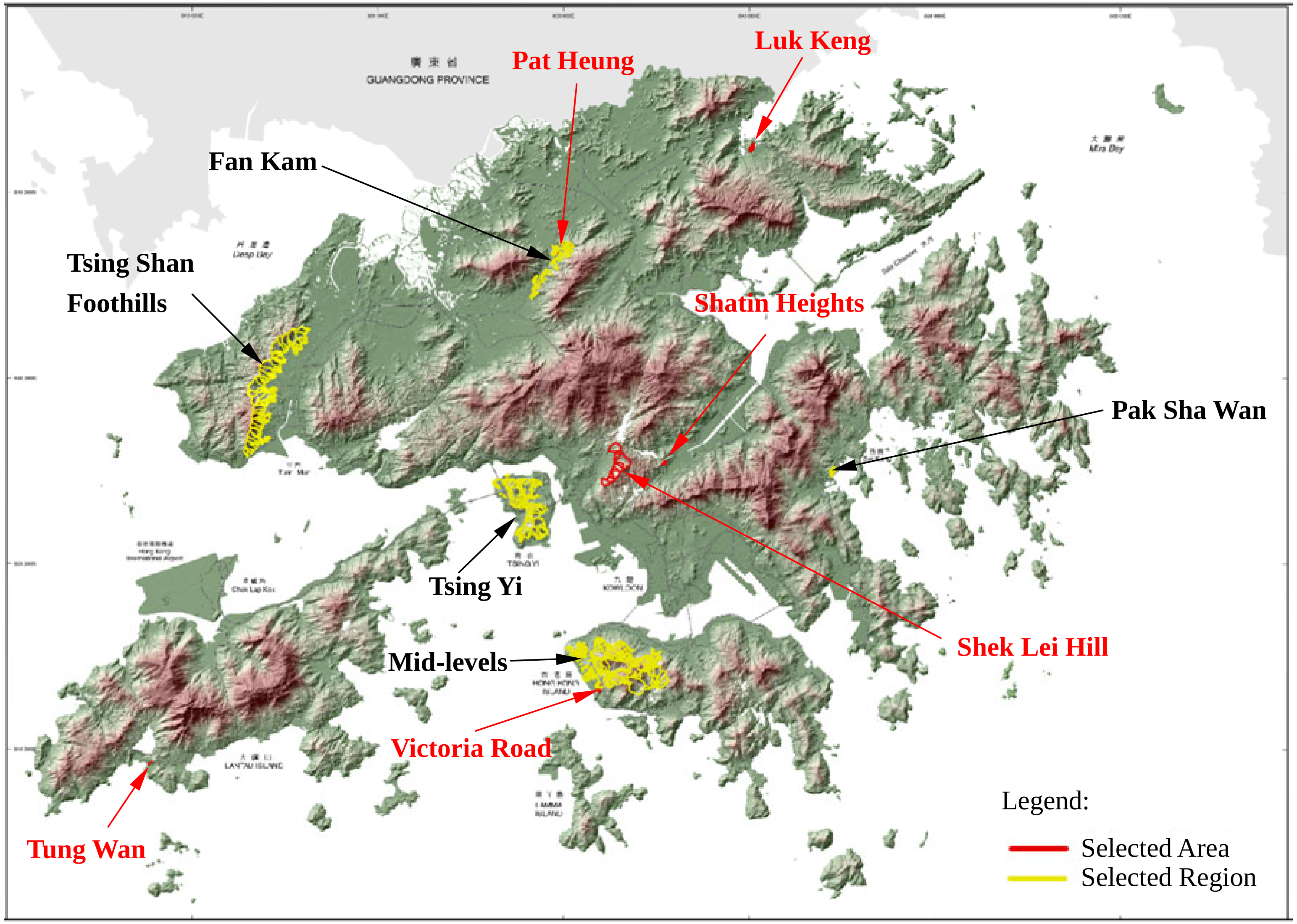


Figure 15 - Location of Supplementary Catchments

Table of Contents
Table of Contents
Table of Contents

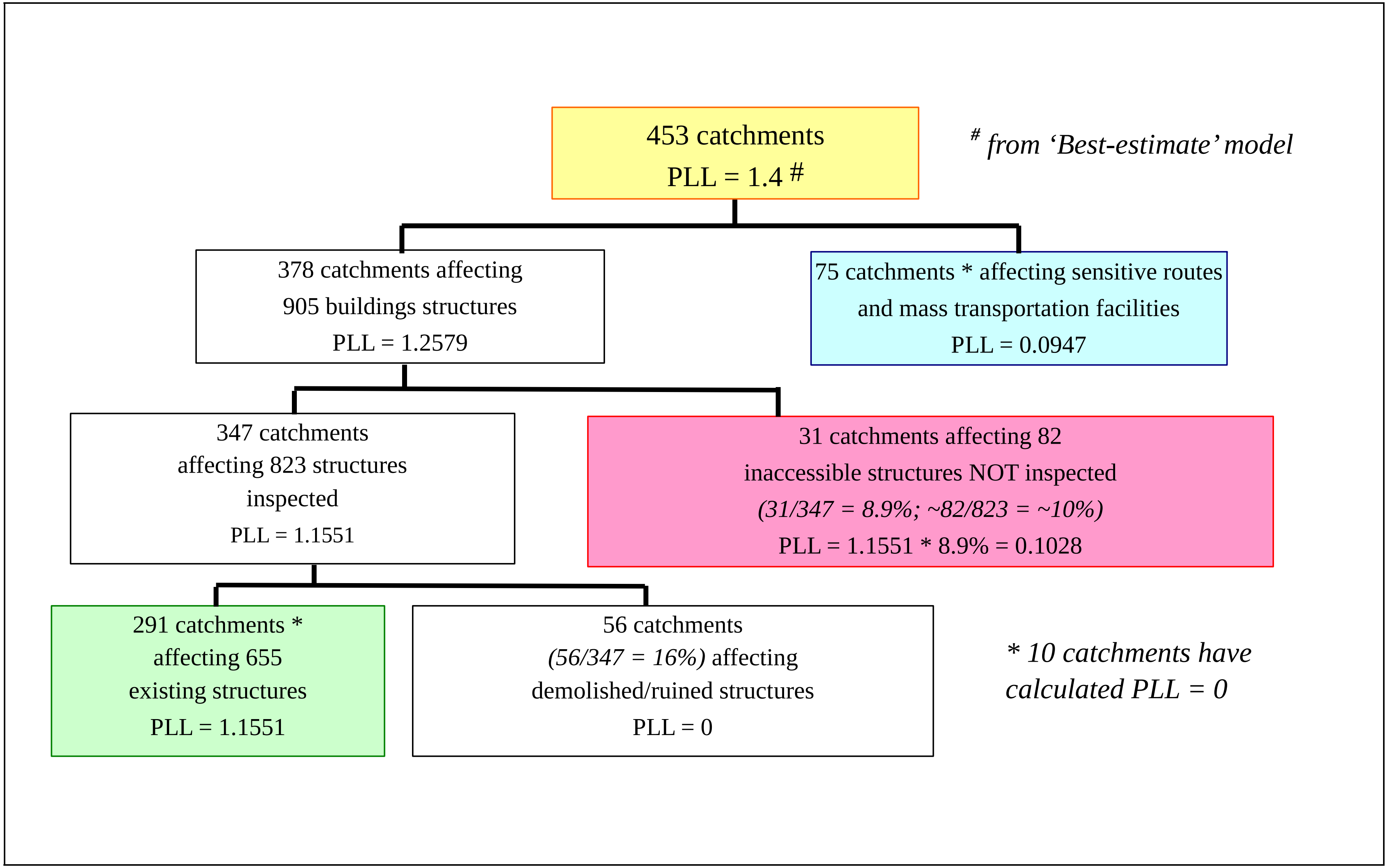
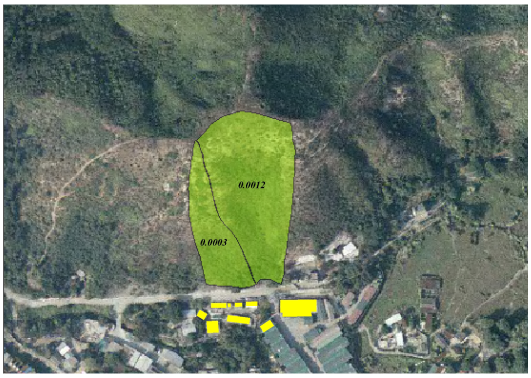


Figure 16 - QRA Results on the 453 Historical NTLI Catchments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

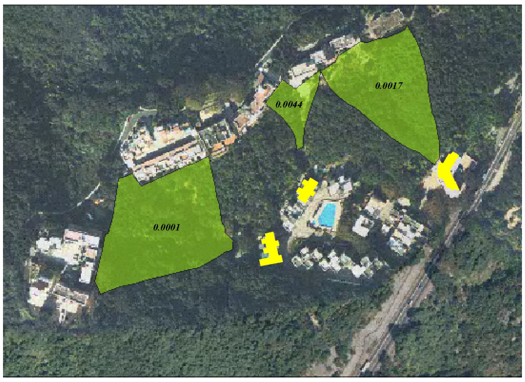


Historical NTLI
Catchments in Inventory

Full Catchments
in Pat Heung Area

	Historical NTLI Catchments in Inventory	Full Catchments in Pat Heung Area
Results from Global QRA	0.0015 (building data validated)	-
	0.0024 (building data not validated)	0.0029 (building data not validated)
Results from Site-specific QRA (OAP, 2003)	-	0.0016 (building data validated)

(a) PLL for Building Structures in Pat Heung Area (in Fam Kam Road Region)



Historical NTLI
Catchments in Inventory

Full Catchments
in Shatin Heights Area

	Historical NTLI Catchments in Inventory	Full Catchments in Shatin Heights Area
Results from Global QRA	0.0062 (building data validated)	-
	0.0066 (building data not validated)	0.0096 (building data not validated)
Results from Site-specific QRA (Fugro Maunsell Scott Wilson Joint Venture, 2001)	-	0.0057 (building data validated)

(b) PLL for Building Structures in Shatin Heights Area

Figure 17 - Comparison between Global QRA Results and Site-specific QRA Results

Table of Contents
Table of Contents
Table of Contents
Table of Contents

	Percentage of Total Risk Value			
	H1	H2	H3	H4
Sensitive Routes and Mass Transportation Facilities	21.2 %	74.1 %	3.4 %	1.3 %
Building Structures including Collapse	13.1 %	75.5 %	8.3 %	3.1 %
Collapse of Building Structures Only	0.0 %	4.1 %	4.7 %	1.3 %
Total Risk	13.7 %	75.4 %	7.9 %	3.0 %

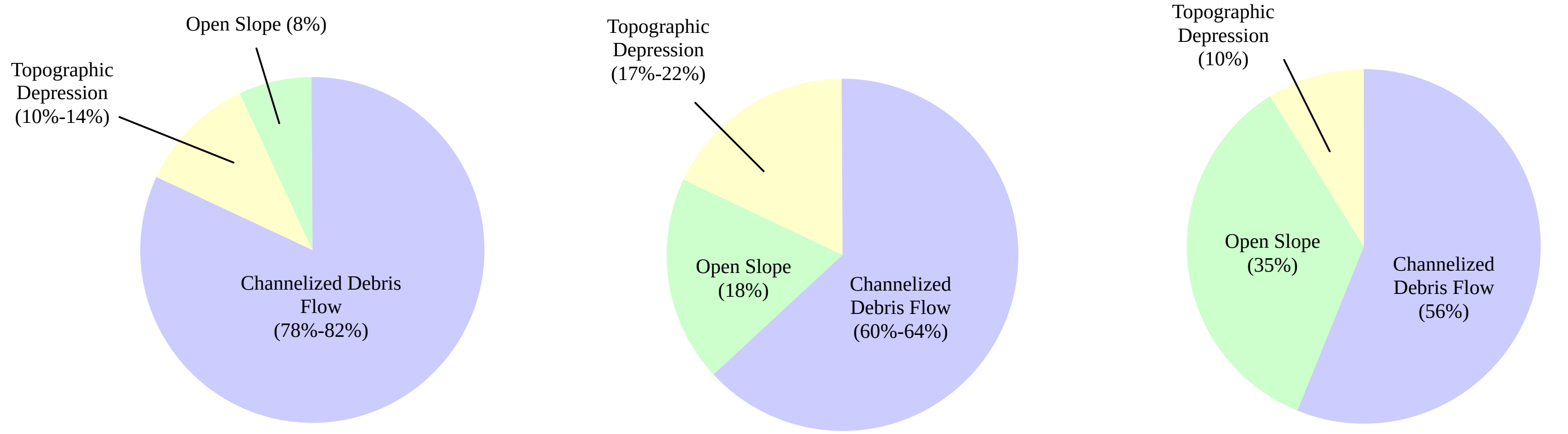
Notes: (1) Total risk of the 453 Historical NTLI Catchments is 1.4 PLL/year.
(2) Refer to Appendix B for definitions of H1, H2, H3 and H4.

Figure 18 - Distribution of Risk among Different Types of Hazard

Table of Contents
Table of Contents
Table of Contents
Table of Contents

		Channelized Debris Flow		Topographic Depression		Open Slope	
		Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Building Structures	Overall including Building Collapse	0.9007	0.9007	0.1150	0.1652	0.0891	0.0891
	Building Collapse Only	0.0699	0.0699	0.0191	0.0255	0.0209	0.0209
Sensitive Routes and Mass Transportation Facilities		0.0520	0.0520	0.0081	0.0104	0.0323	0.0323

Risk Proportion according to Type of Catchment:



Overall Risk on Building Structures, including Collapse

Risk on Building Collapse

Risk on Sensitive Routes and Mass Transportation Facilities

Figure 19 - Distribution of Risk among Different Types of Catchment

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Types of Facility	Building Structures (Refer to Appendix C for Descriptions of B1 to B6)					Sensitive Routes and Mass Transportation Facilities
	Houses up to 3-storey	Multi-storey Buildings				
	B1 & B2	B3	B4	B5	B6	
Overall Risk	0.6736 (58.3%)	0.2897 (25.1%)	0.1016 (8.8%)	0.0860 (7.4%)	0.0042 (0.4%)	0.0947 (100%)
No. of Catchments	238	29	10	12	2	75
No. of Facilities	586 (89.5%)	37 (5.6%)	12 (1.8%)	18 (2.7%)	2 (0.3%)	75 (100%)
Average Risk per Facility (PLL/year)	1.1×10^{-3}	7.0×10^{-3}				1.3×10^{-3}

Figure 20 - Distribution of Risk among Different Types of Facility

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Zone (Refer to Appendix C for Definitions)	No. of Building Structures	Total Risk in the Zone (PLL/year)	Proportion of All Risk	Risk/Building Structures (PLL/year)
1	24 (3.7%)	0.0721	6.2%	3.0×10^{-3}
2	38 (5.8%)	0.0953	8.3%	2.5×10^{-3}
3	117 (17.9%)	0.4007	34.7%	3.4×10^{-3}
4	223 (34.0%)	0.4925	42.6%	2.2×10^{-3}
5	177 (27.0%)	0.0904	7.8%	5.1×10^{-4}
6	56 (8.5%)	0.0040	0.35%	7.1×10^{-5}
7	19 (2.9%)	0.0001	0.009%	5.3×10^{-6}
8	1 (0.2%)	0.0000	0%	~ 0
Sum	655	1.1551	Average risk per building structures = 1.8×10^{-3}	

Note: Average risk of a Historical NTLI Catchment affecting building structures = 4×10^{-3}

Figure 21 - Distribution of Risk among Facilities in Different Proximity Zones

Ranking	No. of Catchments	Total Risk (PLL/year)	Average Risk per Catchment (PLL/year)
1 to 50	50	0.9695	2×10^{-2}
51 to 100	50	0.1315	3×10^{-3}
101 to 150	50	0.0403	8×10^{-4}
151 to 200	50	0.0112	2×10^{-4}
201 to 283	83	0.0025	3×10^{-5}
284 to 291	8	Negligible	Negligible

(a) Historical NTLI Catchments affecting building structures

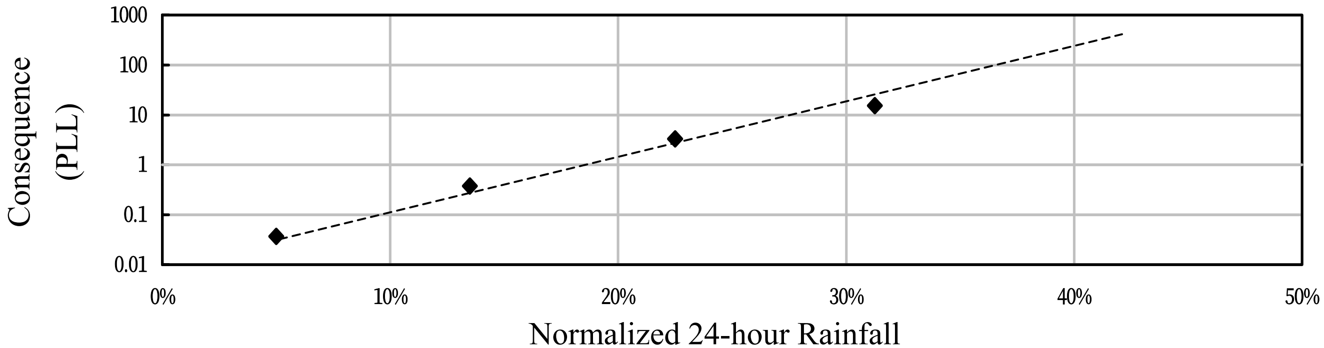
Ranking	No. of Catchments	Total Risk (PLL/year)	Average Risk per Catchment (PLL/year)
1 to 25	25	0.0810	3×10^{-3}
26 to 50	25	0.0118	5×10^{-4}
51 to 73	23	0.0019	8×10^{-5}
74 to 75	2	Negligible	Negligible

(b) Historical NTLI Catchments affecting sensitive routes and mass transportation facilities

Figure 22 - Risk Ranking of Historical NTLI Catchments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Rainfall Scenario	Normalized 24-hour Rainfall	Risk (PLL/year)			Annual Frequency of Occurrence	Consequence in Case of Occurrence of the Rainfall Scenario (PLL)
		Inspected Building Structures	Sensitive Routes and Mass Transportation Facilities	453 Historical NTLI Catchments		
A	≤ 10%	0.025795	0.002282	0.03037	0.8130	0.037
B	10 – 20%	0.154022	0.013166	0.18090	0.4785	0.378
C	20 – 30%	0.172853	0.014131	0.20237	0.0608	3.328
D	30 – 35%	0.046168	0.003774	0.05405	0.0035	15.443
			Total	0.5[1]		
E	> 35%	-	-	0.4 [3]	0.0020	200[2]



Notes:

(1) The risk (0.5 PLL/year) is due to that from theoretical landslide frequency in the 'Best-estimate' model using Half-Bayesian Update. The total calculated risk for the 453 Historical NTLI Catchments is 1.4.

(2) Based on extrapolation in the Consequence vs Normalized 24-hour Rainfall plot.

(3) Based on 0.002 x 200 = 0.4 PLL/year.

(4) Rainfall Scenario E would result in an increase in risk of 0.4/1.4 ≈ 30%.

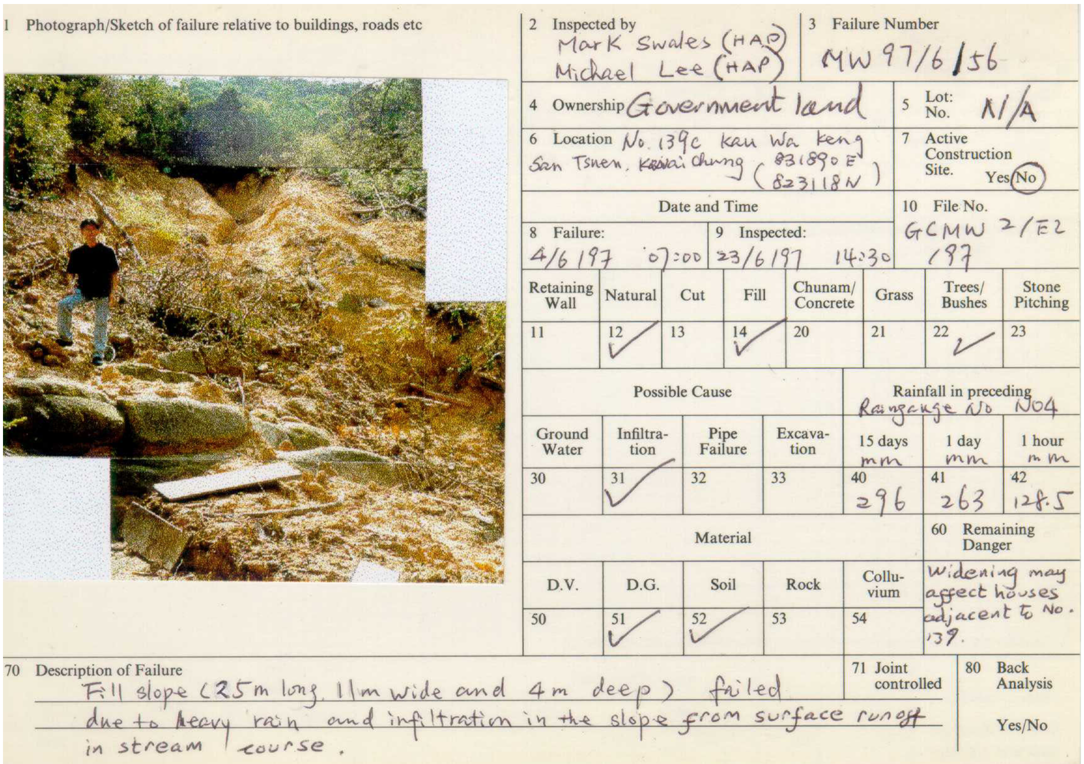
Figure 23 - Risk Projection to Extreme Event

Table of Contents Table of Contents Table of Contents Table of Contents

Figure 24 - Local, Small-scale Landslides on Disturbed Hillside

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(a) Landslide covering a large area, where small cuttings and pockets of filll materials are present



1 Photograph/Sketch of failure relative to buildings, roads etc

2 Inspected by Mark Swales (HAP) Michael Lee (HAP)

3 Failure Number MW 97/6/56

4 Ownership Government land

5 Lot: No. N/A

6 Location No. 139c Kau Wa Keng San Tsuen, Kwai Chung (831890 E 823118 N)

7 Active Construction Site. Yes/No

Date and Time

8 Failure: 4/6/97 07:00

9 Inspected: 23/6/97 14:30

10 File No. GCMW 2/E2/97

Retaining Wall	Natural	Cut	Fill	Chunam/ Concrete	Grass	Trees/ Bushes	Stone Pitching
11	12 ✓	13	14 ✓	20	21	22 ✓	23

Possible Cause				Rainfall in preceding Raingauge No N04		
Ground Water	Infiltra-tion	Pipe Failure	Excava-tion	15 days mm	1 day mm	1 hour mm
30	31 ✓	32	33	40 296	41 263	42 128.5

Material					60 Remaining Danger
D.V.	D.G.	Soil	Rock	Collu-vium	Widening may affect houses adjacent to No. 139.
50	51 ✓	52 ✓	53	54	

70 Description of Failure Fill slope (25m long, 11m wide and 4m deep) failed due to heavy rain and infiltration in the slope from surface runoff in stream course.

71 Joint controlled

80 Back Analysis Yes/No

(b) Record of a 500 m^3 debris flow (1997) on a hillside partly involving unregisterable fill materials

Figure 25 - Large-scale Landslides on Hillside within or Close to Development Lines

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table of Contents

Table of Contents

APPENDIX A

CATCHMENT DATABASE

Table of Contents

Table of Contents

A.1 INTRODUCTION

This Appendix describes the methodology adopted in compiling a database of natural terrain catchments, for identifying sites of existing developments affected by historical natural terrain landslides and for assessing the overall natural terrain landslide risk in Hong Kong. The database comprises two parts:

(a) An inventory of selected natural terrain catchments where historical NTLI landslides had occurred close to important existing facilities. These catchments are denoted as 'Historical NTLI Catchments'.

(b) An inventory of all natural terrain catchments, excluding the 'Historical NTLI Catchments', adjoining selected developed areas. These catchments are denoted as 'Supplementary Catchments'.

For the selected regions where both Historical NTLI Catchments and Supplementary Catchments are recorded, they form a complete inventory of the natural terrain catchments adjoining the developed areas. For other areas, the inventory only covers Historical NTLI Catchments.

A.2 HISTORICAL NTLI CATCHMENTS

Historical NTLI Catchments were identified based on the following information held in GEO's GIS:

(a) Historical natural terrain landslides recorded in GEO's NTLI updated to the year 2000 - the NTLI dataset was stored in GEO's GS Server (file path: G:\natural_terrain\NTLIs\ntli_merge_upto_2000 dated April 2003). In total, there are 29,229 nos. of NTLI crowns (i.e. sources of landslide) and 29,199 nos. of NTLI trails (i.e. debris runout trails).

(b) Building structures recorded in LIC's 1:1,000-scale topographic maps - the dataset was stored in GEO's GS Server (file path: R:\lic\arc_1k_merge_2003\bldgpoly dated June 2003). In total, there are 192,302 nos. of building polygons and 307,494 nos. of building lines. Building polygons are typically permanent structures such as residential block, commercial sector, school and habitable facilities. Building lines are typically balcony, podium, pavilion, ruin, open-sided and temporary structures.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(c) Sensitive routes recorded in Highways Department's strategic routes database - the dataset was stored in GEO's GS Server (file path: R:\HyD_Route dated April 2003). Sensitive routes include red routes, pink routes, routes to vulnerable area, bus routes and bus depot routes, as defined in Highways Department's strategic routes database (Highways Department, 2001).

(d) Mass transportation facilities, including KCR, MTR, LRT, Tramway and Peak Tram.

The facilities referred to in (b) to (d) above are referred to as "important facilities" in this Appendix.

The inventory of Historical NTLI Catchments was compiled as follows:

(a) Identification of NTLI landslides that occurred close to existing developments by GIS search, if one of the following criteria is satisfied:

  (i) Criterion 1 - The crown of a NTLI landslide is within 100 m of the upslope edge of an important facility; or

  (ii) Criterion 2 - The toe of a NTLI landslide trail is within 40 m or 40% of the trail length, whichever is greater, of the upslope edge of an important facility.

  A total of 3,226 NTLI crowns and 1,473 NTLI trails were identified from GIS search satisfying the criteria.

(b) Validation of the NTLI landslides identified in (a) above using Aerial Photograph Interpretation (API):

  (i) whether the NTLI landslides identified in (a) above are genuine landslides;

  (ii) whether the important facilities are still in existence; and

  (iii) whether there is a credible flow path that the NTLI landslides may affect the important facilities.

  After the validation, a total of 656 NTLI crowns and 462 NTLI trails were found to be genuine and affecting important facilities, i.e. satisfying all the conditions listed in (b)(i) to (b)(iii). These are denoted as 'validated NTLI landslides'.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(c) Delineation of Historical Landslide Catchments

The boundaries of the catchments that contain the validated NTLI landslides were delineated by API and by reference to topographic maps. These are referred to as 'Historical NTLI Catchments'. Each of the catchments contains at least one validated NTLI landslide that is related to at least one important facility at risk. Furthermore, the catchments are categorized into different types according to the predominant debris runout mechanism, i.e. channelized debris flow along a well-defined drainage line or major topographic depression (C), mixed debris avalanche and flow along topographic depression (T) and open slope debris slide or avalanche (S), as defined in Table B1.

A total of 453 Historical NTLI Catchments were delineated, including 205 nos. of Type C, 44 nos. of Type T and 204 nos. of Type S (Table 3).

(d) Collation of catchment data

For each of the Historical NTLI Catchments, the key data on the catchment and the important facilities were collated from API, topographic maps and ortho-rectified images. Site visits were carried out to check the type and condition of the important facilities, and to take photographs of the sites. Figure A1 shows the types and format of the data that were collated.

The inventory of Historical NTLI Catchments was compiled into GIS format by digitizing the catchment and facility polygons and uploading the relevant data onto the relevant GIS attribute tables. The dataset was stored in GEO's GS Server (file path: g:\natural_terrain\high_priority_area\hpa_datafr_MGSFugro dated July 2004).

A.3 SUPPLEMENTARY CATCHMENTS

An inventory of Supplementary Catchments was prepared for the following five selected regions and six selected areas (Figure 15):

(a) Region:

(i) Fan Kam
(ii) Mid-levels
(iii) Pak Sha Wan
(iv) Tsing Shan Foothills
(v) Tsing Yi

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(b) Area:

(i) Shek Lei Hill
(ii) Luk Keng
(iii) Pat Heung
(iv) Shatin Heights
(v) Tung Wan
(vi) Victoria Road

The Supplementary Catchments were delineated and the relevant catchment and important facility data were collated following procedures similar to those adopted for the Historical NTLI Catchments, except that the NTLI records at the Supplementary Catchments were not validated and site visits not carried out. The data collated were compiled into GIS format, as in the case of the Historical NTLI Catchments. The dataset was stored in GEO's GS Server (file path: P:\catchment_drainage\catchment_mapping\supplementary catchments dated June 2004).

Table of Contents
Table of Contents
Table of Contents
Table of Contents

HPA Field Inspection Proforma

Use with Guidance Notes

INSPECTION TEAM NO./INITIALS		INSPECTION DATE	
CATCHMENT NO. E.g. 11SEA_C01		FACILITY REF. NO. Use a, b, c .... where 'a' = Critical Facility. Mark all Ref. Nos. on base plan	
		Facility similar to Critical Facility 'a':	Yes ☐ No ☐
Number of Facilities Reported for Catchment:		Newly constructed facility (I.e. not seen on plan; please mark on):	Yes ☐ No ☐

POSTAL ADDRESS

Squatter Number Evident:	Yes		No		Squatter Number + Colour of No.:
Co-ordinate Source	GPS		Plan		Coordinates:

FACILITY TYPE for whole structure				BUILDING CLASS			
Squatter Structure		Petrol Station		B1 Isolated Building ≤ 3 storeys			
Cottage				B2 Cluster of ≥ 2 B1's		Permanent	
Village House		P.H.I.		B3 Building 4 to 10 storeys		Temporary	
Residential Building		School		B4 Multistorey 11 to 20 storeys		Mixed (for B2;	
Commercial Office		Factory		B5 Multistorey >20 storeys		= both P. and T.)	
Other (detail):				B6 Sensitive Structure (detail):			

STRENGTH of whole structure			MATERIAL of structure			
Flimsy		E.g. Wood	Wood		Corregated Metal	
Solid		E.g. Brick/Stone	Brick		Stone	
Massive		E.g. R/C Structure	Concrete		Container	
Comment:			Other (detail):			

NUMBER OF STOREYS (tick a box)

1		2		3		4		5		6		7		8		9		10	
11 to 20 storeys										>20 storeys									

PERCENTAGE COVERAGE OF FACILITY GROUND FLOOR (mark on plan)

	Residential Building	Store (Private or Industrial)	Lobby	Car Park	Playground/ sitting-area	Open Space	Others (describe)		Total
In Use									
Not In Use									

PHOTOGRAPH REFERENCE NOS. (mark on plan)

	Field Number (from camera)	Reference No. (Facility No. (E.g. 11SEA_C01_a) with no. 1, 2, 3 ....
Ground Floor of Facility		
Overview of Facility		
Catchment		
Any Existing Mitigation		

GENERAL COMMENTS

Especially site features such as redevelopment, mitigation features with registration no., access difficulties, etc.

Figure A1 - Types and Format of the Data Collated

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table of Contents

Table of Contents

APPENDIX B

FREQUENCY MODEL

Table of Contents

Table of Contents

B.1 INTRODUCTION

'Frequency' refers to the probability of occurrence of a given type of natural terrain landslide hazard within a given area. In this global QRA, a 'frequency model' has been developed for assessing the probability of occurrence of different types of hazard. This Appendix presents the details of the frequency model.

The frequency model is based on rainfall-landslide density correlation and is statistically rigorous. The overall landslide frequency given by the model is aligned to correspond with the NTLI landslides recorded from 1985 to 2000. While such alignment would ensure that the overall landslide frequency is consistent with the available historical landslide data, it is noted that more severe rainfall events may not have been adequately represented in a relatively short observation period. Hence, an 'extreme' Rainfall Scenario E, at an annual frequency of occurrence of 0.002, has been excluded from the frequency model. The contribution of this rainfall scenario is examined via extrapolation of the calculated risk as part of the sensitivity analysis (Section 5.2 of the report), and not via the use of the frequency model.

Bayesian updating has been adopted in the frequency model, to ensure that due account is taken of the actual performance of the catchments in the NTLI observation period. The NTLI observation period, which generally dated back to pre-1950s, is much longer than the observation period adopted in the rainfall-landslide correlation (1985 to 2000). Application of the Bayesian updating would help to calibrate the estimated frequency of landslides in a catchment with that of the historical landslides in the catchment. The effects of using different levels of Bayesian updating have been examined as part of the sensitivity analysis.

B.2 HAZARD CLASSIFICATION

Different types of natural terrain landslide hazard are considered in the frequency model, based on the following classification:

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(a) Debris runout mechanism, which is based on the characteristics of the catchment concerned:

Type	Nature	Criteria
C	Channelized debris flow	For catchments with a definite channelized flow path. In practice, this applies to catchments with the presence of a drainage line in the Land Information Centre's (LIC) topographic map and to other catchments with channelization ratio <7.5.
T	Mixed debris avalanche and flow along topographic depression	For catchments without a definite channelized flow path but with the presence of a topographic depression where debris would converge and travel downslope. In practice, this applies to catchments without the presence of a drainage line in the LIC map, catchments with channelization ratio >7.5, and catchments with channelization ratio <7.5 but the topographic depression does not extend to reach important facility.
S	Open slope debris slide or avalanche	For catchments where debris would travel downslope from the source of failure without entering a drainage line or topographic depression. In practice, this applies to catchments that are relatively planar and hence not satisfying the criteria of 'C' and 'T'.

Table B1 - Classification of Catchments based on Debris Runout Mechanism

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(b) Total debris volume, including debris from the source of failure and from entrainment along the debris runout path:

Type	Notional Volume (m^3)	Typical Range of Volume (m^3)
H1	50	20 to 200
H2	500	200 to 2,000
H3	5,000	2,000 to 20,000
H4	20,000+	>20,000

Table B2 - Classification of Hazards based on Total Debris Volume

Hence, a total of 12 types of natural terrain landslide hazard (i.e. CH1 to CH4, TH1 to TH4 and SH1 to SH4) are considered.

B.3 RAINFALL SCENARIOS

Correlation between normalized 24-hour rainfall (i.e. maximum rolling 24-hr rainfall divided by the mean annual rainfall) and NTLI landslide density is established by Ko (2003). 'NTLI landslides' refer to landslides recorded in GEO's Natural Terrain Landslide Inventory (NTLI) up to the year 2000, based on interpretation of the available aerial photographs as described in King (1999).

Based on Ko (2003) with minor changes to accommodate improvements made with the use of enhanced GIS analysis, four storm-based Rainfall Scenarios are considered in the frequency model:

Rainfall Scenario	Normalized 24-hour Rainfall	Mean Annual Frequency of Occurrence	NTLI Landslide Density (No./km^2)
A	≤0.10	F_a = 1/1.23 = 0.8130	D_a = 0.0593
B	>0.10 - 0.20	F_b = 1/2.09 = 0.4785	D_b = 0.4387
C	>0.20 - 0.30	F_c = 1/16.46 = 0.0608	D_c = 2.3354
D	>0.30 - 0.35	F_d = 1/281.81 = 0.0035	D_d = 10.6811

Table B3 - Rainfall Scenarios

An extreme Rainfall Scenario E, with normalized 24-hour rainfall >0.35, is also assessed in the sensitivity analysis, as described in Section 5.3(f) of this report.

B.4 ESTIMATED NTLI LANDSLIDE FREQUENCY CALCULATION

'Estimated NTLI landslide frequency' refers to the estimated annual frequency of occurrence of landslides that, if occur, can be recognized by interpretation of high-flight aerial photographs based on the methodology adopted in compiling the NTLI. The NTLI landslide frequency in a given natural terrain catchment with a plan area A is calculated from consideration of: (a) the Theoretical NTLI Landslide Frequency based on rainfall-landslide density correlation, and (b) the Actual NTLI Landslide Frequency at the catchment.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

The Theoretical NTLI Landslide Frequencies, without consideration of any recognition factors, arising from different Rainfall Scenarios (Table B3) are:

Rainfall Scenario	Normalized 24-hour Rainfall	Theoretical NTLI Landslide Frequency (No./year)
A	≤0.10	$F_a D_a A$
B	>0.10 - 0.20	$F_b D_b A$
C	>0.20 - 0.30	$F_c D_c A$
D	>0.30 - 0.35	$F_d D_d A$

Table B4 - Theoretical NTLI Landslide Frequencies in Different Rainfall Scenarios

The annual Theoretical NTLI Landslide Frequency in the catchment is $F_{T,}$ which is calculated as ($F_a D_a A$ + $F_b D_b A$ + $F_c D_c A$ + $F_d D_d A$).

The historical NTLI landslides in the catchment are grouped into ‘recent’ and ‘relict’, as defined by King (1999) and categorized in the NTLI. The numbers of ‘recent’ and ‘relict’ NTLI landslides in the catchment are counted as N_n and N_o, respectively.

From analysis of the NTLI, it can be taken that on average, ‘recent’ and ‘relict’ NTLI landslides came from an observation period of 31 years and 50 years, respectively. Hence, the annual NTLI landslide frequencies in the catchment derived from ‘recent’ and ‘relict’ landslides are N_n / 31 and N_o / 50 respectively. By giving more weight to ‘recent’ landslides, the annual Actual NTLI Landslide Frequency is F_A, which is calculated as [2 (N_n / 31) + N_o / 50] / 3.

In calculating the Estimated NTLI Landslide Frequency, F_E, the degree of Bayesian Update of the Theoretical NTLI Landslide Frequency, F_T, based on the Actual NTLI Landslide Frequency (F_A) needs to be considered. The Bayesian updating serves to adjust F_T, which is based on theoretical rainfall-landslide correlation to a more realistic estimate using the information on the actual performance of the catchment (i.e. F_A). In this global QRA, a Half-Bayesian Update (i.e. $F_E = (F_T + F_A)/2$) is adopted in the ‘Best-estimate’ model (Section 4.3 of the report), whereas different degrees of Bayesian Update (Table 7) are considered in the sensitivity analysis.

To facilitate application of recognition factors and magnitude-frequency model, the Bayesian Update has been applied to the calculation of the Estimated NTLI Landslide Frequencies in different Rainfall Scenarios, as shown in Table B5. The adjustment factor, F', is defined as F_E/F_T.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Rainfall Scenario	Normalized 24-hour Rainfall	Estimated NTLI Landslide Frequency (No./year)
A	≤0.10	$F' F_a D_a A$
B	>0.10 - 0.20	$F' F_b D_b A$
C	>0.20 - 0.30	$F' F_c D_c A$
D	>0.30 - 0.35	$F' F_d D_d A$

Table B5 - Estimated NTLI Landslide Frequencies in Different Rainfall Scenarios

B.5 MAGNITUDE-FREQUENCY MODEL AND USE OF RECOGNITION FACTORS

A magnitude-frequency model is adopted to work out the magnitude-frequency distribution of natural terrain landslides, based on the relevant catchment characteristics and Rainfall Scenarios.

Channelized debris flow catchments and topographic depression catchments are further classified as follows:

(a) Size of Catchment

Catchment Size	Plan Area of the Portion of Catchment ≥15° Gradient	Adjustment
S	≤5,000 m^2	Where applicable, the catchment size is upgraded or downgraded based on consideration of (b) to (d) below. Note that 'S' is the lowest category and 'VL' is the highest category.
M	5,000 m^2 - 20,000 m^2	
L	>20,000 m^2	
VL		

Table B6 - Size of Channelized Debris Flow and Topographic Depression Catchments

(b) Maximum Elevation Difference and Overall Gradient of the Catchment

- If the maximum elevation difference is <50 m, the catchment size is downgraded by one category (e.g. from 'L' to 'M')
- If the maximum elevation difference is between ≥50 m and <100 m, no upgrading or downgrading is applied to the catchment size
- If the maximum elevation difference is ≥100 m and the overall gradient (measured along the credible flow path of the portion of the catchment ≥15° gradient) is ≥30°, then the catchment size is upgraded by half a category (to combine with the category 'Yes-Many' in (c) below)

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(c) Entrainment Potential

Is the Credible Flow Path along a LIC Drainage Line?	Presence of Debris Deposits along Credible Flow Path, based on Information from Geological Map and Aerial Photographs		
	Not much	Some	Many
Yes	Downgrade by one category	Not applicable	Upgrade by half a category
No	Downgrade by one category	Not applicable	Not applicable

Table B7 - Adjustment for Entrainment Potential at Channelized Debris Flow and Topographic Depression Catchments

(d) Historical NTLI Landslides

		Sum of Trail Length (m)				
		<5	5 - 50	50 - 100	100 - 200	>200
Maximum Trail Length (m)	<5	Downgrade by one category	Downgrade by one category	Downgrade by one category	Downgrade by one category	Downgrade by one category
	5 - 25	-	Downgrade by one category	Not applicable	Not applicable	Not applicable
	25 - 50	-	Not applicable	Not applicable	Not applicable	Not applicable
	50 - 100	-	-	Not applicable	Not applicable	Not applicable
	>100	-	-	-	Not applicable	Upgrade by one category

Table B8 - Adjustment for Historical NTLI Landslides for Channelized Debris Flow and Topographic Depression Catchments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Open slope debris slide or avalanche catchments are further classified as follows:

(a) Size of Catchment

<table>
<tr><th>Catchment Size</th><th>Plan Area of the Portion of Catchment ≥15° Gradient</th><th>Adjustment</th></tr>
<tr><td>S</td><td>≤3,000 m^2</td><td rowspan="4">Where applicable, the catchment size is upgraded or downgraded based on consideration of (b) to (c) below. Note that ‘S’ is the lowest category and ‘VL’ is the highest category.</td></tr>
<tr><td>M</td><td>3,000 m^2 - 10,000 m^2</td></tr>
<tr><td>L</td><td rowspan="2">>10,000 m^2</td></tr>
<tr><td>VL</td></tr>
</table>

Table B9 - Size of Open Slope Catchments

(b) Maximum Elevation Difference and Overall Gradient of the Catchment

- If the maximum elevation difference is <40 m, the catchment size is downgraded by one category (e.g. from ‘L’ to ‘M’)
- If the maximum elevation difference is between ≥40 m and <60 m, no upgrading or downgrading is applied to the catchment size
- If the maximum elevation difference is ≥60 m and the overall gradient (measured along the credible flow path of the portion of the catchment ≥15° gradient) is ≥30°, then the catchment size is upgraded by one category

(c) Historical NTLI Landslides

- If there are two or more historical NTLI landslides with width ≥20 m, the catchment size is upgraded by one category

Table of Contents
Table of Contents
Table of Contents
Table of Contents

The following groups of magnitude-frequency distribution in relation to different Rainfall Scenarios and catchment sizes are adopted:

(a) For channelized debris flow catchments and topographic depression catchments

Rainfall Scenario	Catchment Size			
	S	M	L	VL
A	(C/T)1	(C/T)1	(C/T)1	(C/T)1
B	(C/T)1	(C/T)1	(C/T)2	(C/T)2
C	(C/T)1	(C/T)2	(C/T)3	(C/T)4
D	(C/T)1	(C/T)2	(C/T)3	(C/T)4

Table B10 - Magnitude-Frequency Grouping for Channelized Debris Flow and Topographic Depression Catchments

(b) For open slope debris slide or avalanche catchments

Rainfall Scenario	Catchment Size			
	S	M	L	VL
A	S1	S1	S1	S1
B	S1	S1	S1	S2
C	S1	S2	S3	S4
D	S1	S2	S3	S4

Table B11 - Magnitude-Frequency Grouping for Open Slope Catchments

Different groups of magnitude-frequency distribution are defined as follows:

(a) For channelized debris flow catchments and topographic depression catchments

Magnitude-Frequency Distribution Group	Total Debris Volume			
	H1	H2	H3	H4
(C/T)1	85.0%	15.0%	-	-
(C/T)2	74.8%	25.0%	0.2%	-
(C/T)3	68.9%	30.0%	1.0%	0.1%
(C/T)4	62.0%	35.0%	2.0%	1.0%

Table B12 - Magnitude-Frequency Distribution for Channelized Debris Flow and Topographic Depression Catchments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

(b) For open slope debris slide or avalanche catchments

Magnitude-Frequency Distribution Group	Total Debris Volume			
	H1	H2	H3	H4
S1	95.00%	5.00%	-	-
S2	89.98%	10.00%	0.02%	-
S3	84.78%	15.00%	0.20%	0.02%
S4	78.90%	20.00%	1.00%	0.10%

Table B13 - Magnitude-Frequency Distribution for Open Slope Catchments

For each Rainfall Scenario, the Estimated NTLI Landslide Frequency of each type of landslide hazard, is calculated from Sections 4 and 5 above. By summing up the Estimated NTLI Landslide Frequencies of each type of natural terrain landslide hazard for all Rainfall Scenarios, the Estimated NTLI Landslide Frequency corresponding to each type of natural terrain landslide hazards is derived. The magnitude-frequency calculation is illustrated in Table B14 using a large channelization debris flow catchment as an example. It should be noted that such frequencies correspond to landslides that can be recognized by high-flight aerial photographs, i.e. recognition factors have not yet been applied.

Rainfall Scenario	Adjusted NTLI Landslide Frequency	Natural Terrain Landslide Hazard			
		CH1	CH2	CH3	CH4
A	$F'F_aD_aA$	$0.850F'F_aD_aA$	$0.150F'F_aD_aA$	0	0
B	$F'F_bD_bA$	$0.748F'F_bD_bA$	$0.25F'F_bD_bA$	$0.002F'F_bD_bA$	0
C	$F'F_cD_cA$	$0.689F'F_cD_cA$	$0.300F'F_cD_cA$	$0.010F'F_cD_cA$	$0.001F'F_cD_cA$
D	$F'F_dD_dA$	$0.620F'F_dD_dA$	$0.350F'F_dD_dA$	$0.020F'F_dD_dA$	$0.010F'F_dD_dA$
Adjusted NTLI Landslide Frequency		$0.850F'F_aD_aA +$ $0.748F'F_bD_bA +$ $0.689F'F_cD_cA +$ $0.620F'F_dD_dA$	$0.150F'F_aD_aA +$ $0.250F'F_bD_bA +$ $0.300F'F_cD_cA +$ $0.350F'F_dD_dA$	$0.002F'F_bD_bA +$ $0.010F'F_cD_cA +$ $0.020F'F_dD_dA$	$0.001F'F_cD_cA +$ $0.010F'F_cD_cA$

Table B14 - Example of Magnitude-Frequency Calculation

Table of Contents
Table of Contents
Table of Contents
Table of Contents

The actual number of historical landslides that can be observed from detailed interpretation of the available low-level aerial photographs exceeds that recorded in the NTLI. The ratio of the number of landslides recorded in NTLI to the actual number of landslides identified from detailed interpretation of low-level aerial photographs is denoted as 'recognition factor'. Based on experience from previous site-specific natural terrain hazard studies, the following recognition factors are adopted:

Landslide Hazard	(C/T/S)H1	(C/T/S)H2	(C/T/S)H3	(C/T/S)H4
Recognition Factor	40%	90%	100%	100%

Table B15 - Recognition Factors

The Estimated NTLI Landside Frequencies calculated above are divided by the corresponding recognition factors (Table B15) to derive the Estimated Landslide Frequencies of different types of natural terrain landslide hazard (Table B16).

Hazard Type		Estimated Landslide Frequency (no/year)
Catchment Type	Scale	
C	H1	F_{CH1}
	H2	F_{CH2}
	H3	F_{CH3}
	H4	F_{CH4}
T	H1	F_{SH1}
	H2	F_{SH2}
	H3	F_{SH3}
	H4	F_{SH4}
S	H1	F_{TH1}
	H2	F_{TH2}
	H3	F_{TH3}
	H4	F_{TH4}

Table B16 - Estimated Landslide Frequencies for Different Types of Hazard

Table of Contents
Table of Contents
Table of Contents

APPENDIX C

CONSEQUENCE MODEL

Table of Contents
Table of Contents
Table of Contents
Table of Contents

C.1 INTRODUCTION

'Consequence' refers to the degree of damage in the event of occurrence of a given type of natural terrain landslide hazard within a given area. In this global QRA, a 'consequence model' has been developed for assessing the consequence in terms of PLL for different types of hazard. This Appendix presents the details of the consequence model, which is denoted as the 'Natural Terrain Landslide Consequence Model'.

The consequence model that has been developed and used in quantitative assessment of the landslide risk of man-made slopes in Hong Kong is presented in Wong el at (1997). This model is denoted as the 'Man-made Slope Consequence Model' (Wong et al, 1997) in this Appendix. The model has been applied to QRA on man-made slopes as described in Wong & Ho (1998a), Wong & Ho (2000), Ho et al (2000), Ho & Wong (2001), Wong (2001), Cheung & Shiu (2002), Fugro (2004) and Lo & Cheung (2004). The consequence model was also used in a preliminary assessment of the average annual natural terrain landslide risk, which is reported in Sun & Evans (1999).

'Travel angle' (or referred to as 'angular elevation' if proximity is concerned) is adopted in the Man-made Slope Consequence Model as the key indicator of debris mobility and proximity of the facility at risk. This is satisfactory for the typical man-made slope setting in Hong Kong, i.e. the facilities at risk are at close proximity to the slope and the slope has a much steeper gradient than the ground between the slope and the facilities at risk. However, this model is not suitable for use in assessing the consequence of natural terrain landslides, where the facilities at risk are often not close to the source of the landslide and the terrain between the facilities and the landslide source is steeply sloping. Also, for debris flows, damage would be confined to the flow path. These problems are resolved in the Natural Terrain Landslide Consequence Model.

In the Natural Terrain Landslide Consequence Model, the consequence of landslide not involving building collapse is denoted as CON1. It is assessed by the following equation:

$$CON1 = Pn \times Vn \times Sn \times Ln \qquad \text{(C1)}$$

where Pn = Population at risk in the event of a direct hit by a referenced natural terrain landside hazard (a landslide of 10 m wide) (Table C1) but without building collapse, see Section 2 below

Vn = Vulnerability Factor, see Section 3 below

Sn = Scale Factor, see Section 4 below

Ln = Location Factor, see Section 5 below

Table of Contents
Table of Contents
Table of Contents
Table of Contents

	Referenced Natural Terrain Landslide Hazards	Non-referenced Natural Terrain Landslide Hazards
Channelised Debris Flow	-	CH1
	CH2	-
	-	CH3
	-	CH4
Topographic Depression	-	TH1
	TH2	-
	-	TH3
	-	TH4
Open Slope	SH1	-
	-	SH2
	-	SH3
	-	SH4

Table C1 - Referenced and Non-referenced Natural Terrain Landslide Hazards

There would be additional PLL due to building collapse. Assessment of the additional PLL is described in Section 6.

Details of the consequence formulation for 'Best-estimate' model are described in Sections 2 to 6 below. The alternative assumptions made in the Natural Terrain Landslide Consequence Model for sensitivity analysis are summarized in Section 7.

C.2 FACILITY CLASSIFICATION

Two types of facilities, viz. (a) building structures and (b) sensitive routes and mass transportation facilities, are considered.

Building structures are classified as shown in Table C2, and the population at risk (Pn) for respective types of building structures in case of full ground floor occupancy are given. The classification of sensitive routes and mass transportation facilities and their population at risk (Pn) are shown in Table C3. Tables C2 and C3 are adopted in the 'Best-estimate' model. They do not cater for building collapse.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Building Type	Description	Population at Risk (Pn) (No.)
B1	Individual houses or structures of one to three storeys	2
B2	Cluster of houses or structures of one to three storeys	4
B3	Buildings of four to ten storeys, including podium and similar area	6
B4	Multi-storey buildings of 11 to 20 storeys, including podium and similar area	6
B5	High-rise buildings of more than 20 storeys, including podium and similar area	6
B6	Sensitive structures that may involve severe consequence, including PHI, tunnel portal, petrol stations, railway platform, MTR exit	6
Note: Individual houses are not necessarily isolated houses. In the QRA, where data are available, some clusters of houses are assessed based on consideration of the risk on the individual houses that form the cluster.		

Table C2 - Population at Risk for Different Types of Building Structures in case of Full Ground Floor Occupancy

Sensitive Route and Mass Transportation Facilities Type	Description	Population at Risk (Pn) (No.)
R1	Bus depots	0.25
R2	Bus routes	0.25
R3	Routes to vulnerable areas	0.5
R4	Pink routes	1
R5	Red routes	3
R6	Mass transportation routes, including MTR, railway, light rail, peak tram, tramway	6

Table C3 - Population at Risk for Different Types of Sensitive Routes and Mass Transportation Facilities

The building structures are further categorized into ‘with protection’ and ‘without protection’, based on consideration of the type and strength of the building structures. For instance, building structures built of brick, stone, reinforced concrete are classified as ‘with protection’ while building structures built of wood and corrugated metal sheets are classified

Table of Contents
Table of Contents
Table of Contents
Table of Contents

as ‘without protection’. Sensitive routes and mass transportation facilities (excluding building structures) are always taken as ‘without protection’.

Where the ground floor of a building is partially occupied, the population at risk (Pn) is modified subject to the distribution of different degrees of usage in the ground floor. Four possible types of building usage are considered for each building structure:

	Residential, Industrial, Commercial	Lobby	Car Park	Stores, Playground, Sitting-out Area, Open Space
Degree of Usage (%)	A	B	C	D

Table C4 - Types of Building Usage in the Ground Floor

For building structures ‘with protection’, the population at risk is modified by a multiplier as given below :

$$\frac{3}{4}\left(A+\frac{B}{5}+\frac{C}{10}+\frac{D}{60}\right)+\frac{1}{4} \quad \text{(C2)}$$

For building structures ‘without protection’, the population at risk is modified by a multiplier as given below:

$$\frac{3}{4}\left(A+\frac{B}{5}+\frac{C}{10}\times 2+\frac{D}{60}\times 2\right)+\frac{1}{4} \quad \text{(C3)}$$

C.3 PROXIMITY CLASSIFICATION AND VULNERABILITY FACTOR

Proximity of the facility at risk to the natural terrain catchment is classified into eight proximity zones, viz, Zone 1 to Zone 8, as shown in Figure C1. The classification is based on consideration of the ‘angular elevation’ and the horizontal distance downslope of the ground where the overall gradient has changed to ≤15°. This is consistent with the principle adopted in the current criteria for preliminary screening of development sites that may be subject to natural terrain hazards (Ng et al, 2003).

The Vulnerability Factor (Vn) is applied to account for partial damage of the facilities when they are located at some distance from the hillside. The Vulnerability Factors (Vn) adopted in the ‘Best-estimate’ model for facilities located at different proximity zones and subject to different types of natural terrain landslide hazard are given in Tables C5 to C10.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

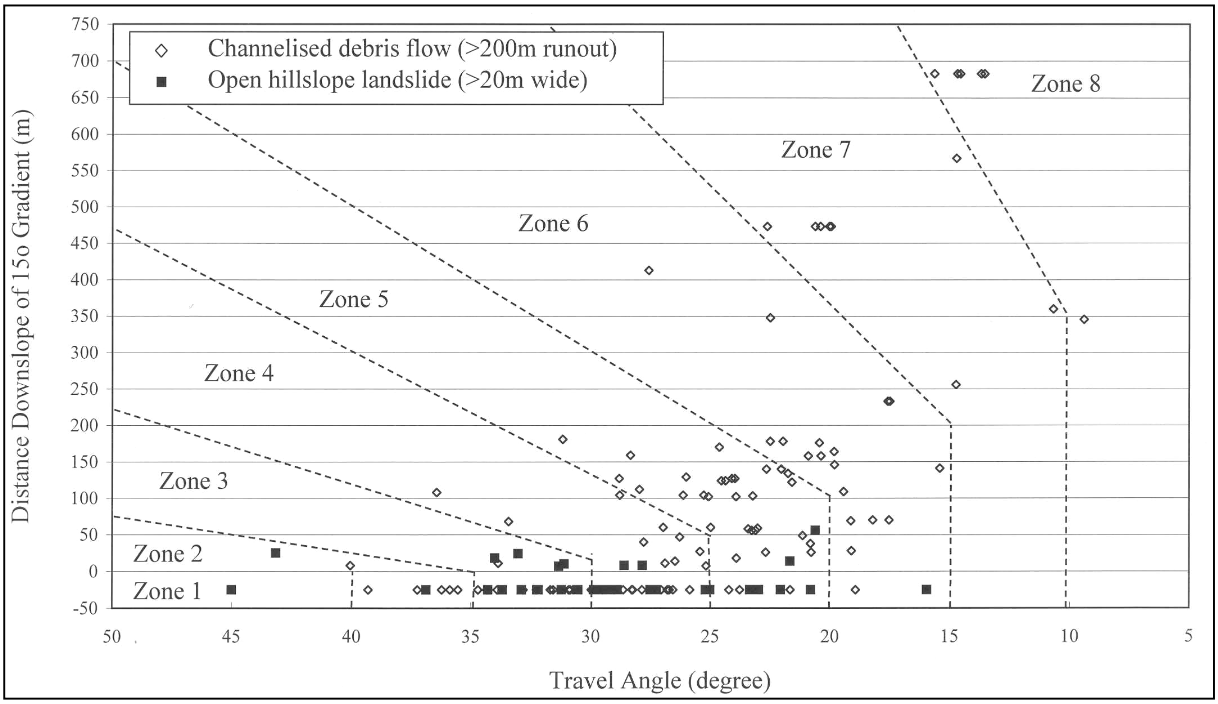


Figure C1 - Classification of Proximity Zones

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
CH1	0.1200	0.0710	0.0318	0.0090	0.0008	0.0000	0.0000	0.0000
CH2	0.9350	0.8480	0.6300	0.3380	0.1100	0.0150	0.0000	0.0000
CH3	0.9500	0.9440	0.8880	0.7000	0.3940	0.1310	0.0190	0.0000
CH4	0.9500	0.9500	0.9450	0.9000	0.7350	0.4300	0.1450	0.0200

Table C5 - Vulnerability Factors for Facilities ‘with Protection’ Subject to Natural Terrain Landslide Hazard from Channelized Debris Flow Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
CH1	0.2400	0.1440	0.0670	0.0210	0.0030	0.0000	0.0000	0.0000
CH2	0.9500	0.9200	0.7750	0.4930	0.2000	0.0380	0.0000	0.0000
CH3	0.9500	0.9500	0.9310	0.8130	0.5310	0.2130	0.0380	0.0000
CH4	0.9500	0.9500	0.9500	0.9400	0.8500	0.5750	0.2250	0.0350

Table C6 - Vulnerability Factors for Facilities ‘without Protection’ Subject to Natural Terrain Landslide Hazard from Channelized Debris Flow Catchments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
TH1	0.0615	0.0230	0.0060	0.0008	0.0000	0.0000	0.0000	0.0000
TH2	0.8290	0.5940	0.2930	0.0860	0.0110	0.0000	0.0000	0.0000
TH3	0.9400	0.8690	0.6580	0.3480	0.1090	0.0150	0.0000	0.0000
TH4	0.9500	0.9410	0.8760	0.6750	0.3640	0.1140	0.0150	0.0000

Table C7 - Vulnerability Factors for Facilities ‘with Protection’ Subject to Natural Terrain Landslide Hazard from Topographic Depression Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
TH1	0.1258	0.0503	0.0143	0.0023	0.0000	0.0000	0.0000	0.0000
TH2	0.9280	0.7730	0.4540	0.1600	0.0260	0.0000	0.0000	0.0000
TH3	0.9500	0.9400	0.8190	0.5110	0.1880	0.0300	0.0000	0.0000
TH4	0.9500	0.9500	0.9410	0.8330	0.5340	0.1980	0.0300	0.0000

Table C8 - Vulnerability Factors for Facilities ‘without Protection’ Subject to Natural Terrain Landslide Hazard from Topographic Depression Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
SH1	0.0473	0.0148	0.0028	0.0003	0.0000	0.0000	0.0000	0.0000
SH2	0.7980	0.5240	0.2130	0.0450	0.0040	0.0000	0.0000	0.0000
SH3	0.9360	0.8440	0.5900	0.2640	0.0610	0.0050	0.0000	0.0000
SH4	0.9500	0.9380	0.8510	0.6080	0.2800	0.0660	0.0050	0.0000

Table C9 - Vulnerability Factors for Facilities ‘with Protection’ Subject to Natural Terrain Landslide Hazard from Open Slope Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
SH1	0.0980	0.0343	0.0070	0.0008	0.0000	0.0000	0.0000	0.0000
SH2	0.9200	0.7230	0.3600	0.0910	0.0090	0.0000	0.0000	0.0000
SH3	0.9500	0.9360	0.7750	0.4160	0.1130	0.0100	0.0000	0.0000
SH4	0.9500	0.9500	0.9380	0.7890	0.4390	0.1230	0.0100	0.0000

Table C10 - Vulnerability Factors for Facilities ‘without Protection’ Subject to Natural Terrain Landslide Hazard from Open Slope Catchments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

C.4 SCALE FACTOR

The Scale Factor (Sn) is applied to account for different spatial extent of damage when the facilities are affected by natural terrain landslides of different sizes (Table C11). As each building structure along the toe of an open slope is included in the calculation and the width of the building structure is taken into account in the Location Factor (see Section 5 below), it is not necessary to consider the spatial extent of damage from an open slope debris slide or avalanche. Hence, a Scale Factor = 1.0 is used for open slope landslides.

Natural Terrain Landslide Hazard	Scale Factor (Sn)	
	Building Structures	Sensitive Routes and Mass Transportation Facilities
CH1	0.5	0.5
CH2	1.0	1.0
CH3	2.0	2.0
CH4	4.0	4.0
TH1	0.5	0.5
TH2	1.0	1.0
TH3	2.0	2.0
TH4	4.0	4.0
SH1	1.0	1.0
SH2	1.0	3.0
SH3	1.0	6.0
SH4	1.0	10.0

Table C11 - Scale Factors for Building Structures, and Sensitive Routes and Mass Transportation Facilities

C.5 LOCATION FACTOR

The Location Factor (Ln) is applied to account for the possibility that a facility may not be subject to direct hit by a landslide if the facility is laterally offset from the credible flow path.

For a debris flow along a channel or topographic depression, the credible flow path is along the drainage line, irrespective of the location of the source of the landslide. The Locaton Factors for facilities at different degrees of lateral offset from the credible flow path are given in Table C12 and the product of the Scale Factor and the Location Factor is capped at 1.50.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Possibility of Direct Hit	Location Factor (Ln)
Less possible	0.25
Possible	0.50
Very possible	1.00
Very possible with aggravation effect, for example a steep cut slope is present at the credible flow path before reaching the facility	1.50

Table C12 - Location Factors for Facilities affected by Natural Terrain Landslides from Channelized Debris Flow and Topographic Depression Catchments

For open slope catchments, the Location Factor should reflect the probability that the landslide source and hence the credible flow path is on the hillside directly overlooking a building structure. For a building structure with width = L_D in front of an open slope catchment of a toe length = L_B, the Location Factor is given by:

If $L_D \leq w$: Location Factor $= w / L_B$ ....(C4)

If $L_D > w$: Location Factor $= (w / L_B)(L_D / w) = L_D / L_B$ ....(C5)

where w is the referenced width of the open slope landslide, as given in Table C13.

	Open Slope Landslide Hazard			
	SH1	SH2	SH3	SH4
Width of Open Slope Landslides, w (m)	10	30	60	100

Table C13 - Width of Open Slope Landslides with respect to Different Open Slope Landslide Hazards

For sensitive routes and mass transportation facilities, Location Factor = 1.0 is adopted for open slope catchments.

C.6 BUILDING COLLAPSE

Where building collapse occurs, PLL additional to that given in equation (C1) would occur due to damage to the upper floors. This additional PLL, denoted as CON2, is assessed as follows:

CON2 = Pcollapse x Vcollapse x Lcollapse.............................(C6)

where Pcollapse = Additional Population at risk due to building collapse
Vcollpase = Probability of building collapse
Lcollapse = Location Factor for building collapse

Pcollapse, the additional population at risk at the upper floors in the event of building collapse adopted in the 'Best-estimate' model, is given in Table C14.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Building Type	Description	Population at Risk (No.)
B1	Individual houses or structures of three storeys	4
B2	Cluster of houses or structures of three storeys	8
B3	Buildings of four to five storeys, including podium and similar area	20
	Buildings of six to ten storeys, including podium and similar area	50
B4	Multi-storey buildings of 11 to 20 storeys, including podium and similar area	150
B5	High-rise buildings of more than 20 storeys, including podium and similar area	200
B6	Sensitive structures that may involve severe consequence, including PHI, tunnel portal, petrol stations, railway platform, MTR exit	200

Table C14 - Additional Population at Risk at the Upper Floors in the Event of Building Collapse

Vcollpase gives account of the probability of occurrence of building collapse, for buildings located at different proximity zones and subject to different types of natural terrain landslide hazard (Tables C15 to C20).

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
CH1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH2	0.1930	0.1600	0.1010	0.0420	0.0090	0.0010	0.0000	0.0000
CH3	0.4880	0.4380	0.3440	0.2200	0.0980	0.0230	0.0010	0.0000
CH4	0.6900	0.6400	0.5400	0.3850	0.1900	0.0500	0.0050	0.0000

Table C15 - Vulnerability Factors for Collapse of Building Structures within Three Storeys Subject to Natural Terrain Landslide Hazard from Channelized Debris Flow Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
CH1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH3	0.3440	0.3130	0.2360	0.1280	0.0400	0.0050	0.0000	0.0000
CH4	0.4900	0.4400	0.3400	0.2020	0.0780	0.0180	0.0020	0.0000

Table C16 - Vulnerability Factors for Collapse of Building Structures of more than Three Storeys Subject to Natural Terrain Landslide Hazard from Channelized Debris Flow Catchments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
TH1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TH2	0.0890	0.0570	0.0230	0.0050	0.0000	0.0000	0.0000	0.0000
TH3	0.6980	0.5430	0.3400	0.1490	0.0380	0.0040	0.0000	0.0000
TH4	0.9240	0.8250	0.6390	0.3880	0.1550	0.0320	0.0020	0.0000

Table C17 - Vulnerability Factors for Collapse of Building Structures within Three Storeys Subject to Natural Terrain Landslide Hazard from Topographic Depression Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
TH1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TH2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TH3	0.4280	0.3360	0.1990	0.0710	0.0110	0.0000	0.0000	0.0000
TH4	0.8250	0.6560	0.4430	0.2180	0.0630	0.0080	0.0000	0.0000

Table C18 - Vulnerability Factors for Collapse of Building Structures of more than Three Storeys Subject to Natural Terrain Landslide Hazard from Topographic Depression Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
SH1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SH2	0.0850	0.0480	0.0150	0.0020	0.0000	0.0000	0.0000	0.0000
SH3	0.6700	0.4980	0.2860	0.1040	0.0190	0.0010	0.0000	0.0000
SH4	0.9130	0.7910	0.5840	0.3200	0.1040	0.0150	0.0010	0.0000

Table C19 - Vulnerability Factors for Collapse of Building Structures within Three Storeys Subject to Natural Terrain Landslide Hazard from Open Slope Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
SH1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SH2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SH3	0.4110	0.3100	0.1600	0.0430	0.0040	0.0000	0.0000	0.0000
SH4	0.7910	0.6090	0.3850	0.1630	0.0350	0.0030	0.0000	0.0000

Table C20 - Vulnerability Factors for Collapse of Building Structures of more than Three Storeys Subject to Natural Terrain Landslide Hazard from Open Slope Catchments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Lcollapse is the Location Factor to be applied with respect to building collapse. For open slope failure affecting building structures, Lcollapse = Ln. For debris flows along drainage lines and topographic depressions, Lcollapse = Ln^2, capped at 1.00.

C.7 SENSITIVITY ANALYSIS

For the purpose of assessing the sensitivity of the QRA results to the assumptions made, alternative sets of the key figures adopted in the Natural Terrain Landslide Consequence Model have been considered in the sensitivity analysis. These include:

(a) More Conservative Estimates of Population at Risk in Building Structures (Table C21)

Building Type	Description	Population at Risk (Pn) (No.)
B1	Individual houses or structures of one to three storeys	3
B2	Cluster of houses or structures of one to three storeys	6
B3	Buildings of four to ten storeys, including podium and similar area	9
B4	Multi-storey buildings of 11 to 20 storeys, including podium and similar area	9
B5	High-rise buildings of more than 20 storeys, including podium and similar area	9
B6	Sensitive structures that may involve severe consequence, including PHI, tunnel portal, petrol stations, railway platform, MTR exit	9

Table C21 - More Conservative Estimates of Population at Risk for Different Types of Building Structures

(b) More Conservative Estimates of Vulnerability Factors for cases without Building Collapse for Hazard H1 (Tables C22 to C27)

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
CH1	0.1550	0.1140	0.0520	0.0113	0.0008	0.0000	0.0000	0.0000
CH2	0.9350	0.8480	0.6300	0.3380	0.1100	0.0150	0.0000	0.0000
CH3	0.9500	0.9440	0.8880	0.7000	0.3940	0.1310	0.0190	0.0000
CH4	0.9500	0.9500	0.9450	0.9000	0.7350	0.4300	0.1450	0.0200

Table C22 - More Conservative Estimates of Vulnerability Factors for Facilities ‘with Protection’ Affected by Channelized Debris Flow Catchments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
CH1	0.3800	0.2900	0.1475	0.0450	0.0075	0.0000	0.0000	0.0000
CH2	0.9500	0.9200	0.7750	0.4930	0.2000	0.0380	0.0000	0.0000
CH3	0.9500	0.9500	0.9310	0.8130	0.5310	0.2130	0.0380	0.0000
CH4	0.9500	0.9500	0.9500	0.9400	0.8500	0.5750	0.2250	0.0350

Table C23 - More Conservative Estimates of Vulnerability Factors for Facilities ‘without Protection’ Affected by Channelized Debris Flow Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
TH1	0.1235	0.0583	0.0150	0.0015	0.0000	0.0000	0.0000	0.0000
TH2	0.8290	0.5940	0.2930	0.0860	0.0110	0.0000	0.0000	0.0000
TH3	0.9400	0.8690	0.6580	0.3480	0.1090	0.0150	0.0000	0.0000
TH4	0.9500	0.9410	0.8760	0.6750	0.3640	0.1140	0.0150	0.0000

Table C24 - More Conservative Estimates of Vulnerability Factors for Facilities ‘with Protection’ Affected by Topographic Depression Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
TH1	0.2663	0.1463	0.0450	0.0075	0.0000	0.0000	0.0000	0.0000
TH2	0.9280	0.7730	0.4540	0.1600	0.0260	0.0000	0.0000	0.0000
TH3	0.9500	0.9400	0.8190	0.5110	0.1880	0.0300	0.0000	0.0000
TH4	0.9500	0.9500	0.9410	0.8330	0.5340	0.1980	0.0300	0.0000

Table C25 - More Conservative Estimates of Vulnerability Factors for Facilities ‘without Protection’ Affected by Topographic Depression Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
SH1	0.1128	0.0440	0.0080	0.0005	0.0000	0.0000	0.0000	0.0000
SH2	0.7980	0.5240	0.2130	0.045	0.0040	0.0000	0.0000	0.0000
SH3	0.9360	0.8440	0.5900	0.2640	0.0610	0.0050	0.0000	0.0000
SH4	0.9500	0.9380	0.8510	0.6080	0.2800	0.0660	0.0050	0.0000

Table C26 - More Conservative Estimates of Vulnerability Factors for Facilities ‘with Protection’ Affected by Open Slope Catchments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
SH1	0.2500	0.1213	0.0263	0.0025	0.0000	0.0000	0.0000	0.0000
SH2	0.9200	0.7230	0.3600	0.0910	0.0090	0.0000	0.0000	0.0000
SH3	0.9500	0.9360	0.7750	0.4160	0.1130	0.0100	0.0000	0.0000
SH4	0.9500	0.9500	0.9380	0.7890	0.4390	0.1230	0.0100	0.0000

Table C27 - More Conservative Estimates of Vulnerability Factors for Facilities ‘without Protection’ Affected by Open Slope Catchments

(c) Less Conservative Estimates of Vulnerability Factors for Building Collapse (Tables C28 to C33)

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
CH1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH2	0.0930	0.0680	0.0340	0.0090	0.0010	0.0000	0.0000	0.0000
CH3	0.3440	0.3130	0.2350	0.1240	0.0370	0.0050	0.0000	0.0000
CH4	0.4950	0.4600	0.3600	0.2070	0.0760	0.0160	0.0020	0.0000

Table C28 - Less Conservative Estimates of Vulnerability Factors for Collapse of Building Structures within Three Storeys Subject to Natural Terrain Landslide Hazard from Channelized Debris Flow Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
CH1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH3	0.2000	0.1880	0.1390	0.0660	0.0160	0.0010	0.0000	0.0000
CH4	0.3000	0.2900	0.2350	0.1320	0.0460	0.0110	0.0020	0.0000

Table C29 - Less Conservative Estimates of Vulnerability Factors for Collapse of Building Structures of more than Three Storeys Subject to Natural Terrain Landslide Hazard from Channelized Debris Flow Catchments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
TH1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TH2	0.0350	0.0140	0.0040	0.0000	0.0000	0.0000	0.0000	0.0000
TH3	0.5180	0.3850	0.2020	0.0640	0.0110	0.0010	0.0000	0.0000
TH4	0.9240	0.8080	0.5610	0.2660	0.0720	0.0090	0.0000	0.0000

Table C30 - Less Conservative Estimates of Vulnerability Factors for Collapse of Building Structures within Three Storeys Subject to Natural Terrain Landslide Hazard from Topographic Depression Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
TH1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TH2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TH3	0.3180	0.2150	0.1040	0.0300	0.0040	0.0000	0.0000	0.0000
TH4	0.8080	0.5790	0.3130	0.1150	0.0250	0.0020	0.0000	0.0000

Table C31 - Less Conservative Estimates of Vulnerability Factors for Collapse of Building Structures of more than Three Storeys Subject to Natural Terrain Landslide Hazard from Topographic Depression Catchments

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
SH1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SH2	0.0280	0.0100	0.0020	0.0000	0.0000	0.0000	0.0000	0.0000
SH3	0.4980	0.3450	0.1530	0.0370	0.0050	0.0000	0.0000	0.0000
SH4	0.9130	0.7660	0.4860	0.1940	0.0400	0.0040	0.0000	0.0000

Table C32 - Less Conservative Estimates of Vulnerability Factors for Collapse of Building Structures within Three Storeys Subject to Natural Terrain Landslide Hazard from Open Slope Catchments

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Landslide Hazard	Proximity Zone							
	1	2	3	4	5	6	7	8
SH1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SH2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SH3	0.2980	0.1860	0.0760	0.0160	0.0010	0.0000	0.0000	0.0000
SH4	0.7660	0.5110	0.2480	0.0770	0.0130	0.0010	0.0000	0.0000

Table C33 - Less Conservative Estimates of Vulnerability Factors for Collapse of Building Structures of more than Three Storeys Subject to Natural Terrain Landslide Hazard from Open Slope Catchments

(d) Less Conservative Estimates of Debris Mobility in Topographic Depression

In the 'Best-estimate' model, risk of natural terrain landslide hazard from topographic depression catchments is calculated on the basis of a combination of 67% of the Vulnerability Factors for topographic depression catchments and 33% of the Vulnerability Factors for channelized debris flow catchments. This is to cater for the chance that debris from topographic depression catchments may behave as a channelized debris flow.

In the sensitivity analysis, less conservative estimates of debris mobility in topographic depression catchments are considered. This is done by excluding the provision for debris behaving as a channelized debris flow (i.e. to adopt 100% of the Vulnerability Factors for topographic depression catchments).

The following combinations are adopted in the 'Low' and 'High' models in the sensitivity analysis (Table C34):

Consequence Model	Population at Risk	Vulnerability Factors (not involving building collapse)	Vulnerability Factors for Building Collapse	Debris Mobility in Topographic Depression
Low	'Best-estimate'	'Best-estimate'	Less Conservative Estimates (Tables C28 to C33)	Less Conservative Estimates (Section 7(d))
High	More Conservative Estimates (Table C21)	More Conservative Estimates (Tables C22 to C27)	'Best-estimate'	'Best-estimate'
Note: 'Best-estimate' refers to figures adopted in the 'Best-estimate' model.				

Table C34 - Combination of Key Figures adopted in the 'Low' and 'High' models in the Sensitivity Analysis

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table of Contents
Table of Contents
Table of Contents
Table of Contents

APPENDIX D

RISK MODEL

D.1 INTRODUCTION

‘Risk’ refers to the probability of harmful consequences due to natural terrain landslide hazards. In this global QRA, societal risk in terms of PLL is assessed as:

$$\text{Risk} = \sum (\text{Frequency x Consequence}) \quad \text{......(D1)}$$

where, for each landslide hazard:

Frequency = Estimated Landslide Frequency of the hazard
(Section 5 of Appendix B and Table B16, based on the frequency model)

Consequence = CON1 + CON2
(Equations C1 & C6, based on the consequence model)

Natural terrain landslides from a catchment may affect more than one facility at risk. By summing up the risk of all landslide hazards from a catchment on each of the facilities at risk, the natural terrain landslide risk on the facility is derived. Summing up the calculated risks on all the facilities at risk gives the natural terrain landslide risk arising from the catchment.

D.2 CALCULATION OF RISK OF HISTORICAL NTLI CATCHMENTS

The risk of each of the Historical NTLI Catchment is calculated by equation D1, using the ‘Best-estimate’ model and Half-Bayesian Update. The total risk of all Historical NTLI Catchments are obtained by summing up the calculated risks of all the Catchments.

Other models and different degrees of Bayesian Update are used in sensitivity analysis (Table 7).

D.3 PROJECTION TO OVERALL RISK IN HONG KONG

The total risk of the Supplementary Catchments in the five selected regions is calculated by equation D1 using the ‘Best-estimate’ model and different degrees of Bayesian Update.

The ‘Global Risk Ratio’ is calculated as:

$$\text{Global Risk Ratio} = \frac{\begin{matrix}\text{Risk of Historical} \\ \text{NTLI Catchments}\end{matrix} + \begin{matrix}\text{Risk of Supplementary} \\ \text{Catchments}\end{matrix}}{\text{Risk of the Historical NTLI Catchments}} \quad \text{.............(D2)}$$

Table of Contents
Table of Contents
Table of Contents
Table of Contents

The overall natural terrain landslide risk in Hong Kong is projected from the total risk of the Historical NTLI Catchments using the Global Risk Ratio:

Overall risk = Global Risk Ratio x Total Risk of Historical NTLI Catchments .....(D3)

As the majority of the Supplementary Catchments have few NTLI landslides, their risk calculated from equation D1 and hence the Global Risk Ratio are more sensitive to the degree of Bayesian Update adopted in the calculation (see Table 8).

Sensitivity analysis is carried out to estimate the probable variations in the calculated total risk of Historical NTLI Catchments and the Global Risk Ratio. Pessimistic Scenario and Optimistic Scenario are assessed to give the probable range of the overall risk of natural terrain landslides in Hong Kong.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

GEO PUBLICATIONS AND ORDERING INFORMATION
土力工程處刊物及訂購資料

A selected list of major GEO publications is given in the next page. An up-to-date full list of GEO publications can be found at the CEDD Website http://www.cedd.gov.hk on the Internet under "Publications". Abstracts for the documents can also be found at the same website. Technical Guidance Notes are published on the CEDD Website from time to time to provide updates to GEO publications prior to their next revision.

部份土力工程處的主要刊物目錄刊載於下頁。而詳盡及最新的土力工程處刊物目錄，則登載於土木工程拓展署的互聯網網頁http://www.cedd.gov.hk 的"刊物"版面之內。刊物的摘要及更新刊物內容的工程技術指引，亦可在這個網址找到。

Copies of GEO publications (except maps and other publications which are free of charge) can be purchased either by:

writing to
Publications Sales Section,
Information Services Department,
Room 402, 4th Floor, Murray Building,
Garden Road, Central, Hong Kong.
Fax: (852) 2598 7482

or

- Calling the Publications Sales Section of Information Services Department (ISD) at (852) 2537 1910
- Visiting the online Government Bookstore at http://bookstore.esdlife.com
- Downloading the order form from the ISD website at http://www.isd.gov.hk and submit the order online or by fax to (852) 2523 7195
- Placing order with ISD by e-mail at puborder@isd.gov.hk

讀者可採用以下方法購買土力工程處刊物(地質圖及免費刊物除外):

書面訂購
香港中環花園道
美利大廈4樓402室
政府新聞處
刊物銷售組
傳真: (852) 2598 7482

或

- 致電政府新聞處刊物銷售小組訂購 (電話：(852) 2537 1910)
- 進入網上「政府書店」選購，網址為 http://bookstore.esdlife.com
- 透過政府新聞處的網站 (http://www.isd.gov.hk) 於網上遞交訂購表格，或將表格傳真至刊物銷售小組 (傳真：(852) 2523 7195)
- 以電郵方式訂購 (電郵地址：puborder@isd.gov.hk)

1:100 000, 1:20 000 and 1:5 000 maps can be purchased from:

Map Publications Centre/HK,
Survey & Mapping Office, Lands Department,
23th Floor, North Point Government Offices,
333 Java Road, North Point, Hong Kong.
Tel: 2231 3187
Fax: (852) 2116 0774

讀者可於下列地點購買1:100 000，1:20 000及1:5 000地質圖：

香港北角渣華道333號
北角政府合署23樓
地政總署測繪處
電話: 2231 3187
傳真: (852) 2116 0774

Requests for copies of Geological Survey Sheet Reports, publications and maps which are free of charge should be sent to:

For Geological Survey Sheet Reports and maps which are free of charge:
Chief Geotechnical Engineer/Planning,
(Attn: Hong Kong Geological Survey Section)
Geotechnical Engineering Office,
Civil Engineering and Development Department,
Civil Engineering and Development Building,
101 Princess Margaret Road,
Homantin, Kowloon, Hong Kong.
Tel: (852) 2762 5380
Fax: (852) 2714 0247
E-mail: jsewell@cedd.gov.hk

For other publications which are free of charge:
Chief Geotechnical Engineer/Standards and Testing,
Geotechnical Engineering Office,
Civil Engineering and Development Department,
Civil Engineering and Development Building,
101 Princess Margaret Road,
Homantin, Kowloon, Hong Kong.
Tel: (852) 2762 5345
Fax: (852) 2714 0275
E-mail: ykhui@cedd.gov.hk

如欲索取地質調查報告、其他免費刊物及地質圖，請致函：

地質調查報告及地質圖:
香港九龍何文田公主道101號
土木工程拓展署大樓
土木工程拓展署
土力工程處
規劃部總土力工程師
(請交:香港地質調查組)
電話: (852) 2762 5380
傳真: (852) 2714 0247
電子郵件: jsewell@cedd.gov.hk

其他免費刊物:
香港九龍何文田公主道101號
土木工程拓展署大樓
土木工程拓展署
土力工程處
標準及測試部總土力工程師
電話: (852) 2762 5345
傳真: (852) 2714 0275
電子郵件: ykhui@cedd.gov.hk

MAJOR GEOTECHNICAL ENGINEERING OFFICE PUBLICATIONS
土力工程處之主要刊物

GEOTECHNICAL MANUALS

Geotechnical Manual for Slopes, 2nd Edition (1984), 300 p. (English Version), (Reprinted, 2000).

斜坡岩土工程手冊(1998)，308頁(1984年英文版的中文譯本)。

Highway Slope Manual (2000), 114 p.

GEOGUIDES

Geoguide 1	Guide to Retaining Wall Design, 2nd Edition (1993), 258 p. (Reprinted, 2000).
Geoguide 2	Guide to Site Investigation (1987), 359 p. (Reprinted, 2000).
Geoguide 3	Guide to Rock and Soil Descriptions (1988), 186 p. (Reprinted, 2000).
Geoguide 4	Guide to Cavern Engineering (1992), 148 p. (Reprinted, 1998).
Geoguide 5	Guide to Slope Maintenance, 3rd Edition (2003), 132 p. (English Version).
岩土指南第五冊	斜坡維修指南，第三版(2003)，120頁(中文版)。
Geoguide 6	Guide to Reinforced Fill Structure and Slope Design (2002), 236 p.

GEOSPECS

Geospec 1	Model Specification for Prestressed Ground Anchors, 2nd Edition (1989), 164 p. (Reprinted, 1997).
Geospec 3	Model Specification for Soil Testing (2001), 340 p.

GEO PUBLICATIONS

GCO Publication No. 1/90	Review of Design Methods for Excavations (1990), 187 p. (Reprinted, 2002).
GEO Publication No. 1/93	Review of Granular and Geotextile Filters (1993), 141 p.
GEO Publication No. 1/2000	Technical Guidelines on Landscape Treatment and Bio-engineering for Man-made Slopes and Retaining Walls (2000), 146 p.
GEO Publication No. 1/2006	Foundation Design and Construction (2006), 376 p.

GEOLOGICAL PUBLICATIONS

The Quaternary Geology of Hong Kong, by J.A. Fyfe, R. Shaw, S.D.G. Campbell, K.W. Lai & P.A. Kirk (2000), 210 p. plus 6 maps.

The Pre-Quaternary Geology of Hong Kong, by R.J. Sewell, S.D.G. Campbell, C.J.N. Fletcher, K.W. Lai & P.A. Kirk (2000), 181 p. plus 4 maps.

TECHNICAL GUIDANCE NOTES

TGN 1	Technical Guidance Documents

Table of Contents
Table of Contents
Table of Contents