LANDSLIDE RISK ASSESSMENT - APPLICATION AND PRACTICE

GEO REPORT No. 195

H.N. Wong & F.W.Y. Ko

GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING AND DEVELOPMENT DEPARTMENT

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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.

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R.K.S. Chan
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December 2006

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FOREWORD

Formal landslide risk assessment emerged in the late 1970s. It was confined to qualitative applications in the early years, but has been extended into quantified assessments since the 1990s. The state of the art in landslide risk assessment as applied to a larger scale is presented in this report. Notable application cases are described to illustrate the approaches adopted and the development trends in risk assessment practice. Particular reference is drawn to applications in Hong Kong, which is internationally recognized as a role model in urban landslide risk management.

Prof. R. Fell, Prof. D. Martin, Dr. A.H. Shamsuddin and S. Tomlinson provided information on selected cases. A.W.T. Fung, F.W.Y. Ko and T.K.C. Wong assisted in reviewing some of the cases and preparing tables and figures. S.D.G. Campbell and Y.C. Chan gave useful suggestions and comments. F.W.Y. Ko assisted in preparing the report.

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ABSTRACT

Geotechnical practice has progressed to the stage that slope engineering is no longer confined to investigation of slope stability. Instead, landslide risk has to be examined and managed in totality. This brings a broad spectrum of landslide-related problems to the agenda of risk assessment. This report addresses landslide risk assessment that is undertaken at a larger scale, in which the facilities at risk are individually recognized and assessed. Selected application cases are presented to illustrate the approaches adopted, their capability and constraints, and the development trends in risk assessment practice. There is a choice between using a qualitative or quantitative approach. There are also significant differences between applying the assessment to a few individual sites and to a large number of slopes. The challenge is for the geotechnical profession to master the diverse range of landslide risk assessment processes, to use the right tools for the right problems, and to become more effective in risk communication with stakeholders.

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1. INTRODUCTION

Many practical slope problems are best tackled by a risk-based approach. The key principle is to examine both the likelihood and adverse consequence of slope failure, and thereby address risk in totality. This concept is implicit in our slope design and engineering practice. It has also been explicitly applied in different places, particularly where formal risk assessment is adopted in managing landslide problems. Over the last decade, many geotechnical researchers and practitioners have contributed to consolidating a landslide risk assessment framework, enhancing techniques and pioneering applications to problems that are otherwise difficult to resolve using conventional methods.

This report deals with landslide risk assessment at a larger scale and its application to risk management. It reviews the methodologies used to assess landslide risk for individual facilities, examines good practice and diagnoses the development trends, with particular attention being given to application and case histories. Selected qualitative risk-based slope rating schemes adopted in various countries are described to illustrate the practice and approaches. Selected examples of qualitative and quantitative risk assessment (QRA) applications, particularly in Hong Kong where QRA has been formally adopted in landslide risk management, are presented to show the range of applications and evolution of techniques.

2. OVERVIEW OF ASSESSMENT OF LANDSLIDE RISK FOR INDIVIDUAL FACILITIES

'Landslide risk' is a measure of the chance of occurrence of slope failure causing a certain amount of harm (e.g. fatalities and economic losses), and can be quantified as the product of the probability and consequence of failure. 'Landslide risk assessment' is the process of identifying the landslide hazard and estimation of the risk of the hazard. 'Landslide risk management' comprises an estimation of the landslide risk, deciding whether or not the risk is tolerable, ad exercising appropriate control measures to reduce the risk where the risk level cannot be tolerated. In a more global context, landslide risk management also refers to the systematic application of management policies, procedures and practices to the tasks of identifying, analyzing, assessing, mitigating and monitoring landslide risk.

In this report, 'landslide risk assessment for individual facilities' refers to the assessment that is undertaken at a resolution and scale sufficient for the elements at risk (i.e. the facilities where adverse consequences may occur) to be individually recognized and their landslide risk evaluated, either by qualitative or quantitative means. This is the most common type of landslide risk assessment that is carried out for location-specific risk management purposes. It differs from risk assessment as applied to general landslide hazard and risk zoning in the following aspects:

(a) It is often carried out at a larger scale, typically 1:2,000 or more detailed, such that both the slopes that pose the risk and the elements at risk can be clearly identified and examined. Landslide hazard and risk zoning is usually carried out at a smaller scale.

(b) The element at risk is known, be it an existing or a planned facility. Hence, not only the likelihood of a landslide but

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also its consequence can be explicitly evaluated. Landslide hazard and risk zoning would not necessarily involve a comparable level of consequence assessment and may in some cases be carried out without examining in detail the specific facilities at risk.

(c) It is often carried out to support or guide risk management decisions affecting specific sites, such as the priority and need for risk mitigation. Its reliability and resolution have to be commensurate with the intended application. The assessment would normally require the use of more detailed data and specific risk analysis techniques.

Depending on the intended application, landslide risk assessment for individual facilities can be carried out in different ways and to different levels of detail. The assessment may be classified according to the analytical approach adopted, i.e. whether it is primarily based on qualitative, semi-quantitative or quantitative methodology. Alternatively, classification may be made in relation to the purpose of the assessment. This typically includes risk rating, screening, prioritization, evaluation of overall risk, formulation of risk management strategy, site-specific risk management action, etc. There is no hard-and-fast rule for classification. It is obvious that the analytical approach must be related to the purpose of the assessment. As a broad categorization to facilitate review and assessment of the current state of practice, a pragmatic classification as summarized in Table 2.1 is adopted in this report.

3. QUALITATIVE RISK RATING

3.1 Overview of Qualitative Risk Rating

Qualitative risk rating is the most common form of application of qualitative landslide risk analysis to a large number of slopes. This is commonly carried out by devising a rating scheme to evaluate the relative likelihood of landslide (i.e. hazard rating) and the relative severity of the consequence of failure (i.e. consequence rating), based on qualitative analysis of the slope attributes and data on the individual facilities affected. The qualitative analysis may be performed by different methods, such as the use of a scoring system, flow charts, qualitative descriptors, a risk matrix, or a combination of these methods. The rating scheme is then applied to a large number of slopes. Provided that the required slope attributes and facility data are collected, the risks of the slopes can be rated and their relative risk compared. Depending on the complexity of the qualitative risk analysis method adopted, the scheme may be targeted on one or many types of slope (e.g. rock cut slopes and fill embankments), and for one specific type of facility (e.g. roads) or different types of facility.

Qualitative risk rating has been formulated and applied in many different places, some dating back to the late 1970s and early 1980s. It is typically adopted by agencies that are responsible for managing the risk for a large number of existing slopes. The risk rating provided a relatively simple but consistent means to achieve the following objectives:

(a) to evaluate and rank their relative risk (i.e. ‘risk ranking’);

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(b) to prioritize the slopes for follow-up study, repair or maintenance (i.e. 'prioritization for action'); and

(c) to assist in the preliminary assessment of the scope and cost of follow-up action (i.e. 'preliminary estimate').

Selected risk rating schemes are described in Sections 3.2 to 3.9 below to illustrate the practice and approaches adopted in different places. A comparison of the key features of the schemes is summarized in Table 3.1.

In some cases, the rating process involves a preliminary screening to first identify the more problematic slopes within a large number of slopes, as candidates for risk rating. This is referred to as 'preliminary screening' in Table 3.1. Some rating systems have also been used as a tool to provide reference data for use in QRA. This is denoted as a 'QRA tool' in Table 3.1. As explained in Item (g) of Section 3.10.4 below, a rating system may also be characterized depending on whether it is principally an 'expert judgment scheme', or an 'expert formulation scheme', or a 'mixed scheme'.

3.2 Cut Slope Ranking System, Hong Kong

3.2.1 Background

Hong Kong has a population of almost 7 million and about 1,100 km^2 of rugged terrain. These, together with high seasonal rainfall and tropically weathered geological profile, make slope engineering in Hong Kong a particular challenge for the geotechnical profession. The dense urban development since the Second World War has resulted in the formation of a large number of cut slopes, fill slopes and retaining walls. Until the mid 1970s, cut slopes were generally built empirically to an angle of 10 vertical to 6 horizontal (Figure 3.1). Fill slopes formed prior to the mid 1970s were generally not compacted to an acceptable standard. These un-engineered man-made slopes were susceptible to landslides. Some resulted in very significant loss of life.

In 1977, upon setting up the Geotechnical Control Office (GCO, which was renamed Geotechnical Engineering Office, GEO, in 1991), the Hong Kong Government embarked on a long-term programme for retro-fitting substandard slopes. A pre-requisite for implementation of this programme was the registration and risk ranking of the existing sizeable man-made slopes in the urban area. This prioritized the slopes, so that the most risky slopes could be stabilized first.

The registration of man-made slopes completed by the GCO at the time identified a total of about 8,500 cut slopes and retaining walls. These were catalogued in a slope inventory (referred to as the 1977/78 Slope Catalogue), which contained the key slope attributes and data on affected facilities. A sample field data sheet used in field inspections to record the data is given in Figure 3.2. In 1979, the GCO and Binnie & Partners jointly formulated the Cut Slope Ranking System, which was a qualitative risk rating scheme. The system was used by the GCO to calculate a 'Total Score' for each of the 8,500 cut slopes and retaining walls registered in the inventory. Based on the Total Score, which reflected the relative landslide risk, the cut slopes and retaining walls were ranked for follow-up studies to assess whether they met the required safety standard and whether retro-fitting was necessary.

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3.2.2 Formulation

The system was described in Koirala & Watkins (1988). The ranking system was based on an assessment of the potential for failure and the consequence of failure. The assessment of the potential for failure involved consideration of a number of key slope attributes, including slope type, slope height, slope angle, slope conditions, geology, presence of adverse jointing, type of slope surface protection, conditions above the slope crest, potential for ponding, presence of water-carrying services, and signs of seepage. Numeric weightings were assigned to the slope attributes, based on the judged significance of the data component with respect to the likelihood of failure. The weightings were used to calculate an ‘Instability Score’ for each slope, which reflected the relative potential for failure. Likewise, a ‘Consequence Score’ was calculated for each slope, based on the types of facility at the crest and toe of the slope, their proximity to the slope, terrain conditions over the slope crest and below the slope toe, with an allowance made for whether the area that might be affected by landslide was densely populated. Details of the numeric weightings and the formulation of the Instability Score and Consequence Score are shown in Table 3.2. The relative risk-to-life of the slope is represented by a Total Score, which is the sum of its Instability Score and Consequence Score.

The development of the scoring system involved considerable deliberation, trial and review to ensure that the various scoring and multiplying factors would reasonably reflect the importance of the components. The objective was that slopes with the greatest risk concern should be assigned the highest Total Score and thereby received highest priority for further investigation. Several trial batches of ranking and on-site re-assessment were carried out to calibrate the outcome of the ranking with independent expert judgment. The trials also helped to train and calibrate the personnel involved in the ranking exercise. Procedures for checking the ranking scores were devised. Most of the slopes were ranked independently by two people and their assessments were checked.

A plot of the Instability Score vs Consequence Score of the ranked slopes is shown in Figure 3.3. It is notable that the Consequence Score has a wider spread than the Instability Score. This was consistent with the fact that the consequence of landslide among the slopes varied to a greater extent than the likelihood of landslide that could be differentiated by the scoring methodology used to assess instability. Experience in using the system indicated that the system performed very satisfactorily in differentiating the 10% to 20% of the slopes with the greatest risk concern, which were subsequently selected by the GCO for investigation and retro-fitting. The calculated Total Score of many of these slopes was dominated by their Consequence Score. There were also cases of slopes which were given a high rank because of their high Consequence Scores, but which were subsequently found by detailed studies to have an adequate margin of safety and hence a low risk of landslide.

3.3 Fill Slope Ranking System, Hong Kong

3.3.1 Background

In parallel with the development of the Cut Slope Ranking System, the Fill Slope Ranking System was formulated jointly by the GCO and Binnie & Partners for risk ranking and prioritization of un-engineered fill slopes for follow-up investigation. The fill slopes constructed before 1977 in Hong Kong were mostly substandard in that the fill material was

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commonly placed by end-tipping with little, if any, compaction effort applied. Static liquefaction failure, in the form of a fast-moving, mobile flow slide, was known to be the key landslide problem from the fill slopes, as was evident from the 1972 and 1976 Sau Mau Ping landslides (Figure 3.4), which together resulted in 90 fatalities. It is implicit in the Fill Slope Ranking System that the ranking is based primarily on the relative risk of liquefaction failure. As the nature of the static liquefaction failure on the fill slopes is entirely different from that of failure of cut slopes and retaining walls, the factors that influence the likelihood and consequence of the failures are different. It was therefore necessary for different ranking systems to be developed at that time for fill slopes and cut slopes.

3.3.2 Formulation

The system was described in Koirala & Watkins (1988). The un-engineered fill slopes were ranked by the Fill Slope Ranking System in two steps. The first step involved a subjective categorization of the consequence of failure, in terms of risk-to-life, into the following classes:

(a) very high - direct risk to many people;

(b) high - direct threat to a few people;

(c) moderate/high - where buildings lie within range of a flow slide;

(d) moderate - buildings at the limit of a flow slide;

(e) low/moderate - buildings outside flow slide limits, major road affected; and

(f) low - buildings outside flow slide limits, minor road affected.

The second step involved rating the potential for failure of the slopes in each class, based on the calculation of an “x” score using the numeric weightings assigned to the slope attributes that were considered important for the stability of the slopes. The slope attributes were grouped into four components. The components, the relevant slope attributes and their weightings are shown in Table 3.3. All of the fill slopes were assumed to be loose, and the degree of compaction of the fill material was not considered in the relative risk rating. This was also a pragmatic arrangement because reliable data on the degree of compaction were generally not available at the time.

The Fill Slope Ranking System was applied by the GCO to about 2,000 fill slopes registered in the 1977/78 Slope Catalogue to establish their relative risk ranking and priority for follow-up treatment. The slopes were first grouped in terms of the consequence of failure. They were further prioritized within each group based on their calculated “x” scores, which reflected their potential for failure. The system was found to have satisfactorily achieved its objective in providing the GCO with a prioritized list of fill slopes for investigation and upgrading according to their failure consequence and potential. The system gave prominence to the failure consequence. This was a necessary response to the

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public expectation at that time that fill embankments threatening densely populated areas should be given the highest priority for treatment.

3.4 New Priority Classification System, Hong Kong

3.4.1 Background

The GEO has been operating a government-funded Landslip Preventive Measures (LPM) Programme to systematically study old man-made slopes and carry out stabilization works on sub-standard slopes that are under Government's responsibility. Until the early 1990s, the LPM Programme was delivering about 60 detailed slope studies and upgrading about 40 sub-standard man-made slopes per year, at an annual expenditure of about HK$ 60 million. The Cut Slope Ranking System and Fill Slope Ranking System formulated in the late 1970s were applied by the GCO in ranking the priority of the man-made slopes registered in the 1977/78 Slope Catalogue, for treatment under the LPM Programme. The two ranking systems served their intended purposes effectively. By the mid 1990s, about 1,000 top-ranking slopes were selected for detailed studies. Over 630 government-owned slopes that were found to be substandard and of serious consequences in the event of failure were upgraded under the LPM programme. Engineering inspections were also carried out on about 4,000 slopes in the Catalogue.

As many high ranking slopes were selected for action under the LPM Programme by the mid 1990, it was evident that a new rating system was required to further improve the effectiveness of prioritizing the remaining slopes. A number of factors contributed to this need:

(a) The old ranking systems were targeted at, and calibrated for, identification of the worst slopes. As a result, many high and sub-standard slopes close to occupied buildings were rightly assigned a high risk ranking and included in the LPM Programme for action before the mid 1990s. The beneficial effects could be gauged from the statistics on the landslides reported to the GEO up to the mid 1990s indicating that the proportion of landslides affecting occupied buildings was reducing (Figure 3.5). This trend implied that landslides affecting roads and other facilities were becoming increasingly important for effective landslide risk reduction under the LPM Programme. However, the old ranking systems were not tailor-made for differentiating the relative risk of these lower ranking slopes. This problem is illustrated by the very large number of closely packed data points that correspond to the lower ranking slopes in Figure 3.3.

(b) The old ranking systems had some inherent technical weaknesses, which hindered the achievement of a better resolution in differentiating the relative risk of the slopes, particularly among the lower ranking slopes. For example, soil and rock cut slopes were not differentiated in the risk rating. Slope height and slope gradient were separately scored without giving due account to the fact that they combined to affect the potential for landslide. Also, the classification of facility was fairly crude, and the performance history of the slopes was not considered. In the engineering inspections completed on the 4,000 slopes by the mid 1990s, each of the slopes was individually assessed by an experienced geotechnical engineer and an engineering judgment was made on the likelihood of preventive measures being necessary to bring the slope to the required safety standards. The slopes were categorized according to this assessed likelihood into three classes: 'HP', 'P' and 'U', which corresponded to 'Highly Probable', 'Probable' and 'Unlikely', respectively. By analyzing the landslide statistics, the relative landslide frequency on slopes in the 'HP', 'P' and 'U' classes was found to be 6:3:1, with comparable volumes of failure (Wong & Ho, 1995). A comparison of the calculated Instability Score and the likelihood class of these slopes (Figure 3.6) indicated that the Instability Score does not provide a clear resolution with respect to the assessed likelihood classes.

(c) Lack of suitable slope data for use in rating was a major constraint faced by the old ranking systems. For example, few slope performance data were available in the late 1970s when the systems were formulated. However, with GEO's effort in systematically collecting landslide data, comprehensive data were available in the mid-1990s and these could be used in an improved rating scheme. In addition, it was known that a large number of slopes, in particular slopes outside the main urban areas, had not yet been registered in the 1977/78 Slope Catalogue. Hence, in the early 1990s, the GEO commenced compilation of a new Catalogue of Slopes to register all sizeable man-made slopes in Hong Kong. The work included systematic interpretation of the historical aerial photographs and field inspections (Lam et al, 1998). This provided an opportunity to collect new data for use in risk rating. The Catalogue of Slopes now comprises some 57,000 man-made slopes, and about 39,000 of these were formed before 1977.

(d) Improved knowledge of landslides and related technical issues provided a basis for improving the slope rating methodology. In particular, the available landslide data, experience gained from applying the old systems, and enhanced capability in assessing the mobility of landslide debris and using QRA, helped to formulate a new rating system that would better achieve the risk management objectives.

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The New Priority Classification System (NPCS) was developed in 1995 and 1996, to replace the old ranking systems as the qualitative risk rating scheme for ranking pre-1977 man-made slopes registered in the new Catalogue of Slopes for treatment under the LPM Programme. There are four main types of man-made slope feature in Hong Kong, viz. soil cut slopes, rock cut slopes, fill slopes and retaining walls. Since the landslide risk of different types of slope feature is affected by different factors, four separate rating schemes have been developed. They combine to form the NPCS.

In each scheme, a Total Score is calculated for each slope, which reflects its relative landslide risk. The Total Score is given by multiplication of the Instability Score and Consequence Score of the slope. The Instability Score is derived from a scoring formula that rates a number of key parameters affecting the likelihood of failure. The Consequence Score is calculated by another formula that scores the parameters reflecting the likely consequence of failure. The higher the Total Score, the higher is the relative risk rating and hence the priority for follow-up action among other slopes of the same type.

In formulating the Consequence Score, factors relevant to the direct consequence-to-life in the event of failure are considered. Hence, the Consequence Score would not necessarily correlate with economic losses. Also, slopes which might pose a significant indirect consequence-to-life, such as slopes affecting cul-de-sacs and catchwaters, might not have received scores that fully reflect their possible consequence.

3.4.2 Formulation of Soil Cut Slope Priority Classification System

The detailed formulation and calibration of the Soil Cut Slope Priority Classification System are described in Wong & Ho (1995). The scoring scheme is summarized in Figure 3.7.

The Instability Score is calculated based on the engineering judgment made in the engineering inspection on the likelihood of preventive measures being necessary to bring the slope to the required safety standards, combined with an objective assessment of the key parameters that affect the likelihood of failure. The Consequence Score rates the consequence of failure, with account taken of the facilities at the slope crest and slope toe. The key groups of factors considered in the scoring scheme and the range of individual scores that may be assigned are summarized in Table 3.4.

The development of the NPCS has incorporated the experience gained from systematic landslide studies and use of the old ranking systems. A large amount of calibration work was carried out to assist in formulating the numeric weightings and the scoring formulae and to validate the ranking results. Some examples on the work done for the Soil Cut Slope Classification System are highlighted as follows:

(a) The scheme has adopted improved classification of slope geometry based on a combined consideration of the cut slope gradient and the effective slope height, as shown in Figure 3.8. The geometry classification has been calibrated with the outcome of the detailed stability assessment of 69 slopes, i.e. different types of statutory

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action were undertaken according to the factor of safety calculated for a 10-year groundwater condition from detailed stability assessment and site-specific ground investigation results. The relevant data points of the cases are shown in Figure 3.8. These data points were adopted in demarcating boundaries between different geometry zones. The worst zone, denoted as 'S1' in Figure 3.8, has about 80% of cases with a calculated factor of safety less than 1.1. Monte Carlo simulation was carried out to validate the boundaries of the geometry zone and to calibrate the landslide probabilistic distributions, using typical ranges of soil parameters and groundwater conditions in Hong Kong. The 'S1' zone has been taken as one of the conditions that give 'prima facie' evidence of a potentially dangerous soil cut slope, if located in the relevant geological setting and involving a significant consequence, for serving a statutory Dangerous Hillside Order. The Order requires the slope owners to investigate the stability of the slope and carry out any necessary stabilization works. In this respect, the rating system also partly serves the purpose of direct determination of site-specific risk management action.

(b) There is an empirical correlation between the Instability Score and the calculated factor of safety under a 10-year groundwater condition for the 69 sites, as shown in Figure 3.9. An Instability Score of less than 80 corresponds with a factor of safety of more than about 1.2, whereas an Instability Score of more than 120 corresponds to a factor of safety of less than 1.1. There is a 'grey' zone in between these Instability Scores where the factor of safety can be within a large range.

(c) The consistency between the Instability Score and the engineering judgment made on the likelihood of preventive works being necessary has also been assessed by a dedicated team using data collated on 23 calibration slopes. The results are given in Figure 3.10, where the correlation with the Instability Score given by the old Cut Slope Ranking System (Section 3.2 above) on the cases is also shown. It can be seen that the new Instability Score achieves a much better correlation with the engineering judgment.

(d) Findings from technical development work on assessment of debris mobility and QRA have been incorporated into the formulation of the Consequence Score. Table 3.5 shows the grouping of different types of facilities adopted in the NPCS and the corresponding potential loss of life (PLL) in the event of a direct hit by a reference landslide, which is

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derived by QRA on alignment of the facility grouping using PLL (Wong et al, 1997). The density of road usage is defined by the traffic volume and road conditions based on the QRA findings (ERM, 1995). The other facility types follow the standard terminology adopted in the Outline Zoning Plans of Hong Kong.

(e) The applicability of the new system has been tested to confirm that it serves the intended purposes. Based on the experience gained, guidelines and explanatory notes for collating field data were prepared (Wong & Ho, 1995) and 'warning criteria' were incorporated into the scoring scheme to assist in checking data consistency and reliability (Figure 3.7).

3.4.3 Formulation of Rock Cut Slopes Priority Classification System

The detailed formulation and calibration of the Rock Cut Slope Priority Classification System are described in Golder Associates (1996) and summarized in Wong (1998). The scoring scheme is summarized in Figure 3.11.

The system for rock cut slopes is similar, in terms of its rationale and structure, to that for soil cut slopes. However, the parameters and their combinations as adopted in the rating were tailor-made to address the nature of rock slope failures in Hong Kong. Summarized in Table 3.6 are the key groups of factors considered in the scoring scheme and the range of individual scores that may be assigned.

Four different mechanisms of rock slope failures were examined in the rating: (a) raveling - small scale (< 5 m^3) detachment of individual overhanging rock blocks or isolated loose blocks from the slope face; (b) toppling; (c) planar failure; and (d) wedge failure. Their risks were rated separately by multiplying the Instability Score with the Consequence Score of each mechanism of failure. These were then summed up to give the combined Total Score.

As in the case for the Cut Slope Priority Classification System, this new ranking system for rock slopes has been tested and 'warning criteria' have also been incorporated into the scoring scheme to assist in checking data consistency and reliability (Figure 3.11). The systems were developed with extensive consultation inside the GEO and with geotechnical practitioners in Hong Kong.

3.4.4 Formulation of Fill Slopes Priority Classification System

Details of the system and the relevant calibration work are described in Wong (1996) and summarized in Wong (1998). The scoring scheme is summarized in Figure 3.12.

The formulation of the system involved a range of technical development work:

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(a) Review of the existing slope data including those collated from compilation of the new Catalogue of Slopes - this assisted in identifying the nature, quality and relevance of the slope data available for use in rating the slopes.

(b) Review of GEO's fill slope landslide records, including over 250 fill slopes failures that occurred between 1984 and 1994 and notable incidents of serious liquefaction failure since the 1960s - this provided insight into the performance of the existing fill slopes and helped to identify cases for calibrating the system.

(c) Examination of the fill slope failure mechanisms and the factors affecting the likelihood and consequence of failure - this enabled qualitative and quantitative analysis of the relevant factors and the observed mechanism of failure.

(d) Slope stability analysis to assist in defining the geometry grouping (Figure 3.13) - this incorporated findings from conventional stability studies and facilitated appreciation of their limitations in reflecting the potential for landslides, which was significantly influenced by other environmental factors.

(e) Study of the mobility of landslide debris under different mechanisms of fill slope failure (Figure 3.14) - this gave the essential information for formulating the scoring formula for use in assessing the consequences of different mechanisms of failure.

(f) Development of frequency and consequence models (Tables 3.7 and 3.8) for use in the risk rating, in conjunction with development of QRA techniques - this enhanced the reliability of the hazard and consequence rating, and aligned the rating with formal QRA results.

Unlike the old Fill Slope Ranking System, which focused on rating the risk of static liquefaction failure, the Fill Slope Priority Classification System rates the total risk arising from three mechanisms of fill slope failure commonly observed in Hong Kong. These included:

(a) Sliding and minor washout - common slope failures that involve neither the build-up of a large excess pore water pressure nor significant influence from external surface water. In such failures, the debris slides downslope and may result in disintegration of the soil mass, particle collision, turbulence effects, and minor erosion and wash-out action; analysis of the historical landslide data showed that about 45% of the major fill slope failures (volume ≥ 50 m^3) in Hong Kong fell into this mechanism.

(b) Liquefaction - mobile failures involving generation of high excess pore water pressures and hence a substantial reduction of the effective stress and shearing resistance in the landslide; analysis of the historical landslide data showed that about 10% of the major fill slope failures (volume ≥ 50 m^3) involved a 'liquefaction' mechanism.

(c) Major washout - mobile failures involving concentrated discharge of water, e.g. surface runoff from a road, resulting in scouring and erosion of the slope and washing the debris downslope; analysis of the historical landslide data showed that about 10% of the major fill slope failures (volume ≥ 50 m^3) involved a 'wash-out' mechanism.

For each fill slope, a separate Instability Score was calculated for each of the failure mechanisms. The Instability Score that reflected the likelihood of slope failure by sliding and minor washout (i.e. IS_1) was based on the product of the scores of the three groups of factors shown in Table 3.9.

The Instability Score that reflected the likelihood of liquefaction failure (i.e. IS_2) was based on IS_1 adjusted by the factors shown in Table 3.9. The adjustment factors were chosen from a consideration of the factors affecting the likelihood of loose fill liquefaction, and the scores were determined from a global calibration based on the available landslide frequency data.

The Instability Score that reflected the likelihood of major washout failure (i.e. IS_3) comprised three groups of factors as shown in Table 3.9.

Consequence Score was evaluated for each of the mechanisms of failure, i.e. CS_1, CS_2 and CS_3 corresponding to IS_1, IS_2 and IS_3, respectively. A QRA-based consequence model (Wong et al, 1997) was adopted, which involved evaluation of the following factors to give a direct indication of the potential loss of life in the event of failure:

(a) The standard priority grouping and the corresponding PLL (Table 3.5), which was also adopted in the other schemes of the NPCS.

(b) The likely scale of failure, which was related to the height and size of the fill slope.

(c) The degree of damage (i.e. vulnerability factor), as expressed by V^1/V_1, V^2/V_2 and V^3/V_3 in Tables 3.7 and 3.8 which corresponds to the mechanisms for IS_1, IS_2 and IS_3 respectively. The factors accounted for the effects of landslide mechanism, proximity of the facility, resistance of the facility to debris impact and ground deformation, and the likely volume of failure.

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The Total Score of a slope was given by the sum of the products of the Instability Score and Consequence Score for each failure mechanism. The system was couched in such a way that the Total Score reflected directly the landslide risk posed by the slope to the community.

As in the case with the other schemes of the NPCS, the Fill Slope Priority Classification has been benchmarked with case histories to calibrate the scoring methodology and to examine whether the risk rating is reasonable. In addition, trial application of the system was undertaken on sixteen cases, including notable fill slope failures and typical fill slopes in Hong Kong (Wong & Ho, 2000). Some of the results of the trial application are extracted and shown in Table 3.10. The results showed that the relative instability ratings for different mechanisms of failure and the potential number of fatalities (i.e. Consequence Score) were reasonable.

3.4.5 Formulation of the Retaining Wall Priority Classification System

The detailed formulation and calibration of the Retaining Wall Priority Classification System are described in Wong (1998). The scoring scheme is summarized in Figure 3.15.

The rating system for retaining walls comprises two scoring formulae for calculating the Instability Score and the Consequence Score. The numeric weightings and the scoring methodology were developed specifically to address the likelihood and consequence of retaining wall failures in Hong Kong. Particular attention was given to failure of old masonry walls, which was the predominant type of wall failure in Hong Kong. The key groups of factors considered in the scoring scheme and the range of individual scores that may be assigned are summarized in Table 3.11.

The available landslide data and knowledge of the performance of old retaining walls in Hong Kong have been examined in devising the system. Wall slenderness ratio and the state of wall deformation were key factors that governed the potential for wall failure. Hence, they were assigned a high weighting in the Instability Score. Guidelines on assessment of wall conditions, consolidated from local experience, were prepared to facilitate the use of the system (Table 3.12). Typical forms of masonry wall construction (Figure 3.16) were examined and illustrative examples (Figure 3.17) were provided to assist in diagnosing the form of wall construction in field inspections (Chan, 1996).

3.4.6 Combined Priority Ranking

The four priority classification systems each provided a list of slopes of the respective type, ranked according to their relative landslide risk as reflected by Total Score (TS). The four ranking lists were merged, to allow different types of slope feature to be rated in a single list to establish their priority for treatment under the LPM Programme. The combined system is collectively referred to as the NPCS, and the combined relative risk was denoted by a calculated Risk Score (RS).

The RS was assessed based on the following methodology:

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(a) A global QRA was performed to assess the overall distribution of landslide risk among different types of slope feature registered in the Catalogue of Slopes. Details of this QRA are described in Wong et al (1997) and Wong & Ho (1998a), and are summarized in Section 6.3 of this report. The QRA found that soil and rock cut slopes, fill slopes and retaining walls constituted about 75%, 12% and 13% respectively of the total risk of failure of all the registered pre-1977 man-made slopes. These proportions of risk formed the basis for a risk-based merging of the four separate ranking lists.

(b) The risk proportion was distributed to each individual slope to derive its RS, based on the calculation TS and the risk proportion of the specific slope type. For soil cut slopes, rock cut slopes and retaining walls, RS is given by:

RS = (TS of Individual Slope / $\sum$ TS of all slopes of the same type) $\times$ Proportion of total risk for the slope type $\times 10^5$ .... (1)

The constant 10^5 is applied to the computation of RS to make its value easier to manage. For fill slopes, e^{TS} is used in place of TS, which reflects the nature of the scoring methodology adopted in the Fill Slope Priority Classification System. Based on the QRA findings and the calculated TS values of the slopes, the scoring formulae of RS for different slope types were derived, as shown in Table 3.13. In some cases, a registered man-made slope feature may comprise more than one slope type, e.g. a fill slope in the upper part and a cut slope with retaining wall in the lower part. Provisions were made in the system and relevant guidelines were prepared on how to deal with these special circumstances.

The NPCS has been adopted by the GEO since the mid 1990s in risk ranking and slope prioritization. It has also been used as a risk rating tool in connection with slope-related technical development work, including rainfall-landslide correlation and QRA. Guidelines on collation of data and calculation of the relevant scores were produced (Wong, 1998). Procedures for updating the slope data and the ranking scores were included as part of GEO's Quality Management System. The performance of the NPCS was evaluated under a Business Re-engineering Project conducted by the GEO on the LPM Programme in 1999, and was found to be promising (Wong et al, 1999; Wong et al, 2000).

Since 2000, the NPCS has been applied as the principal slope prioritization scheme to set out the risk-based priority of all the registered pre-1977 man-made slope features registered in the Catalogue of Slopes, for inclusion into the LPM Programme for detailed slope stability assessment and retro-fitting. The Government of the HKSAR has pledged that in the 10-year period from 2000 to 2010, detailed studies would be carried out on 5,500 pre-1977 man-made slopes. Among these slopes, 2,500 government-owned would be upgraded to current safety standards. The total capital investment in this 10-year programme is about HK$ 8.5 billion.

The distribution of RS for different slope types as in 1999 is shown in Figure 3.18.

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The percentages of different slope types in the top-ranking 5,500 pre-1977 man-made slopes are shown in Figure 3.19.

The NPCS is also serving some other landslide risk management purposes in Hong Kong. For example, it has been estimated that the ‘cut-off’ value of RS for selection of government-owned slopes into the 10-year LPM Programme is 8, i.e. slopes with an RS of less than 8 would not become eligible for action under the LPM Programme before 2010. Hence, regular slope maintenance has to play an important role in maintaining the continued stability of these lower ranking slopes. The calculated RS provides a useful risk-based rating for use by the relevant Government departments in planning their slope maintenance works. The definition of a cut-off value by reference to the calculated RS for each slope has greatly facilitated the planning of landslide risk management action and assessment of resource requirements. This illustrates the benefits offered by qualitative risk rating in landslide risk management. However, it should be noted that the NPCS is primarily developed for priority ranking and its resolution in differentiating the relative risk of the slopes is constrained by the available slope data.

3.4.7 Management and Dissemination of Slope Data

The GEO operates two Geographic Information Systems (GIS) for managing and serving slope and related geotechnical information. The technical details of the systems, their background development and application in the context of use of digital technology in Hong Kong are described in Wong et al (2004a).

The first system, known as the Slope Information System (SIS), is designed to provide the public and professional users with access to the Catalogue of Slopes and other slope-related information. The SIS is GEO’s hub for information on man-made slopes, and it plays a unique role in providing slope information services via a user-friendly interface. In the SIS, pertinent information on all registered man-made slopes is linked by the slope registration number to a database with site photographs showing the slope conditions and configuration and other slope information, such as slope location, physical dimensions, drainage conditions, history of development and maintenance records. The GIS graphical searching interface, including the web-service functionality, is powered by GeoMedia. The SIS can be accessed either from workstations that are linked with the centralized server in the GEO or via a Local Area Network through the Government Intranet system. The SIS also disseminates data through the Internet via the Hong Kong Slope Safety (HKSS) Website (http://hkss.cedd.gov.hk), where members of the public have free access to on-line spatial queries and browsing of the slope information (Figure 3.20). This Internet module is of great assistance to property owners and managers and their engineers who are involved in slope management, maintenance and upgrading works. The system was granted the ‘Geospatial Achievement Award - Certificate of Merit’ by the Intergraph Corporation in 2003, in recognition of its contribution to free dissemination of slope information on the Internet to the public.

The GEO also operates another high-end GIS for professional application. This GIS is commonly referred to as the Geological Modeling System (GMS), which was the title given to the system when it was set up in the early 1990s as a GIS platform for management of geotechnical data and geological modeling. The GIS datasets that are accessible through the

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system and its GIS functionalities have expanded considerably over the years. The GMS is now a core GIS in the GEO for professional application that covers the full range of GIS management, information service, analysis and modeling. The system architecture of the GMS comprises a suite of ESRI software as GIS and graphic engines. Workstations of the GMS are connected to dedicated GIS servers via different configurations, including a Local Area Network and Internet and mobile connections, for enterprise-based GIS applications powered by Spatial Database Engine (ArcSDE) and Internet Map Server (ArcIMS) (Figure 3.21). The GMS has access to all the spatial datasets including information on the Catalogue of Slopes held in the GEO (Figure 3.22). Due to security control and copyright requirements for some of the datasets, the GMS only permits restricted access to pre-registered users, who are typically GEO staff and nominated users from other government departments and consultants working on government projects. The system received an international 'Special Achievement in GIS Award' from ESRI in 2002 for its technological advances and benefits to the engineering field.

Unlike the GMS, the SIS is designed as a popular platform that allows free access to users, who may not be skilled in GIS. The SIS itself has limited GIS functionalities for advanced GIS analysis and modeling, as are available in the GMS. Although the SIS and GMS interact with users as two separate platforms, their back-end data are from the same sources that are centrally managed by the GEO.

3.5 Rockfall Hazard Rating System, Oregon & Colorado, USA

3.5.1 Background

The Oregon Department of Transport (ODOT) has developed a Rockfall Hazard Rating System (RHRS) for qualitative rating of the risk of rockfalls from existing rock cut slopes alongside transportation routes.

Pierson et al (1990) described the background of the development of the system. Oregon has many miles of highways passing through steep terrain with rock cut slopes formed alongside the roads. In the past, the rock cut slopes were typically formed on 4:1 steep with a berm every 30 feet, and often with the use of aggressive blasting and ripping techniques. Many of the slopes are therefore prone to rockfalls that pose a risk to the road users. In the mid 1980s, ODOT noted the need to develop a procedure, together with the use of a risk rating system, to assist in identifying problematic slopes and prioritizing repair works. Pilot work was carried out from 1985 to 1987 on recording rockfall areas, reviewing rating methodologies, and developing a prototype system. The prototype was modeled on the work of Wyllie et al (1975) and Wyllie & Duncan (1987). A series of field evaluations, including rating of 51 rock slope areas, were undertaken in 1998. These resulted in further modifications and improvements. Finalization of the RHRS began in 1989, with funding support from ten State Highway Departments and three Federal Highway Administration agencies in USA. As at 1990, the RHRS was tested at about 3,000 sites, and of these, 1,340 were included in Oregon's RHRS database.

3.5.2 Formulation

Procedures and guidelines for implementation of the system were given in Pierson et al

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(1990). The RHRS formed part of a process that helped agencies to rationally manage the landslide risk from rock slopes affecting a highway system. The process involved slope survey, risk rating and preparation for follow-up action, such as cost estimation and preliminary design.

In Oregon, the slope survey resulted in identification of about 3,000 potential rockfall sections. A ‘rockfall section’ referred to any interrupted slope alongside a highway where the level and occurrence mode of rockfall were deemed to be the same. In the survey, the key slope data were recorded and rated, and the rockfall and related maintenance history was identified with the help of maintenance personnel.

The rating system comprised two parts, viz. a preliminary rating and a detailed rating.

The preliminary rating was a subjective evaluation of the rockfall potential tempered by the past rockfall activity. It was carried out on all the rockfall sections, so as to group them into three broad classes as shown in Table 3.14. The ‘estimated potential for rock on roadway’ was judged by the rater, based on observations on the slope conditions. ‘Historical rockfall activity’ was assessed based on information provided by the maintenance personnel. If, for instance, either the estimated potential or the historical rockfall activity was judged to be ‘High’, then the section would be rated as Class A.

Among the approximately 3,000 rockfall sections surveyed in Oregon, 501 were given Class A, and 839 received Class B preliminary ratings. The preliminary rating helped to focus use of resources on the more problematic slopes.

The detailed rating system includes twelve attributes to be evaluated and scored (Table 3.15). The numeric weightings of the attributes increase in exponential steps, which reflects the nature of the relative risk and gives a better differentiation of the more risky sites. The sum of the scores gives the relative risk rating, i.e. the higher the sum, the greater is the relative risk. Provisions are made for use of continuum points, e.g. the score for slope height (H in feet) can be expressed as $3^{(H/25)}$. Some attributes can be directly measured and scored, e.g. slope height and road width. However, some attributes, e.g. ditch effectiveness and geologic character, require an evaluation by expert judgment.

Since the system was devised for use on rock slopes alongside roads, where the consequence setting is fairly uniform, its consequence evaluation was relatively simple. Apart from assigning scores to ditch effectiveness, sight distance and carriage width, the consequence to road users was rated with the parameter ‘Average Vehicle Risk’, which reflected the percentage of the time that, on average, a car would be present within the hazard section. This was rated by reference to the average daily traffic, the speed limit and slope length.

A preliminary assessment of the rockfall mitigation measures and cost were made as part of the rating process for the high-ranking sites. In determining the priority for risk mitigation, it was intended that consideration should be given to the relative risk as reflected by the total scores of the sites, as well as to the scores relative to the estimated costs, which reflected cost-benefit deliberation.

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3.5.3 Development and Application in Colorado, USA

In parallel with the development of the RHRS process in Oregon, the Colorado Department of Transport was also devising a system to identify and rank, by milepost, those segments of state highways that had chronic rockfall problems (Stover, 1992).

Based on the premise that life-threatening highway rockfall accidents most often occur at places where they have occurred in the past, road segments with rockfall problems were either recognized by the occurrence of vehicle accidents caused by rockfall, or identified by highway maintenance personnel as rock-fall prone areas. This was carried out as follows:

(a) A computer programme, Colorado Rockfall Accidents on State Highways (CRASH), was compiled to combine the highway mileage data from the Colorado Roadway Information System with the accident database of the Colorado Department of Highways. The mileage data as at 1987 was used, and the accident database was dated back to 1976. This generated a count of the number of accidents due to rockfall at each milepost of a given highway.

(b) Information from the highway maintenance personnel was obtained from a drive-through programme, during which the personnel assigned a ranking for the frequency of occurrence of rockfall to each segment of the road according to the scale shown in Table 3.16.

The accident data generated by CRASH, when combined with rockfall information from the maintenance personnel, were used to identify rockfall-prone segments for more detailed evaluation. An example is shown in Figure 3.23. Road segments that had a high accident data and frequency ranking by maintenance personnel formed the primary targets for more detailed evaluation. Segments with a high frequency ranking but low accident data were secondary targets. This process of identification of rockfall-prone segments served a similar purpose to that of ODOT's preliminary rating system.

ODOT's RHRS was selected as a risk-rating tool for the next phase of more detailed evaluation of the identified rockfall-prone segments. Stover (1992) noted that ODOT's system was selected as it "was most adaptable for scoring natural rockfall from the cliffs, steep slopes and canyon walls commonly found above many highways in Colorado". Some modifications were however made to adapt ODOT's system for use in Colorado. New parameters that were considered relevant, including accident data, slope inclination and segment length, were added. However, sight distance, roadway width, average traffic risk and ditch effectiveness were excluded. Their exclusion was noted by Stover (1992) as due to the consideration that their effects were factored in by the accident data and that some of the parameters were difficult to acquire. Details of the adapted system are given in Table 3.17.

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3.6 Rock Slope Hazard Rating, Canada

3.6.1 Background

Qualitative risk rating systems have been used in Canada for many years in managing the risk of rockfalls on transportation routes. Bunce et al (1997) reported that, prior to the Just incident in 1982 (Cory & Sopinka, 1989), the British Columbia Ministry of Transportation and Highways (MOTH) specified locations for rock scaling where resources were available. Subsequently, MOTH developed a comparative method to rank areas by hazard, based on which the limited resources were deployed to reduce the risks posed by the areas with the greatest ranked hazard. Since 1993, the RHRS was adopted by MOTH as the risk rating scheme, which reduced the subjective aspects of the rating.

The Canadian Pacific Railway (CPR) manages over 1,500 rock slopes alongside over more than 2,100 km of railway track. More recently, a new rock slope hazard rating system was formulated (Hungr et al, 2003), which provided a method of characterizing the relative risk posed by the slopes to CPR's track. This was intended to help to prioritize allocation of mitigation resources.

In developing the new system, existing systems from Canada, USA and Europe were reviewed. Information on rockfall incidents, mitigation measures, inspections, etc. has been collected bi-annually and recorded in a database by CPR since 1976. The database held more than 2,000 records categorized by site mileage, and provided a basis for correlating the rating parameters with historical rockfalls. Rock slopes are sub-divided into linear segments, along which the slope geometry, geology, rock characteristics, failure mode and degree of any existing mitigation provisions are broadly constant.

3.6.2 Formulation

The rating system comprised two parts of assessment, viz. 'random rockfall' and 'structurally controlled failure'.

'Random rockfall' referred to small-scale (volume less than 10 m^3) detachment of individual rock blocks from a rock slope. It was rated by a rock mass classification system, with adjustments to cater for effects of any slope stabilization measures that had been provided, recent instability and overburden materials. The rock mass classification system adopted in the rating follows the Rock Mass Quality Index (Q) formulated by Barton et al (1974), with modification made to replace the stress reduction factor (SRS) by a face looseness (FL) factor, as defined in Table 3.18. FL was intended to account for any weakness zones in the rock slope and loosening due to mechanical degradation.

The empirical correlation between the modified rock mass index and the rockfall frequency (Q_{rf}) recorded in CPR's database was examined. The relevant data points and upper-bound envelope derived by Hungr et al (2003) are shown in Figure 3.24. For a slope with a given Q_{rf} and slope area, the correlated number of rockfall can be calculated based on the upper-bound correlation envelope, and the corresponding random rockfall hazard rating of the slope established. This rating is further adjusted by (i) Stability Rating, which is a subjective indication of the effectiveness of the existing stabilization measures; (ii) Evidence of Recent Activity, which reflects the recent performance of the slope; and (iii) Overburden

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Stability Index, which accounts for the potential for rockfall originating from the coarse overburden material mantling or bordering parts of the rock slopes. Details of the rating and adjustments are shown in Figure 3.24.

'Structurally controlled failure' refers to large-scale failure of the rock slope that is controlled by well-defined discontinuities. The degree of hazard for this mode of failure was assessed by a deterministic approach, based on mapping of dominant discontinuities and supported by simple analysis if necessary. Given the nature of the assessment, subjective rating was made on the relative likelihood of the most likely failure magnitude.

Overall, the system is principally a hazard rating scheme that is independent of the consequence evaluation. Hungr et al (2003) noted that a separate parameter denoted as 'probability of rock delivery' should be applied to both modes of failure, to reflect the likelihood of the detached rock mass landing on the track.

3.7 Slope Risk Rating System, Australia

3.7.1 Background

The Roads and Traffic Authority (RTA) of New South Wales (NSW), Australia, in conjunction with external consultants, has developed a scheme for rating the landslide risk of cut and fill slopes and retaining structures, adjacent to main roads in NSW. The scheme is intended to be used in rating the relative risk of the slopes and thereby setting priorities for further work, such as investigation, monitoring and remediation.

Stewart et al (2002) described the background of the formulation of this RTA Slope Risk Analysis scheme. The development of a systematic slope risk rating procedure by the RTA first started in the early 1990s. The early procedures (denoted as Guide to Slope Risk Rating System, Versions 1 and 2), completed in 1994/95, were based on weighted scoring of slope attributes and a subjective assessment of consequences. These were grouped via a risk matrix that combined the likelihood and consequence of slope failure. The landslide risk levels as given by the risk matrix were to set priorities for inspection by a geotechnical practitioner. According to Stewart el al (2002), the procedures were used in a very limited way prior to 1997, but in late 1997 and early 1998, Version 2 was used statewide in NSW to rate about 2,500 slopes. However, review of the results indicated that its reproducibility was poor and that the risk levels derived were not sufficiently accurate for the use in priority setting.

Development of Version 3.0 of the procedure commenced in mid 1999. It was tested in late 2000 with about 700 slopes by a panel of consultants. The test identified further revisions to the rating scheme (Baynes et al, 2002). Together with some other changes arising from additional development work, these were incorporated into Version 3.1 of the procedures, which is the scheme described in this Section.

3.7.2 Formulation

The details of the formulation of the RTA Slope Risk Analysis scheme are given in RTA (2002). Details are summarized in Figure 3.25.

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The relative risk of a slope was rated in terms of an Assessed Risk Level (ARL), which was given by combining the Likelihood Rating (L) and Consequence Rating (C). The system was aligned with a QRA framework. The rating was principally assigned by expert judgment combined via qualitative rules and risk matrices, without any quantified risk analyses. The slope unit is generally defined by its physical boundary, but a large slope may be sub-divided based on differences in geological or landform conditions.

The rating L reflects the probability of a landslide occurring and reaching a point where the element at risk may be present. With respect to the main failure mechanism(s) identified, the rating L is assigned by the rater based on a subjective judgment of the combined likelihood of failure and the detached material reaching the location of the element at risk. A six-class likelihood rating, which is aligned with a range of indicative probabilities, is adopted. Stewart et al (2002) noted that small rockfalls were found to be a significant hazard in about two-thirds of the slopes examined. For such failures from road-side cut slopes, a chart (Figure 3.25) was developed, based on the results of rockfall modeling, to assist the raters in assessing the likelihood of the detached material reaching the location of the element at risk.

The rating C reflects the severity of the hazard on the element at risk. Apart from road users, other facilities that may be affected by landslides on the slope, such as buildings and services, are to be identified and considered in rating the consequence. Both loss of life and social/economic impact are examined in the rating. In respect of loss of life, a five-class consequence rating (i.e. C) is adopted, as defined by the consequence matrix that combines a five-class rating of the vulnerability and a five-class rating of the relevant temporal probability of an individual being present at the time of failure. For each slope, its temporal probability class and the vulnerability class are judged by the rater. A chart (Figure 3.25) was developed based on consideration of the effects of the landslide on road traffic, to assist the raters in assessing the temporal probability rating with respect to road users.

Social/economic impact is judged by the rater with respect to the relevant indicative cost ranges that are to align with the five-class consequence rating (i.e. C).

The risk rating, in terms of a five-class ARL, is given by the risk matrix that combines the L and C ratings. Although each ARL appears to correspond to a quantitative risk level, this is only indicative of relative risk, instead of absolute risk, because the rating process is principally subjective and does not involve any formal risk quantification.

Apart from assigning the ratings, the raters also record the key attributes of the slopes on a standardized form. The attributes are not directly used in the risk rating. They are scored for internal check and reference. As noted by Stewart et al (2002), the ratings and data on the slopes assessed were to be incorporated into RTA's Road Slope Inventory Database that was under development.

This system is a notable development in respect of qualitative slope risk-rating methodology, in view of its attempt to align with the QRA framework and its extensive use of expert judgment in the rating process. The findings of a study on the reproducibility and accuracy of the different versions of the RTA system are given in Baynes et al (2002). They noted the subjective nature of the rating process and the need for the rating to be carried out by trained personnel to improve the accuracy and precision of the results.

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3.8 Slope Management and Risk Tracking System, Malaysia

3.8.1 Background

Malaysia is a hilly country where landslides on the tropically weathered slopes are common during heavy rainfall. Landslides from slopes alongside roads are known to be a problem that has resulted in loss of life, as well as major economic consequences due to closures of the road network.

A comprehensive study was carried out on the slopes along the Tamparuli-Sandakan Road (TSR, i.e. Federal Route 22) in Sabah from 2001 to 2004 (PWD Malaysia, 2004). The section of the road is about 300 km long, and it traverses the Crocker and Trusmadi Ranges with elevations varying from 200 m to 1,700 m. The study comprised collection of data on the slopes along the TSR, development of a GIS-based system for management and dissemination of the slope data, formulation of a qualitative slope risk rating scheme to assist in prioritizing remedial and maintenance works on the slopes. The study was aimed to provide the Government of Malaysia with a slope management system for the TSR. The project was also a ‘test-bed’ for development of a system with the potential for application to the whole of the Malaysian road network. This would enable more efficient management of the public works resources on a country-wide basis. The slope risk rating and management system that has been developed is known as the Slope Management and Risk Tracking System (SMART).

Before commencement of the project, little information on the slopes along the TSR was available. The vast majority of the slope data that was used in the risk rating was collected in the project by airborne Light Detection and Ranging (LIDAR) survey and field mapping. Information on a total of 4,740 slopes features was recorded.

3.8.2 Formulation

SMART rates the risk of slopes through the use of a scoring scheme, which is akin to that adopted by the GEO. The risk rating is represented by a Total Score (TS), which is given by the product of the Instability Score (IS) and Consequence Score (CS).

The Instability Score (IS) reflects the likelihood of slope failure. The details of its formulation are given in Figure 3.26. IS is calculated by a weighted average of two probabilities of failure, DS and MC. DS is the discriminant probability score, based on a discriminant function obtained from a step-wise discriminant analysis that a slope feature would fall into the failed slope groups. Two separate discriminant functions were adopted, one for cut and natural slopes, and another for fill embankments. A total of eleven slope attributes were used as the input variables in the discriminant function for cut and natural slopes. Seven attributes were adopted in the fill embankment function.

MC is the Monte Carlo probability score, based on findings from Monte Carlo analysis on the probability that the theoretical factor of safety of the slope would fall below 1.0 under a 1 in 100 year rainstorm condition. The Monte Carlo analysis was performed using a Combined Hydrology and Stability Model (CHASM). The method combined the standard Bishop slope stability analysis with consideration of dynamic hydrology and parameter variability using a forward explicit finite difference scheme. The model was tested in Hong

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Kong, Malaysia and New Zealand, and relevant parameters were extracted for use in the analysis for this project (PWD Malaysia, 2004). The results of the Monte-Carlo analysis are summarized in a series of design charts that give the calculated probability of failure for different rainfall and slope conditions. A sample chart is reproduced in Figure 3.26. In applying the scoring scheme to the TSR project, a 90% weighting factor was applied to DS and only 10% was assigned to MC. These reflect the perceived relative reliability of the probability scores obtained from the two approaches.

The Consequence Score (CS) reflects the relative severity of the consequence of slope failure. The scoring methodology was modified from the NPCS of GEO, with the inclusion of a specific term for the road facility because SMART is intended for application to rating landslide risk on roads. The key groups of factors considered and the range of scores that may be assigned are summarized in Table 3.19.

Details of the formulation of CS are given in Figure 3.27. The calculated CS has been normalized by 480, and hence falls within the range of 0 to 1.

Typical IS and CS ratings on the TSR slopes are shown in Figure 3.28. The calculated TS scores may be categorized into five descriptive categories, as shown in Figure 3.28.

SMART also includes a GIS-based inventory of the slope data and computer modules for managing and disseminating the data. It is planned that the SMART rating would be used to prioritize the slopes for maintenance and stabilization works.

3.9 Other Rating Systems

3.9.1 Slope Rating

The systems were selected for a more in-depth description in the above sections in consideration of their more extensive scope of actual or planned application. These are by no means exhaustive. Other systems exist, and each has its own characteristics that serve particular purposes or address specific problems. Some examples are described below:

(a) Rating of Relative Landslide Risk of Clay Slopes, Tasmania, Australia

Stevenson (1977) described a simple method of evaluating the relative landslide risk of clay slopes. This was one of the earliest reported qualitative, risk-based rating schemes. However, compared with current practice, the scheme is coarse and may at best be taken as a general zoning system. The method was developed as an empirical tool to give a measure of the relative risk of landslide for consideration in land use planning. A scoring scheme was adopted for calculating the risk score, based on combinations of numeric weightings on the following slope attributes: Plasticity Index of the slope-forming material; the assessed annual maximum groundwater level with respect to the typical

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failure plane; slope angle; past and recent instabilities including erosion; and land use. Stevenson (1977) reported that the method was applied to selected areas in Tasmania, and noted that a risk score of about 50 to 60 might be taken as a warning of possible instability.

(b) Stability Evaluation Method, Road Bureau of the Ministry of Construction, Japan

A Stability Evaluation System developed and adopted in Japan for qualitative rating of the relative risk of landslides on roads in Japan was described in Ministry of Construction (1990), and summarized in Escartio et al (1997). A scoring scheme was adopted for evaluating the hazard of rockfalls, rock topples, rock slides, deep-seated failures and debris flows from the slopes. Parameters that were scored for rating the degree of hazard included: slope height and inclination; topographical conditions; geological structures; type of slope surface protection; signs of seepage and slope deformation; and effectiveness of preventive measures. Detailed consequence rating was not included, but additional scores were given to the road traffic volume and history of past landslides that resulted in damage to the road.

(c) Slope Condition and Risk Rating, New Zealand

The Slope Condition and Risk Rating (SCARR) method was developed as a systematic means of assessing the condition and performance of slopes, via data obtained from visual survey and simple field measurement. It was intended for use on cut and fill slopes alongside highways, railway and canals, to highlight areas of landslide concern and allow priorities to be set for further investigation and treatment (Sinclair, 1991). The method includes assigning numeric weightings to the following slope attributes for each element of the route (e.g. 100 m length): stability condition based on the severity of landslips; erosion based on the severity of erosion; slope geometry; seepage; topography; vegetation and land use; drainage; and soil and rock type. The scores were combined to give a Combined Risk Rating. The scheme gave little consideration to evaluating the relative consequence of landslides and was hence principally a hazard rating system. Sinclair (1991) reported that the method was applied to data obtained for the design of improvement works of a 50 km section of the Kuala Lumpur to Seremban Expressway in Malaysia.

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(d) Rock Slope Hazard Index system, Scotland

This rock slope rating system was developed in 1996 for use as a first stage assessment of the relative risk of rock slopes affecting roads and determination of the required follow-up actions. Development of the system was supported by the Scottish Office Industrial Department, and the system was tested on 179 rock slopes alongside a 50 km section of Trunk Road in the Scottish Western Highlands (McMillan & Matheson, 1997). The risk rating was based on a number of rock slope attributes and geometry, and traffic volume of the road affected. Four follow-up action categories were determined based on the calculated Rock Slope Hazard Index, which is a risk rating score, as shown in Table 3.20.

3.9.2 Terrain Susceptibility and Risk Zoning

There are a range of methodologies developed for assessing the relative susceptibility and risk of landslides originating from undeveloped hillsides. Qualitative and semi-quantitative risk assessment techniques, together with statistical analyses and expert judgment, are commonly adopted. A review of the methodologies and practice was given in Leroi (1996) and Cascini et al (2005). It is notable that most of the applications are couched at a smaller scale, and do not clearly differentiate the individual facilities.

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), 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). The following points summarize the current thinking and practice in Hong Kong in respect of regional hazard and risk zoning:

(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

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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.

(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. 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

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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. 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 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 near future will enable reliable prediction of where and when natural hillside landslides would occur.

3.10 Observations on State of Good Practice

A total of 15 different slope rating schemes are described above. While most of the schemes have certain features in common, the schemes developed in various places differ because of particular circumstances of their formulation and different key issues that they address. There is no hard-and-fast rule as to which particular rating methodology is the best scheme. The best scheme is that which best meets the landslide risk management needs under the particular circumstances. However, some observations can be made on the state of good practice in formulation and application of qualitative slope rating systems, as summarized below.

3.10.1 Objective of the Rating System

A rating system is designed for specific purposes. The intended objectives of the system and the circumstances of its application should be clearly defined, in order to guide the formulation of the system. This would also help to ensure that the system would be correctly applied. For example, a system for use in preliminary rating would be entirely different from that for more detailed rating, as is evident in the case of the RHRS (Section 3.5 above). GEO's experience in development and use of rating systems in slope priority ranking also illustrates that even if the intended purposes remain the same, different systems may be required at different times because of changing circumstances in which the systems are applied (Section 3.4 above).

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It is evident from the cases reviewed that slope rating systems are typically adopted to provide a relative risk ranking of existing, potentially hazardous slopes. The systems are commonly required by agencies that are responsible for managing the risk of a large stock of slopes, to set out the priority and direct resources for follow-up studies and treatment works. A wealth of experience of successful use of qualitative slope rating in this area is available. There are indications that such applications are receiving increasing attention by many agencies in different countries.

3.10.2 Risk Management Process

A rating scheme provides a means of relative risk ranking. Although it is a useful tool that plays an important role in the risk management process, it is not the totality of the process. Effective landslide risk management calls not only for the formulation of a slope rating scheme, but also the establishment of a suitable risk management process to which the rating scheme applies. Such a process typically involves systematic collection of landslide and maintenance records, compilation of a comprehensive slope inventory, formulation of a slope rating scheme, collation of data for use in slope rating, establishment of procedures for initiation of follow-up actions, maintenance and dissemination of information, etc. The slope rating scheme would best serve its intended purposes when it is applied in the context of a risk management process. Such applications would in turn provide useful feedback on how the rating scheme should be further improved to achieve better performance.

3.10.3 Slope Inventory

Compilation of a slope inventory and collation of the relevant slope data are prerequisites for relative slope rating. This work is an important investment for landslide risk management, and it often constitutes the most resource-demanding component of the task. For example, the compilation of the new Catalogue of Slopes in Hong Kong, which comprises about 57,000 man-made slope features, cost about HK$ 120 million to produce. In comparison, the NPCS was principally formulated in-house by the GEO and the staff cost was less than HK$ 1 million, i.e. less than 1% of the cost of compiling the slope inventory. It is therefore essential that in devising a rating scheme, due consideration is given to the practicality of obtaining the required input data. A detailed and sophisticated system may not be the most suitable scheme to adopt if inadequate resources are available to support the data collection.

Where there are major resource constraints, it may be necessary to implement the rating in phases, i.e. the more problematic slopes are first identified with the use of a preliminary rating that is less resource-demanding, and then a more detailed rating is applied to the identified slopes for risk ranking and prioritization. Due consideration should be given to proper demarcation of slope units, which has significant implications for the cost and rating resolution. For example, if a coarse demarcation is adopted, such as one based on the average slope conditions per mile or km along a road, the work would be less costly. However, if individual slopes with broadly similar characteristics are registered and rated separately, a much better resolution would be achieved although the cost would also escalate.

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To avoid double handling in data collation, it has been good practice adopted by some agencies to develop the rating scheme in advance of compiling the full slope inventory. This is done to ensure that slope parameters required for use in the rating are identified in time, such that the data can be collected when the slope inventory is compiled. In practice, the rating system would inevitably require field trials and calibration, which would often lead to refinements in the rating scheme and changes in either the types or forms of the required slope parameters. Hence, the compilation of the slope inventory and formulation of the rating system have to be carried out in an interactive manner, preferably under the coordination of a dedicated team.

Different methods can be used to assist in identifying the slopes and collating slope data. Advances in digital technology, such as in the use of GIS, remote-sensing, digital photogrammetry and global positioning techniques, have led to improved capability, enhanced efficiency and reduced human error. It is also common practice now to operate the slope inventory on a GIS platform that incorporates spatial functionality for retrieval, analysis and web-based dissemination of the data.

3.10.4 Slope Rating Methodology

Although there is no unique methodology for relative slope rating, some good principles that are embodied within many of the more successful systems are notable:

(a) Risk-rating, which accounts for both the relative likelihood and consequence of landslide, is preferred to simply rating the hazard (or the consequence). For slopes affecting a linear facility, e.g. a road or railway track, the type of facility and characteristics of the population at risk are often relatively uniform. Hence, system developed for linear facilities would tend to place more emphasis on hazard rating. However, due account should also be taken of the key factors that affect the likely consequence of a landslide, e.g. proximity of the facility to the slope, any presence of protective ditches or buffer zones and the scale of failure, if the systems are designed for risk rating. For systems that are applied to slopes affecting different types of facility, the consequence rating would warrant considerable attention because it has a very significant contribution to make in assessing the relative risk. For example, in compiling the NPCS (Section 3.4 above), it was found that the relative consequence of slopes affecting different types of facility could differ by several orders of magnitude and some QRA findings were incorporated into the consequence rating to ensure better performance.

(b) A rating scheme is always subject to constraints associated with data availability, and it should be formulated with due consideration taken of these constraints. The effects are two-fold. Firstly, if the data are not readily available and

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cannot be made available, the rating scheme cannot incorporate the use of the data irrespective of their relevance to assessing the relative risk. For example, it is known that unfavorable hydrogeological conditions adversely affect stability. However, many rating systems do not incorporate the use of this factor because the relevant data cannot be consistently acquired from visual inspections, nor from available documentary records. Secondly, even if data on a slope attribute are available and used in the rating scheme, the relative weighting assigned to the slope attribute in the scheme depends not only on the relevance of the attribute to assessing the relative risk, but also on the quality and resolution of the data available. For example, in some schemes where signs of water seepage were included in the rating, a relatively low weighting score was given to this parameter irrespective of the knowledge that groundwater has a significant effect on slope instability. This is appropriate given the relatively poor quality and resolution of the data available for this attribute, e.g. observations being made in different weather conditions and hence not being entirely reliable and consistent. In other cases, subjective judgment is required to be made on, say, the likelihood of landslide. It is fairly common for the rating scheme to involve categorizing the likelihood into different classes that are aligned with notional ranges of probability. These notional ranges of probability typically differ by orders of magnitude. However, the weightings to be assigned to the different classes should not represent a likelihood of failure that differs by such orders of magnitude, if the subjective judgment made by the raters could not support a resolution that could truly differentiate the likelihood of landslide by these orders of magnitude. Otherwise, the significance of this subjective judgment would be mis-represented in the rating scheme, and the overall reliability of the scheme adversely affected.

(c) Separate rating schemes may have to be devised for different types of slope. Many of the existing rating schemes deal with rock slopes alongside transportation routes. In such cases, use of a single rating scheme that is tailor-made for application in a particular place would usually be adequate for use in rating rock slopes of different size and geological condition. In other cases, a system may be required for rating different types of slope, such as cut slopes and fill slopes. It is often necessary to formulate different rating schemes, each tailor-made for a specific type of slope, because the factors that govern the likelihood and consequence of landslides on different types of slope may differ very significantly. A key technical challenge to

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overcome in these cases is the merging of different schemes into a single rating system. Alignment with the findings of QRA (e.g. NPCS, Section 3.4 above) and probabilistic analyses (e.g. SMART, Section 3.8 above) has been adopted as the solution.

(d) Parameters that are often adopted in hazard rating include: slope height; slope gradient; history of instability; signs of distress; type of slope forming material; presence of geological weaknesses or adverse discontinuities; unfavorable groundwater conditions; unfavorable surface water conditions including the type of slope cover; and the effectiveness of any existing slope stabilization measures. To ensure consistency in rating the likelihood of landslide, it is essential that the hazard rating is applied to slopes of a similar class, e.g. un-engineered soil cut slopes should not be mixed in the rating with engineered slopes. It is notable that in a more sophisticated rating system, different mechanisms of failure may be rated separately using different hazard rating methods.

(e) Parameters that are often adopted in consequence rating include: type and proximity of crest facility; type and proximity of crest facility; slope size or volume of landslide; mobility of landslide debris; and effectiveness of any existing provisions for protecting the facility from landslide effects. Consequence rating for slopes affecting a linear facility, e.g. transportation routes, usually involves the use of simpler methods. For slopes that affect a diverse range of facilities under different site settings, a detailed consequence rating may call for the use of a more complicated methodology, and may involve the use of QRA consequence assessment techniques. Loss of life is typically considered in consequence rating. However, the more sophisticated rating systems may include consideration of economic loss and aversion effects associated with multiple fatalities.

(f) Use of a scoring formula is as popular as use of a qualitative risk matrix. They vary in presentation, and have pros and cons. However, in terms of capability as a relative risk rating tool, they have practically little difference between them. The trend is evident that the more updated rating systems tend to use qualitative risk descriptors, which are aligned with some standardized categorization (e.g. AGS, 2000) or notional ranges of probability figures. This helps to provide a reference point for subjective assessment and communication, and gives the rating schemes a semi-quantitative connotation. However, the probability

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figures are often loosely defined and the standardized descriptors are not intended to be precise. They would not necessarily improve the reliability of the quality rating, which is to a large extent governed by the rating methodology, quality of the input parameters and reliability of the subjective judgment made.

(g) Two different approaches in formulating the rating methodology are notable: (i) ‘expert judgment schemes’, which require considerable judgment to be exercised in rating the slopes (e.g. RTA Slope Risk Analysis, Section 3.7 above); and (ii) ‘expert formulation schemes’, which require the use of relatively simple, factual data (e.g. NPCS, Section 3.4 above). An expert judgment scheme refers to that which requires considerable subjective judgment to be made by the raters in acquiring the input data or in rating the hazard or consequence, e.g. making a subjective rating of ‘the likelihood of landslide’ or of ‘the likelihood that the detached material would reach the downslope facility’. Formulation of an expert judgment scheme may not require much supporting correlation and analytical work to define the effects of different slope data on the likelihood and consequence of landslide. However, its application requires input from experts in exercising subjective judgment (e.g. rating the potential for structurally controlled failure in CPR’s Rock Slope Hazard Rating Scheme, Section 3.6 above). The schemes may be less difficult to formulate, but the demand on data collection is high and their application can be sensitive to reproducibility and consistency issues. An expert formulation scheme adopts relatively simple and factual data as input parameters, and does not require the raters to exercise much subjective judgment in collecting the data and applying the scheme. This is made possible because the relative significance of the various input data and their appropriate weightings have already been assessed, correlated and incorporated into an expert system when the rating scheme is formulated. The work typically involves correlation with historical landslide data, statistical analysis and numerical modeling. These effectively replace the subjective judgment that would otherwise have to be made by the individual raters in applying an expert judgment scheme. An expert formulation scheme is usually more repeatable and less operator-dependent. However, formulating such a scheme is practical only when suitable data and techniques for establishing the correlations are available. The reliability of an expert formulation scheme is inevitability governed by that of correlations established. Rating random rockfall in CPR’s Rock Slope Rating System is an example of an

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expert formulation scheme. In some cases, a mixed scheme, i.e. a hybrid of the two approaches, may be adopted in a single rating system. CPR's Rock Slope Rating System is one such example.

3.10.5 Testing and Calibration

All rating systems require trial uses for testing and calibrating their performance. The key aspects to be evaluated include:

(a) Repeatability of data collection, i.e. whether the judgment made by different raters or data collected by different personnel are reasonably consistent.

(b) Reproducibility of the system, i.e. whether the system can give relatively consistent results for slopes of comparable conditions.

(c) Performance of the system, i.e. whether the rating given by the system is reliable as compared with the available statistics, actual slope behavior and other indicators (e.g. professional judgment), and whether the system can adequately fulfill its intended purposes.

(d) Ease of use of the system, i.e. any scope to streamline the system and data collection, without adversely affecting the performance of the system.

Systems that are being more extensively applied have all been subject to improvements and refinements after repeated testing and calibration. The testing and calibration work also facilitates the documentation of guidelines on collection of data and use of the systems.

3.10.6 Maintenance of System

A rating system would easily become outdated if not properly maintained. There are two key aspects of maintenance. Firstly, the data that are adopted as input parameters should be updated to reflect the latest slope conditions. This may have significant resource implications, which should be duly factored in when designing the risk management process. For example, quality procedures are in place in Hong Kong for checking the key components of the input parameters of each rated slope before it is selected for action under the LPM Programme, and for regularly updating the slope data based on findings from an inspection by a qualified geotechnical professional at least once every five years on each registered slope (GEO, 1998a). Secondly, the rating methodology would require enhancement from time to time when new experience in using the system becomes available, or when there are new requirements to be met.

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3.10.7 Public Perception of Qualitative Rating System

The public perception of landslides and their risk management is affected by many social, economical and political factors, which vary in place and time. There is little published information available on the public perception of use of qualitative risk rating methodology, and this is an area deserving further study and experience sharing. Hong Kong has almost 30 years of experience in using risk ranking methods for prioritizing un-engineered man-made slopes for detailed studies and retro-fitting under the LPM Programme, which involves considerable public works expenditure. Experience shows that application of qualitative risk rating is fairly well received by the public as a rational and pragmatic approach for prioritization where resources should be used for landslide risk reduction. Challenges, either on the technical or administrative aspects, are rarely received from the public on the rating systems. When a slope that is ranked low fails and results in notable consequences, the case would inevitably attract public concern. However, it seems that the public would tend to more tolerant towards imperfections in the rating methodology due to technical limitations, rather than human errors in collecting the slope data and in exercising professional judgment. In this respect, use of an expert formulation scheme would probably be less prone to criticism than use of an expert judgment scheme. At least, this is the case as far as the raters are concerned.

3.10.8 Limitations of Rating System

Proper awareness of the capability, as well as the limitations, of a qualitative rating system is fundamental in applying the system successfully. The various systems that have been developed have differing degrees of complexity, with differing resolutions and reliabilities. Overall, it should be recognized that these systems are, by nature, relative risk rating tools that operate with the use of relatively simple, readily acquired, qualitative parameters and subjective judgment. They may give a useful indication of the relative risk, but cannot provide a sufficiently reliable, absolute risk figure. Even if they have been aligned with some quantitative or semi-quantitative figures, the alignment typically involves subjective judgment and contains significant uncertainties. The supporting correlation and calibration work, if carried out and incorporated into a rating system, is usually confined to benchmarking the performance of the rating over a certain zone of the rating results. This helps to improve the reliability of the rating if it is applied within the zone. However, outside this calibration zone, the rating scheme may not perform as satisfactorily and could even give misleading results. The rating should only be applied in the circumstances for which it is intended. A rating scheme that has been successfully applied in one place may be entirely inappropriate for use elsewhere, if the nature of slope problems and the risk management objectives are different.

In applying a rating system, attention should be given to the possibility that some key factors critically affecting the risk of landslide may not have been included in the rating methodology. In particular, potential problems associated with freezing the perceptive of risk assessment by treating each slope in the inventory as a distinct and separate unit, as illustrated by the case described in Section 4.5 below, can be a major pitfall.

Due care should also be exercised when a system is used for purposes other than relative risk rating, such as risk-screening or risk-based decision making on individual slopes.

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Examples include: no further action required on a slope rated below a given score; and urgent mitigation actions being contingent on slopes categorized as being in a certain risk class. This is often beyond the capability and reliability of a qualitative rating system, unless it has been specifically calibrated for such applications. Site-specific landslide risk assessment and decision-making would normally call for the use of more detailed data and enhanced risk assessment techniques, such as site-specific qualitative risk assessment and formal QRA as described in the following Sections.

4. SITE-SPECIFIC QUALITATIVE RISK ASSESSMENT

4.1 Overview of Site-specific Qualitative Risk Assessment

Site-specific qualitative risk assessment embraces a broad range of qualitative and semi-quantitative processes applied to analyzing and managing the landslide risk at individual sites. The work is carried out with a resolution and reliability that are deemed to be adequate for use in making site-specific risk management decisions, without formally quantifying the risk. Landslide and slope engineering have always involved some form of risk assessment and management, although it may not have been formally recognized as such (Fell and Hartfort, 1997). Less formal risk assessment has generally relied on professional appraisal, engineering analysis and expert judgment. This forms part of the geotechnical practice for identifying the hazard, mapping areas susceptible to failure, estimating the possible influence zones and gauging the severity of possible damage.

A variety of qualitative and semi-qualitative risk assessment methods are available, e.g. a summary is given in Lee & Jones (2004). Relative risk rating as described in Section 3 above is a major application that covers a large number of sites. Unlike qualitative risk rating, site-specific qualitative risk assessment deals with the landslide problems at individual sites, instead of rating the relative risk among many sites. In practice, the method of assessment varies from site to site, and there would rarely be many sites assessed by exactly the same method. The results of the assessment tend to be subjective and descriptive. The implied risks assessed by different methods for different sites are difficult to compare. However, provided that due consideration is taken of its potential constraints, qualitative risk assessment can play a useful role in dealing with landslide issues from a risk perspective. In many circumstances, the process has supported sound risk management decisions to be made without explicitly quantifying the risk.

Professional skills are applied to site-specific qualitative landslide risk assessment for solving a spectrum of landslide problems. The conventional approach for dealing with landslide problems at individual sites is to provide for a safety margin in slope design based on deterministic stability assessment. This Factor of Safety approach is aimed at reducing the chance of failure. It neither evaluates risk directly, nor manages risk in a holistic manner. The evolution of geotechnical engineering from this conventional approach to a risk-based process is described at length by Fell (1994); Wu et al (1996); Morgenstern (1997); Fell and Hartford (1997); Wong et al (1997); Ho et al (2000) and Stewart (2000). For managing landslide problems at specific sites, the following are some typical circumstances that require the use of a risk-based assessment, either supplementary to, or as a replacement of, the conventional factor of safety approach:

(a) Where slope stability can be controlled via the provision of

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a safety margin against failure, but assessment of risk and the uncertainties involved is required to assist in determining the extent of the safety margin to be adopted.

(b) Although slope stability can largely be controlled via the use of a design factor of safety, the residual chance of failure has to be considered, typically because of the severity of the failure consequence.

(c) Where control of slope stability is not practical (or ineffective) and the landslide risk has to be managed by other means, e.g. mitigating the consequence of failure.

(d) Where potential landslide hazards are known, but their risk needs to be evaluated to assist in determining the risk mitigation requirements and the preferred mitigation option.

(e) Where the exact nature of the potential landslide hazards and their possible consequences are not entirely known, and are to be assessed to assist in identifying the hazards and evaluating their risk.

These issues are beyond the scope of conventional stability assessment, and can only be tackled from a risk perspective. This often applies to small slopes, natural hillsides and large distressed sites, where detailed characterization of the ground and pore water conditions is not practical, and where prevention of slope failure can be difficult. Risk-based thinking is the key to addressing the problems. Depending on the needs of the particular case, the risk-based assessment process may or may not involve formal quantification of the risk. Qualitative risk analysis had been the principal approach of risk assessment before QRA methodology emerged. Over the years, it has supported sound risk management decisions to be made in many circumstances, without explicitly quantifying the risk. Provided that the assessors and decision-makers take due consideration of its potential constraints, qualitative risk assessment can play a useful role in landslide risk management. It would continue to be an important tool for dealing with many day-to-day risk-based slope design and landslide problems, as well as an essential step that precedes and facilitates the quantification of risk.

Many examples of site-specific application of qualitative risk assessment have previously been reported in the literature (e.g. Hutchinson, 1992; Morgenstern, 1995; Vick, 2002 and Morgenstern, 2000). Selected cases are described in the following Sections to illustrate its unique role and diverse range of applications in landslide risk management.

4.2 Risk Assessment in Conventional Slope Design, Hong Kong

As in many other places, the recommended good practice for man-made slope design in Hong Kong is set out in a factor of safety framework. GCO (1984) stipulated that slopes are to be designed to a required minimum factor of safety based on consideration of the consequences in the event of slope failure (Table 4.1). As more stringent design requirements (which govern the likelihood of failure) are required for slopes with more

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serious failure consequences, a risk-based thinking is embodied in the design practice. The design of an individual slope is a process of stability assessment. On surface, it seems that this process does not extend into risk assessment, although the design requirements are implicitly aligned with some risk considerations. However, a site-specific qualitative risk assessment is in practice always carried out in the slope design process when the designer selects the factor of safety to be adopted for the slope. This involves a risk-based deliberation in relation to the following three issues:

(a) What the failure consequence is and specifically the type of facility that would be affected, and the likelihood of loss of life, in the event of slope failure.

(b) Whether the slope should be regarded as an existing slope with known geological and groundwater conditions and thereby the use of a reduced margin of safety is justified (Table 4.1).

(c) Whether there are other factors, such as uncertainties in the design parameters and any need to ensure better slope performance, that warrant the use of a factor of safety higher than the minimum stipulated value.

Duly addressing all these issues is not an easy task, whether by qualitative or quantitative means. However, they do not normally pose any insurmountable difficulties to the slope designers, who may not be very familiar with detailed consequence and uncertainty assessments. Two factors are relevant:

(a) The designer may play safe, i.e. in the absence of data, capability, resources or time to do otherwise, he simply adopts a higher factor of safety in design.

(b) The designer may exercise his judgment (or an 'opinion', as noted by Stewart, 2000) to select his preferred design factor of safety and let the geotechnical checking process 'validate' whether his choice is appropriate, i.e. whether the design including the safety margin adopted is accepted by the approving authority.

There are merits for being conservative in design and with an additional safety net provided by independent checking. However, there remain the questions of how conservative is safe, and whether checking endorsement is an adequate guarantee of good practice.

To improve slope design practice and ensure consistency in assessment, the GEO has stipulated the technical principles on qualitative assessment of the consequence category and the required slope design factor of safety (Figure 4.1). Some empirical criteria (Figure 4.2) have also been formulated, based on findings from a review of the available landslide data, for assessing typical slope conditions in Hong Kong.

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Observation: Although conventional slope design is typically carried out by a deterministic approach, qualitative risk assessment is implicit in the design standard and practice. There is scope for further integration of qualitative risk assessment with conventional slope design methodology. There is also a demand for enhanced capability in risk assessment to ensure that it can be effectively and reliability carried out in practice.

4.3 Assessment of Natural Terrain Landslide Hazard, Hong Kong

The strategy for dealing with natural terrain landslide risk in Hong Kong has been to avoid, as far as possible, new developments in vulnerable areas (Wong, 2003). Where this is not practicable, the conventional approach in the past has been to design the natural hillside to the factors of safety stipulated in GCO (1984). As in the case of design of man-made slopes, this Factor of Safety Approach aims to avert landslides by ensuring a prescribed margin of safety. The approach is applicable if the design objective is to reduce the chance of natural terrain failure. It has occasionally been used to assess the stability of hillsides against major failures, particularly where signs of distress are observed and development of large-scale instability may result in serious consequences. However, in many other circumstances, this approach is fraught with inherent difficulties and its use in natural terrain is not practical in that:

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

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

For these reasons, two alternative approaches, viz. the QRA approach and the Design Event approach, have been introduced for use in assessment and mitigation of natural terrain landslide risk in Hong Kong (Wong, 2001; Ng et al, 2003). The QRA approach is applicable when the designers opt for quantification and management of the natural terrain landslide risk instead of relying solely on stabilization works at the source areas. The landslide risk is quantified by formal QRA techniques, and the need for any necessary risk mitigation measures is assessed by reference to the interim risk guidelines (ERM, 1998) that have been adopted in Hong Kong since 1998. This approach would require a detailed assessment of the probability and consequence of natural terrain landslides, together with consideration of the tolerability of the assessed risk level. It may be considered as the most rigorous and comprehensive assessment. The assessment often requires expert input and may be fairly involved and costly. Some examples are described in Section 5.

The Design Event approach is a qualitative risk assessment and design framework, which is applicable when designers opt for mitigation of natural terrain landslide risk without carrying out a formal QRA. Under this approach, the mitigation measures (e.g.

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debris-resisting barriers) required to protect a development from natural terrain landslides are determined by reference to an assessment of the design landslide event that may occur on the hillside affecting the development. Uncertainties are generally considered in an implicit and lumped manner through the assessment of the design event (e.g. a landslide of a certain size with a given degree of mobility).

The framework for the Design Event approach takes account of the failure consequence and the susceptibility of the hillside to landsliding in a semi-quantitative manner. Under the framework, the susceptibility of the hillside to failure is categorized into four classes, based on its historical landslide activity and assessment of geomorphological features and other relevant information (Table 4.2). The ranges of notional probability of landslide occurrence indicated for each of the classes serve as yardsticks to aid the assessment. The consequence of failure is categorized into 5 classes based on the types of facilities affected and their proximity to the hillside (Table 4.3). The facility grouping follows that adopted in the generalized landslide consequence model developed by Wong et al (1997).

The design requirements for mitigation measures are given in Table 4.4. Further studies will not be required if the consequence of failure and the landslide susceptibility of the hillside are insignificant. Otherwise, further studies should be carried out to establish the need for any mitigation measures to deal with the relevant design events. Depending on the consequence and susceptibility classifications of the site, the required design event may be either a ‘conservative’ event or a ‘worst credible’ event (Table 4.4).

For the purposes of calibration, the design requirements for the Design Event approach have been applied to 17 cases where developed areas have been affected by natural terrain landslides or where the landslide hazards have previously been studied. The framework has been found to be relatively easy to apply and it gave reasonable results.

Applying the Design Event approach is in essence going through a qualitative risk assessment process. This calls for use of geotechnical professional skills to identify the nature of the landslide hazards, assess their severity, establish the required design event requirements (i.e. notional return periods) following the design framework, and determine the magnitude of the landslide for risk mitigation (i.e. the design event). This qualitative (or in some respects, semi-quantitative) method of risk assessment is relatively easy to apply. It does not demand formal and rigorous quantification of risk, and is favored by many geotechnical practitioners in Hong Kong.

However, there is always a trade-off between simplicity and versatility. This qualitative risk assessment methodology does not explicitly consider the practicality and cost-effectiveness of risk mitigation. Such consideration is inherent in the QRA approach if the risk level is found to be within the ‘As Low As Reasonably Practicable (ALARP)’ region.

Observation: The Design Event approach is an illustration of integration of risk assessment and conventional geotechnical practice, to offer a tailor-made methodology for qualitative landslide risk assessment for individual sites.

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4.4 Lessons from the 1994 Kwun Lung Lau Landslide, Hong Kong

In the evening of 23 July 1994, a landslide occurred on a 10 m high, old masonry wall (Figure 4.3) below a high-rise residential block at Kwun Lung Lau housing estate, Kennedy Town, Hong Kong. The landslide had a volume of about 1,000 m^3. It resulted in five fatalities and serious injuries to another three people. The case provoked significant public concern and resulted in extensive technical and public policy inquiries. This was understandable given that the fatal landslide was not prevented even though the wall that failed had been catalogued, ranked and inspected under a comprehensive slope management system.

The technical causes of the landslide were established in a detailed investigation (GEO, 1994; Wong & Ho, 1997), which was independently reviewed by Morgenstern (1994). A cross-section through the landslide site is shown in Figure 4.4. The masonry wall was built shortly before 1900. The residential block was erected in the mid 1960s, together with placement of loose fill and construction of the subsurface storm water and foul water drainage systems. During the heavy rain that commenced some 48 hours before the landslide, storm water collected by the drainage network migrated into the ground via two leaky drain pipes beneath the yard area to the south of the residential block (Figure 4.5). The storm water reached the fill body over the crest of the masonry wall. Slope deformation and local failure occurred, which disrupted the foul water drain and resulted in more water entering the ground behind the masonry wall. The process lasted for hours until the wall finally buckled and collapsed in a brittle manner.

Many landslide risk management lessons were learnt from the case (Morgenstern, 1994; Morgenstern 2000). Among these, there is an important issue regarding the slope risk rating process and slope study methodology. The setting giving rise to the landslide problem, i.e. presence of leaky drains and loose fill bodies that provided permeable pathways for subsurface water flow, was not unique to the wall that failed in 1994. Instead, it was a general setting in Kwun Lung Lau housing estate. In 1985, a 500 m^3 failure, which was also caused by a leaky drain buried in loose fill, occurred on an adjacent registered slope in a housing estate about 50 m to the east of the 1994 landslide location (Figure 4.5). The problem (i.e. leaky drains in loose fill) was revealed by the failure in 1985, but the insight was neither transmitted to the ranking nor used effectively in the assessment of the other slopes in the estate, including the wall that failed in 1994. With the benefit of hindsight, it was recognized that the technical perspective in assessing the risk for individual slopes might have been frozen as a result of the slopes having been separated into numerous distinct units in the Catalogue. The subsequent slope prioritization and studies were conditioned to deal with each slope separately and individually, without an integrated consideration that the slopes might have shared some defects in common.

Following the incident, a systematic landslide investigation programme has been introduced into the GEO's risk management process. Under the programme, landslides reported to the GEO are inspected and selected for detailed study. Any generic factors associated with the landslides are examined. The need for any out-of-turn action on failed slopes and on any other slopes that may be affected by the generic factors, is identified. This process provides an integrated risk assessment procedure that supplements the catalogue-based approach of slope ranking and assessment. Details of the landslide investigation programme and some of the findings that have major implications for landslide

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risk management in Hong Kong are described in Wong & Ho (2000). An example of qualitative risk assessment with an integrated perspective is presented in Section 4.5 below.

Observation: By separating the slopes into distinct and individual compartments, the commonly adopted catalogue-based approach of slope registration, relative risk rating and assessment may hamper the appreciation of possible generic factors that affect the performance of a slope, as well as deterring effective sharing of such technical perspective to other slopes in the catalogue. Systematic landslide investigation and integrated slope studies provide a means to break the barrier and to assess the risk of individual slopes in an integrated manner.

4.5 Risk Analysis for Landslides below Wah Yan College, Hong Kong

In the morning of 8 May 1992, a 500 m^3 landslide occurred on a loose fill slope bordering the building platform of Wah Yan College, Hong Kong. The liquefied fill material ran onto Kennedy Road (Figure 4.6). The landslide did not result in any serious consequences at Wah Yan College, but the driver of a car on Kennedy Road was buried and killed by the liquefied debris. The landslide highlighted the landslide concern in the area because in 1989, another landslide of similar size had also occurred on an adjoining fill slope bordering Wah Yan College. Fortunately, the debris of this landslide did not liquefy and was deposited on the pedestrian pavement without running onto Kennedy Road (Figure 4.7). In 1989, the slope that failed was largely covered by chunam (a 75 mm think cement-soil slope cover), which prevented the loose fill from reaching a high degree of saturation, thereby making it less susceptible to liquefaction. An imminent risk management issue to address after the 1992 landslide was whether there were other potentially unstable loose fill slopes bordering Wah Yan College, and if so, what were their liquefaction potential and risk implications.

A qualitative risk assessment was carried out by Wong (1993), and the following were established:

(a) The development history of the site was reviewed by a detailed interpretation of the old aerial photographs, and the locations and extent of the loose fill bodies bordering Wah Yan College were identified. Wah Yan College was built on the top of a hill in the mid 1950s. During site formation, the hill top was leveled to create the building platform. Part of the excavated material (completely weathered granite) was end-tipped from the platform and was formed in a series of fill slopes bordering the platform. Apart from the slopes that failed in 1989 and 1992, another sizeable fill slope was present to the north of Wah Yan College overlooking Queen's Road East and the Ruttonjee Clinic (Figure 4.7). It was necessary to assess the risk associated with this slope.

(b) A detailed ground investigation was carried out on the slope to verify the geological conditions of the site, and in

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particular, the extent and conditions of the fill. It was found that the upper part of the slope was overlain by about 2 m of loose, granitic fill (Figure 4.8). The fill density was at about 80% of standard compaction, which was similar to that in the 1992 failed slope. As the conditions of two slopes were very similar, it was assessed that they should have comparable susceptibility to liquefaction failure. The findings provided the technical basis to serve a Dangerous Hillside Order to the owners of the Queen's Road East fill slope (i.e. Wah Yan College). The Order required the owners to investigate the slope and carry out the necessary slope stabilization works. However, the investigation and works would take some time to arrange. Hence, further assessment was made, in particular on the consequences of failure, to assist in managing the risk.

(c) The consequence assessment involved modeling the mobility of landslide debris. The operating apparent angles of friction along the failure surface and along the debris path in the event of a liquefaction failure were back-analyzed from the 1992 landslide. These were found to be 20° to 25°, and 30°, respectively. A range of apparent angles of friction, from 10° to 25° along the potential failure surface, and 27° to 33° for the debris path, were adopted in the modeling for the Queen's Road East fill slope. Based on the results, the area that might be affected by the landslide debris was classified into a primary impact zone and a secondary impact zone (Figure 4.7). The two zones were delineated on the basis of qualitative assessment, without formally quantifying the risk. The primary zone was taken to be of high risk, where serious damage would result, as in the case of the 1992 fatal landslide. The secondary zone represented a lower risk region, where serious damage might also occur in case of a larger volume of failure, or more mobile debris than the 1992 landslide.

(d) The risk at the Ruttonjee Clinic was also assessed. It was found that the road together with the 1.5 m high retaining wall in front of the clinic would protect the clinic from direct impact from the most of the debris.

The risk assessment offered invaluable information on the likely scale of the problem, which was adopted in emergency planning and implementation of precautionary measures. The case may be taken as an example of Consequent Risk Analysis (CRA), which was advocated by Morgenstern (2000) as a qualitative risk assessment process to assure geotechnical performance and control risk.

Observation: Landslide study, geotechnical investigation, engineering appraisal and consequence analysis can be combined in a qualitative risk assessment to resolve landslide

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risk management issues that would otherwise be difficult to handle by conventional means.

4.6 Failure Modes and Effects Analysis of Natural Terrain Landslide Risk, Shatin Heights, Hong Kong

Over the years, a suite of technical methods have been developed and adopted in qualitative risk assessment. Examples include Failure Modes and Effects Analysis (FMEA), Hazard and Operability Study (HAZOP) and Potential Problem Analysis (PPA). An overview of these methods was given in Neowhouse (1993), and their applications to qualitative risk analysis were described in Morgenstern (1995). Among these methods, FMEA was fairly commonly adopted in geotechnical risk assessment, e.g. geo-environmental risk management in mining projects (Dushnisky & Vick, 1996), dam risk management (Hughes et al, 2000; Stewart, 2000) and ground improvement (Vick, 2002). A FMEA framework developed for natural terrain landslide risk assessment in Hong Kong is illustrated below with an example.

FMEA is a qualitative risk analysis technique. It directs attention towards understanding the behavior of the physical components of a system, the possible modes of their failure, and the influence their failure would have on each other and on the system as a whole. FMEA can be performed with the use of a FMEA table. The table typically comprises a number of columns, which guide the analysis of the failure modes and their effects. By examining the likelihood of failure and its consequence, a qualitative risk assessment is carried out. There is often a need to tailor-make the FMEA table to meet the needs of the specific problem being analyzed. Different qualitative or semi-quantitative classification schemes may also be adopted to facilitate the FMEA assessment.

FMEA is usually used in two ways, as noted by Vick (2002):

(a) to assist in hazard identification and risk screening, typically as a precursor to more detailed risk assessment; and

(b) to serve as a stand-alone preliminary risk assessment procedure.

Assessing the risk of natural terrain landslides involves consideration of the possible failure modes and their effects and consequences. An example of applying FMEA to assessing the risk of natural terrain landslides in Shatin Heights, Hong Kong is shown in Table 4.5. The FMEA table was devised to address the specific circumstances of the site. The classification schemes that accompanied the FMEA are explained in Figure 4.9.

The natural hillside at Shatin Heights is bounded by residential buildings at the crest and toe of the hillside (Figure 4.10). In 1997, a total of six landslides occurred on the hillside, and three of these developed into debris flows that ran into the buildings at the toe of the hillside (Figure 4.11). After the failures, the landslides were studied in detail under GEO’s landslide investigation programme (GEO, 1998b). Subsequently, a Natural Terrain Hazard Study was also carried out on the site (FMSW, 2001). The studies provided data and technical insight for assessing the landslide risk. These were incorporated into the FMEA as a basis for working out the semi-quantitative hazard and consequence categories in the FMEA

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table. The case showed the following:

(a) The two typical functions of FMEA are applicable to landslide risk assessment, i.e. FMEA facilitates hazard identification and it provides a preliminary assessment of the risk. In this case, out of the 15 possible hazard scenarios, five were identified by FMEA as of risk concern and requiring further risk assessment. The likely order of risk of each of the five hazards was also estimated. Although these are not formal QRA figures, they give a preliminary indication of the possible level and severity of the risk.

(b) Availability of data and technical understanding of the landslide hazards at the site is a prerequisite for successfully using FMEA in site-specific qualitative risk assessment. Otherwise, the reliability of the assessment and its suitability for supporting site-specific risk management application are in question. In such cases, the FMEA assessment would practically be reduced to at best a relative risk rating process.

(c) Some technical issues in applying FMEA to landslide risk assessment deserve attention. 'Component' typically refers to the catchment or sub-catchment units. Definition of such components is relatively straightforward. However, they (i.e. the catchment or sub-catchment units) seldom interact with each other in causing adverse consequences. 'Failure mode' tends to be fairly complicated. It involves consideration of different types of failure (e.g. landslide or boulder fall), different scales of failure (i.e. failure volume), different mechanisms of debris movement (e.g. channelized debris flow or open slope debris avalanche), different degrees of mobility (i.e. more mobile or less mobile debris), etc. 'Effects' typically refer to different degrees of damage to the facilities at risk and hence the potential for resulting in loss of life or economic loss. Unlike in the case of other more complicated systems that involve many inter-related components, assessing the 'effects' in NTHS does not usually call for detailed consideration of the different components (i.e. catchment or sub-catchment units) and their interaction. However, it involves consideration of the debris runout path, debris mobility, any protection provided by structures, etc. Such assessment requires considerable professional judgment. As pointed out by Vick (2002), FMEA as a broad screening tool can isolate the major elements of risk, but it cannot explore at a detailed level the specific conditions and events that produce it. FMEA is best suited for addressing complex systems. However,

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complex failure modes are different from complex systems. For risk scenarios associated with landslides and debris flows, the 'system' may not be complex, but the failure modes could be fairly complicated.

(d) Use of a risk-matrix (Figure 4.9) would help to evaluate the risk category and hence provide a basis for risk estimation and hazard identification. However, the FMEA table can become very long (i.e. with many rows) when applied to a large site. Formulating a suitable FMEA table that addresses the particular circumstances of the site is important in the efficient and effective use of FMEA. Although the format of the FMEA table has to be adjusted to suit the particular needs of the case that is being analyzed, the FMEA framework (Figure 4.9) is sufficiently representative for use in different sites. This also helps to ensure consistency in applying FMEA.

(e) The case also illustrates the use of a risk-matrix (Figure 4.9) in evaluating the risk category and thereby providing a basis for risk estimation and hazard identification. The risk matrix combines different classes of the frequency and consequence of landslide, which are aligned with some notional probabilities of failure and descriptions of the severity of landslide consequence respectively. An interesting example of application of risk-matrix to assessing the landslide risk on a proposed house on the western slope of the Warringah Peninsula, Northern Sydney is described in Walker (2002). In this example, the qualitative descriptors given in AGS (2000) were adopted. For each type of landslide that might affect the house, the frequency and consequence classes are determined from judgmental assessment and the corresponding risk level established in a semi-quantitative manner via a risk-matrix.

Observation: Established methods, such as FMEA, can be used in qualitative landslide risk assessment, to assist in hazard identification, risk screening and evaluation. It may be carried out as a stand-alone qualitative or semi-quantitative risk assessment procedure, or as a precursor to more detailed risk assessment, and in particular QRA.

5. SITE-SPECIFIC QUANTITATIVE RISK ASSESSMENT

5.1 Overview of Site-specific Quantitative Risk Assessment

Quantitative risk assessment (QRA) is characterized by quantification of risk, for risk tolerability evaluation and risk management applications. Undertaking landslide QRA at individual sites requires the use of formal risk quantification techniques to calculate the landslide risk, typically in terms of individual risk and societal risk, for comparison with the

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relevant risk criteria. It is arguably the most detailed and elaborated approach to risk assessment. It differs from qualitative landslide risk assessment as applied to site-specific level in two key aspects:

(a) The landslide risk, typically in terms of risk-to-life, is explicitly quantified.

(b) The quantified risk figures are formally compared with the corresponding risk criteria for evaluation of risk management action, based on risk tolerability and risk-cost-benefit considerations.

Uncertainty is chronic in geotechnical engineering. Geotechnical practice is fundamentally about assessing and managing risk, but the approach taken by geotechnical practitioners to handling risk has evolved with time. Whereas qualitative deliberation prevailed in the 1970s and 1980s, geotechnical application of QRA emerged in the 1990s, particularly in relation to the mining industry, dam management and slope safety. Factors that gave impetus to the increasing use of QRA were discussed in Morgenstern (1997). Notable development and pilot applications have taken place in Australia (e.g. Fell, 1994; ANCOLD, 1994; Fell & Hartford, 1997; AGS, 2000; ANCOLD, 2003), Canada (e.g. Canadian Standards Association, 1991; BC Hydro, 1993; Bunce et al, 1997; Stewart, 2000), France (e.g. Mornpelat, 1994; Leroi, 1996; Rezig, 1998) and Hong Kong (e.g. Wong et al, 1997; ERM, 1998; Ho et al, 2000; Wong, 2001).

Over the past few years, formal QRA has found a broader and more specific application to landslide risk assessment. The methodology and techniques continue to evolve. There is now a wide spectrum of cases in which QRA was applied to varying degrees of complexity and detail, and conceivably with differing degrees of rigor. A summary of QRA methodology and selected examples of site-specific QRA applications are given in the following Sections. While the examples are selected from the more detailed end of the spectrum of QRA cases to illustrate the state of good practice, they also demonstrate the evolution of QRA techniques in recent years.

5.2 Quantitative Risk Assessment Methodology

QRA is a method of quantifying the order of risk through a systematic examination of the factors contributing to the landslide hazard and affecting the severity of consequence, and establishing probabilities for the individual factors. In simple terms, the following questions are addressed in a QRA of landslides or slope failures, with the view of risk quantifying:

(a) Hazard identification, i.e. what can cause harm?

(b) Frequency assessment, i.e. how often would landslide occur?

(c) Consequence assessment, i.e. what are the results and how bad?

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(d) Risk evaluation, i.e. so what?

(e) Risk management, i.e. what should be done?

The outcome of a QRA is an estimate of the probability of occurrence of different types of adverse consequences, such as the death of individuals (i.e. individual risk), multiple deaths (i.e. societal risk), and damage to property or closure of a major road for a certain period of time (i.e. economic risk).

A generic framework for landslide risk assessment and management is summarized in Fell et al (2005). Ho et al (2000) describes tools, misconceptions and main issues related to use of QRA. The International Society of Soil Mechanics and Geotechnical Engineering Technical Committee on Risk Assessment and Management (TC32) has developed a Glossary of Terms for Risk Assessment, based on IUGS (1997), ICOLD (2003) and relevant National Standards, such as British Standard BS 8444, Australia-New Zealand Standard AS/NZS 4360:1999 and Canadian Standard CAN/CSA-Q634-91.

5.3 QRA of Notable Landslides

Landslide back-analyses are conventionally undertaken primarily for examining the mechanisms and causes of slope failure. The analyses have given the geotechnical profession an improved understanding of slope performance, as well as of the factors that combine to result in failure. QRA offers another dimension to landslide back-analysis. Use of QRA makes it possible to assess retrospectively not only the instability, but also the landslide risk. This therefore provides a basis for a landslide to be evaluated in the light of its theoretical risk, damage potential and consequence scenarios. It also facilitates the interpretation of ‘near-miss’ events and examination of potential landslide loss figures and risk tolerability.

5.3.1 The 1995 Fei Tsui Road Landslide, Hong Kong

The Fei Tsui Road landslide occurred in a 27 m high cut slope in weathered tuff in Hong Kong at about 1:15 a.m. on 13 August 1995. The failure volume was approximately 14,000 m^3 (Figure 5.1). A 12 m wide strip of open space at the toe of the slope and the 11 m wide Fei Tsui Road Road beyond were totally engulfed by the landslide debris. The debris piled 6 m high against a kindergarten, located on the ground floor of Chai Wan Baptist Church on the far side of Fei Tsui Road, and some ran yet further into a playground (Figure 5.2). The incident resulted in one fatality and one other person was injured. Both individuals were walking on the far side of the road at the time of the landslide. The cut slope had previously been assessed by a number of parties. However, the scale of the failure, which was controlled by a laterally extensive, weak kaolin-rich altered tuff layer, was not anticipated. It was also the largest cut slope failure since systematic landslide records began in Hong Kong in 1984.

A forensic investigation into the landslide was carried out. The failure was back-analyzed and the causes established by GEO (1996), and independently reviewed by Knill (1996). In addition, the risk of the incident was assessed with the use of formal QRA

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techniques, as reported in Wong et al (1997). In the QRA, the consequence model formulated in Wong et al (1997) was adopted, with refinements made to incorporate event-tree analysis into the model. The model included a consideration of the probabilistic distribution of differing degrees of debris mobility, up to a worst credible limit of a 20° travel distance for this landslide (Figure 5.3). The vulnerability factors of different proximity zones, which were assessed by Wong et al (1997), with account taken of the probabilistic distribution of debris mobility, are shown in Figure 5.4. The theoretical population at risk for each of the facilities followed the classification shown in Table 3.5. The temporal probability was also considered in deriving the F-N curve.

The back-analysis predicted that the landslide had a potential loss of life (PLL) of about 4. In terms of relative contributions (Table 5.1), the kindergarten would constitute about 50% of the total risk, with a calculated PLL of over 2. The QRA illustrates the 'near-miss' nature of the incident in that if the landslide had occurred during the day time, when substantially more traffic would have been on the road and when the kindergarten was open, the fatality figures would have been much higher. This emphasizes the difficulty of extrapolating historical data in the absence of a rational framework. Consideration of the actual fatality figures alone does not permit much progress to be made in the understanding of possible landslide consequences in a risk-based framework.

The level of societal risk posed to the affected community is expressed by the F-N curve for the landslide (Figure 5.5). The F-N curve had incorporated the frequency of occurrence of the landslide, which was established as a 100-year event based on analysis of recorded rainfall intensities for different durations before the landslide was triggered. The findings indicated that the slope had a significant probability of resulting in multiple fatalities. For example, the chance of 10 fatalities or more occurring was 0.015% per year.

Using the QRA results, it is possible to examine the predicted consequences if the same landslide were to occur alongside a road that is more heavily-used than Fei Tsui Road. Table 5.2 shows the expected extent of damage for roads with differing degrees of traffic usage. This facilitates examination of possible hazard scenarios and risk projections, and provides information for consideration in risk management, including emergency planning.

5.3.2 The 1982 Argillite Cut Rockfall, Canada

In 1982, a rock fell on a vehicle in the Argillite Cut on British Columbia Highway 99 and killed a woman and disabled her father while they were delayed in traffic on the road. The risk of this landslide was quantified by QRA and its implications examined by Bunce et al (1997). The rockfall frequency was quantified from historical rockfall and road accident records were used to estimate the rockfall frequency. Rockfall travel distances were estimated from data obtained from mapping impact marks caused by rockfalls on the asphalt road surface. Rockfall consequences on stationary and moving vehicles were also calculated. The annual potential loss of life for rockfalls in the Argillite Cut was assessed to be 8×10^{-2}. The annual probabilities of death of one time user and a daily commuter on the highway were 6×10^{-8} and 3×10^{-5} respectively.

The man who was injured in the incident successfully sued the provincial Ministry of Transportation and Highways for damages. The British Columbia Supreme Court found that

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the Ministry "could readily foresee the risk that harm might befall users of a highway if it were not reasonably maintained" and that "maintenance could be found to extend to the prevention of injury from falling rock" (Cory & Sopinka, 1989). It was recognized that the case set a legal precedent when compensation was awarded to the father by the British Columbia Supreme Court. Bunce et al (1997) and Morgenstern (1997) noted that the case set a legal precedent because it effectively identified the level of risk at which the judicial system considered the public should be protected, although no QRA results were offered in evidence. This QRA back-analysis, which was carried out subsequently to the court case, helped to quantify the likely level of risk posed by the Argillite Cut to road users, and thereby facilitated the interpretation of risk tolerability.

5.3.3 The 1999 Shek Kip Mei Landslide, Hong Kong

In the late afternoon of 25 August 1999, a 21 m high cut slope in weathered granite behind Blocks 36 and 38, Shek Kip Mei Estate, Hong Kong exhibited significant movement (Figure 5.6). This took place suddenly after four days of heavy rain. The displayed mass of about 6,000 m^3 in volume, moved about 1 m downslope (Figure 5.7). About 700 residents in the housing blocks were temporarily evacuated on the evening of 25 August 1999, following emergency inspection by the GEO. Permanent evacuation was implemented on 26 August 1999 following detailed mapping of the distressed slope, and after account had been taken of the risk of further slope failure and the difficulty of stabilizing the slope within a short time. The incident involved the largest landslide-related permanent evacuation of residents in Hong Kong since the GEO set up its landslide emergency system in the early 1980s. The case attracted considerable public and media attention, although the evacuation decision itself was not challenged.

A detailed investigation into the landslide was carried out by the GEO (FMSW, 2000) and was independently reviewed by Burland (2000). The slope included weak layers of kaolin- and manganese-infilled discontinuities within granite and these formed part of the failure surface. The landslide was triggered by heavy rain, which was most severe over the 48-hour duration and had a return period of 31 years.

A back-analysis of the landslide using QRA was reported by El-Ramly et al (2003). Three hazard scenarios, No. 1 to 3, in terms of the volume of failure (Table 5.3), were considered. The frequency of landslide was estimated from the return period of the rainfall that triggered the failure, i.e. 3.2×10^{-2} per year for hazard scenario No. 1. The consequence of the landslide was assessed, based on a consideration of debris mobility (Wong & Ho, 1996) and the probability of death (Wong & Ho, 1998a; ERM, 1998). Event tree analysis was adopted to examine different combinations of the timing of landslide, possible development of signs of distress before uncontrolled failure, efficiency of warning and response measures, travel distance of debris and possible building collapse.

The QRA suggested that the potential loss of life (PLL) of the slope was 8×10^{-4} per year. As shown in Table 5.3, 95% of this risk came from large-scale failure (i.e. hazard scenario No. 1), and collapse of a building at night constituted about 70% of the total risk. The F-N curve derived by El-Ramly et al (2003) is reproduced in Figure 5.8. The F-N calculations indicated that collapse of Block 36 following an impact by a sudden, large detachment could have resulted in more than 40 fatalities during the daytime and over 150

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fatalities at night. Although the probability of occurrence was low (about 5 x 10^{-6} per year), the high fatalities made this relatively rare scenario a major contributor to the total risk. If evacuation was not implemented in time, the probability of occurrence would double, i.e. about 10^{-5} per year.

When the slope failed in the evening of 25 August 1999, the frequency of landslide effectively turned from a theoretical probability into a matter of reality. With account also taken of the fact that the slope was distressed and extensively cracked after the initial displacement, thereby creating a higher chance of a large detachment, the probability of multiple fatalities (in this example, over 40 fatalities) in this circumstance could have increased by two to three orders of magnitude. Applying this to the QRA results obtained by El-Ramly et al (2003), the probability of multiple fatalities would be in the order of 10^{-2} to 10^{-3}, i.e. 1 in 100 to 1,000. Although there are uncertainties due to the simplified assumptions adopted, the results give a quantified estimate of the likely order of risk perceived at the time when evacuation was recommended on the basis of engineering judgment.

5.3.4 The 1997 Thredbo Landslide, Australia

In the 1997 Thredbo landslide, NSW, Australia, a fill embankment below the Alpine Way collapsed and the mobile debris destroyed two buildings, which resulted in 18 fatalities. QRA by Mostyn & Sullivan (2002), which was based on consideration of the historical fill embankment failure data in the Alpine Way, debris mobility and consequence analysis, found that the individual risks at the two buildings before the landslide (2.2 x 10^{-3} and 5.3 x 10^{-3} per year) exceeded the unacceptable limit (10^{-6} per year) suggested by the NSW Department of Planning for tourist resorts. The societal risk was also found to be high, and was within the unacceptable zone according to the societal risk criteria reviewed by Fell & Hartford (1997). The QRA findings were presented to the Coroner Inquest, and the Coroner took the view that the community would regard the individual risk as 'totally unacceptable' (Hand, 2000).

5.4 Lei Yue Mun Squatter Area QRA, Hong Kong

QRA has been used in Hong Kong for about a decade in formally assessing landslide risk for evaluating site-specific risk management strategy. The QRA of the Lei Yue Mun squatter area (Hardingham et al, 1998) was an early application. The QRA methodology adopted at the time was relatively simplistic. However, all the essential components of a formal QRA, e.g. quantification of individual and societal risks and evaluation in comparison with risk criteria, were in place.

The abandoned quarry faces of the slopes flanking the Lei Yue Mun squatter villages in Hong Kong were between 20 m and 40 m high, and typically sloping at 65°-80°. The granitic natural terrain was inclined at approximately 35° and rose some 200 m above the squatter huts. The abandoned quarry faces and the hillside (with a variable colluvial cover and signs of active sheet and gully erosion) had a history of instability. A number of significant landslides occurred during a major rainstorm in August 1995. These resulted in severe damage to some squatter dwellings and loss of life was narrowly avoided (Figure 5.9). QRA was adopted to quantify the landslide risk and to assist in decision-making with regard

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to the extent of rehousing the squatter residents.

(a) Hazard identification

Hazard identification is aimed at determining the nature of the landslide process and the types of hazard that may pose a risk to the affected facilities. This was carried out in the Lei Yue Mun study through a geotechnical study, which included interpretation of all the available historical aerial photographs, landslide inspections, geological mapping and field reconnaissance. The principal hazards threatening the squatter village included rockfalls and debris slides arising from failure of the un-engineered cut and fill slopes. The hazards were categorized according to the volume of failure as: small (<50 m^3); medium (50-500 m^3); large (500-1,000 m^3); very large (1,000-5,000 m^3); and extremely large (>5,000 m^3).

(b) Frequency assessment

Frequency assessment serves to quantify the failure frequencies of different types of landslide hazard. From interpretation of the aerial photographs, which dated back to 1945 at this site, a total of 115 landslides were identified. The relevant data were extracted and compiled into a database. 'Recognition factors' of 30% and 90% were adopted for small and medium landslides, respectively. This factor represented the proportion of landslides that could be recognized, to address the problem that some of the smaller failures could have been missed by aerial photograph interpretation. Using the historical distribution of landslide volume together with the relevant recognition factors, the base-line annual landslide frequencies for the site were found to be 3.3 for small, 1.3 for medium, 0.24 for large, 2.4×10^{-3} for very large, and 2.4×10^{-4} for extremely large failures.

An empirical slope hazard rating scheme was used to assess the relative landslide susceptibility of different types of slope, which were sub-divided into 20 m wide segments. The scheme was based on a combination of factors, including slope gradient, presence of drainage lines, evidence of colluvium accumulation, depth of weathering, evidence of erosion and past instabilities. For each type of landslide, the annual landslide frequency was spatially apportioned to each slope segment according to the relative weighting of the slope segment assessed by the slope rating scheme.

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(c) Consequence assessment

The consequence of a landslide, typically in terms of loss of life, is quantified by consequence assessment. In this QRA, landslide consequence was defined in terms of three different hazard groupings, each with its own level of associated casualties. The hazard groupings took into account the type of landslides and debris travel distance, as well as the proximity of the dwellings. Debris travel distances were evaluated from the landslide database. Site surveys were carried out on about 10% of the population and 45 dwellings, to identify the numbers of people at risk and their temporal distributions at different types of facility. Although the consequence model that was adopted in this QRA was relatively primitive, it covered most of the key features required for quantification of landslide consequence.

(d) Risk calculation and evaluation

Risk calculation in QRA is typically a numerical operation that integrates the frequency and consequence assessments, for all types of hazard from all slope segments. Both the individual risk and societal risk to the squatter residents were quantified in this QRA. In the risk calculation, the dwellings were grouped into 20 m by 20 m grid cells. The number of people and the temporal presence in each grid were determined from a population survey, and an event tree was generated for each grid using standard QRA techniques. A total of 130 slope segments and 149 reference grids were considered. An Event Tree was generated for each of the reference grids, which traced the different credible scenarios by combining the hazard grouping, timing of failure, responses to landslip warning, level of emergency services, secondary hazards, etc. (Figure 5.10). Sensitivity analyses were also carried out to examine the effects of alternative assumptions made in the population distribution.

By integrating the hazard model, frequency assessment and consequence assessment, individual risk levels at different locations were computed and contoured. The site-specific risk acceptance criteria were determined through a review of different safety acceptance criteria and consideration of the situation involving squatters at Lei Yue Mun. The proposed individual risk criteria ranged from an upper boundary (unacceptable) of 10^{-4} to a lower boundary (acceptable) of 10^{-6}. The risk criteria that are currently adopted in Hong Kong (ERM, 1998) had not been developed at the time.

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The results of the QRA indicated that a large area of the squatter area fell within the unacceptable region in terms of individual risk (Figure 5.11). The assessed societal risk was also found to be unacceptable (Figure 5.12). Risk calculations further showed that if the squatter residents within the area recommended for clearance were re-housed, the societal risk would reduce to the ALARP region. Cost-benefit calculations indicated that the residents in areas where the landslide risk was within the ALARP region did not justify immediate re-housing.

Quantification of landslide risk using a formal QRA framework provided a rational basis for decisions to be made on risk mitigation or clearance in this case. The QRA results allowed calibration of expert judgment on the extent of clearance required. The large number of past landslides in this study provided a reasonable basis for assessing the frequency and consequence of potential failures for risk quantification, without the need for more sophisticated probabilistic analyses and detailed ground investigations.

5.5 Shatin Heights QRA, Hong Kong

Hong Kong's natural terrain is susceptible to shallow, small-to-medium-sized landslides (Figure 5.13), which can develop into debris flows after entering drainage lines (Wong & Lam, 1998). Should the debris reach densely developed areas, serious consequences may occur, even if the volume of the landslide is relatively small (Figure 5.14). The strategy that is being adopted in Hong Kong for management of natural terrain landslide risk entails two principles (Chan, 2003):

(a) For existing developments, deal with natural terrain landslide risk following a 'react-to-known-hazard' principle, i.e. to carry out studies and mitigation actions where significant risk becomes evident. This typically corresponds to developed sites that are affected by recent natural terrain landslides. As almost all natural terrain in Hong Kong is on Government land, the risk study and mitigation actions are undertaken by the GEO using public works funding.

(b) For new developments, contain the increase in overall risk through studying and undertaking any necessary mitigation actions on sites subject to natural terrain landslide hazards. The developers are responsible for undertaking the risk study and mitigation actions for their own development projects.

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Use of QRA as an accepted approach for studying natural terrain landslide risk and determining required mitigation actions, as explained in Section 4.3 above, was formally introduced in Hong Kong in 2000 (Wong, 2001). A set of guidelines on individual risk and societal risk criteria for natural terrain landslides is being adopted (ERM, 1998).

The natural terrain landslide problem at the Shatin Heights site is described in Section 4.6 above. The QRA of the site, which is documented in FMSW (2001), is one of the earliest QRA applications to natural terrain landslide risk in Hong Kong. The GEO selected the case for risk assessment based on the 'react-to-known-hazard' principle, following six natural terrain landslides that occurred on the hillside in 1997.

The study area (Figure 5.15) was sub-divided into seven catchments and a total of 45 segments, based on topographic conditions. The QRA included the following key tasks:

(a) Hazard identification

This was carried out with a desk review of the available data, interpretation of historical aerial photographs, study of the 1997 landslides, ground investigations, geological mapping, geotechnical appraisal and use of engineering judgment. The hillside was typically sloping at 30° to 35°. It comprises weathered granite overlain by a thin layer of top soil and colluvium, together with local pockets of fill materials near the crest of the hillside. The landslide process involved shallow rain-induced failures, which were partly also affected by uncontrolled discharge of surface water from the building platforms at the crest of the hillside. The landslide hazards were classified according to two types of mechanisms (open hillslope landslide and channelized debris flow) and three failure scales ('small' for volumes of less than 50 m^3, 'medium' for volumes between 50 m^3 and 200 m^3, and 'large' for volumes between 200 m^3 and 1,000 m^3). Failure exceeding 1,000 m^3 in volume was not considered credible. More recently, a more structured framework of hazard identification using FMEA techniques has been developed, and its application to one of the catchments (No. 7 overlooking K.K. Terrace) was described in Section 4.6 above.

(b) Frequency assessment

The base-line landslide frequency was assessed from historical landslide data collated from detailed interpretation of aerial photographs dating back to 1963, with allowance being made for 'recognition factors'. The volume-frequency relationship (Figure 5.16) was established from the landslide data, together with a consideration of the data available from elsewhere in Hong Kong (Wong et al, 1998; Franks, 1998). Probabilistic

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slope stability analyses were carried out to provide a basis for spatial distribution of the landslide frequency to the different segments, as follows:

$$F_i = \frac{F \times (A_i \times P_{fi})}{[\sum (A_i \times P_{fi})]} \text{ .... (2)}$$

for all segments

where F_i = landslide frequency distributed to Segment i
F = base-line frequency of a particular landslide hazard
A_i = area of Segment i
P_{fi} = failure probability of Segment i from probabilistic stability analysis

The distributed landslide frequency was further adjusted by a Bayesian approach to take account of any historical landslide frequencies occurring in the segment. Where required, further adjustments were also made to cater for changes in site conditions, including improved surface protection and surface drainage systems.

(c) Consequence assessment

Site surveys were undertaken to collate information on the usage of the existing facilities, population density and relevant temporal characteristics. A site-specific consequence model was formulated, based on the generalized model developed by Wong et al (1997) for man-made slope failures. This modified consequence model entailed the use of site-specific data on debris mobility, an empirical runout model (Figure 5.17), and vulnerability factors for different types of facility at different proximity zones. Scaling factors were applied for adjusting the vulnerability factors under different circumstances (Table 5.4). Landslide consequence was quantified by multiplying the expected number of vulnerable people (Table 5.5) with the relevant vulnerability factor.

(d) Risk Calculation and Evaluation

The landslide risk was calculated by combining the frequency and consequence assessments. The Personal Individual Risk (PIR) adopted in Hong Kong refers to the frequency of harm per year to a theoretical individual who is exposed to the hazard with account being taken of the temporal factors which expose the individual to the hazard (ERM, 1998). The distribution of the calculated PIR at Shatin Heights is shown in Figure 5.18. Parts of the site

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had an unacceptable PIR, i.e. exceeding 10^{-4} per year for an existing facility (ERM, 1998).

The societal risk in terms of potential loss of life (PLL) was found to be 5.7 x 10^{-3} PLL per year. The corresponding F-N curve is shown in Figure 5.19, together with the societal risk criteria. The societal risk criteria apply to a consultation zone that is equivalent to a maximum 500 m long segment of natural hillside. If the hillside segment is longer than 500 m, then the criteria have to be scaled up linearly to ensure consistency in applying the criteria. The Shatin Heights hillside was less than 500 m long. Hence, scaling-up of the criteria was not required. The derived F-N curve showed that the societal risk was within the ALARP region except for the single-fatality portion which was in the unacceptable zone. Some sensitivity analyses were carried out, which suggested that the calculated risk results were reasonably representative.

(e) Risk mitigation strategy

As both the calculated PIR and societal risk were found to be unacceptable, and given that the hazards were evident from the recent landslides, it was concluded that the risk should be mitigated. The mitigation strategy that was adopted in this case included a qualitative assessment of the design hazard, which was followed by risk-cost-benefit analysis based on the ALARP principle. The design hazard was established with the use of the Design Event Approach (as described in Section 4.3 above), which indicated that a worst credible event (i.e. notionally a 1,000-year event) was to be mitigated. From analysis of the magnitude-frequency data, the design landslide volumes were estimated to be 600 m^3 for catchment No. 3, and 500 m^3 for catchments No. 5 and No. 7. Possible risk mitigation schemes, including use of debris-resisting barriers and local slope stabilization, were examined. The cost of risk mitigation was found to be about HK$ 6.5 million, which would result in mitigation of about 80% of the societal risk. After risk mitigation, the PIR distribution (Figure 5.18) and F-N curve (Figure 5.19) would be well below the unacceptable zone. The risk mitigation was found to be justified from risk-cost-benefit analysis, based on consideration of an equivalent value of life of HK$ 24 to 33 million and an aversion factor of unity.

The risk mitigation works at Shatin Heights were implemented in close liaison with the local residents, and were completed in 2004. The case demonstrates the value of use of QRA in quantifying the risk level and formulating risk mitigation strategy. It also illustrates that qualitative risk assessment techniques, including hazard identification and evaluation of

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design events, can be integrated with QRA to give an effective risk management solution.

5.6 Pat Heung QRA, Hong Kong

In August 1999, two landslides occurred on the natural hillside above No. 92 to 94 Ta Shek Wu Kiu Tau, Pat Heung, Hong Kong (Figure 5.20). The landslides, each about 350 m^3 in volume, affected the village houses at the toe of the hillside. Based on the 'react-to-known-hazard' principle, the GEO arranged a QRA of the natural terrain landslide risk on the existing developments at the site. The study was documented by OAP (2003) and summarized in Pappin et al (2004).

The QRA at Pat Heung followed formal quantified risk assessment procedures. These were similar to those developed and adopted in the Shatin Heights study. Use of GIS techniques enabled a more refined sub-division of the hillside into regular 10-m grid cells, which facilitated spatial analysis. Debris runout and consequence models were developed for use in consequence assessment. The risk-cost-benefit analysis has become 'standardized', by adopting assumptions that are consistent with those made in other landslide QRAs in Hong Kong.

(a) Hazard identification

The hillside was divided into six catchments. The landslide history, geology, geomorphology and hydrogeology were evaluated by aerial photograph interpretation, field mapping, and ground investigation comprising boreholes, trial pits and gravity surveys. A total of 18 historical natural terrain landslides were identified since the earliest available aerial photographs of 1949. The landslides occurred mainly in the surface layer of colluvium, and occasionally with part of the slip surface extending into the underlying weathered volcanic tuff. The landslides were triggered by heavy rain, which resulted in development of a perched water table in the surface soil mantle. The landslide hazards were identified as shallow landslides, either in the form of an open hillslope failure or channelized debris flow. Landslide volume was categorized into the following ranges: within 20 m^3; 20 to 30 m^3; 30 to 60 m^3; 60 to 100 m^3; 100 to 180 m^3; 180 to 320 m^3; and 320 m^3 to the worst credible volume.

(b) Frequency assessment

The base-line landslide frequency was established from the historical landslide data, with allowance for 'recognition factors'. The relevant terrain attributes, including slope gradient, slope aspect and regolith type, were analyzed to examine their correlation with the historical landslide distribution. A grid-based landslide susceptibility index

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was calculated, based on the following equation:

Susceptibility index, N_s
= (Slope angle factor + Slope aspect factor) × Regolith factor..(3)

where each of the factors is given by the total area of landslide sources that are characterized by the attribute (e.g. the range of slope angle), divided by the total area of the hillside that is characterized by the same attribute, i.e. the percentage area where landslides have occurred.

The base-line landslide frequency was distributed to each of the 10-m grid cells based on the N_s of the corresponding grid, as given by the following equation:

Landslide frequency
= $(N_s / \sum N_s)$ × base-line landslide number........................(4)

The calculated landslide frequency distribution in the catchments is shown in Figure 5.21. The landslide volume-frequency distribution was established from historical landslides (Figure 5.22). A worst credible volume (i.e. notional 1,000-year event) of 400 m^3 for open hillslope debris flow was determined from a geotechnical appraisal of the terrain conditions, together with a projection of the volume-frequency distribution. The worst credible volume of channelized debris flow was assessed as 550 m^3, with allowance being made for entrainment along the debris trail.

(c) Consequence assessment

Historical debris runout data at the site were analyzed to establish the mean and standard deviation relationships of debris runout for open hillslope failures and for channelized debris flows (Figure 5.23). Runout distance was adopted as an empirical indicator of debris mobility, whereas the mean travel angle minus two standard deviations was taken as the upper limit of debris runout. A probabilistic distribution of runout distance was adopted, assuming that the deviation from the mean was normally distributed.

The landslide consequence at a given facility was calculated by:

Landslide consequence
= Expected no. of vulnerable people × Vulnerability factor ....(5)

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For houses including dwellings and industrial buildings, the expected number of vulnerable people and their temporal distribution were identified from field surveys and interviews. For roads and footpaths, it was estimated from vehicle and pedestrian densities. The vulnerability factor was calculated as the product of a base-line factor, a volume factor and a protection factor. The base-line factor reflected the probability of fatality for a person in an unprotected facility located at a given distance from the distal end of the debris from a reference landslide (Figure 5.24). The volume factor and protection factor allowed for adjustment to the base-line vulnerability to cater for effects related to landslide volume and protection provided by the facility respectively (Figure 5.24).

(d) Risk calculation and evaluation

The risk arising from landslides originating from each grid cell was calculated by summing the product of the distributed landslide frequency and the consequence at the affected facilities, for all relevant types of landslide hazard. The overall risk for each facility was obtained by summing the risks from all grid cells that affected the facility. The PIR at the three occupied houses below catchments No. 4 & No.5 (i.e. houses No. 92, No. 93a & 93b) ranged from 1.2 x 10^{-4} to 2 x 10^{-4} per year, which was unacceptable (ERM, 1998). House No. 94, near the western end of catchment No. 4 had a PIR of 5 x 10^{-5} per year, i.e. was marginal in terms of risk tolerability.

The societal risk was found to be 2.1 x 10^{-3} PLL per year. About 77% of this came from people in buildings, 18% from pedestrians and 5 % from vehicle occupants. The derived F-N curve (Figure 5.25) showed that the single-fatality portion was within the unacceptable zone (ERM, 1998).

(e) Risk mitigation strategy

Possible risk mitigation options were examined. The recommended option comprised debris deflector walls together with local soil nailing to protect buildings No. 92, 93a, 93b and 94. These would reduce the societal risk to about 5 x 10^{-4} PLL per year, i.e. by over 80%. The F-N curve after risk mitigation is shown in Figure 5.25. The cost of the mitigation works was about HK$ 8 million. The maximum justifiable expenditure was assessed to be HK$ 6 to 16 million, based on the following equation:

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Maximum justifiable expenditure
= Total life saved × Value of life × Aversion factor .... (6)

where
Total life saved
= PLL reduction × design life = $1.6 \times 10^{-3} \times 120 = 0.192$
Value of life
= HK$ 24 to 33 million (ERM, 1998)
Aversion factor
= 1 to 2, given that four fatalities could occur at a frequency within one order of magnitude below the unacceptable zone

The recommended mitigation works were therefore considered justified based on the ALARP principle. The mitigation measures were being constructed in 2004/05.

5.7 North Lantau Expressway QRA, Hong Kong

The North Lantau Expressway is the sole vehicular access to the Hong Kong International Airport and the adjacent Tung Chung New Town, Lantau, Hong Kong. The road is a two-way highway with 3 lanes each way. It runs for about 20 km along the toe of the steep natural hillside of north Lantau (Figure 5.26). The hillside has numerous records of historical natural terrain failures, and some of these have reached the present position of the highway.

A qualitative assessment of the risk of natural terrain landslide on the highway was carried out (Ng & Wong, 2002). Based on a review of the historical landslide records and the geological and terrain conditions, a total of nine clusters of natural terrain landslides on the hillside overlooking four sections of the highway were identified. The four sections covered about 60% of the length of the hillside overlooking the highway. In a hazard identification process that involved consideration of the historical landslide activity, proximity of the highway to the hillside and empirical debris runout criteria, one of the sections (4 km long) near the Tung Chung New Town was found to be of significant risk concern. In view of the importance of the highway, this section of the hillside was further assessed by a QRA. The findings were documented in OAP (2005).

The QRA followed the procedures and techniques developed and adopted in previous QRA in Hong Kong. Three notable aspects of this QRA are highlighted below:

(a) The natural hillside to be assessed covered a large area, and involved more variable geological conditions and landslide types. Hence, in this QRA, particular attention was given to geological assessment of the terrain morphology and landslide process, which formed an integral part of hazard identification and frequency assessment. The information was synthesized into detailed morphology-based regolith maps, as recommended by GEO (2004b). Landslide process models were developed (Figure 5.27). Slope

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attributes and geological factors were correlated with the landslide data for susceptibility analysis, which supported the frequency assessment.

(b) The highway was located at some distance from the steep natural hillside (angular elevation typically less than 25°). Also, the highway was partly protected by buffer zones that were present between the road and the hillside, which included open spaces, road reserves and drainage ditches and chambers. The QRA showed that both the PIR and societal risk in terms of risk-to-life were not in the unacceptable zone. The PIR for the most affected people, i.e. bus drivers, was found to be 1.7×10^{-7} per year. This is well within the acceptable limit of 10^{-4} for an existing facility (ERM, 1998). For societal risk, the total calculated PLL is 6.8×10^{-3} per year. The spatial distribution of the PLL at different sections of the road is shown in Figure 5.28. The highest risk sections were located between chainage 1,000 to 2,500, which contributed over 70% of the risk. The risk principally came from channelized debris flows. The risk from open hillslope landslides was found to be very small. The F-N curves for the eight sections (each 500 m long) of the highway are shown in Figure 5.29. All the F-N curves were within the ALARP region. Two sections were closer to the unacceptable limit, and the other six sections were at least half-an-order of magnitude outside the unacceptable zone.

(c) While risk-to-life was found to be in the ALARP region, it was perceivable that the potential economic loss arising from landslides could be significant. This was confirmed by the QRA through quantifying the risk in respect of economic loss. Four types of potential economic loss were examined:

(i) damage to vehicle;

(ii) vehicle delay;

(iii) air travel passenger delay; and

(iv) air cargo delay.

The scope of each type of economic loss and the QRA findings are summarized in Table 5.6. The total economic loss was found to be about HK$ 450 million in 120 years. The vast majority of these came from losses due to delay to air travel passengers and cargo. The calculated loss figures have been benchmarked with the reported losses in two incidents that resulted in interruption of freight operations in 1998 and in 2004. The benchmarking indicated that the estimated potential economic loss due to landslides was of a reasonable

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order of magnitude.

Options of risk mitigation were examined and the relevant design events analyzed. The preferred scheme comprised provision of check dam basins at six vulnerable debris flow channels (Figure 5.30). The cost of the mitigation works was about HK$ 28 million. Based on the ALARP principle, the maximum justifiable expenditure for mitigating loss of life alone was found to be about HK$ 20 to 27 million, which was less than the cost of the preferred scheme. However, with account also taken of the significant potential economic loss, risk mitigation was considered justified. This case illustrates that for major highways and infrastructures, economic loss can be substantial and may have significant effects on the risk-cost-benefit analysis. In such circumstances, the potential economic loss may have to be assessed in a QRA.

5.8 Ling Pei QRA, Hong Kong

In 2004, a land use concept plan was drafted by the Planning Department, Government of the Hong Kong Special Administrative Region (HKSAR) to guide the development of the Ling Pei area, Tung Chung, Hong Kong. An existing village is present in Ling Pei. The planned development comprised construction of an additional 76 numbers of 3-storey houses at the toe of the hillside that overlooks the existing village (Figure 5.31). The GEO noted that the planned development might be subject to natural terrain landslide hazards, and carried out a QRA to establish the risk and formulate the development strategy. The findings are reported in Wong et al (2004c). The case was a notable development in the application of landslide QRA in Hong Kong in the following respects:

(a) This is a case that extends the application of formal landslide QRA to land-use and development planning at a specific site in Hong Kong.

(b) As an attempt to standardize the QRA process and further improve practice of QRA on natural terrain landslides, a recent review on the use of QRA has identified 16 key modules of work, as listed in Table 5.7. The Ling Pei QRA served as a reference case that was undertaken in alignment with the 16 key modules of work.

(c) As part of the work, further enhancements of site-specific QRA techniques were made. These included, in particular, matching of catchments and facilities, consideration of rainfall-landslide correlation, improved consequence models, evaluation of F-N distribution with account taken of concurrent occurrences of damaging landslides, and integration of QRA with GIS. The enhancements helped to improve the rigor of the assessment and to overcome some known technical problems that have been encountered in previous QRA.

The procedures for the QRA and the key findings are summarized below, under the

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headings of the relevant modules of work:

(a) Study objectives, approach and area (Modules Nos. 1 & 2)

The study served to assess the risk on the planned development and formulate a development strategy in line with good risk management practice. Formal QRA was adopted. The study objectives, scope and approach were agreed by the client (i.e. Planning Department).

The hillside that overlooked the planned development (denoted as Area B in Figure 5.32) had a plan area of about 0.1 km^2. As good practice in site-specific QRA on natural terrain landslides, a larger region was studied for thorough examination of the landslide process and characteristics. The region covered about 0.4 km^2 (Areas A to D, Figure 5.32),

(b) Landslide history and rainfall effects (Module Nos. 3 & 4)

Historical landslide activities and characteristics in the region were evaluated from an interpretation of aerial photographs, field inspections and geomorphological mapping. A total of 91 recent natural terrain landslides and five large relict landslide-related morphological features were identified (Figure 5.32). These were classified according to the type of failure, landslide volume and mode of debris movement, and their key attributes were mapped and recorded in a GIS database.

The correlation of natural terrain landslide density with normalized rainfall intensity in Hong Kong was established from spatial and temporal GIS analysis using comprehensive landslide and rainfall data available since 1985 (Ko, 2003; Wong et al, 2004c). Normalized rainfall intensity at a location refers to the maximum rolling rainfall normalized by the mean annual rainfall at the location. Figure 5.33 shows a correlation with the combined 24-hour and 4-hour normalized rainfall. The correlation was applied to the rainfall records at the site, available since 1985, to calculate the theoretical landslide densities and to assist in interpretation of the historical landslide activity. It was established that the historical natural terrain landslides at the site were triggered by heavy rainfall. The landslide and rainfall histories were broadly consistent with the Hong Kong-wide trend, and the available historical landslide data would therefore give a reasonably conservative base-line landslide density for use in frequency assessment.

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(c) Catchment definition and facility identification (Module Nos. 5 & 6)

The existing facilities (3-storey reinforced concrete buildings in the village) were mapped from the available GIS base map and field reconnaissance. The topographic conditions of the hillside was assessed with the use of a 2-m grid digital elevation model (DEM), together with geotechnical terrain evaluation based on field mapping and interpretation of aerial photographs. This resulted in demarcating the hillside in Area B into a total of twelve catchments, which were sub-divided into 21 sub-catchments (Figure 5.31). The sub-catchments were classified into three types according to the mechanisms of debris movement (Table 5.8). The sub-catchments were also matched with the existing and planned houses that may be affected by landslides originating from the sub-catchments. Experience suggested that a broad matching undertaken at this stage would facilitate hazard identification and streamline the subsequent QRA work.

(d) Geological assessment and hazard identification (Module Nos. 7 & 8)

The geological assessment entailed geological mapping, investigation and appraisal to establish the landslide processes at the site, examine the landslide mechanisms, classify the terrain according to its geological and geomorphological characteristics, formulate a geological model, diagnose possible hazards, etc. Factors that might have affected landslide susceptibility, such as regolith type, proximity to the heads of drainage lines and breaks in slope, and slope gradient, were examined. A terrain model was developed, based on which the hillside in Area B, excluding catchment No. 1, was categorized into two terrain types (Figure 5.34). The geological assessment provided a technical basis for identifying the landslide hazards and developing a hazard model (Table 5.8) for the site.

(e) Debris runout path and influence zone (Module No. 9)

There are two main aspects of evaluation of debris runout for use in consequence assessment. Firstly, the mobility of the landslide debris has to be assessed. In the Ling Pei site, this was done by statistical analysis of the historical runout data. Given the relatively uniform terrain conditions in Area B, travel distance was adopted as the principal operating parameter. This is expressed in a probabilistic framework, together with the use of a worst credible runout

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distance as the upper limit (Figure 5.35). Secondly, the debris runout path has to be predicted. To do so, sub-catchments in Area B were further divided into small hillside units (Figure 5.36). Each hillside unit should have practically the same landslide susceptibility and debris runout path. Hence, the units were irregular polygons, which follow the terrain classification and topographic conditions, instead of regular grid cells. Based on 3-D GIS analysis and terrain evaluation, the possible debris paths originating from each hillside unit were determined. Each cell was then matched with the segments of the lower boundary of the catchments, and with the existing and planned houses. To cater for uncertainties in predicting the debris flow paths, some cells were matched with more than one possible path, and this was assessed in the QRA by Fault Tree analysis. The spatial data on the possible debris paths, the matching and the fault tree probabilities were compiled as GIS datasets.

(f) Frequency assessment (Module No. 10)

The base-line landslide densities (i.e. no/km^2/year) for different terrain types were established from analysis of the historical landslide data and landslide density-rainfall correlation. The base-line density was spatially distributed to each terrain unit based on susceptibility analysis. In this QRA, different susceptibility models were adopted for different terrain types, to cater for the fact that their landslide processes were not exactly the same. Landslide volume-frequency relationships, with account taken of recognition factors, were developed and incorporated into the frequency model. Figure 5.37 shows the landslide frequency distribution derived for a given type of hazard. The landslide frequency was the calculated annual probability of occurrence of landslide of the given type at each terrain unit. The runout mechanism was controlled by the catchment type, and this was considered as part of the consequence assessment.

(g) Consequence assessment (Module No. 11)

An enhanced consequence model, which incorporated consideration of the hazard type, runout mechanism, runout path, debris mobility and vulnerability formulation, was developed for use in this QRA. The vulnerability factors for the ground floor of the houses are shown in Tables 5.9 and 5.10. These were derived from integrating the probabilistic function of debris runout distance and a model for the degree of damage (Figure 5.38). The expected

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number of people at risk in each of the houses followed the 'standard' figures established from previous QRA (Wong et al, 1997). A model that combined the temporal distribution of the population and the chances of concurrent occurrence of damaging landslides was formulated, to calculate the probabilities of different numbers of people at risk from single and multiple landslides in a rainstorm. This gave the temporal probability figures for use in F-N calculations.

(h) Risk analysis and evaluation (Module Nos. 12 & 13)

By integrating the frequency and consequence assessments, the PIR at each of the planned houses was calculated (Figure 5.39). The assessments and risk integration were carried out on a GIS platform via GIS plug-in modules specifically developed for the task. The calculated PIR of an individual at the planned houses ranged from 3.3×10^{-7} to 8.9×10^{-6} per year, which was within the maximum permissible level of 10^{-5} per year for new developments (ERM, 1998). The societal risk for the planned houses was 1.8×10^{-4} per year. The corresponding F-N curve (Figure 5.40), which corresponded to a consultation boundary length of about 320 m, was within the ALARP zone. The risk results suggested that while there is a residual natural terrain landslide risk for the planned development, the risk level was deemed to be tolerable for an individual living in any of the planned houses. However, the planned development involved a high concentration of newly added houses near the steep natural hillside. The overall risk posed by natural terrain landslides on such a community, although not found to be 'unacceptable', should be evaluated following the ALARP principle for assessing whether risk mitigation would be warranted.

The risk on the existing houses was also assessed. The PIR ranged from 5.2×10^{-7} to 1.8×10^{-5} per year, which was within the maximum permissible level of 10^{-4} per year for existing developments (ERM, 1998). The societal risk on the existing development houses was 4.3×10^{-4} per year. Hence, the planned development would result in a more than 60% increase in societal risk. The F-N curve of the total societal risk for both the existing and planned houses was also entirely within the ALARP zone (Figure 5.40).

(i) Risk management strategy (Module No. 13)

The maximum justifiable expenditure calculated from the ALARP principle was found to be about HK$ 0.7 million,

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based on a value of life up to HK$ 33 million, an aversion factor of unity and a 120 year design life. This gave an indication of the likely order of the upper bound expenditure for risk mitigation, which was justified based on direct risk-cost-benefit consideration.

At this order of maximum expenditure, adopting extensive slope stabilization measures (e.g. soil nailing) and provision of heavy debris-retaining structures would not be practical. Use of such measures was less cost-effective in this site, given the linear nature of the boundary between the hillside and the planned development and that the natural terrain landslide risk was relatively uniformly distributed along the boundary.

Two possible risk mitigation options were evaluated (Figure 5.41). These included use of a flexible barrier along the toe of the natural hillside and adoption of a raised platform for the front row of the planned houses. Both schemes were within the order of the maximum justifiable expenditure. The total cost of the planned houses was assessed to be about HK$ 230 million. Hence, provision of the landslide mitigation measures would only amount to about 0.3% of the total cost. This is not excessive.

(j) Risk communication and documentation (Module Nos. 14, 15 &16)

The importance of risk communication cannot be over-emphasized. The QRA findings were presented to the stakeholders and the two possible risk mitigation options were recommended to the Planning Department for formulating the development strategy at the site. The QRA was documented in Wong et al (2004c).

5.9 Commentary on Site-specific QRA

5.9.1 Application

QRA has been applied to many sites in Hong Kong to quantify and evaluate natural terrain landslide risk. The F-N curves derived from some the sites, which are representative of the Hong Kong conditions, are shown in Figure 5.42. From the wealth of experience and QRA results available, some observations on the current state of applications can be made:

(a) All the QRAs are currently carried out by geotechnical professionals as an integral part of geotechnical assessment. The geotechnical practitioners have acquired the skills, and input from risk analyists and QRA specialists are generally not required. QRA is becoming part of local professional

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practice in slope engineering and landslide risk mitigation.

(b) The QRA results have been taken as a sufficiently reliable estimate of the landslide risk, to support risk management decisions to be made at individual sites. This reflects a general recognition among the geotechnical profession that the risk levels assessed by QRA are consistent with professional judgment of the scale of the problem, and that the risk mitigation actions found necessary by QRA are reasonable and practical to implement. This also shows the practicality of use of the risk criteria.

(c) The calculated risk levels for the sites cover a broad range, which spans from the unacceptable zone to well within the ALARP region. Comparison of the site-specific QRA results with those of the global QRA (Section 6.5.1 below) shows that they are in reasonable agreement. This gives reassurance that the site-specific QRA results are of the right order of magnitude. This is based on the concept that if the risks calculated for individual sites are of the right order, adding the site-specific risks of all sites should give an overall risk level that is consistent with the risk determined from the global QRA.

(d) Most of the QRA cases were triggered by the ‘react-to-known-hazard’ principle adopted in Hong Kong for managing natural terrain landslide risk for existing developments. The QRA results reveal that the PIR and the societal risk for these cases fall into the unacceptable zone. Substantial risk mitigation (typically reducing about 80% of the risk) has been found to be justified by the ALARP principle. These cases indicate that the ‘react-to-known-hazard’ principle has been exercised with consistent professional judgment in identifying sites with a genuine risk concern. Experience suggests that for similar sites, QRA can continue to provide an effective and practical means for assessing and managing their natural terrain landslide risk.

(e) QRA has been applied to a lesser number of new development sites affected by natural terrain landslide risk. Some new development sites in Hong Kong are known to be subject to significant natural terrain landslide risk. For these sites, use of QRA should be as effective as the ‘react-to-known-hazard’ cases. However, many other new development sites may only be marginally affected by natural terrain landslide hazards. The Ling Pei site is an example (Section 5.8 above), with the risk found to be well within the ALARP zone. The Ling Pei QRA suggests that

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QRA could also have a promising role to play for sites at such risk levels. It is notable that relatively minor risk mitigation provisions at Ling Pei were found to be justified from the ALARP consideration. However, it is not entirely clear as to whether the use of a simplistic risk-cost-benefit evaluation to formulate the risk mitigation strategy is defensible and prudent in such cases, where the calculated risk-to-life is low. The North Lantau Expressway QRA (Section 5.7) has demonstrated that for strategic roads and major infrastructures, the requirements for risk mitigation may be governed by consideration of economic loss.

(f) A number of factors have been essential to the progress made in natural terrain landslide QRA in Hong Kong. These include:

(i) The public has a high expectation of slope safety, and the landslide-prone setting of Hong Kong calls for vigilant risk management in order to meet the public's expectation.

(ii) Good quality data are more readily available, in particular historical landslide data and other geotechnical and geological information that are required for use in QRA.

(iii) QRA has already been formally used in assessing and managing the risk of Potentially Hazardous Installations.

(iv) Guidelines on natural terrain landslide risk tolerability criteria have been formulated.

(v) Other approaches cannot deal with the natural terrain landslide problems more effectively.

(vi) Continued development and enhancement of techniques during QRA applications

(g) Despite the significant progress in using QRA to deal with natural terrain landslide problems, there have only been limited site-specific QRA applications to man-made slopes in Hong Kong. The availability of other established and effective approaches (factor of safety approach and other qualitative methodologies) is a key factor. The lack of agreed risk criteria for landslide risk from man-made slopes is also relevant.

(h) There is less experience in quantification of the potential

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landslide social-economic loss. The techniques are not very well developed.

The various cases described above probably represent the more detailed end of the spectrum of QRA undertaken on individual sites. It can be seen that the landslide QRA techniques have been evolving during the last decade. While there is room for further advances, the available techniques are now fairly well established. An attempt to 'standardize' the techniques and systematically set out the procedures would help to consolidate good practice and promote application.

5.9.2 Practice

The distinct advantages of QRA over qualitative assessment rest on the ability to quantify risk instead of analyzing risk in relative terms, and on the explicit consideration of risk tolerability and the ALARP principle to provide a rational basis for evaluating the risk mitigation strategy. To realize the full benefits, the following two fundamental conditions must be fulfilled:

(a) The relevant quantified risk criteria must be available (and endorsed for use in QRA). Otherwise, a common basis for risk evaluation is lacking. Hence, for places without any agreed risk criteria, or where there is strong objection to using quantified risk criteria, QRA application would be significantly constrained.

(b) The quantified risk levels must be sufficiently reliable. The quantified risk levels should never be taken as precise numbers. However, the figures should at least be adequately representative to ensure that their use in risk evaluation and formulation of risk mitigation strategy is meaningful and would not be misleading. In practice, quantified risk levels with +/- one order of magnitude may be taken as being reliable. If the accuracy falls outside +/- two orders of magnitude, the risk assessment could be of questionable reliability. Sensitivity analysis would help to assess the reliability of the risk results. Achievement of reasonable accuracy is critically dependent on the availability of reliable data to support the required risk quantification work and on the use of rigorous risk assessment methods. While the rigor of the risk analysis is typically a matter skill, experience and discipline, lack of data is critical and difficult to overcome.

Based on the experience gained from QRA applications, the following developments are notable:

(a) Hazard identification

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Hazard identification may be regarded as the most important component of landslide QRA. It is not only concerned with classifying the hazards for risk quantification. In order to classify the hazard, the available data and site conditions should be thoroughly examined, the landslide processes and mechanisms assessed, and potential hazards identified. Such work is not new to the geotechnical profession. It has long been undertaken in geotechnical assessments, although in the past, the assessments would not normally proceed as far as risk quantification. In a QRA, it is essential that good practice in geotechnical assessments is integrated into the QRA process, particularly in hazard identification. Sound hazard identification is fundamental to the success of a QRA. However, if the landslide processes and the nature of the potential hazards are not understood, there is little hope that the risk can be reliably quantified. This has been the key reason for the increasing acceptance in Hong Kong, and elsewhere, that landslide QRA is best undertaken by geotechnical professionals.

In Hong Kong, considerable efforts have been made in recent years in developing geotechnical techniques for hazard identification. Examples include landslide investigations, regolith and process-based geomorpohological mapping (GEO, 2004b), age-dating of landslides and debris (Sewell & Campbell, 2004), rainfall-landslide correlations (Ko, 2003), and applications of remote sensing and GIS technology (Wong et al, 2004a). The need to develop models and acquire data for use in risk quantification has called for improved geotechnical skills and enhanced capability in hazard assessment. This is an area requiring further development to support future advances in landslide QRA.

(b) Frequency assessment

While a number of methods can be adopted in frequency assessment, use of historical landslide data is the most common and probably most reliable, if the data are available. However, to properly assess landslide frequency would often require due attention be given to the following area:

(i) Consideration should be given as to whether the historical landslide data are complete and sufficiently representative for use in frequency assessment. In a more detailed QRA, addressing this issue could involve assessing the extent of depletion at the potential landslide sources, evaluating the rainfall history and historical landslide activity, examining the

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effects of 'recognition factors', etc.

(ii) Where the site that is being assessed is relatively small in size, it is useful to study a larger area with a similar geological setting in the geotechnical assessment. This helps to provide more data for statistical analysis and for assessment of the relevant landslide processes and mechanisms.

(iii) Where only limited or incomplete historical data are available, use of other methods (e.g. probabilistic analysis and expert judgment) become more important. Due consideration should be given to the reliability of the results and their sensitivity to the assumptions made.

(iv) Proper classification of the potential hazards is essential, and typically includes consideration of both the scale and mechanisms of failure. It should avoid lumping frequency data relating to different types of hazard, which would adversely affect the resolution and accuracy of the frequency assessment. Proper classification is also required to support a more refined consequence assessment.

(v) Spatially distributing the base-line frequency to different parts of the slope/hillside would often require application of susceptibility analysis. There are different forms of susceptibility analysis. Where possible, it is good practice to perform the susceptibility analysis using site-specific data, instead of adopting general susceptibility classification or correlations that may be of limited direct relevance to the site. Use of a Bayesian methodology to give a balanced consideration of the theoretical susceptibility correlation and historical slope performance is preferable.

(vi) It is common practice to distribute spatially the base-line landslide frequency before applying the volume-frequency relationship. This simplifies the frequency assessment, but the rationale is questionable. There are technical merits in applying the volume-frequency split first, followed by spatial distribution of landslides of different volumes. However, this would require separate susceptibility analyses be carried out for landslides of different volumes, which may not be practical for sites with few data available for analysis.

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(vii) Frequency assessment for low-frequency large magnitude events is more difficult. Use of expert judgment based on findings from geotechnical assessment of the relevant relict events, geomorphology, rainfall-landslide correlation and worst credible failure volume, is a possible approach. Benchmarking with regional data and results of modeling may provide useful information.

(c) Consequence assessment

Models for consequence assessment are available and are used in landslide QRA. These models typically follow a standard framework, which includes consideration of the proximity of the element at risk, the average number of people at risk, their temporal distribution and vulnerability factors. Experience in formulating and applying consequence models suggests the need to give heed to the following to ensure a sound consequence assessment:

(i) The consequences of landslides with different mechanisms and scales would affect the elements at risk to differing degrees. They should be analyzed separately in consequence assessment. The methodology adopted in consequence assessment should duly cater for the effects of landslide mechanism and scale, and particularly on the average number of people at risk and the vulnerability factors adopted in the assessment.

(ii) It is a good practice in landslide QRA to sub-divide the potential landslide sources into small units. Previously, the sub-division was primarily aimed at improving the frequency assessment by separating the slope or hillside into cells according to their degree of landslide susceptibility. More recently, the sub-division has been made to permit also a more rational consequence assessment, particularly in respect of the debris runout path and influence zone. This may necessitate the use of irregular cells, instead of grid cells with a standard size. It would also require that the consequence model be set up as early as the frequency assessment stage, to ensure that the sub-division would produce cells that meet the requirements of both the frequency and consequence assessments.

(iii) Consideration of debris mobility is a key component of consequence assessment. However, attention should

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be given not only to assessing the runout distance, but also the potential runout paths. The latter was often not very well addressed in many landslide QRAs, and this could lead to gross mistakes. Predicting the potential debris runout paths requires reliable topographic information (e.g. a high resolution DEM), which may be difficult to obtain. For instance, presence of thick vegetation may hinder detailed topographic survey and terrain mapping. The available topographic maps may not be entirely reliable and sufficiently accurate. Remote-sensing technology, in particular multi-return air-borne Light Detection and Ranging (LIDAR), has been promising in producing high resolution DEM that can 'see through' vegetation (e.g. National Research Council, 2004).

(iv) In addition, it should be noted that landslide debris would not always travel downslope along the steepest path. Other factors, such as the orientation of the sliding surface at the landslide source, momentum of fast-moving debris, presence of drainage channels and building platforms, etc, would affect the debris runout path. The example of a bifurcated debris flow in Figure 5.43 illustrates the uncertainties in predicting the debris runout path. The uncertainties should be duly considered in consequence assessment. Event-tree analysis has been adopted, together with a cell-facility matching procedure, as a tool in consequence assessment to cater for such uncertainties.

(v) The assessment of the width of a landslide and its effects on the average number of people at risk, vulnerability factors, etc. is fairly rudimentary in many of the existing approaches of consequence assessment. Further work is required to improve the assessment and its integration with the consequence model.

(vi) Less experience is available in quantification of the consequence of building collapse and socio-economic loss. This is an area where input from specialists in the relevant field would be useful.

(d) Risk Calculation and evaluation

Risk calculation in QRA is relatively straightforward. Integration of QRA with GIS techniques, which significantly enhances the capability and efficiency of analysis of spatial data in QRA, is notable.

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Sensitivity analysis has been carried out in many QRA to examine the effects of the assumptions made and uncertainties involved on the calculated risk results. This is good practice. There is scope for further improving the practice in that many of the sensitive analyses that have been carried out only cover selected aspects of the QRA, and not a complete assessment of the likely order of accuracy of the calculated risk figures.

Furthermore, no provisions are available in the risk assessment framework and risk criteria for formally assessing and addressing uncertainties in QRA. The current practice of not using the calculated risk figures and risk criteria in absolute terms is a preferred approach (IUGS, 1997). QRA is only one input to the risk management process. Apart from the uncertainties in the risk quantification, other socio-economic and political factors can play a key role in making risk decisions.

The practicality and credibility of the use of risk criteria are to be tested with time. There is no established practice in evaluating economic loss, which requires further attention to ensure that the full range of risk is adequately addressed by QRA.

6. GLOBAL QUANTITATIVE RISK ASSESSMENT

6.1 Overview of Global Quantitative Risk Assessment

The advantages of QRA are evident when it is used to guide risk management decisions at individual sites. However, QRA is not confined to site-specific applications. Just as qualitative landslide risk assessment can be carried out on a large number of slopes (Section 3 above), QRA may also be applied to a large group of slopes for quantifying and evaluating the overall risk. This is referred to as global QRA (Wong et al, 1997; Wong & Ho, 2000; Ho et al, 2000). It typically serves to examine the overall scale of a problem and to identify the relative contributions from different components.

Global QRA has been used fairly extensively in Hong Kong, and has proven to be crucial in landslide risk management, particularly in formulating risk management strategy. However, it has not been as popular elsewhere, where landslide-related issues are conventionally addressed by qualitative means.

Global QRA differs from site-specific QRA in a number of aspects:

(a) Unlike site-specific QRA, global QRA is not aimed at quantifying the risk on individual site basis, nor evaluating site-specific risk management actions. Global QRA quantifies risk for the purposes of formulating risk management strategy and identifying risk-based actions that

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affect a large number of sites. Site-specific QRA is of interest to designers and slope owners. Global QRA, if carried out properly, would provide quantified risk results that are of interest to policy makers and organizations tasked with an overall landslide risk management mission. However, site-specific QRA and global QRA are not entirely independent of one another. They often provide a benchmark for calibrating each other's results.

(b) As a large number of slopes are assessed in a global QRA, carrying out detailed investigations and geotechnical appraisals at each slope in the QRA is normally not practical. This limits the types and quality of data that may be consulted in global QRA. Simplified frequency and consequence models, which do not require the use of sophisticated site-specific data, are adopted in global QRA.

(c) Use of simplified models and less detailed data would not necessarily degrade the reliability and useful functions of global QRA. As global QRA is intended for quantifying and evaluating overall risk, the QRA results are less sensitive to the models, data and assumptions adopted, as compared with site-specific QRA. However, as in all QRA, regardless of whether site-specific or global, it is essential that realistic models be developed, relevant data be used, rigorous analysis be carried out and the findings be applied to the scope for which the QRA is intended.

A range of applications of global QRA are described below to illustrate how it has contributed to strategic landslide risk management.

6.2 Evaluation of Adequacy of Slope Design Standard

The assessment of the risk of earthquake-induced landslides on engineered man-made slopes in Hong Kong described in Wong & Ho (1998b) was an early example of the application of global QRA. The vast majority of landslides in cut and fill slopes in Hong Kong are triggered by heavy rainfall. In the prevailing geotechnical practice in Hong Kong, no explicit provision is made for earthquake loading in routine slope design. This global QRA was adopted to evaluate the adequacy of conventional slope design in covering the risk of seismic-induced landslides.

(a) Hazard identification

The QRA incorporated the use of a model that captured the likely slope performance under earthquake loading. The seismicity of Hong Kong was assessed based on the available macro-seismic and instrumental earthquake data, identification of potential source zones and empirical strong

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motion attenuation relationships. From seismic hazard analysis, the return periods for different peak ground accelerations (PGA) in bedrock were calculated. Based on the results of dynamic response analysis, it was found that dynamic magnification of about 60% could be associated with local slope failures. Given that man-made slopes within developed areas in Hong Kong were not underlain by soft soils, significant amplification of ground motions due to possible site-response effects of the foundation material was not considered credible.

The quantified risk assessment included a model that evaluated slope stability with the use of a pseudo-static framework. The responses of slopes when subjected to an earthquake were examined using the critical acceleration concept (i.e. determining the net acceleration under which the soil mass would be brought to a state of limit equilibrium according to a pseudo-static analysis). The relationships between critical acceleration and the static Factor of Safety (F_s) were derived analytically from a range of typical soil cut and fill slopes in Hong Kong. When the acceleration imposed on the soil mass exceeds its critical acceleration, displacement will result because the net disturbing force will be larger than the net resisting force. Published correlations were used to estimate the likely orders of seismic-induced slope displacements for different levels of acceleration in excess of the critical values.

Except in the case of prolonged rain, the degree of saturation of the majority of slopes in Hong Kong is fairly low. The available unsaturated shear strength will provide an additional margin of safety compared with that computed in current slope design practice in Hong Kong with the using of fully saturated strength. The likelihood of slopes having different degrees of saturation at the time of an earthquake, which would occur randomly in time and would last only for a very short period, was examined based on the wetting band approach and consideration of real-time rainfall data. In the assessment, the likely threshold rainfall required to bring a typical slope to a significant degree of soil saturation was predicted and the frequency of occurrence of rainfall exceeding the predicted threshold values was determined. The findings suggest that the likelihood of low, moderate and high degrees of soil saturation prevailing at the time of an earthquake in Hong Kong may be taken as 95%, 4.5% and 0.5% respectively. An assessment was also made of the additional margin of stability in typical unsaturated slopes in Hong Kong, assuming soil suctions as measured in the field. The

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results suggested that the typical additional margin of stability due to suction might be taken to correspond to an increase in factor of safety (FOS) of at least 0.3 and 0.15, for low and moderate degrees of saturation respectively.

Differing earthquake motions will affect slopes to differing degrees and the corresponding consequences of slope failure will also vary. The range of earthquake-induced landslide hazards considered in the QRA are classified into four failure modes (Figure 6.1), as follows:

(i) overall slope failure (denoted as OF);

(ii) overall slope deformation with localized slope failure (denoted as OD);

(iii) localized slope failure (denoted as LF); and

(iv) localized slope deformation (denoted as LD).

The criteria for triggering a failure can be expressed in terms of the ratio of PGA to the critical acceleration for each of the failure modes. The failure triggers were derived by reference to the dynamic response characteristics of the slope and the likely range of earthquake-induced slope displacements.

(b) Frequency assessment

The critical acceleration values will depend on the slope type and the prevailing F_s. Typical soil cut slopes and compacted fill slopes, with design FOS values of 1.4, 1.2 and 1.1 respectively which comply with current required safety standards for different facilities, were examined.

Based on the failure trigger criteria together with the PGA-return period relationship, the annual frequencies of occurrence of the respective PGA values triggering failure may be calculated (Table 6.1). Simplified fault trees were used to account for the occurrence of the different modes of earthquake-induced failure for slopes with different degrees of saturation.

(c) Consequence assessment

In analyzing the consequence of failures, reference was made to the available historical landslide data, the generalized landslide consequence model, and the results of the global QRA for failure of old man-made slopes in Hong

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Kong as described in Wong et al (1997).

(d) Risk calculation and evaluation

The output of the frequency and consequence analyses for the different hazards was combined to give the risk components, which were then summed to obtain the overall risk associated with the different modes of failure for a given man-made slope designed to a certain FOS value.

To put the assessed risk of seismic-induced landslides in context, the calculated risk levels were compared with the risk of rain-induced landslides of old substandard man-made slopes (Table 6.2). The results suggest that the risk of earthquake-induced landslides for engineered slopes is only a small proportion of the risk posed by rain-induced failures of old slopes (i.e. not engineered to current safety standards). The risk of earthquake-induced landslides at slopes that comply with current design standards would be one to three orders of magnitude lower than the risk posed by rain-induced landslides at old slopes. Hence, the current design standards for slopes were considered to be generally adequate in maintaining the overall risk of earthquake-induced failures on new, or engineered, slopes at a relatively low level. Efforts should continue to be directed to upgrading old man-made slopes that are susceptible to failures triggered by rainfall.

This global QRA extended the risk assessment beyond the conventional seismic hazard and slope stability analyses, and provided insights into overall slope design strategy in Hong Kong. It lent support to the current approach taken in directing efforts towards studying and upgrading old man-made slopes, rather than undertaking further stability assessment and seismic retrofitting of slopes that comply with the current required safety standards in Hong Kong. Such insights cannot be readily obtained from qualitative risk assessment or from site-specific QRA of individual slopes.

6.3 Assessment and Application of Quantified Overall Landslide Risk

6.3.1 Background

As noted in Section 3.4.1 above, the mid 1990s was a time of major development of landslide risk management in Hong Kong. After many years of investment in retrofitting sub-standard slopes, there was a need to consolidate the practice and review progress. The compilation of a new and comprehensive Catalogue of Slopes, with the number of identified old, unengineered man-made slopes increasing from about 12,000 to over 35,000 (subsequently known to be 39,000, Figure 6.2), showed that potential landslide problems could be of a much

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larger scale than previously envisaged. Also, an increasing slope safety expectation among the public was evident from the strong public reaction to the fatal landslides that occurred in the early 1990s. Improved awareness and capability in risk assessment also brought about an impetus to use formal risk assessment in landslide risk management. In this context, and as a pioneer application at the time, QRA was formally adopted in a global framework to quantify the overall risk of the old, un-engineered man-made slopes in Hong Kong and to guide the formulation of a strategy for their risk management. The work and findings were described in Wong et al (1997) and Wong & Ho (1998a).

Where comprehensive landslide fatality figures are available, these may be analyzed to give an indication of the level of landslide risk as experienced in the past. Shown in Figure 6.3 is a plot of the historical landslide fatalities reported in Hong Kong, as well as the cumulative landslide fatalities. The total known death toll since the late 1940s was more than 470. However, historical fatality figures can rarely be a reliable representation of the inherent level of risk level. A number of factors contribute to this:

(a) The historical data may not be entirely reliable and complete.

(b) The reported data are frozen in the historical setting, but population growth and change in the state of development, particularly in a rapidly developing urban environment, would result in risk increase with time.

(c) The landslide triggering factors, e.g. rainfall, experienced over a relatively short period of observation, may not be representative of the long-term conditions.

(d) ‘Near-miss’ events, in which potentially more severe consequences have been narrowly escaped, are not reflected in the historical data.

(e) Historical fatality figures are sensitive to occurrence, or lack of occurrence, of extreme events, e.g. large-magnitude-low-frequency events.

These constraints were known to have affected the available historical fatality figures in Hong Kong. Hence, a key objective of the global QRA was to quantify the theoretical risk of all the landslide-prone, unengineered man-made slopes.

6.3.2 Methodology

The hazard model (Figure 6.4) adopted reflected the different types of hazard assessed in the QRA, with the following combinations:

(a) Types of features - cut slope, fill slope and retaining wall (Figure 6.5);

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(b) Mechanism of failure - failure may take place via different mechanisms, each posing a different degree of risk. In fill slopes, for instance, the landslide records showed that the dominant mechanisms of sliding, 'wash-out' and liquefaction had a relative base-line likelihood in the ratio of 45%:10%:10%; and

(c) Size of failure - hazard was also classified according to size, taking into account the height of the slope. In addition, knock-on effects, such as scenarios involving escalation of failure consequences (e.g. a small sliding failure developing into a major 'wash-out') were also considered.

Thus, a multitude of landslide hazards were considered. The frequency of occurrence of each type of hazard was calculated from a detailed analysis of the historical landslide data collected systematically in Hong Kong since 1985. The analysis included matching the landslides with the slopes, categorizing the slopes according to slope type, size and characteristics, evaluating the base-line frequency for each category and spatially distributing the frequency to each slope via a frequency model. The large body of information on over 5,000 landslides in Hong Kong was essential to the use of this approach.

A generalized consequence model was developed and this was described in Wong et al (1997). The consequence model included consideration of the categorization of the facility at risk (Table 3.5), the expected number of fatalities for each category of facility, size of failure, landslide mechanism, proximity of the facility, vulnerability factor and any aversion effects due to multiple fatalities. By this consequence model, the consequence in terms of PLL was evaluated for each type of hazard on each slope.

The relevant slope attributes and data on the facilities were obtained from the Catalogue of Slope. These provided the required input data for the global QRA framework (Figure 6.6). By integrating the hazard and consequence models, the total risk and the risk components were quantified. Summing the risks of all possible hazard of a slope gave the PLL of the slope. Summing the risk of all slopes of the same type gave the total PLL of this slope type. The overall risk of all old slopes was the sum of the risks of all types of slope.

6.3.3 Findings and Application

The global QRA assessed a total of 35,000 unengineered man-made slopes that were registered in the Catalogue of Slopes at the time. A summary of the calculated PLL for different classes of slope is shown in Table 6.3. The total PLL of the slopes (as at 1997) was estimated to be about eleven per year. By projection, it was also found that the risk of all unengineered (i.e. pre-1977) slopes should have been over 20 per year as at 1977. This estimated risk included the risk that previously existed in those pre-1977 slopes that had been upgraded since 1977, i.e. their risk before upgrading.

Apart from giving an estimate of the over risk level, the global QRA also provided invaluable information on the risk distribution and characteristics. Some examples of applying the information to formulating the risk management strategy for the LPM

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Programme are described below:

(a) Application of the calculated risk distribution to priority ranking

The global distribution of the quantified risk from cut slopes, fill slopes and retaining walls is in the ratio of 6:1:1 (Table 6.4). In terms of average risk per slope feature, the corresponding ratios were about 3:1:1. Experience from the LPM Programme suggested that the stabilization costs of a cut slope, fill slope and retaining wall were comparable. Hence, the ratio of risk per feature (3:1:1) reflected the relative proportions of different slope types to be retro-fitted under the LPM Programme, as an optimal risk-cost-benefit strategy for effective reduction of the landslide risks associated with different slope types. This has formed the basis for allocation of retro-fitting resources to different slope types under the LPM Programme since the mid 1990s. This was implemented by converting the risk ratio into equivalent risk weight factors for use in slope priority ranking under the New Priority Classification System (Section 3.4.6 above). It is notable that before the mid 1990s, priority attention has been given to retro-fitting fill slopes under the LPM Programme. This was in response to the high perceived risk of fill slopes as experienced in the disastrous fill slope failures in the 1970s. By the mid 1990s, many large, substandard fill slopes affecting major developments were fixed. The global QRA resulted in a major and timely change in the strategy of allocation of resources (i.e. more cut slopes were to be upgraded) based on an objective assessment of the prevailing risk distribution.

(b) Application of the calculated risk profile to formulating quantified risk reduction targets

The risk profile in Figure 6.7 shows the overall risk distribution among slopes in different groups, based on the categorization of the facilities at risk. About half of the overall risk came from approximately 10% of the slope population that had the highest potential risk. This indicated that upgrading of a relatively small proportion of the old slopes that posed the highest potential risk would result in a major global risk reduction. It also demonstrated the importance of using an appropriate risk-based ranking system for prioritizing landslide preventive actions, to ensure that the risk reduction effort was expended in a cost-effective manner. This risk reduction ratio (i.e. reduction of 50% risk by retro-fitting the worst 10% slopes) reflected the likely order of the beneficial

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return of the retro-fitting programme, which could be achieved by implementing a risk-based slope rating system. This has been formally adopted as quantified risk reduction targets pledged by the HKSAR Government. The LPM Programme was tasked to upgrade about 10% of the pre-1977 slopes by year 2000, and another 10% by 2010. The pledged risk reduction targets entailed: (a) by the year 2000, the overall landslide risk from the pre-1977 man-made slopes would be reduced to 50% of the level in 1977; and (b) by 2010, the risk would be further reduced to 25% of the level in 1977 (Works Bureau, 1998). The targets are now a key yardstick by which the performance of the LPM Programme is being measured.

(c) Application to cost-benefit evaluation and risk communication

Using the global QRA methodology, the overall theoretical annual fatalities can be predicted with some confidence to determine longer-term trends and project future performance, as well as to quantify the effectiveness of the risk mitigating actions over time. Cost-benefit calculations were performed to evaluate the investment made relative to the projected number of lives saved as a result of the efforts of the LPM Programme. It was found that for the 10-year period from 2000 to 2010, the LPM Programme would be operating at about HK$ 15 million per statistical life saved. This figure was within the limit of maximum justifiable expenditure as derived from the ALARP principle using the risk guidelines (ERM, 1998). There has been strong and unanimous public option that the GEO should implement the 2000 to 2010 LPM Programme. Hence, the findings of the global QRA provided a means of quantifying and benchmarking the expectation of the public in terms of landslide risk tolerability and ALARP deliberation.

6.4 Evaluation of Performance of Risk Mitigation Programme

6.4.1 Performance from 1977 to 2000

The global QRA described in Section 6.3 above was updated in year 2000. The update was aimed at assessing whether the pledged 50% landslide risk reduction target from 1977 to 2000 was achieved by the LPM Programme. The methodology adopted in the update followed that of Wong & Ho (1998a), and the findings were presented in Cheung & Shiu (2000).

In this update, the overall landslide risk of all registered pre-1977 slopes in 2000 was quantified. This included the risk of the remaining pre-1977 slopes that had not yet been upgraded by 2000 and the residual risk of the pre-1977 slopes that had been upgraded by 2000.

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The total PLL in 2000 of all pre-1977 slopes was found to be 10.3 per year. The PLL of all the pre-1977 man-made slopes as at 1977 was back-analyzed, and was assessed to be 21.8 per year. These indicated that the risk reduction from 1977 to 2000 as a result of the LPM Programme was 53% (Table 6.5), which met the pledged risk reduction target.

6.4.2 Performance from 2000 to 2004

The 10-year LPM Programme from 2000 to 2010 is currently in progress. A global QRA was completed in 2004 by the GEO as an interim review of the progress made in the overall landslide risk reduction.

The methodology adopted in the previous global QRA was adopted, with enhancement made in expressing the landslide frequency in terms of the number of landslides per year per unit slope area (m^2) instead of the number of landslides per year per slope. This refinement improved the reliability of applying the frequency model to slopes of different sizes. In addition, systematic landslide investigations carried out by the GEO on failures of engineered slopes provided improved data for estimating the landslide frequencies of different types of engineered slopes (Wong & Ho, 2000). This improved the assessment of the residual risk of engineered slopes, i.e. slopes formed or upgraded to the required geotechnical standards after 1977. Table 6.6 shows the established base-line landslide frequency of different classes of slope. In the QRA, the base-line frequencies were spatially distributed to individual slopes with account taken of the slope type, size, landslide mechanism, and method of slope design and stabilization adopted.

It was planned that a total of 2,500 Government-own man-made slope features would be upgraded under the LPM Programme from 2000 to 2010. Detailed studies would also be carried out on another 3,000 privately-owned slopes. It was projected that about 75% of these private slopes would be found to be sub-standard and would be upgraded following the issue of statutory orders to the private owners. Enhanced slope maintenance works would be arranged on another 2,000 Government slopes that were of relatively lower risk ranking, but which might affect facilities with more severe consequences. The enhanced maintenance works comprised typically the use of prescriptive soil nails, surface protection and drainage improvement measures (Wong et al, 1999). The risk reduction that would be achieved with the use of these measures was assessed, based on the findings of Wong & Ho (1995).

The findings of the QRA are presented in Lo & Cheung (2004). It was found that by 2010, the risk of all the pre-1977 registered man-made slopes, based on a projection from the progress made in the current LPM Programme, would be reduced to about 25% of the risk in 2000 (Figure 6.8). This indicated that the pledged risk reduction for the 2000 to 2010 LPM Programme was achievable, and that the LPM Programme was making satisfactory progress towards achieving this target. The projected distribution of risk among different types of pre-1977 slopes by 2010 is shown in Figure 6.9.

The overall risk level of all of the 57,000 registered man-made slopes in 2010, including pre- and post-1977 slopes, was also assessed in this global QRA. The risk was found to be about 5 PLL per year. The numbers and risks of different classes of slope are shown in Figure 6.10.

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6.5 Development of Risk Management Strategy

6.5.1 Global Risk from Natural Terrain Landslides

Hong Kong has about 650 km^2 area of natural hillsides that have not been significantly modified by man-made activities (Figure 6.11). The natural hillsides were not registered in the Catalogue of Slopes, but they posed a landslide risk too the community. Previously, the landslide risk in Hong Kong was predominantly associated with the large stock of unengineered man-made slopes that existed within the developed areas. The landslide risk reduction programme therefore focused on retro-fitting these unengineered slopes. However, following many years of landslide risk reduction efforts, it is evident from the risk distribution assessed by the global QRA that the risk of the remaining unengineered man-made slopes in Hong Kong will be reduce to a lower level in 2010. This highlights the need to assess the risk of other types of landslide hazards, in particular natural terrain landslides, for formulating the post-2010 risk management strategy.

Wong et al (2004b) completed a global QRA of the overall risk of natural terrain landslides in Hong Kong. It was necessary for this global QRA to resolve some technical problems, which were not previously faced in the global QRA on man-made slopes. These included:

(a) A complete inventory of natural hillsides affecting developed areas was not available. Therefore, a global risk assessment methodology was developed in this QRA for projecting the risk quantified from an inventory of selected natural hillsides to the overall risk in Hong Kong (Figure 6.12)

(b) The lack of data on extreme events was known to be a particularly significant problem, given the nature of natural terrain landslides. This constraint was dealt with in the QRA by incorporating rainfall-landslide correlations into the QRA model.

(c) Assessment of natural terrain landslides involved more elaborated consideration of the catchment characteristics and debris runout mechanisms. The generalized consequence model previously developed in Wong et al (1997) for man-made slope failure was not suitable for QRA on natural terrain landslides. An improved consequence model was therefore developed, specifically for typical natural terrain landslides in Hong Kong’s setting, for use in the global QRA.

(d) The risk assessment required the use of a large amount of spatial data, which were difficult to manage and analyze using conventional methods. In this global QRA, all data were compiled in GIS format and the analysis was performed on a GIS platform using object-oriented GIS modules specifically developed for the task.

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The key components of the global QRA are described below to illustrate the work involved in a task of this kind:

(a) Review of natural terrain landslides and data compilation and analysis

A review was carried out on the notable incidents where natural terrain landslides were reported to have occurred close to developed area, as a qualitative appraisal of the nature of natural terrain landslides, hazard characteristics and possible risk scenarios. An inventory of over 30,000 natural terrain landslides (Figure 6.13) from interpretation of historical aerial photographs was compiled (King, 1999). Rainfall-natural terrain landslide correlation was established by Ko (2003) and Wong et al (2004c) from spatial analysis of the 5-minute rainfall data available since 1985 (Figure 6.14). Susceptibility analysis was carried out (Evans & King, 1998) to establish the base-line landslide density for terrains with different characteristics (Figure 6.15).

(b) Identification of vulnerable catchments

While many of the natural hillsides adjoin developed areas, not all of them would pose a significant risk. As part of the global QRA, a search of vulnerable catchments was carried out. This included identification of the following two types of catchments:

(i) Historical landslide catchments - these refer to catchments with known historical natural terrain landslides occurring close to existing important facilities, including buildings, major roads and mass transportation facilities. The identification was made by GIS analysis using some established spatial criteria applied to the Natural Terrain Landslide Inventory and the geographic locations of important facilities, together with validation by detailed aerial photograph interpretation and field inspections. A total of 453 historical landslide catchments were identified. The relevant data on the catchments and affected facilities were collated and compiled into a GIS inventory (Figure 6.16). These 453 catchments had a total area of about 5 km^2, i.e. within about 1% of the natural terrain in Hong Kong.

(ii) Supplementary catchments - these refer to catchments without any known historical natural terrain landslides occurring close to existing important facilities. These included catchments affecting existing facilities but

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without known historical landslides, as well as catchments with known historical natural terrain landslides occurring far away from any important facilities. It was estimated that more than 10,000 of such catchments are present in Hong Kong, bordering the development boundaries. It was not practical to record and evaluate all these catchments in the global QRA. Hence, only samples of supplementary catchments were recorded and analyzed in the QRA. To ensure that the samples were sufficiently representative of the typical setting in Hong Kong, a total of 1,018 supplementary catchments (about 23 km^2) in five selected regions were compiled. In addition, 43 catchments (about 1.5 km^2) in six selected areas, where site-specific natural terrain landslide QRA had been carried out, were also registered for benchmarking purposes. The supplementary catchments were also recorded in a GIS inventory (Figure 6.16)

(c) Hazard identification

A total of twelve types of hazard were analyzed in the QRA, based on a combination of the scale of failure and mechanism of debris movement (Table 6.7). Four rainfall scenarios, with normalized maximum rolling 24-hour rainfall up to 35%, were explicitly considered in the analysis (Table 6.8). In view of the significant uncertainties involved and the lack of reference data, the risk arising from extreme rainfall events with normalized rainfall exceeding 35% was assessed separately by extrapolation of the QRA results.

(d) Frequency assessment

The frequencies of occurrence of different types of hazard were assessed with the use of a frequency model. The model included consideration of the probabilities of occurrence of different rainfall scenarios, the base-line landslide density at each rainfall scenario, catchment characteristics, susceptibility of the hillside, and spatial distribution of the overall volume-frequency relationship (Figure 6.17) to individual catchments based on the catchment characteristics. Allowance was made in the model for recognition factors and Bayesian updating with respect to the actual performance of the catchments.

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(e) Consequence assessment

A new generalized consequence model was developed specifically for use in this global QRA (Wong et al, 2004b). The consequence of natural terrain landslides, in terms of PLL, was quantified by the model (Figure 6.18). The formulation of the vulnerability factors followed the framework adopted in Wong et al (1997), with enhancement made in the empirical definition of proximity zones as a combination of travel angle and travel distance calibrated with historical debris runout data (Figure 6.19). Account was taken of the nature of usage in the ground floor of a building in assessing the population at risk. A ‘location factor’ was introduced to cater for the location of the facility at risk with respect to the debris path. Consequence due to building collapse was explicitly analyzed by the model.

(f) Risk calculation

Integration of the frequency and consequence models gave the landslide risk of each catchment and for each of the affected facilities. The calculation involved a large volume of work on spatial analysis, and was performed by GIS (Figure 6.20). To ensure performance, the global QRA was calibrated with results from sites where detailed site-specific QRA were carried out. An example of the calibration is shown in Figure 6.21.

The overall risk of natural terrain landslides in Hong Kong, based on the state of development at 2004, was assessed to be about 5 PLL per year. As shown by the breakdown of risk (Table 6.9), the total PLL of the 453 historical landslide catchments was 1.8 per year. This included a contribution of 0.4 PLL per year (i.e. 22%) from the extreme rainfall scenario based on extrapolation. The risk results showed that the 453 historical landslide catchments constituted about one-third of the overall risk, i.e. the other two-thirds of the overall risk would come from supplementary catchments. The risk of the supplementary catchments was projected from analysis of the samples of supplementary catchments in the global QRA using the risk model (Figure 6.12). This two-thirds of the overall risk was dispersed among a large number of supplementary catchments. Neither the exact locations of these supplementary catchments nor the risk distribution among them were known.

A series of sensitivity analyses were carried out to examine the reliability of the quantified risk results and their sensitivity to the assumptions made in the frequency,

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consequence and risk models. It was established that the overall risk might range from about 1 to 10 PLL per year, with 5 PLL per year as the best estimate. The range reflected the uncertainties in the assessment.

6.5.2 Risk Management Strategy

Global QRA is not intended for evaluation of risk tolerability and mitigation requirements at individual sites. Instead, the risk evaluation in global QRA is aimed at diagnosing the risk distribution, hazard characteristics and risk management strategy.

The global QRA on natural terrain landslides revealed the nature and distribution of natural terrain landslide hazards in Hong Kong. The risk distribution according to the scale of landslide showed that H2 (200 m^3 to 2,000 m^3, see Table 6.7) constituted about 75% of the overall risk (Table 6.10). This is consistent with the fact that the risk mitigation works undertaken by the GEO in recent years based on the ‘react-to-known-hazard’ principle has primarily been dealing with natural terrain landslide hazards at such a scale. Hazard H3 (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.

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 historical landslide catchments, their proximity to the catchments concerned and the risk distribution are shown in Table 6.11. Building structures within Zones 1 to 4 (as defined in Figure 6.19) had high calculated risk to life, with an average risk per building exceeding 10^{-3} PLL per year. Building structures within these zones were vulnerable to natural terrain landslide hazards. The calculated risk for building structures in Zone 5 and beyond reduced rapidly.

The distribution of the calculated risk for the historical landslide catchments is shown in Figure 6.22. Also shown in the Figure are the PLLs assessed from some recently completed site-specific QRA on sites that met the ‘react-to-known-hazard’ principle. The results proved that the historical landslide catchments were of comparable risk-to-life level as those of the ‘react-to-known-hazard’ cases. In particular, about 75% of the historical landslide catchments were within the range of risk for the ‘react-to-known-hazard’ cases that were found to require substantial landslide risk mitigation from risk tolerability and ALARP considerations. The remaining 25% of the historical landslide catchments would probably fall within the ALARP region, and the extent of any necessary risk mitigation might be affected by other factors. These included aversion effects due to multiple fatalities, social-economic factors and political considerations, as is illustrated by the North Lantau Expressway case (Section 5.7).

The quantified natural terrain landslide risk has been compared with the risk of other types of landslides quantified from the global QRA on man-made slopes. The estimated profile of different types of landslide risk in year 2010 is shown in Table 6.12. The overall risk of natural terrain landslides and man-made slope failures in Hong Kong would be at comparable levels by 2010. By that time, the historical landslide catchments would be a

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distinct batch with the highest average risk-to-life per feature, as well as the highest risk-cost ratio per feature. This batch would deserve priority for allocation of resources for risk mitigation. This would be followed by un-engineered man-made slopes affecting Groups No. 2(b) and 3 facilities (see Table 3.5) and engineered slopes treated by old technology. Un-engineered man-made slopes affecting Groups No. 4 and 5 facilities have a much lower risk per feature because of the negligible failure consequences. Although these slopes are susceptible to landslides, they should be given the lowest priority for retro-fitting based on risk-to-life consideration. The global QRA findings provided a rational and consistent basis for formulating risk management strategy for Hong Kong after 2010.

7. CONCLUSIONS

Landslide risk assessment that is undertaken at a large scale, in which the facilities at risk are individually recognized and assessed, is described in this report. Selected cases of applications are presented to illustrate the approaches adopted and the developing trends in risk assessment practice.

Assessment at this scale may be regarded as the most detailed form of landslide risk assessment. The professional practice has clearly evolved to the stage that landslide and slope engineering is more than simply an investigation of slope stability. The consequence of landslides has to be examined, and landslide risk has to be assessed and evaluated in totality. In essence, what matters is not just the landslide itself, but also its outcome. This risk-based perspective is fundamental to addressing and managing landslide problems, and it aligns the geotechnical profession with many other fields that explicitly practice risk management.

There is a broad spectrum of landslide risk assessments, in terms of the objectives, methodologies and levels of detail of the assessment. In particular, there is a choice between using a qualitative or quantitative approach. There are also significant differences between applying the assessment to a few individual sites and to a large number of sites. The trend of increasing use of a quantitative approach is evident, and will continue. The available cases of QRA applications have demonstrated the advantages of QRA. They have also helped to refute misunderstandings and misconceptions about QRA. However, this should not detract from the importance also of qualitative assessments. The level of complexity of the analysis should be compatible with the nature of the problem to be solved, as well as with the resources available for solving the problem. Qualitative risk assessment will continue to be the most appropriate solution for some types of problem (e.g. slope risk rating), and it can also be complementary to, or be used in combination with, a detailed QRA.

With the increasing awareness that landslide risk has to be managed, slope owners, regulators and the public as a whole have become more ready to consider the balance between risk and cost, and less tolerant of any perceived risk that can be reduced without excessive cost. This brings a diverse range of landslide problems to the agenda of risk assessment. The challenge is for the geotechnical profession to master the diverse range of landslide risk assessment techniques and to choose the right tools for the right problems.

Finally, while use of QRA is fashionable, the profession must not lose sight of the fact that quantification does not necessarily improve accuracy and reliability. When risk is

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expressed in subjective and relative terms, it is by nature qualitative and intended to be indefinite. When risk is quantified, it can be expressed and communicated as exact figures, even though they may be far from accurate. The quantitative framework can provide quantified figures, but it cannot guarantee that the QRA will give reliable results. The accuracy and reliability of QRA come only with the rigor of the assessment and with the use of data, techniques and procedures that are appropriate to the specific problem being analyzed. In many practical cases, the resources available for QRA are less than satisfactory, so rendering the results unreliable, and potentially misleading, and likely to do more harm than good. In such circumstances, it is imperative that the assessor should maintain good professional discipline in clearly communicating the limitations of the assessment and not overselling the QRA results.

This is not at all an impediment to use of QRA. Instead, it forms part of the momentum for the geotechnical profession to further improve the skills and practice in quantified risk assessment, and to become more effective in risk communication with stakeholders.

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Table 2.1 - Different Types of Landslide Risk Assessment for Individual Facilities

Extent of Application	Approach	
	Qualitative[1]	Quantitative[2]
A large number of slopes	Qualitative risk rating	Global quantitative risk assessment (QRA)
Individual slopes	Site-specific qualitative risk assessment	Site-specific quantitative risk assessment (QRA)

Notes: (1) This includes semi-quantitative risk assessment.
(2) This refers to quantification and evaluation of risk using formal quantified risk assessment methodology.

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Table 3.1 - Comparison of Different Qualitative Slope Rating Systems

Case No. / Place (Section in Report)	Primary Application	Type of Slope for Rating		Rating Method
		Slope	Facility	
1 / Hong Kong (Section 3.2)	– Risk ranking – Prioritization for action	Un-engineered cut slopes and retaining walls	All types	– Scoring system, with hazard and consequence ratings – Expert formulation scheme
2 / Hong Kong (Section 3.3)	– Risk ranking – Prioritization for action	Un-engineered fill slopes	All types	– Scoring system, with consequence rating before hazard rating – Expert formulation scheme
3 to 6 / Hong Kong (Section 3.4)	– Risk ranking – Prioritization for action – QRA tool	Un-engineered cut slopes, fill slopes and retaining walls	All types	– Scoring system, with hazard and consequence ratings – Expert formulation scheme
7 & 8 / USA (Section 3.5)	– Preliminary screening – Risk ranking – Prioritization for action – Preliminary estimate	Rock cut slopes	Roads	– Scoring system, with emphasis in hazard rating – Mixed scheme
9 / Canada (Section 3.6)	– Risk ranking – Prioritization for action	Rock cut slopes	Railway	– Hazard rating system – Mixed scheme
10 / Australia (Section 3.7)	– Risk ranking – Prioritization for action	Man-made slopes but primarily rock cut slopes	Primarily Roads	– Risk matrix system, with hazard and consequence ratings – Expert judgment scheme
11 / Malaysia (Section 3.8)	– Risk ranking – Prioritization for action	All types including natural slopes	Primarily Roads	– Scoring system, with hazard and consequence ratings – Expert formulation scheme
12 / Australia (Section 3.9)	– Risk ranking – Land-use planning	Clay slopes	Different types of land-use	– Scoring system, with simple hazard and consequence ratings – Expert formulation scheme
13 / Japan (Section 3.9)	– Risk ranking – Prioritization for action	Rock slopes, deep-seated landslides and debris flows	Roads	– Scoring system, with emphasis in hazard rating – Expert formulation scheme
14 / New Zealand (Section 3.9)	– Risk ranking – Prioritization for action	Cut and fill slopes	Roads	– Scoring system; primarily hazard rating – Mixed scheme
15 / UK (Section 3.9)	– Risk ranking – Prioritization for action	Rock slopes	Roads	– Scoring system; primarily hazard rating – Mixed scheme

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Table 3.2 - Numeric Weightings and Scoring Formulae of Cut Slope Ranking System, Hong Kong (Koirala & Watkins, 1988) (Sheet 1 of 2)

Component	Score	Maximum Score	Component	Score	Maximum Score
e) Height, H (metre)	Soil slopes, H x 1 Rock slopes, H x 0.5 Mixed slopes, H x 1	Unlimited	o) Ponding potential at crest	Ponding area at crest = 5	5
f) Slope angle	Rock: 90° = 10; ≥ 80° = 8; ≥ 70° = 5; ≥ 60° = 2; < 60° = 0 Others: ≥ 60° = 20; ≥ 55° = 15; ≥ 50° = 10; ≥ 45° = 5; 35° = 3; < 35° = 0	20	p) Channels	None, incomplete = 10 Complete – major cracks = 10 Complete = 0	10
			q) Water carrying services	Services within "H" of crest - Yes = 5 - No = 0	5
g) Angle of slope above, or presence of roads above	Slope ≥ 45° =15 Slope ≥ 35°, or Major road =10 Slope ≥ 20°, or Minor road = 5 Slope < 20° = 0	15	r) Seepage	Amount Position / Heavy / Slight Mid-height & above / 15 / 5 Near toe / 10 / 2	15
i) Associated wall	Height of associated wall (metre) × 2	Unlimited	t) Distance to building, road or playground from toe of slope (metre)	Buildings = actual distance Roadways = distance + 2 metres Playground = greater of actual distance or ½H	Unlimited
j) Slope condition	Loose blocks =10 Signs of distress =10 Poor = 5 Good = 0	10	u) Distance to buildings, roads or playgrounds from toe of slope (metre)	As for (t)	

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Table 3.2 - Numeric Weightings and Scoring Formulae of Cut Slope Ranking System, Hong Kong (Koirala & Watkins, 1988) (Sheet 2 of 2)

Component	Score	Maximum Score	Component	Score	Maximum Score
k) Condition of associated wall	Poor =10 Fair = 5 Good = 0	10	v) Extensive slope at toe or slope	Extensive slope at top 0.5 Extensive slope below 20	25
l) Adverse jointing	Adverse joints noted = 5	5	w) Multiplier for type of property at risk at top	Hospitals, schools, residential 2 Factories, playgrounds 1.5 Major roads 1.0 Minor roads 0.5 Open space 0	2
m) Geology	Colluvium/shattered rock, thin soil mantle =15 Thick Volcanic soil =10 Thick Granitic soil = 5 Sound rock (massive) = 0	15	x) Multiplier for type of property at risk at top	As above	2
n) Water access - impermeable surface on and above slope	None =15 50% (partial) = 8 Complete - poor = 5 Complete - good = 0	15	y) Multiplier for risk factor	For densely populated area or where buildings may collapse 1.25 Otherwise 1.0	1.25

Instability Score $= \sum(e,f,g,l,j,k,l,m,n,o,p,q,r)$

Consequence Score $= y\left\{20w\left(\frac{1.5\,(e+i)-t}{1.5\,(e+i)}\right)+(40\ x)\left(\frac{(e+i)-u}{(e+i)}\right)+(vx)+2\,(e+i)\right\}$

Total Score = Instability Score + Consequence Score

Table 3.3 - Calculation of “x” Score for Fill Slope Ranking System, Hong Kong (Koirala & Watkins, 1988)

Main Component	Sub-component		Score
Surface quality and susceptibility to infiltration (S)	(i)	Vegetation or bare earth 100% Bare/50% Bare/None	20/10/0
	(ii)	Condition of paving or other seal Poor/Fair/Good	10/5/0
	(iii)	Surface drainage Blocked or Broken/Inadequate/Good	10/5/0
		Maximum for this component	40
Potential access to water (W)	(i)	Observed seepage	10
	(ii)	Watermain or sever in the fill	5
	(iii)	Fill blocking a natural water course	5
	(iv)	None of the above	0
		Maximum for this component	20
Slope angle (O)	80(tan ϕ' – 0.5)		
		Maximum for this component	20
Slope height (H)	1 point for every 4 m of height		
		Maximum for this component	10
		Total Maximum	90

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Table 3.4 - Key Groups of Factors and Range of Scores for Soil Cut Slope Priority Classification System, Hong Kong (based on Wong & Ho, 1995)

Type of Score	Key Groups of Factors	Range of Scores
Instability Score	Slope geometry	0 - 60
	Signs of distress	0 - 40
	Evidence of past instability	0 - 40
	Potential for water ingress	0 - 60
	Nature of slope forming material	0 - 40
	Engineering judgment	0 - 60
Consequence Score	Type and proximity of crest facility	0 - 450
	Type and proximity of toe facility	
	Upslope and downslope topography	
	Likely scale of failure	
	Consequence factor/vulnerability	

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Table 3.5 - Group of Facilities Adopted in NPCS (based on Wong & Ho, 1995)

Group	Facilities	Potential Loss of Life
1(a)	Buildings - any residential building, commercial office, store and shop, hotel, factory, school, power station, ambulance depot, market, hospital/polyclinic/clinic, welfare centre	3
1(b)	Others - Bus shelter, railway platform and -other sheltered public waiting area - cottage, licensed and squatter area - dangerous goods storage site (e.g. petrol station) - road with very heavy vehicular or pedestrian traffic density	3
2(a)	Buildings - built-up area (e.g. indoor car park, building within barracks, abattoir, incinerator, indoor games' sport hall, sewage treatment plant, refuse transfer station, church, temple, monastery, civic centre, manned substation)	2
2(b)	Others - road with heavy vehicular or pedestrian traffic density - major infrastructure facility (e.g. railway, tramway, flyover, subway, tunnel portal, service reservoir) - construction sites (if future use not certain)	1
3	- densely-used open space and public waiting area (e.g. densely used playground, open car park, densely-used sitting out area, horticulture garden) - quarry - road with moderate vehicular or pedestrian traffic density	0.25
4	- lightly-used open-aired recreation area (e.g. district open space, lightly-used playground, cemetery, columbarium) - non-dangerous goods storage site - road with low vehicular or pedestrian traffic density	0.03
5	- remote area (e.g. country park, undeveloped green belt, abandoned quarry) - road with very low vehicular or pedestrian traffic density	0.001

Notes: (1) To account for the different types of building structure with different detailing of windows and other perforations, etc, a multiple fatality factor ranging from 1 to 5 is considered appropriate for Group No. 1(a) facilities to account for the possibility that some incidents may result in a disproportionately larger number of fatalities than that envisaged.

(2) 'Potential loss of life' in this Table refers to the average number of fatalities in the event of a direct hit (i.e. 100% vulnerability) by a referenced landslide that is 10 m wide and 50 m^3 in volume, as derived from formal consequence assessment (Wong et al, 1997).

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Table 3.6 - Key Groups of Factors for Rock Cut Slope Priority Classification System, Hong Kong (based on Golder Associates, 1996)

Type of Score	Key Groups of Factors	Range of Scores
Instability Score	Slope geometry	10 - 80
	Mode of slope failure	0.5 - 5
	Evidence of distress or past instability	0 - 70
	Potential for water ingress	0 - 30
	Rock mass condition	0 - 110
	Engineering judgment	0 - 30
Consequence Score	Type and proximity of crest facility	0 - 450
	Type and proximity of toe facility	
	Upslope and downslope topography	
	Likely scale of failure	
	Consequence factor/vulnerability	

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Table 3.7 - Vulnerability of Toe Facilities for Different Mechanisms of Fill Slope Failure (Wong, 1996)

(a) Buildings

Slope Height, H (m)		Angle, α (degree)								
		>50	45 - 50	40 - 45	35 - 40	30 - 35	25 - 30	20 - 25	15 - 20	10 - 15
<5	V^1	0.0225	0.0225	0.0155	0.005	0.001	0.0001	0	0	0
	V^2	0.0225	0.0225	0.0225	0.0155	0.005	0.001	0.0001	0	0
	V^3	0.0010	0.008	0.004	0.002	0.0005	0.00008	0.000005	0	0
5 to 10	V^1	0.1125	0.1125	0.0775	0.025	0.005	0.0005	0	0	0
	V^2	0.1125	0.1125	0.1125	0.0775	0.025	0.005	0.0005	0	0
	V^3	0.05	0.04	0.02	0.01	0.0025	0.0004	0.000025	0	0
10 to 15	V^1	0.45	0.45	0.31	0.10	0.02	0.002	0	0	0
	V^2	0.45	0.45	0.45	0.31	0.10	0.02	0.002	0	0
	V^3	0.25	0.24	0.18	0.10	0.0425	0.0104	0.001525	0	0
15 to 20	V^1	0.95	0.92	0.70	0.35	0.11	0.02	0	0	0
	V^2	0.95	0.95	0.95	0.8	0.48	0.18	0.045	0.005	0
	V^3	0.60	0.60	0.56	0.45	0.29	0.135	0.0435	0.0076	0
≥20	V^1	0.95	0.95	0.86	0.59	0.26	0.075	0.013	0	0
	V^2	0.95	0.95	0.95	0.95	0.87	0.63	0.34	0.12	0.015
	V^3	0.80	0.80	.80	0.72	0.50	0.25	0.084	0.015	0.001

(b) Others

Slope Height, H (m)		Angle, α (degree)								
		>50	45 - 50	40 - 45	35 - 40	30 - 35	25 - 30	20 - 25	15 - 20	10 - 15
<5	V^1	0.03	0.03	0.026	0.016	0.006	0.00075	0	0	0
	V^2	0.03	0.03	0.03	0.026	0.016	0.006	0.00075	0	0
	V^3	0.040	0.036	0.025	0.013	0.004	0.001	0.0001	0	0
5 to 10	V^1	0.150	0.150	0.130	0.08	0.030	0.00375	0	0	0
	V^2	0.15	0.15	0.15	0.13	0.08	0.03	0.00375	0	0
	V^3	0.20	0.18	0.125	0.0625	0.02	0.005	0.0005	0	0
10 to 15	V^1	0.60	0.60	0.52	0.32	0.12	0.015	0	0	0
	V^2	0.6	0.60	0.6	0.52	0.32	0.12	0.015	0	0
	V^3	0.6	0.58	0.435	0.315	0.145	0.05	0.0105	0	0
15 to 20	V^1	0.95	0.92	0.92	0.70	0.49	0.08	0	0	0
	V^2	0.95	0.95	0.95	0.95	0.80	0.50	0.20	0.02	0
	V^3	0.875	0.875	0.835	0.725	0.530	0.285	0.1	0.0235	0
≥20	V^1	0.95	0.95	0.95	0.86	0.59	0.25	0.03	0	0
	V^2	0.95	0.95	0.95	0.95	0.95	0.8	0.50	0.20	0.02
	V^3	0.95	0.95	0.95	0.95	0.81	0.48	0.18	0.045	0.005

Note: See Figure 3.13(a) for definition of slope geometry H, α.

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Table 3.8 - Vulnerability of Crest Facilities for Different Mechanisms of Fill Slope Failure (Wong, 1996)

(a) Buildings				
Slope Height, H (m)		Distance from Crest, D (m)		
		6 to 10	3 to 6	< 3
<5	$V_1 = V_2$	0	0.0000125	0.0003
	V_3	0	0.00023	0.0023
5 to 10	$V_1 = V_2$	0	0.0000625	0.0015
	V_3	0	0.00115	0.0115
10 to 15	$V_1 = V_2$	0	0.00025	0.006
	V_3	0	0.00715	0.0375
15 to 20	$V_1 = V_2$	0.0002	0.003	0.02
	V_3	0.008	0.0285	0.101
≥20	$V_1 = V_2$	0.0005	0.001	0.05
	V_3	0.015	0.045	0.15
(b) Others				
Slope Height, H (m)		Distance from Crest, D (m)		
		6 to 10	3 to 6	< 3
<5	$V_1 = V_2$	0	0.00025	0.0075
	V_3	0	0.0022	0.011
5 to 10	$V_1 = V_2$	0	0.00125	0.0375
	V_3	0	0.011	0.055
10 to 15	$V_1 = V_2$	0	0.005	0.015
	V_3	0	0.043	0.18
15 to 20	$V_1 = V_2$	0.002	0.04	0.4
	V_3	0.004	0.092	0.2825
≥20	$V_1 = V_2$	0.002	0.074	0.54
	V_3	0.006	0.12	0.315
Note: See Figure 3.13(a) for definition of slope geometry H, D.				

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Table 3.9 - Scoring Scheme of Fill Slope Priority Classification System, Hong Kong (Wong, 1996)

Slope Data

Slope No. :	SIFT No. :	SIFT Class :
Slope Height, H = ______ m Slope Angle, θ = ______ °	Crest Wall Height, H_{wc} = ______ m Toe Wall Height, H_{wt} = ______ m	
SIFT Section Profile No.	Part of Larger Fill Body : Yes / No	

Instability Score (IS)

Sliding (IS_1 = a.b.c.d.e.f.g =)

(a) Geometry (From Figure C1)
S1 = 32
S2 = 16
S3 = 8
S4 = 4
S5 = 2
S6 = 1

(b) Type of Surface Cover
Bare = 4
Vegetated = 3
Chunam = 1.5
Shotcrete = 1

(c) Surface Drainage Provision
No = 2
Yes = 1

(d) Signs of Seepage
Yes = 2
No = 1

(e) Potential Leaking Services
Leaking = 2
Presence = 1.5
None = 1

(f) Past Instability
Major = 8
Minor = 2
No = 1

(g) Signs of Distress
Yes = 4
No = 1

Liquefaction (IS_2 = ¼.IS_1.h.i =)

(h) Slope Height
≥30 m = 4
≥20 - <30 = 3
≥10 - <20 = 1
<10 m = 0.5

(i) Type of Surface Cover
Bare = 1.1
Vegetated = 1.1
Chunam = 0.5
Shotcrete = 0.25

Major Washout (IS_3 = $(IS_1)^{1/3}$ .j.k.l.m.n.o.p.q =)

(j) Catchment Characteristics : Topographic Setting and Size of Catchment

Topographic Setting	Size of Catchment (m^2)				
	≤100	100 - 500	500 - 1000	1000 - 10000	>10000
Traverse Drainage Line	2	4	8	16	32
Adjacent Drainage Line	2	3	6	12	24
Traverse Topographic Depression	1	2	4	8	16
Adjacent Topographic Depression	1	2	3	6	12
Planar Slope	0.5	1	3	5	10
Spur	0.5	1	2	4	8

(k) Type of Crest Facility

Road	Platform & Urban development	Catch-water	Minor Development eg. Rural Footpath	Natural
1.0	0.5	0.25	0.10	0.05

(l) Volume of Fill Body (m^3)

≤100	100 - 500	500 - 1000	1000 - 10000	>10000
0.10	0.25	0.5	1	2

(m) Channelisation of Debris — Yes = 2.0, No = 0.5

(n) Erosion and Entrainment along Debris Trail — Yes = 2.0, No = 1.0

(o) Spread of Debris — Yes = 0.5, No = 1.0

(p) Unstable Terrain — Yes = 2.0, No = 1.0

(q) Masonry Wall at Crest

Wall Height ≥ 3 m	2.0
Wall Height < 3 m	1.5
No Masonry Wall	1.0

Consequence Score (CS)

Facility	Type	Group No.	Proximity			K	L	V			C = H * K * L * V / 10		
								V_1	V_2	V_3	C_1	C_2	C_3
Toe (1)			α =										
Toe (2)			α =										
Crest (1)			<3 m	3 - 6 m	6 - 10 m								
Crest (2)			<3 m	3 - 6 m	6 - 10 m								
										CS = ΣC			

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Table 3.10 - Results Extracted from Trial Application of Fill Slope Priority Classification Sytem, Hong Kong (Wong & Ho, 2000)

Cases (Year of Failure)	Sliding		Liquefaction		Wash-out		Total Score	Description of Failure
	IS1	CS1	IS2	CS2	IS3	CS3		
Sau Mau Ping - A (1976)	2304	0.85	2534	10.27	106	3.19	4.45	4,000 m^3 liquefaction failure; 18 fatalities. IS includes consideration of 1972 failure.
Sau Mau Ping - B (1972)	576	1.16	634	18.08	133	6.60	4.11	6,000 m^3 liquefaction failure; 71 fatalities (high fatalities due to flimsy structures completely damaged by landslide debris).
Kennedy Road - A (1992)	3072	1.71	845	3.91	5	3.49	3.93	500 m^3 liquefaction failure; 1 fatality. Slope exhibited signs of distress before failure.
Kennedy Road - B (1989)	96	1.63	36	3.90	1	4.18	2.48	500 m^3 sliding failure; no fatality: a near-miss event.
Baguio Villas (1992)	192	0.32	53	1.32	277	0.60	2.47	3,000 m^3 wash-out failure; 2 fatalities (a child and an engineer on inspection duty).
Waterloo Road (1989)	96	0.43	26	0.67	11	0.43	1.80	50 m^3 liquefaction failure; blockage of 3 lanes of road but no fatality.
Broadcast Drive (1988)	72	0.05	10	0.16	4	0.05	0.73	120 m^3 wash-out failure due to burst of water main; insignificant consequence.
Kung Lok Rd. Park (1988)	24	0.01	3	0.02	46	0.01	-0.02	200 m^3 wash-out failure; insignificant consequence

Notes:
(1) IS = Instability Score, which reflects the likelihood of the respective mechanism of failure
(2) CS = Consequence Score, which is the potential loss of life (PLL) for the respective mechanism of failure
(3) Total Score = log ($\sum$ IS $\times$ CS)

Table 3.11 - Key Groups of Factors for Retaining Wall Priority Classification System, Hong Kong (Wong, 1998)

Type of Score	Key Groups of Factors	Range of Scores
Instability Score	Wall slenderness ratio and nature of retained material	0 - 100
	Past instability	0 - 30
	Type of wall	0 - 30
	Potential for water ingress	0 - 60
	Wall condition	0 - 110
	Gradient of terrain below wall	0 - 60
Consequence Score	Type and proximity of crest facility	0 - 600
	Type and proximity of toe facility	
	Upslope and downslope topography	

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Table 3.12 - Guidelines for Assessment of Wall Condition (Wong, 1998)

Observed State of Wall Deformation	Forward Movement	Bulging
Minimal deformation	Forward movement of wall as indicated by: (a) long continuous movement cracks at wall crest sub-parallel to wall, total width at any section < 0.1% of wall height; or (b) sub-vertical through cracks in return wall of total width at each level <0.1% h where h is height of measurement point from ground surface level in front of toe.	Negligible bulging of wall.
Moderate deformation	Forward movements as (1) except crack width totalling between 0.1% and 0.2% h.	Minor bulging of wall face noticeable to naked eye.
Onset of severe deformation	Forward movements as (1) except crack width totalling between 0.2% and 0.6% h.	Bulged profile of wall face sufficient to touch a vertical line drawn through wall toe, or maximum bulging of wall approaching or equal to 75 mm.
Advanced stage of severe deformation	Forward movements as (1) except crack width totalling to a value > 0.6% h.	Bulging as (3) but protruding beyond a vertical line drawn through toe, or maximum bulging of wall > 75 mm.
Note: In using this Table, engineering judgement is crucial since different walls are likely to present different degrees of difficulty in deformation determination. The proposed deformation limits shown in this Table should not be regarded as absolute.		

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Table 3.13 - Risk Score Adopted in Combined Ranking Using the New Priority Classification System, Hong Kong

Slope Type	Risk Score
Soil cut slopes	$0.19 \times TS$
Rock cut slopes	$0.20 \times TS$
Retaining walls	$0.038 \times TS$
Fill slopes	$0.64 \times e^{TS}$

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Table 3.14 - Preliminary Rating System of Rockfall Hazard Rating System, ODOT, USA (Pierson et al, 1990)

Criteria	Class		
	A	B	C
Estimated potential for rock on roadway [1]	High	Moderate	Low
Historical rock fall activity [2]	High	Moderate	Low
Follow-up action	To be evaluated with the detailed rating system	To be evaluated with the detailed system as time and funding allows	No further attention

Notes:
(1) In rating the estimated potential, the following should be considered: estimated size of material, estimated quantity of material/event, amount available and ditch effectiveness.
(2) In rating the historical rock fall activity, the following should be considered: frequency of rock fall on highway, quantity of material, size of material and frequency of clean out.

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Table 3.15 - Rockfall Hazard Rating System, ODOT, USA (after Pierson et al, 1990)

Category			Rating Criteria and Score			
			Points 3	Points 9	Points 27	Points 81
Slope height			25 ft	50 ft	75 ft	100 ft
Ditch effectiveness			Good catchment	Moderate catchment	Limited catchment	No catchment
Average vehicle risk			25% of the time	50% of the time	75% of the time	100% of the time
Percent of decision site distance			Adequate site distance, 100% of low design value	Moderate site distance, 80% of low design value	Limited site distance, 60% of low design value	Very limited site distance, 40% of low design value
Roadway width including paved shoulders			44 ft	46 ft	28 ft	20 ft
Geologic character	Case 1	Structural condition	Discontinuous joints, favorable orientation	Discontinuous joints, random orientation	Discontinuous joints, adverse orientation	Continuous joints, adverse orientation
		Rock friction	Rough, irregular	Undulating	Planar	Clay infilling, or slickensided
	Case 2	Structural condition	Few differential erosion features	Occasional erosion features	Many erosion features	Major erosion features
		Difference in erosion rates	Small difference	Moderate difference	Large difference	Extreme difference
Block size			1 ft	2 ft	3 ft	4 ft
Quantity of rockfall/event			3 cubic yards	6 cubic yards	9 cubic yards	12 cubic yards
Climate and presence of water on slope			Low to moderate precipitation; no freezing periods; no water on slope	Moderate precipitation or short freezing periods or intermittent water on slope	High precipitation or long freezing periods or continual water on slope	High precipitation and long freezing periods or continual water on slope and long freezing periods
Rockfall history			Few falls	Occasional falls	Many falls	Constant falls

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Table 3.16 - Ranking of Rockfall Frequency made by Maintenance Personnel during Drive-through (Stover, 1992)

Rank	Description
0	No Falls - No rockfall maintenance activity
1	Few Falls - Rockfalls have occurred several times according to historical information but it is not a persistent problem
2	Occasion Falls - Rockfall occurs regularly. Rockfall can be expected several times per year and during most storms.
3	Many Falls - Typically rockfall occurs frequently during a certain season, such as the winter or spring wet period, or the winter freeze-thaw, etc. However, rockfall is not a significant problem during the rest of the year.
4	Constant Falls - Rockfall occur frequently throughout the year. This category is also for sites where severe rockfall events are common

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Table 3.17 - Colorado Rockfall Hazard Rating System (Stover, 1992)

Factor				Rank: Points 3	Rank: Points 9	Rank: Points 27	Rank: Points 81
Slope profile	Slope height			25 to 50 ft	50 to 75 ft	75 to 100 ft	100 ft
Slope profile	Segment length			0 to 250 ft	250 to 500 ft	500 to 750 ft	750 ft
Slope profile	Slope inclination			15° to 25°	25° to 35°	35° to 50°	50°
Slope profile	Slope continuity			Possible launching features	Some minor launching features	Many launching features	Major rock launching features
Geologic character	Average block or clast size			6 to 12 in	1 to 2 ft	2 to 5 ft	5 ft
Geologic character	Quantity of rockfall event			1 cu ft to 1 cu yd	1 to 3 cu yds	3 to 10 cu yds	10 cu yds
Geologic character	Case 1	Structural condition		Discontinuous fractures, favorable orientation	Discontinuous fractures, random orientation	Discontinuous fractures, adverse orientation	Continuous fractures, adverse orientation
Geologic character	Case 1	Rock friction		Rough, irregular	Undulating smooth	Planar	Clay, gouge infilling, or slickensided
Geologic character	Case 2	Structural condition		Few differential erosion features	Occasional erosion features	Many erosion features	Major erosion features
Geologic character	Case 2	Difference in erosion rates		Small difference	Moderate difference	Large difference	Extreme difference
Climate and presence of water on slope				Low to moderate precipitation; no freezing periods; no water on slope	Moderate precipitation or short freezing periods or intermittent water on slope	High precipitation or long freezing periods or continual water on slope	High precipitation and long freezing periods or continual water on slope and long freezing periods
Rockfall history				Few falls	Occasional falls	Many falls	Constant falls
Number of accidents reported in mile				0 to 5	5 to 10	10 to 15	15 and over

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Table 3.18 - Face Looseness Factor Adopted in the Modified Q System, Rock Slope Hazard Rating, Canada (Hungr et al, 2003)

Definition	FL
Consider either: Loosening due to intersecting weakness zones	
Very tight rock structure, no visible weak or sheared zones	1
Single shear zones in competent rock (clay free)	2.5
Single weakness zones containing clay, or chemically disintegrated rock	5
Multiple shear zones in competent rock (clay free), loose surrounding rock	7.5
Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock	10

Or: Loosening due to mechanical degradation (blasting or natural loosening)	
Most joints tight, can only be chipped by machine, typical apertures 0-1 mm	1
Most joints tight, a few loose, open as much as 5 mm	2.5
Moderately loose, some joints open as much as 2 cm, readily scaled by machine	5
Significant disturbance, many open joints, as much as 20 cm and crushed zones	7.5
Heavily jointed rock mass, many open joints, and loose blocks, easily scaled by hand	10

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Table 3.19 - Key Groups of Factors and Range of Scores for Computation of Consequence Score, SMART, Malaysia (based on PWD Malaysia, 2004)

Type of Score	Key Groups of Factors	Range of Scores
Consequence Score	Type and proximity of crest facility	0 - 480
	Type and proximity of toe facility	
	Type and proximity of road facility	
	Upslope and downslope topography	
	Likely scale of failure	
	Consequence factor/vulnerability	

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Table 3.20 - Categories of Follow-up Action based on Rock Slope Hazard Index, Scotland (McMillan & Matheson, 1997)

Rock Slope Hazard Index	Action Category	Percentage of Sites Assessed in the Category in a Trial Use on 179 Slopes
≤ 1	No action	~ 50%
1 to 10	Review in five years	~ 36%
10 to 100	Detailed inspection	~ 12%
>100	Urgent detailed inspection	~ 2 %

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Table 4.1 - Recommended Factors of Safety for Slopes for a Ten-year Return Period Rainfall (based on GCO, 1984) (Sheet 1 of 2)

Consequence-to-Life	Category 1	Category 2	Category 3
New Slope	1.4	1.2	>1.0
Existing Slope	1.2	1.1	>1.0

Notes:

(1) In this Table, only Consequence-to-Life is considered. Economic Consequence is not included.

(2) The factors of safety given in this Table are recommended minimum values.

(3) For new slope, in addition to a minimum factor of safety of 1.4 for a ten-year return period rainfall, a slope in the Consequence-to-Life category 1 should have a factor of safety of at least 1.1 for the predicted worst groundwater conditions.

(4) The minimum safety factors recommended for existing slope may be used for the stability assessment of and design of modifications to any existing slope which is associated with new works, as long as rigorous geological and geotechnical investigations are conducted (which should include a thorough examination of slope maintenance history, groundwater records, rainfall records and any slope monitoring records) and there is sufficient knowledge of the geology, groundwater and performance history of the slope. Under these conditions, the minimum safety factors recommended for existing slope can be used for stability assessment for known changes in imposed loadings, and for the design of remedial or preventive works, including slope flattening, improvements to surface and subsurface drainage, and the installation of support measures.

(5) Should the back-analysis approach be adopted for the design of remedial or preventive works for existing slope, it may be assumed that the existing slope had a minimum factor of safety of 1.0 for the worst known loading and groundwater conditions.

(6) For a failed or distressed slope, the causes of the failure or distress must be specifically identified and taken into account in the design of the remedial works for the existing slope.

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Table 4.1 - Recommended Factors of Safety for Slopes for a Ten-year Return Period Rainfall (based on GCO, 1984) (Sheet 2 of 2)

Examples	Consequence-to-life		
	Category 1	Category 2	Category 3
(1) Failures affecting occupied buildings (e.g. residential, educational, commercial or industrial buildings, bus shelters, railway platforms).	✓		
(2) Failures affecting buildings storing dangerous goods.	✓		
(3) Failures affecting heavily used open spaces and recreational facilities (e.g. sitting-out areas, playgrounds, car parks).		✓	
(4) Failures affecting roads with high vehicular or pedestrian traffic density.		✓	
(5) Failures affecting public waiting areas (e.g. bus stops, petrol stations).		✓	
(6) Failures affecting country parks and lightly used open-air recreation areas.			✓
(7) Failures affecting roads with low traffic density.			✓
(8) Failures affecting storage compounds (non-dangerous goods).			✓
Note: (1) In the context of this Table, bus shelters are those with a cover that shelters people waiting there from direct sunlight or rainfall, while bus stops are those without such a cover.			

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Table 4.2 - Natural Terrain Susceptibility Class (Wong, 2001)

Susceptibility Class	Description
A	The natural terrain is extremely susceptible to the type of failure under consideration, with a notional annual probability of occurrence in the order of 1/10 or higher. For example: there are signs of instability, continued movement, or records of repeated recent failures (say over the past 50 to 100 years as observed from aerial photographs) in the catchment and its relevant vicinity.
B	The natural terrain is highly susceptible to the type of failure under consideration, with a notional annual probability of occurrence within the order of 1/10 to 1/100. For example: there are records of occasional recent failures in the catchment and its relevant vicinity.
C	The natural terrain is moderately susceptible to the type of failure under consideration, with a notional annual probability of occurrence within the order of 1/100 to 1/1,000. For example: there are few records of recent failures, but there are indications of relic failures, or geomorphological evidence of potential problems in the catchment and its relevant vicinity, or any other evidence from similar terrain in Hong Kong.
D	The natural terrain is of low susceptibility to the type of failure under consideration, with a notional annual probability of occurrence less than 1/1,000. For example: there are no records of recent and relic failures, little geomorphological and other evidence of potential problems in the catchment and its relevant vicinity, and little other evidence from similar terrain in Hong Kong.
Note: (1) In assessing the susceptibility of the hillside to failure, consideration should be taken of potential effects of changes in environmental factors, e.g. any changes to the overall setting of the terrain such as hill fires and construction upslope, and the relevance of the available historical landslide records.	

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Table 4.3 - Consequence Class for Facility (Wong, 2001)

Proximity	Facility Group No.			
	1 & 2	3	4	5
Very Close (e.g. if angular elevation from the site is ≥ 30°)	I	II	III	IV
Moderately Close (e.g. if angular elevation from the site is ≥ 25°)	II	III	IV	V
Far (e.g. if angular elevation from the site is < 25°)	III	IV	V	V

Notes:
(1) Facility groups are described in Table 3.5.
(2) For channelized debris flow, if the worst credible event affecting the site is judged to have a volume exceeding 2,000 m^3, the angular elevation given in the above examples should be reduced by 5°.
(3) The above are for general guidance only. Other factors, such as credible debris path, topographical conditions and site-specific historical data, should also be taken into account in assessing the 'proximity' of the natural terrain to the site.

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Table 4.4 - Design Requirements for Design Event Approach (Wong, 2001)

Susceptibility Class	Consequence Class				
	I	II	III	IV	V
A	WCE	WCE	WCE	CE	N
B	WCE	WCE	CE	CE	N
C	WCE	CE	CE	N	N
D	N	N	N	N	N

Notes:
(1) See Table 4.2 for definition of Susceptibility Class.
(2) See Table 4.3 for definition of Consequence Class.
(3) WCE = Adopt a 'worst credible' event as the design event. A 'worst credible' event is a very conservative estimate such that the occurrence of a more severe event is sufficiently unlikely. Its notional return period is in the order of 1,000 years.
CE = Adopt a 'conservative' event as the design event. A 'conservative' event is a reasonably safe estimate of the hazard that may affect the site, with a notional return period in the order of 100 years.
N = Further study is not required

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Table 4.5 - FMEA on Shatin Heights Catchment No. 7

Component	Failure Mode (Notes (1))	Effects on K.K. Terrace	Likelihood Category			Loss of Life		Economic Loss & Disruption to Community		Risk Category (Proceed to Detailed Assessment?)
			Failure	Effect	Hazard	Consequence Category	Risk Category	Consequence Category	Risk Category	
Catchments 7a, 7d & 7h	Shallow landslide resulting in small-scaled open-slope debris slide/avalanche (SH1)	Debris run into and affect 1/F of K.K. Terrace	C to D	z	D to E	2	L to V	III	N	Low (Yes)
	Deep landslide resulting in medium- to large-scaled fast moving debris slide/avalanche (SH2 to SH3)	Debris run into and affect 1/F of K.K. Terrace	E	x	E	2	V	III	N	Very Low (No)
		Debris hit K.K. Terrance and result in building collapse or major structural damage		z	E-	1	V	II	N	Very Low (No)
	Deep landslide resulting in medium- to large-scaled debris with limited mobility (SH2 to SH3)	Prolonged evacuation of K.K. Terrace	E	y	E-	5	N	II to III	N	Residual (No)
Catchments 7b, 7e, 7f, 7i & 7j	Shallow landslide resulting in small- to medium-scaled debris flow without significant entrainment (TH1 to TH2)	Debris run into and affect 1/F of K.K. Terrace	B	x	B	2	H	III	L	High (Yes)
		Debris hit and affect the entrance to K.K. Terrace		y	B to C	3	M to L	IV	N	Moderate (Yes)
	Shallow landslide resulting in medium- to large-scaled debris flow with significant entrainment (TH2 to TH3)	Debris run into and affect 1/F of K.K. Terrace	D	x	D	2	L	III	N	Low (Yes)
		Debris hit and affect the entrance to K.K. Terrace		y	D to E	3	V to N	IV	N	Very Low (No)
		Debris hit K.K. Terrance and result in building collapse or major structural damage		z	E	1	L	II	N	Low (Yes)
	Shallow landslide resulting in small-scaled debris with limited mobility (TH1)	Temporary evacuation of 1/F of K.K. Terrace	B	y	B to C	5	N	IV	V to N	Very Low (No)
Catchments 7c, 7g & 7k	Shallow landslide resulting in small-scaled open-slope debris slide/avalanche (SH1)	Debris hit and affect the entrance to K.K. Terrace	C to D	z	D to E	3 to 4	V to N	IV	V	Very Low (No)
	Deep landslide resulting in medium-to-large scaled fast moving debris (SH2 to SH3)	Debris hit and affect the G/F of K.K. Terrace, including the entrance, G/F lobby, car park and drive way	E	x	E	2	V	III	N	Very Low (No)
		Debris hit K.K. Terrance and result in building collapse or major structural damage		z	E-	1	V	II	N	Very Low (No)
	Deep landslide resulting in medium- to large-scaled debris with limited mobility (SH2 to SH3)	Temporary evacuation of K.K. Terrace and the sole vehicular access to K.K. Terrace and Woodcrest	E	x	E	5	N	III	N	Residual (No)
		Prolonged closure of the sole vehicular access to K.K. Terrace and Woodcrest		z	E-	5	N	II	N	Residual (No)

Notes:
(1) See Table 6.7 for definition of 'SH1' to 'SH4' and 'TH1' to 'TH4'.
(2) See Figure 4.9 for likelihood, consequence and risk categorization. See Figure 5.15 for site plan.

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Table 5.1 - Results of Consequence Assessment for the Fei Tsui Road Landslide (Wong et al, 1997)

Facility Affected	Facility Group No. (Reference PLL)	Vulnerability to Death in the Event of Debris Impact	Scaling Factor for Actual Size of Landslide	PLL	Proportion of Total PLL
Open space	Group 5 (0.001)	0.95	90/10 = 9	0.01	0.2%
Fei Tsui Road	Group 3 (0.25)	0.85	90/10 = 9	1.91	47.9%
Baptist Church	Group 1 (3*2)	0.17	20/10 = 2	2.04	51.4%
Playground	Group 4 (0.03)	0.15	50/10 = 5	0.02	0.5%
				$\sum = 3.98$	

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Table 5.2 - Expected Extent of Damage for Roads with Differing Degrees of Traffic Usage (Wong et al, 1997)

Facility Group No.	Total Number of Slope Features	Distribution of Total Risk [RATIO]	Average Risk per Feature [RATIO]
Roads - very high traffic density	3900	44.5% [445]	3.5×10^{-4} [875]
Roads - high traffic density	7400	33.5% [335]	1.35×10^{-4} [340]
Roads - moderate traffic density	6000	17.9% [179]	9.0×10^{-5} [225]
Roads - low traffic density	11900	4% [40]	1.0×10^{-5} [25]
Roads - very low traffic density	7500	0.1% [1]	4.0×10^{-7} [1]

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Table 5.3 - Annual Potential Loss of Life for the Shek Kip Mei Landslide (El-Ramly et at, 2003)

Hazard Scenario	Volume of Failure (m^3)	Potential Loss of Life (per Year)		
		For All Event Tree Scenarios	% of Total	Due to Building Collapse at Night
1	2,500 - 5,000	7.67×10^{-4}	94.9	5.49×10^{-4}
2	300 - 600	4.08×10^{-5}	5.1	2.21×10^{-5}
3	25 - 50	0.00	0.0	0.00
Total PLL =		8.08×10^{-4}	100.0	5.57×10^{-4}

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Table 5.4 - Scaling Factors for Adjusting Vulnerability Factors at Shatin Heights (FMSW, 2001)

Scale of Landslide	Protected Facility	Unprotected Facility
Small ($V < 50\ m^3$)	0.4	0.6
Medium ($50\ m^3 \leq V < 200\ m^3$)	0.7	0.8
Large ($200\ m^3 \leq V < 1{,}000\ m^3$)	0.9	1.0

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Table 5.5 - Expected Number of People Affected by Landslide at Shatin Heights (FMSW, 2001)

Scale of Landslide	Type of Facility			
	Residential Building	Guard House	Car Park	Open Space
Small ($V < 50\ m^3$)	1.5	0.25	0.05	0.015
Medium ($50\ m^3 \leq V < 200\ m^3$)	3	0.5	0.1	0.03
Large ($200\ m^3 \leq V < 1,000\ m^3$)	6	1	0.2	0.06

Notes:
(1) The above values are applicable to both open hillslope landslides and channelized debris flows.
(2) Building collapse is not considered credible.

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Table 5.6 - Potential 120-year Economic Loss for North Lantau Expressway (extracted from OAP, 2005)

Type	Scope	Potential Economic Loss
Damage to vehicles	Economic loss associated with direct damage to vehicle on North Lantau Expressway due to debris impact	HK$ 22 million
Air travel passengers delay	Economic loss associated with potential delays to air travel passengers due to temporary closure of the expressway and thereby causing delayed traffic access the Hong Kong International Airport	HK$ 94 million
Air cargo delay	Economic loss associated with potential delay to air cargo due to temporary closure of the expressway and thereby causing delay to good vehicles' access the Hong Kong International Airport	HK$ 334 million

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Table 5.7 - Key Modules of Work in Natural Terrain Landslide QRA (Sheet 1 of 2)

Module of Work	Scope
(1) Determine study objectives and approach	– Identify the background and purposes of the study, and any special requirements – Determine the objectives and the level of details required – Select the approaches to be adopted
(2) Delineate study area	– Identify the extent of the site that may be at risk from landslide hazards – Set out the extent of the study area
(3) Validate historical landslides	– Collate information on historical landslides based on documentary records, aerial photograph interpretation, and findings from field mapping and geomorphological assessment – Validate the data and compile a dataset of landslides and related attributes
(4) Examine rainfall records and effects	– Collate information on the rainfall history – Examine any relevant rainfall-landslide pattern/correlation – Establish any need to adjust figures on the historical landslide activity to account for rainfall effects
(5) Demarcate boundaries and types of catchments	– Delineate the boundaries of catchments – Sub-divide the catchments where necessary, e.g. based on topographic conditions and mechanism of debris movement – Match the catchments with the facilities at risk
(6) Identify facilities and population at risk, and their degree of proximity	– Identify the types and locations of the facilities at risk – Establish degree of usage and temporal distribution of population at risk – Examine degree of proximity with reference to GEO's screening criteria, empirical models, relevant historical runout data, etc.
(7) Geological assessment	– Carry out field mapping to establish the engineering geological and geomorphological conditions – Examine landslide processes and mechanisms, regolith type and distribution, signs of distress, and other relevant terrain attributes – Classify terrain, and develop geological and landslide process models
(8) Formulate hazard and hazard models	– Identify potential landslide hazards and the relevant hazard scenarios that require risk quantification – Formulate hazard models for use in QRA and in assessment of Design Events

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Table 5.7 - Key Modules of Work in Natural Terrain Landslide QRA (Sheet 2 of 2)

Module of Work	Scope
(9) Identify possible debris runout paths and influence zones	– Divide potential landslide sources into cells – Identify possible debris runout paths for each cell – Match the cells with the facilities at risk – Assess the degree of proximity and the degree of damage to the facilities at risk
(10) Carry out frequency assessment	– Formulate frequency model – Establish the frequencies of occurrence of different types of hazard – Assess the spatial distribution of the landslide frequency, together with the use of susceptibility analysis and Bayesian methodology as appropriate – Assess the frequency of occurrence of special hazard scenarios, e.g. building collapse and events with knock-on effects
(11) Carry out consequence assessment	– Formulate consequence model – Assess the consequence of occurrence of different types of hazards – Assess the consequence of occurrence of special hazard scenarios, e.g. building collapse and events with knock-on effects
(12) Analyze risk	– Calculate the risk by integrating frequency and consequence – Evaluate the distribution of risk – Carry out sensitivity analysis and examine the reliability of the findings of the risk assessment
(13) Assess design events	– Assess the magnitudes of Design Events
(14) Evaluate risk management strategy	– Compare risk results with risk criteria – Formulate possible risk management options – Evaluate the pros and cons of different risk management options and identify the preferred risk management strategy – Interact with and obtain feedback from stakeholders
(15) Draw conclusion and recommendation	– Conclude the findings of the study – Recommend risk management strategy and follow-up actions
(16) Document findings	– Document the findings of the study – File the relevant information, data and calculations – Update the relevant documentary and digital records

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Table 5.8 - Hazard Classification (Wong et al, 2004c)

Hazard	Classification	Definition
Mechanism of debris movement (which was related to catchment characteristics)	C	Channelized debris flow
	T	Mixed debris flow/avalanche at topographic depression
	S	Open hillslope debris slide/avalanche
Scale of landslide (which was established from volume-frequency relationships for different classes of catchment)	H1a	30 m^3 notional (20 m^3 to 60 m^3)
	H1b	100 m^3 notional (60 m^3 to 200 m^3)
	H2a	300 m^3 notional (200 m^3 to 600 m^3)
	H2b	1,000 m^3 notional (600 m^3 to 2,000 m^3)

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Table 5.9 - Vulnerability Factors for Open Slope Debris Slide/ Avalanche, Ling Pei (Wong et al, 2004c)

Landslide Hazard	Proximity Zone (Plan Distance (m) of Facility from Source of Landslide)												
	5	10	15	20	25	30	35	40	45	50	55	60	65
SH1a	0.0977	0.0750	0.0523	0.0324	0.0172	0.0074	0.0023	0.0004	0.0000	0.0000	0.0000	0.0000	0.0000
SH1b	0.4071	0.3679	0.3224	0.2730	0.2217	0.1714	0.1253	0.0860	0.0551	0.0324	0.0168	0.0073	0.0023
SH2a	0.7656	0.7300	0.6864	0.6354	0.5779	0.5151	0.4489	0.3813	0.3146	0.2515	0.1944	0.1451	0.1040
SH2b	0.9044	0.8835	0.8570	0.8249	0.7873	0.7443	0.6964	0.6440	0.5878	0.5283	0.4666	0.4042	0.3433

Landslide Hazard	Proximity Zone (Plan Distance (m) of Facility from Source of Landslide)												
	70	75	80	85	90	95	100	105	110	115	120	125	130
SH1a	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SH1b	0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SH2a	0.0709	0.0453	0.0265	0.0138	0.0059	0.0019	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SH2b	0.2860	0.2338	0.1872	0.1462	0.1108	0.0809	0.0563	0.0367	0.0218	0.0114	0.0049	0.0016	0.0003

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Table 5.10 - Vulnerability Factors for Channelized Debris Flow, Ling Pei (Wong et al, 2004c)

Landslide Hazard	Proximity Zone (Plan Distance (m) of Facility from Source of Landslide)												
	5	10	15	20	25	30	35	40	45	50	55	60	65
CH1a	0.4071	0.3679	0.3224	0.2730	0.2217	0.1714	0.1253	0.0860	0.0551	0.0324	0.0168	0.0073	0.0023
CH1b	0.7656	0.7300	0.6864	0.6354	0.5779	0.5151	0.4489	0.3813	0.3146	0.2515	0.1944	0.1451	0.1040
CH2a	0.9044	0.8835	0.8570	0.8249	0.7873	0.7443	0.6964	0.6440	0.5878	0.5283	0.4666	0.4042	0.3433
CH2b	0.9584	0.9466	0.9310	0.9116	0.8884	0.8613	0.8304	0.7957	0.7573	0.7153	0.6699	0.6214	0.5701

Landslide Hazard	Proximity Zone (Plan Distance (m) of Facility from Source of Landslide)												
	70	75	80	85	90	95	100	105	110	115	120	125	130
CH1a	0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH1b	0.0709	0.0453	0.0265	0.0138	0.0059	0.0019	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH2a	0.2860	0.2338	0.1872	0.1462	0.1108	0.0809	0.0563	0.0367	0.0218	0.0114	0.0049	0.0016	0.0003
CH2b	0.5165	0.4617	0.4070	0.3541	0.3046	0.2590	0.2171	0.1791	0.1449	0.1146	0.0881	0.0653	0.0462

Landslide Hazard	Proximity Zone (Plan Distance (m) of Facility from Source of Landslide)					
	135	140	145	150	155	160
CH1a	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH1b	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH2a	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH2b	0.0308	0.0188	0.0102	0.0045	0.0015	0.0002

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Table 6.1 - Frequency of Occurrence of PGA Levels Triggering Different Failure Modes (Wong & Ho, 1998b)

Margin of Static Factor of Safety	Failure Mode	Range of PGA for Different Failure Modes (g)	Return Period, T (years)	Annual Frequency of Occurrence, f
10%	OF	> 0.084	> 500	2.000×10^{-3}
	OD	0.06 - 0.084	150 - 500	4.667×10^{-3}
	LF	0.053 - 0.06	100 - 150	3.333×10^{-3}
	LD	0.038 - 0.053	30 -100	2.333×10^{-2}
20%	OF	> 0.168	> 5,500	1.818×10^{-4}
	OD	0.12 - 0.168	1,600 - 5,500	4.432×10^{-4}
	LF	0.106 - 0.12	1,150 - 1,600	2.446×10^{-4}
	LD	0.076 - 0.106	350 - 1,150	1.988×10^{-3}
40%	OF	> 0.308	> 120,000	8.333×10^{-6}
	OD	0.22 - 0.308	18,000 - 120,000	4.722×10^{-5}
	LF	0.194 - 0.22	10,000 - 18,000	4.444×10^{-5}
	LD	0.139 - 0.194	3,000 - 10,000	2.333×10^{-4}

Legend:

OF denotes overall failure
OD denotes overall deformation with local slope failure
LF denotes local failure
LD denotes local slope deformation
PGA denotes peak ground acceleration

$$f = \left(\frac{1}{T_1} - \frac{1}{T_2} \right)$$

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Table 6.2 - Comparison of Risks of Landslides Caused by Rainfall and Earthquake (Wong & Ho, 1998b)

(a) Soil Cut Slopes

Factor of Safety	Buildings	Roads
1.4	2.862×10^{-7} (≈ 0.08%)	N/A
1.2	2.21×10^{-6} (≈ 0.7%)	1.66×10^{-6} (≈ 0.7%)
1.1	N/A	7.279×10^{-6} (≈ 2.9%)
Note: The figure shown in bracket is the ratio of the risk of earthquake-induced failure for engineered soil cut slopes to the risk of rain-induced failure for old substandard soil cut slopes.		

(b) Fill Slopes

Factor of Safety	Buildings	Roads
1.4	1.721×10^{-6} (≈ 0.9%)	N/A
1.2	5.459×10^{-6} (≈ 2.9%)	7.278×10^{-7} (≈ 2.7%)
1.1	N/A	1.903×10^{-6} (≈ 7%)
Note: The figure shown in bracket is the ratio of the risk of earthquake-induced failure for engineered fill slopes to the risk of rain-induced failure for old substandard fill slopes.		

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Table 6.3 - Results of Global QRA of Unengineered Man-made Slopes in Hong Kong (Wong & Ho, 1998)

(a) PLL for Cut Slopes (per Year)

Group No.		1	1	2	2	3	4	5	Building Colleagues	Total
Type of Facility		Buildings	Roads	Buildings	Roads	Roads & Open Space	Roads & Open Space	Roads & Open Space		
Slope Height	< 10 m	1.53	0.43	0.51	1.07	0.86	0.215	4.66×10^{-3}	0	4.62
	10 - 20 m	0.61	0.23	0.20	0.58	0.46	0.111	2.36×10^{-3}	0	2.20
	> 20 m	0.26	0.20	8.60×10^{-2}	0.49	0.39	6.88×10^{-2}	1.15×10^{-3}	0.171	1.67
	Total	2.40	0.86	0.80	2.14	1.72	0.395	8.17×10^{-3}	0.171	8.49

(b) PLL for Fill Slopes (per Year)

Group No.		1	1	2	2	3	4	5	Total
Type of Facility		Buildings	Roads	Buildings	Roads	Roads & Open Space	Roads & Open Space	Roads & Open Space	
Slope Height	< 10 m	0.14	0.05	0.05	0.13	0.10	1.81×10^{-2}	3.03×10^{-4}	0.49
	10 - 20 m	0.12	0.03	0.04	0.07	0.06	1.00×10^{-2}	1.71×10^{-4}	0.32
	> 20 m	0.31	2.38×10^{-2}	1.03×10^{-1}	5.95×10^{-2}	4.76×10^{-2}	9.00×10^{-3}	1.61×10^{-4}	0.55
	Total	0.57	0.10	0.19	0.26	0.21	3.71×10^{-2}	6.35×10^{-4}	1.36

(c) PLL for Retaining Wall (per Year)

Group No.		1	1	2	2	3	4	5	Total
Type of Facility		Buildings	Roads	Buildings	Roads	Roads & Open Space	Roads & Open Space	Roads & Open Space	
Wall Height	≤ 5 m	3.76×10^{-1}	2.21×10^{-2}	1.25×10^{-1}	5.53×10^{-2}	4.42×10^{-2}	7.31×10^{-3}	1.15×10^{-4}	0.63
	> 5 m	4.44×10^{-1}	6.32×10^{-3}	1.48×10^{-1}	1.58×10^{-2}	1.26×10^{-2}	1.93×10^{-3}	2.74×10^{-5}	0.63
	Total	8.20×10^{-1}	2.84×10^{-2}	2.73×10^{-1}	7.11×10^{-2}	5.69×10^{-2}	9.24×10^{-3}	1.42×10^{-4}	1.26

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Table 6.4 - Risk Distribution According to Type of Slope (Wong & Ho, 1998)

Slope Type	Unengineered Man-made Slopes		
	Cut Slopes	Fill Slopes	Retaining Walls
Number of Slopes	19,100	9,500	8,100
Global Failure Frequency (per Year)	1 in 100	1 in 500	1 in 350
Proportion of Total Risk [Risk Ratio]	75% [6]	12% [1]	13% [1]
Average Ratio of Risk per Feature	3.2	1	1.3

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Table 6.5 - Landslide Risk Reduction from 1977 to 2000 by the LPM Programme (Cheung & Shiu, 2000)

Slope Type	Landslide Risk (PLL per Year)		
	As at 1977	As at 2002	Risk Reduction from 1997 to 2000
Soil cut slopes	18.52	8.51	10.01 (55%)
Rock cut slopes	1.18	0.74	0.44 (37%)
Retaining walls	0.62	0.41	0.21 (34%)
Fill slopes	1.51	0.61	0.90 (60%)
Total	21.80	10.30	11.50 (53%)

Table 6.6 - Average Base-line Annual Landslide Frequency of Man-made Slope Features (Lo & Cheung, 2004)

Slope Type		No. of Slopes	No. of Failures (1984 - 2003)	Total Slope Area ($\times 10^3$ m^2)	Average Annual Failure Frequency	
					per Slope ($\times 10^{-3}$/year)	per Unit Area ($\times 10^{-6}$/year/m^2)
Un-engineered Man-made Slope feature	Soil cut slopes	17,563	1,980	9,597	5.6	10.3
	Rock cut slopes	1,838	311	2,123	8.5	7.3
	Retaining wall	6,026	128	1,437	1.1	4.5
	Fill slope	5,423	214	5,357	2.0	2.0
	Total	30,850	2,633	18,514	4.3	7.1

Slope Type		No. of Slopes	No. of Failures (1997 - 2003)	Total Slope Area ($\times 10^3$ m^2)	Average Annual Failure Frequency	
					per Slope ($\times 10^{-6}$/year)	per Unit Area ($\times 10^{-6}$/year/m^2)
Engineered Man-made Slope feature	Soil cut slopes	10,191	36	20,528	0.50	0.27
	Rock cut slopes	725	10	2,296	2.00	0.62
	Retaining wall	4,237	3	1,377	0.10	0.31
	Fill slope	5,925	7	10,911	0.17	0.09
	Total	21,078	56	35,112	0.38	0.23

Notes:
(1) The frequencies of landslide have been further classified according to the slope height.
(2) For engineered slopes, the frequencies of landslide have been further classified according to whether the slopes were treated by old technology or robust technology.

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Table 6.7 - Hazard Classification (Wong et al, 2004b)

Hazard Combination	Classification	Definition
Mechanism of debris movement (which was related with catchment characteristics)	C	Channelized debris flow
	T	Mixed debris flow/avalanche at topographic depression
	S	Open hillslope debris slide/avalanche
Scale of landslide (which was established from volume-frequency relationships for different classes of catchment)	H1	50 m^3 notional (20 m^3 to 200 m^3)
	H2	500 m^3 notional (200 m^3 to 2,000 m^3)
	H3	5,000 m^3 notional (2,000 m^3 to 20,000 m^3)
	H4	20,000+ m^3 notional (>20,000 m^3)

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Table 6.8 - Rainfall Scenario (Wong et al, 2004b)

Rainfall Scenario	Normalized Maximum Rolling 24-hour Rainfall	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% at 500-year return period, was assessed by extrapolation of the QRA results.

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Table 6.9 - Summary of Results of Global QRA (based on Wong et al, 2004b)

<table>
<tr><th colspan="2">Component</th><th>Method of Quantification</th><th>Risk (PLL per Year)</th></tr>
<tr><td rowspan="2">453 historical landslide catchments</td><td>Rainfall Scenarios A to D (≤ 35% normalized rainfall)</td><td>Global QRA on the historical catchments using the QRA models</td><td>1.4</td></tr>
<tr><td>Rainfall Scenario E (> 35% normalized rainfall)</td><td>~30% increase, from extrapolation of QRA results using rainfall-landslide correlation</td><td>0.4</td></tr>
<tr><td colspan="2">Supplementary catchments</td><td>~ 200% increase, from projection based on global QRA using the risk model (Figure 6.12)</td><td>3.2</td></tr>
<tr><td colspan="3">Total</td><td>5.0</td></tr>
<tr><td colspan="4">Notes: (1) Other consequences, e.g. economic loss, disruption to community and public aversion to multiple fatalities, not reflected in the calculated PLL.
(2) No. of historical landslide catchments would increase at about 10 no. per year. Risk could increase with more developments taking place near steep hillsides.</td></tr>
</table>

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Table 6.10 - Risk Distribution According to Scale of Landslide (Wong et al, 2004b)

	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%

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Table 6.11 - Risk Distribution According to Proximity Zone (Wong et al, 2004b)

Proximity Zone	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 $= 1.8 \times 10^{-3}$	

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Table 6.12 - Landslide Risk Profile in Year 2010 (based on Wong et al, 2004b; Lo & Cheung, 2004)

Type of Slope		Approximate No.	Proportion of Risk	Average PLL per No.	Relative Risk-Cost Ratio
Natural hillside	Historical landslide catchments	450 catchments	~ 15%	3.3×10^{-2}	10
	Supplementary catchments	Many (exact number not known)	~ 35%	Not known	Not known
Unengineered man-made slopes	Affecting Groups No. 2(b) & 3 facilities and unplanned structures	12,000 slopes	~ 25%	2.1×10^{-4}	1
	Affecting Groups No. 4 & 5 facilities	14,000 slopes	< 1%	$< 7 \times 10^{-6}$	0.03
Engineered man-made slopes	by old technology	10,000 slopes	~ 20%	2.0×10^{-4}	1
	by robust technology	20,000 slopes	~ 5%	2.5×10^{-5}	0.13

Notes:
(1) See Table 3.5 for definitions of Facility Groups.
(2) Un-engineered man-made slopes affecting Groups No. 1 & 2(a) facilities would have been retro-fitted by year 2010, i.e. they become engineered slopes.
(3) In calculating the relative risk-cost ratio, it is conservatively assumed that the average cost of risk mitigating for a natural terrain catchment is 10 times as that for a man-made slope.
(4) 'Old technology' slopes refer to slopes treated in the early years of setting up Hong Kong's Slope Safety System (typically in late 1970s to mid 1980s) based on the geotechnical knowledge and skills at the time. These are less robust than those treated using structural support or reinforcement, such as soil nails.

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Figure 3.1 - An Un-engineered Cut Slope Formed in Hong Kong before 1977

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Cut Slope Location Between Wanchai Gap Road and Stone Nullsh Lane						Cut Slope Reference No. 11SW-D/CR411				
Map 11-SW-14D	Scale 1:1000	Aerial Photo 12645		Date 28.1.76		Risk	Moderate to high			
						Type of Slope	Cut			
Nearest rainfall station		Happy Valley Race Course				Coordinates	E 35920	N 14950		
Elevation	18 mPD					Inspected/Date	DS/30.3.78	Weather Cloudy		
Description	Slope					Associated Structure				
	□ soil	□ soil & rock		□ rock		□ retaining wall	□ buttress	□ other		
Medical/Construction	Decomposed granite					Masonry				
Condition	Fair					Fair				
Height/Length	H 8 m	L 30 m				H 3 m	L 15 m			
Angle	45° some 50°					90°				
Berms	No. None	Width m				Associated Walls	Masony H 2 m/L 5 m			
Covering	Chunam, bare rock at toe									
Drainage :		Size (mm)	Spacing (m)	Condition	Flow		Size (mm)	Spacing (m)	Condition	Flow
Weepholes		50	Occ.	Blocked	Dry	None	-	-	-	-
U Channels: on slope		225	-	Fair	Dry	-				
at top	None		-			None	-	-	-	-
at toe	None		-			None	-	-	-	-
Comments										
Seepage : Location/ Amount	None apparent					None apparent				
Sign of distress : Location/ Form	Sheet joints dipping 25° to 30° towards building					None				
Service conduits	On slope 75 mm pipe along top of slope					Elsewhere	None visible			
Nearest structure										
Distance from toe	0.7 m to houses					m	to			
Distance from top	Adjacent to road					m	to			
History & Documents						Date of Construction				
Previous instability	None apparent									
Site investigation										
Drawings										
B & P reports	None									
Other reports										
Remarks	Associated wall at middle of slope; concrete toe wall H 1 m/L 10 m									
Action										
Maintenance & repair :	Remove vegetation. Clear weepholes.					Responsibility : Carried out :				
Further action	Phase II - Detailed Study - Second Priority for checking possibility of wedge failure.					Responsibility : Carried Out :				
						B & P (HK)				

Figure 3.2 - Sample of Field Data Sheet Used in the Cut Slope Scoring System, Hong Kong (Koirala & Watkins, 1988)

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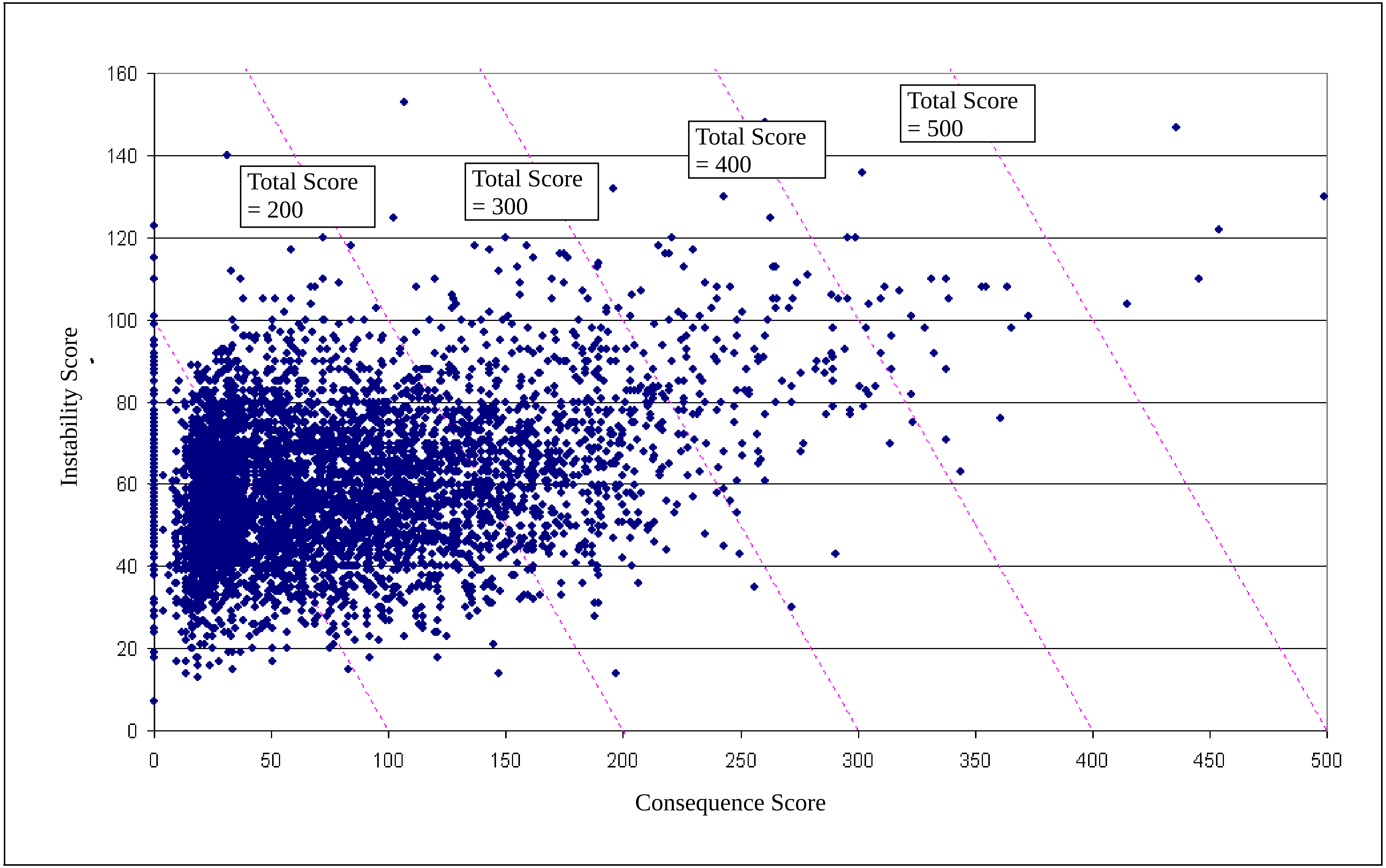

Figure 3.3 - Instability Score vs Consequence Score of Slopes Ranked by the Cut Slopes Ranking System, Hong Kong (Wong & Ho, 1995)

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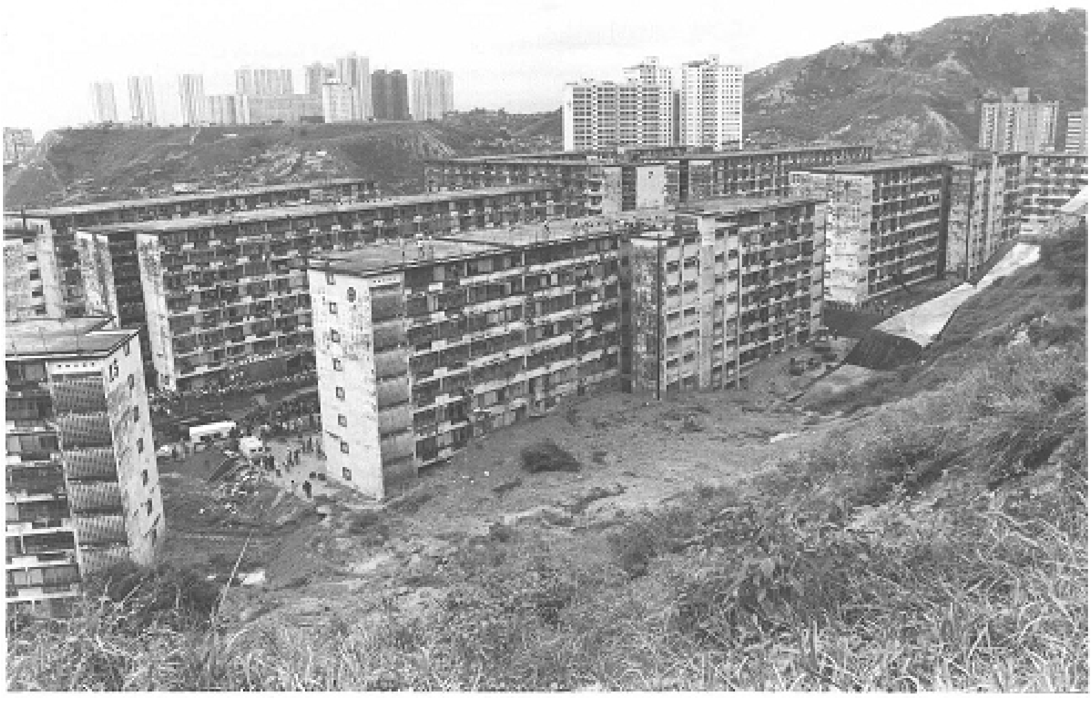
(a) 1972 Sau Mau Ping Landslides, Hong Kong



(b) 1976 Sau Mau Ping Landslides, Hong Kong

Figure 3.4 - The 1972 and 1976 Sau Mau Ping Landslides

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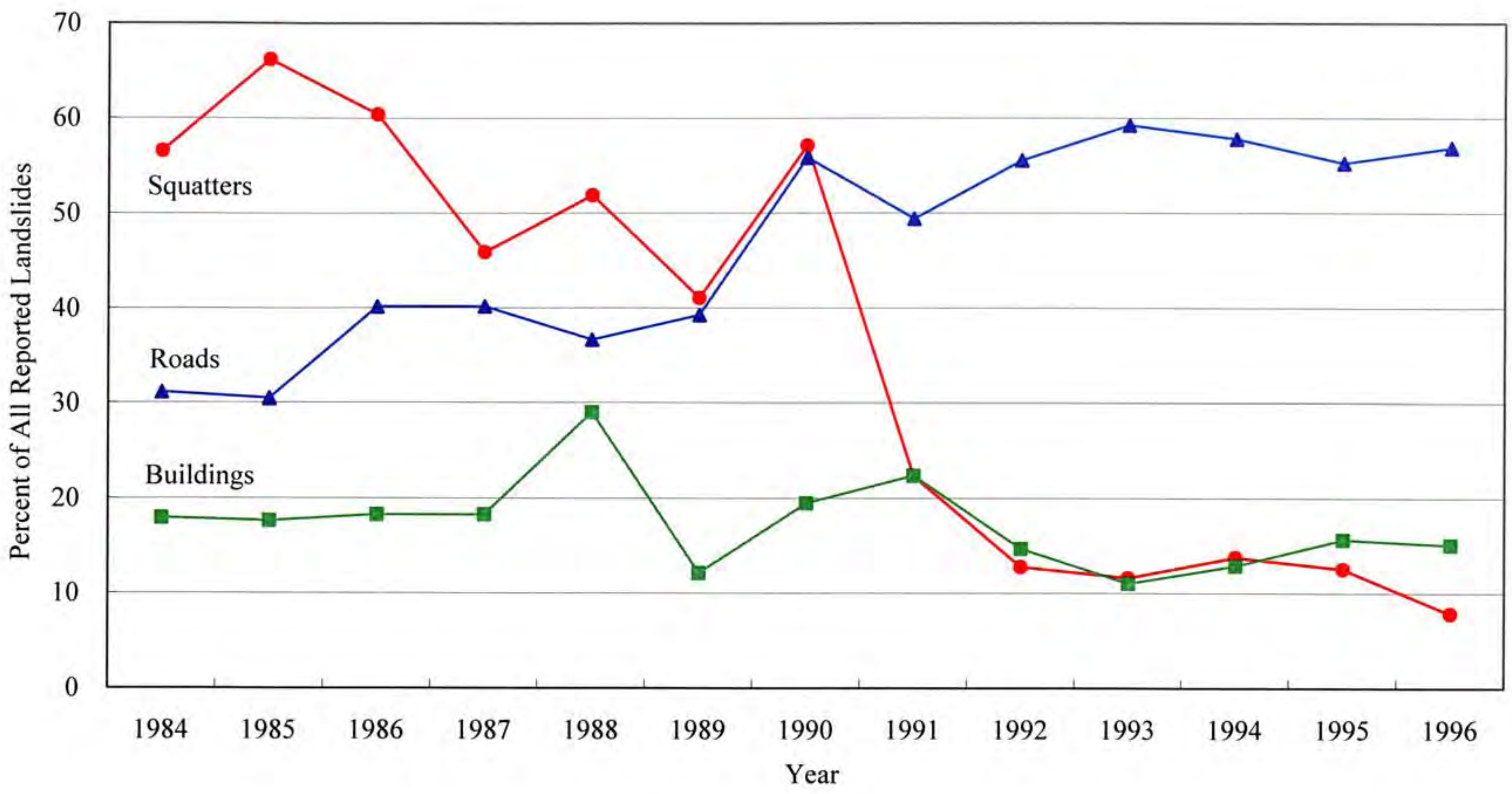

Figure 3.5 - Statistics on Damaging Landslides Reported to the GEO before mid 1990s in Hong Kong

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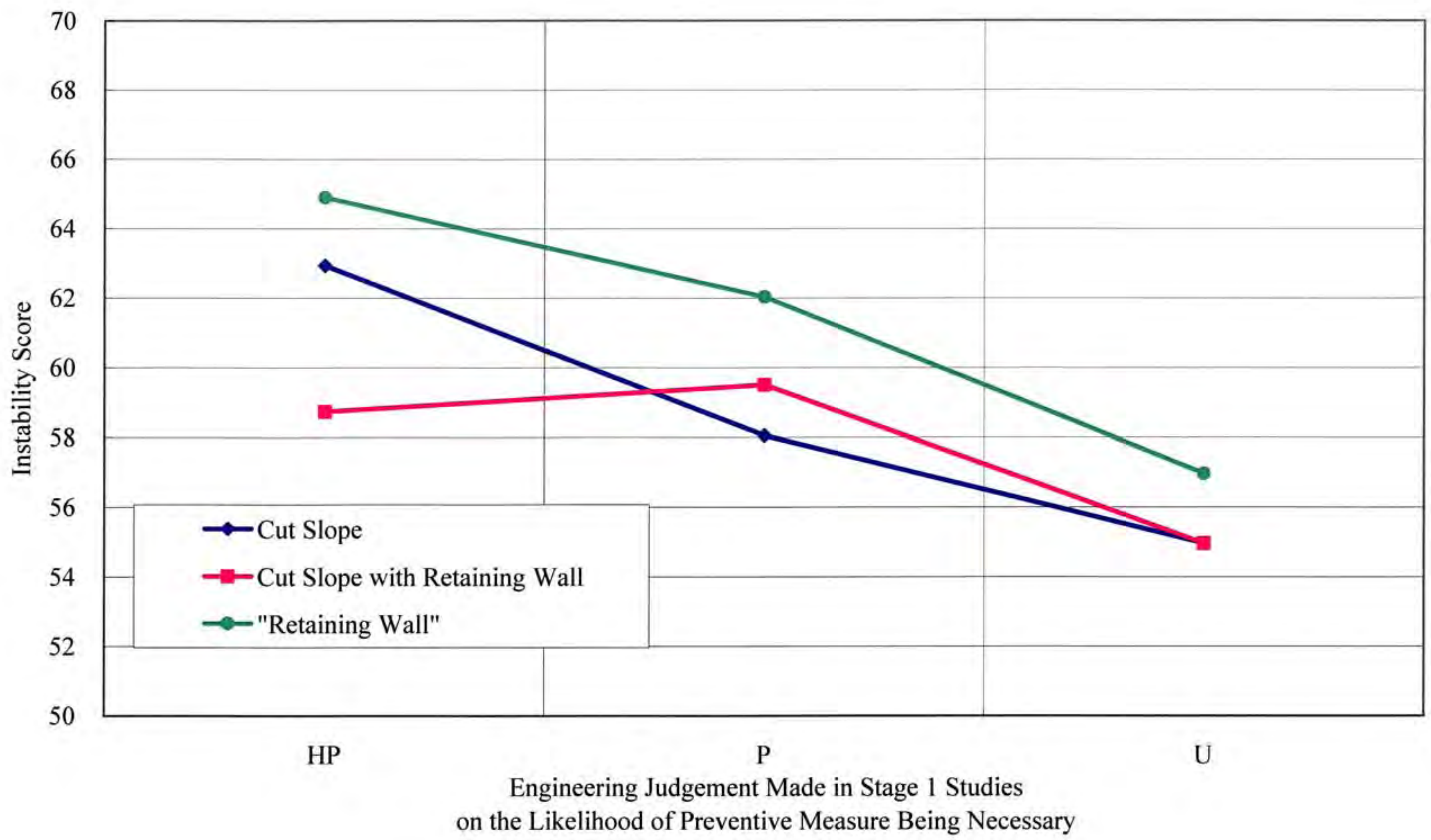

Notes: (1) Mean values of B&P Instability Scores are plotted.
(2) HP stands for highly probable, P for probable and U for unlikely.

Figure 3.6 - Comparison of Instability Scores and Likelihood Classes of the Cut Slope Scoring System, Hong Kong (Wong & Ho, 1995)

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Slope No. ____________________ **Section** : ○ 1-1 (Most Severe Consequence) ○ 2-2 (Maximum Feature Height)

(A) GEOMETRY (Figure A1)

		1-1	2-2
(i)	H_s	m	m
(ii)	H_r	m	m
(iii)	H_{cw}	m	m
(iv)	H_{tw}	m	m
(v)	β	°	°
(vi)	θ	°	°
(vii)	α	°	°
(viii)	Toe of realistic slip surface within Hs portion	Yes/No*	Yes/No*

· Feature Height, H $= H_s + H_r + H_{cw} + H_{tw}$ [m]

· $H_w = H_{cw} + H_{tw}$ [m]

· $H_c = H_s + H_r$ [m]

· $H_o = H_s + H_{cw}$ (see Figure 3.8) [m]

· $H_e = H_o\,(1 + 0.35 \tan\beta) + \frac{s}{\gamma_b}$ [m]

· Geometry Classification (Figure 3.8)

S1/S2/S3/S4*

Feature Type [ ]

For		
S1	A	=60
S2		40
S3		20
S4		0

A [ ]

(B) EVIDENCE OF INSTABILITY

(B1) Signs of Distress

(i) Severe signs of distress, e.g. large tension cracks behind crest, distortion of channels and berms, severe cracking or bulging ○

(ii) Minor signs of distress, e.g. cracked chunam, damaged channels ○

(iii) Reasonable condition (including minor random cracks on surface cover) ○

For		
(i)	B1	=40
(ii)		20
(iii)		0

B1 [ ]

(B2) Past Instability

Confirmed Past Instability	B21	Inferred Past Instability	B22
○ Major	40	○ Major	30
○ Multiple Minor	20	○ Multiple Minor	15
○ Minor	10	○ Minor	5
○ None	0	○ None	0

B2 = B21 or B22, whichever is the greater

B2 [ ]

(C) POTENTIAL FOR WATER INGRESS

(C1) Water Ingress through Surface

(i) Soil slope and crest area substantially unprotected ○

(ii) Either soil slope or crest area substantially unprotected ○

(iii) Either soil slope or crest area or both are partially protected but none of them substantially unprotected ○

(iv) Soil slope and crest area substantially protected ○

For		
(i)	C1	=15
(ii)		10
(iii)		5
(iv)		0

C1 [ ]

Figure 3.7 - Scoring Scheme of Soil Cut Slope Priority Classification System, Hong Kong (Wong & Ho, 1995) (Sheet 1 of 4)

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(C2) Drainage Provisions for Surface Water

			For
(i)	Few or no channels + potential for convergent flow of surface water above crest	○	(i) C2 = 15
(ii)	Few or no channels	○	(ii) 10
(iii)	Some channels but insufficient in size or number	○	(iii) 5
(iv)	Adequate channels	○	(iv) 0

C2	

(C3) Water-carrying Services

			For
(i)	Presence of potentially leaky services and signs of leakage noted	○	(i) C3 = 15
(ii)	Presence of potentially leaky services but no signs of leakage noted	○	(ii) 10
(iii)	No potentially leaky services	○	(iii) 0

C3	

(C4) Seepage

			For
(i)	Heavy seepage at mid-height of H_o or above	○	(i) C4 = 15
(ii)	Slight to moderate seepage at mid-height of H_o or above, or heavy seepage below mid-height of H_o	○	(ii) 10
(iii)	Slight to moderate seepage below mid-height of H_o, or signs of seepage at soil slope or crest wall	○	(iii) 5
(iv)	No signs of seepage	○	(iv) 0

C4	

(D) NATURE OF SLOPE-FORMING MATERIAL

Slope-forming Material (Soil Slope)		Weighting Factor, W_i
(i) Good	- saprolite derived from granitic and volcanic rocks, mainly composed of Grade IV material	
(ii) Uncertain-A	- not certain but expected to be between Good and Moderate material	
(iii) Moderate	- saprolite derived from granitic and volcanic rocks, mainly composed of Grade V material; saprolite of any grade of decomposition derived from rocks other than granite and volcanics; Pleistocene colluvium (Qpd on geological map)	
(iv) Uncertain-B	- not certain but expected to be between Moderate and Poor Material; not certain and can be any material.	
(v) Poor	- residual soil; all transported soils except Pleistocene colluvium	

Material	Score, D_i
Good	0
Uncertain-A	10
Moderate	20
Uncertain-B	30
Poor	40

$D = \Sigma(D_i)(W_i) / \Sigma(W_i)$

D	

Lithology: Typical Granite or Volcanics / Atypical Granite or Volcanics / Other*

Adverse Geological Features: Yes/No*

(E) ENGINEERING JUDGEMENT

Engineering judgement on the likelihood of preventive measures being necessary :

			For
(i)	Highly Probable (HP)	○	(i) E = 60
(ii)	Probable (P)	○	(ii) 30
(iii)	Unlikely (U)	○	(iii) 0

E	

Figure 3.7 - Scoring Scheme of Soil Cut Slope Priority Classification System, Hong Kong (Wong & Ho, 1995) (Sheet 2 of 4)

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(F) FACILITIES ABOVE CREST OF FEATURE

Type of crest facility
(For roads and footpaths, give also the name)

Group No.

Distance from crest of feature to the facility, F2

m

Group	F1 =
1	4
2	2
3	1
4	0.5
5	0.1

F1

F2

(G) FACILITY BELOW CREST OF FEATURE

Type of toe facility
(for roads and footpaths, give also the name)

Group No.

Distance from the toe of the feature to the facility, G2
(for facility on the feature, G2 = 0)

m

Group	G1 =
1	4
2	2
3	1
4	0.5
5	0.1

G1

G2

(J) UPSLOPE AND DOWNSLOPE TOPOGRAPHY

(i) Upslope angle β above crest $< 35°$ & downslope angle α below toe $< 15°$ ○
(ii) Upslope angle β above crest $\geq 35°$ ○
(iii) Downslope angle α below toe : $15° \leq \alpha < 30°$ ○
(iv) Downslope angle α below toe $\geq 30°$ ○
(v) Conditions (ii) & (iii) ○
(vi) Conditions (ii) & (iv) ○

For	J =
(i)	0
(ii)	0.3
(iii)	0.6
(iv)	1.2
(v)	0.9
(vi)	1.5

J

(K) CONSEQUENCE FACTOR

Priority Group No.
from Stage 1 Study (if available)

Consequence-to-life category
(i) "1" ○
(ii) "2" ○
(iii) "3" ○

Consequence factor is used if a large number of fatalities, say more than 10, will result from the landslip. The following conditions are typical for such situation :

(a) the Consequence-to-life Category of the feature is "1" or "2", ○
(b) large volume of failure is expected, and ○
(c) occupied buildings may collapse or be covered in the event of landslip, or mass transportation is seriously affected. ○

If large number of casualty will result in the event of a failure (e.g. conditions (a), (b) & (c) apply), K = 1.25
Otherwise, K = 1.0

K

Figure 3.7 - Scoring Scheme of Soil Cut Slope Priority Classification System, Hong Kong (Wong & Ho, 1995) (Sheet 3 of 4)

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CALCULATED SCORES AND WARNING MESSAGES

REVISED INSTABILITY SCORE (I.S.)

I.S. = A + B1 + B2 + C1 + C2 + C3 + C4 + D + E | I.S. | |

REVISED CONSEQUENCE SCORE (C.S.)

C.S. = K (F + GJ) V | C.S. | |

where :

$$F = F_1 \left[\frac{H_o - F_2}{H_o} \right] \nless 0$$

$$GJ = 2G_1 \left[\frac{(1.5+J)H - G_2}{(1.5+J)H} \right] \nless 0$$

$$V = \gamma H_o$$

Notes: (1) γ = 1.0 for full-scale failure

= 0.7 for partial failure

= 0.4 for minor failure

(2) If $H_o > 30$ m, take $H_o = 30$ m in calculating V

REVISED TOTAL SCORE (T.S.)

T.S. = (I.S.) (C.S.) / 100 | T.S. | |

WARNING MESSAGES

W1 = Warning, if H of Section 1-1 < 75% of H of Section 2-2.	W1	
W2 = Warning, if Item (A)(viii) is "No".	W2	
W3 = Warning, if $H_{cw} > H_s/3$.	W3	
W4 = Warning, if E = 0 and (A + B1 + B2 + C1 + C2 + C3 + C4 + D) ≥ 90, or if E = 60 and (A + B1 + B2 + C1 + C2 + C3 + C4 + D) ≤ 60.	W4	
W5 = Warning, if C.S. ≤ 20 and Priority Group = 1 or 2, or if C.S. ≤ 20 and Consequence-to-life Category = "1".	W5	
W6 = Warning, if slope reinforcement is present.	W6	
W7 = Warning, if feature is "post-GCO".	W7	
W8 = Warning, if lithology is not "Typical Granite or Volcanics" or adverse geological features are observed	W8	

Figure 3.7 - Scoring Scheme of Soil Cut Slope Priority Classification System, Hong Kong (Wong & Ho, 1995) (Sheet 4 of 4)

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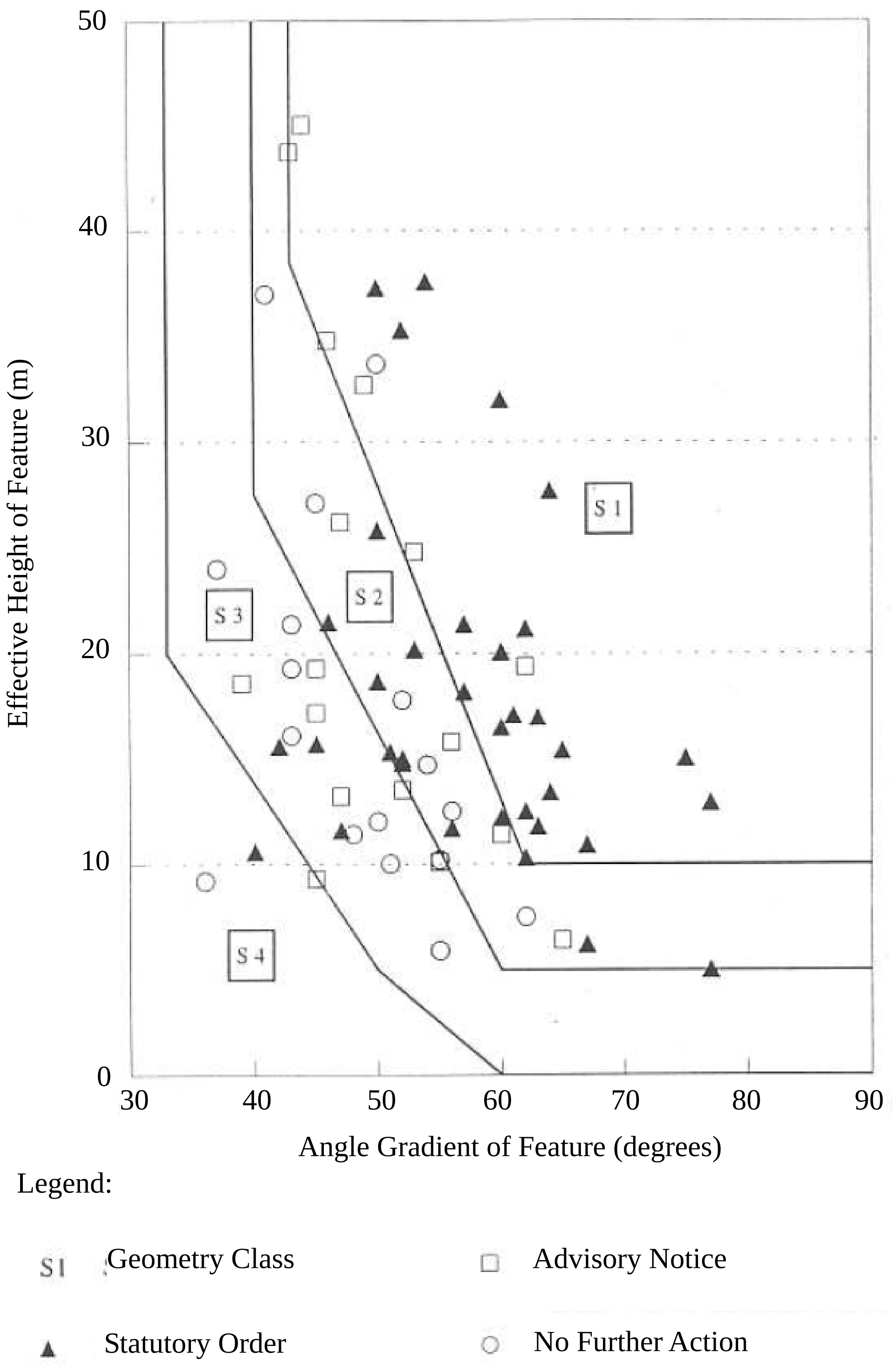

Figure 3.8 - Cut Slope Geometry Classification (Wong & Ho, 1995)

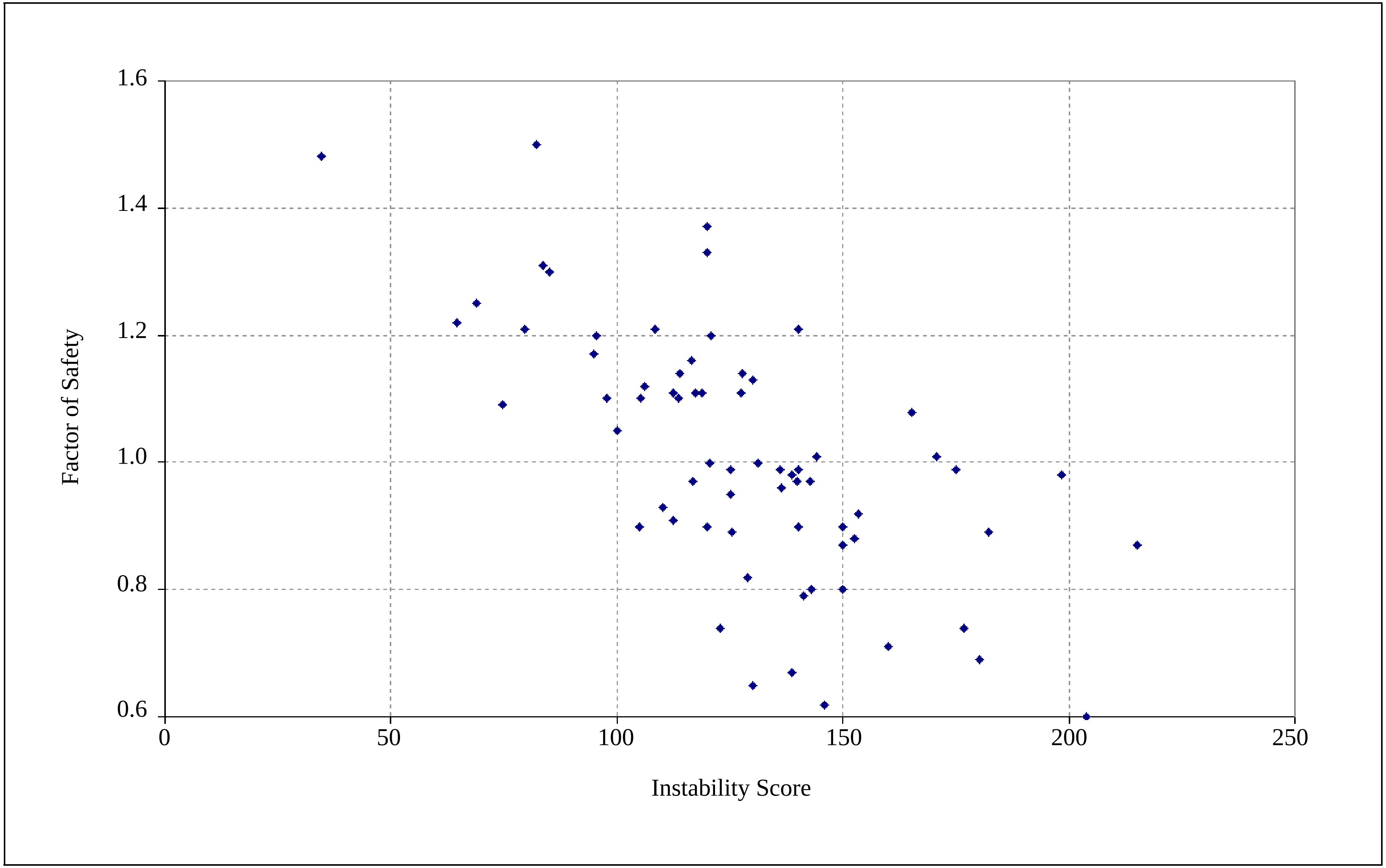

Figure 3.9 - Correlation between Instability Score and Calculated Factor of Safety of Soil Cut Slopes (Wong & Ho, 1995)

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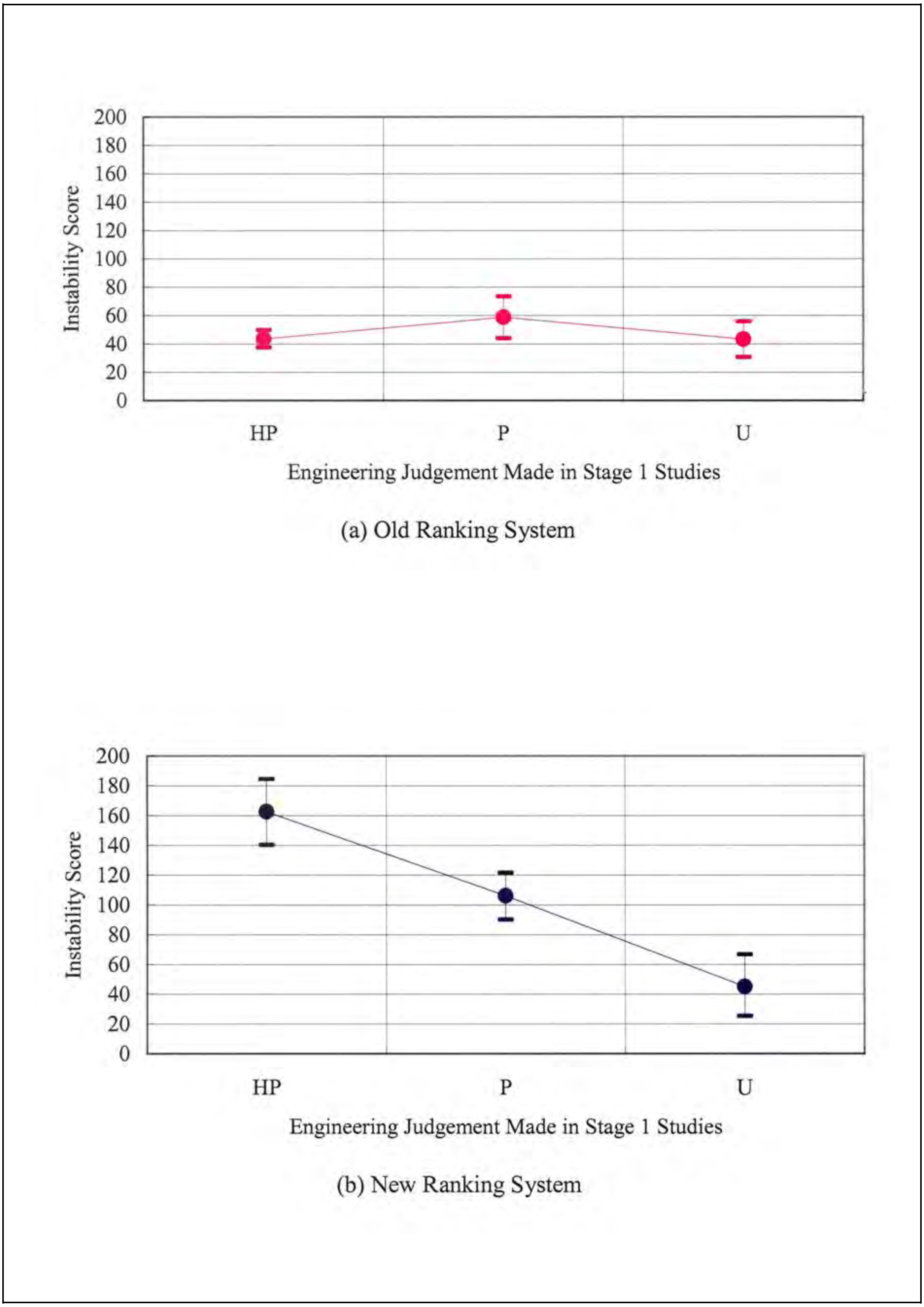

Figure 3.10 - Correlation of Engineering Judgment with Instability Score Calculated by the New and Old Ranking Systems (Wong & Ho, 1995)

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INSTABILITY FACTORS

Factor	Categories and Description	Score
SLOPE GEOMETRY		
(A1) Overall Height of Rock Cut (H)	1) $0 < H \leq 5$ m 2) $5 < H \leq 10$ m 3) $10 < H \leq 15$ m 4) $15 < H \leq 20$ m 5) $H > 20$	5 10 25 35 40
(A2) Overall Angle of Rock Cut (θ)	1) $\theta < 45°$ 2) $45° < \theta \leq 60°$ 3) $60° < \theta \leq 70°$ 4) $70° < \theta \leq 80°$ 5) $\theta > 80°$	5 10 25 35 40
(A3) Presence of concentrated Surcharge Load at Crest	Note the form of concentrated surcharge (i.e. building footing, caissons, etc.)	
MODE OF SLOPE FAILURE		
(B1) Ravelling	Discontinuities favourably oriented with respect to slope face. Slope failure limited to individual overhanging blocks or isolated loose blocks (< 5 m^3) falling off slope face.	3.0
(B2) Toppling	Dominant discontinuity set dips into the slope face. Orthogonal cross discontinuities in combination with the dominant set produce blocks which could topple from the slope.	3.0
(B3) Planar Failure	1) Dominant discontinuity set strikes sub-parallel to slope face and daylight into slope; shallow dipping discontinuities. 2) Dominant discontinuity set strikes sub-parallel to slope face and daylight into slope; moderately dipping discontinuities. 3) Dominant discontinuity set strikes sub-parallel to slope face and daylight into slope, steeply dipping discontinuities.	0.75 3.0 5.0
(B4) Wedge Failure	1) Two dominant discontinuity sets daylight and strike obliquely into slope face; shallow dipping discontinuity intersection. 2) Two dominant discontinuity sets daylight and strike obliquely into slope face; moderately dipping discontinuity intersection. 3) Two dominant discontinuity sets daylight and strike obliquely into slope face; steeply dipping discontinuity intersection.	0.5 2.0 4.0
ROCK MASS CONDITION		
(C1) Discontinuity Spacing of Rock Mass	1) Average Discontinuity Spacing $\geq$ 2 m 2) 1 $\leq$ Average Discontinuity Spacing < 2 m 3) 0.5 $\leq$ Average Discontinuity Spacing < 1 m 4) 0.2 $\leq$ Average Discontinuity Spacing < 0.5 m 5) Average Discontinuity Spacing < 0.2 m	0 5 10 20 30

Figure 3.11 - Scoring Scheme of Rock Slope Priority Classification System, Hong Kong (Golder Associates, 1996) (Sheet 1 of 4)

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INSTABILITY FACTORS (Continued)

Factor	Categories and Description	Score	
(C2) Discontinuity Roughness and Infilling	1) Rough, tight, unweathered or slightly weathered. 2) Slightly rough, aperture < 1mm, open. 3) Slightly rough, aperture 1 to 5 mm, open. 4) Slightly rough, aperture < 1mm, weak, soft, infilling 5) Smooth, aperture 1 to 5mm, weak, soft, infilling. 6) Smooth, aperture > 5mm, weak, soft infilling. Note: **Ravelling Failure**, maximum value for C2 = 10 **Toppling Failure**, maximum value for C2 = 20	0 10 20 30 40 50	
		Toppling /Planar	Wedge
(C3) Persistence of Discontinuity	1) Persistent 2) Sub-Presistent 3) Non-Persistent	30 15 0	10 5 0
(C4) Rock Lithology + Nature of Discontinuity	Note the dominant lithology of the rock cut (Granite, Granodiorite, Volcanics etc.) Note the nature of dominant discontinuities (Fault Zone, Fault, Joint, Cleavage, Schistosity, Shear Plane, Fissure, Tension Crack, Foliation,Bedding)		
POTENTIAL FOR WATER INGRESS			
(D1) Drainage Provisions	1) Drainage measures adequately direct water away from the crest and face of the slope. 2) Drainage measures insufficient in size or extent to direct water away from crest and face of slope. 3) No drainage measures in place to direct water away from the crest and face of the slope. 4) Potential for convergence of runoff at crest and/or potential for water ingress into open discontinuities.	0 5 10 15	
(D2) Seepage Conditions	1) No sign of seepage from discontinuities. 2) Slight to moderate seepage from isolated rock discontinuities. 3) Slight to moderate seepage from several rock discontinuities or heavy seepage from isolated rock discontinuities. 4) Heavy seepage from several rock discontinuities.	0 5 10 15	
EVIDENCE OF DISTRESS/PAST FAILURE			
(E1) Signs of Distress	1) No evidence of surficial loosening. 2) Localised surficial loosening, or small overhanging blocks. 3) Surficial loosening and small overhanging blocks in several areas of slope. 4) Tension cracks exist along crest of slope. 5) Large overhanging blocks with potential release surfaces visible.	0 5 15 25 30	
(E2) Evidence of Past Instability	1) No recorded or observed evidence of past instability. 2) Observed evidence of past instability (rock blocks and fragments accumulated at toe of slope). 3) Documented evidence of past instability - minor rockfall (volume < 50 m^3). 4) Documented evidence of past instability - major rockfall (volume ≥ 50 m^3).	0 10 30 40	

Figure 3.11 - Scoring Scheme of Rock Slope Priority Classification System, Hong Kong (Golder Associates, 1996) (Sheet 2 of 4)

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CONSEQUENCE FACTORS

Factor	Categories and Description	Score
ENGINEERING JUDGEMENT		
(EJ) Potential for Failure to Occur	1) Low potential for failure 2) Moderate potential for failure 3) High potential for failure	0 10 30
FACILITY ABOVE CREST OF SLOPE		
(F1) Grouping of Facility Above Crest Type of Facility: (Road, Footpath, Building, give name)	1) Group 1 (Indicate Type of Facility) 2) Group 2 (Indicate Type of Facility) 3) Group 3 (Indicate Type of Facility) 4) Group 4 (Indicate Type of Facility) 5) Group 5 (Indicate Type of Facility)	4 2 1 0.5 0.1
(F2) Distance from slope crest to facility (m)		
FACILITY BELOW CREST OF SLOPE		
(G1) Grouping of Facility Below Toe Type of Facility: (Road, Footpath, Building, give name)	1) Group 1 (Indicate Type of Facility) 2) Group 2 (Indicate Type of Facility) 3) Group 3 (Indicate Type of Facility) 4) Group 4 (Indicate Type of Facility) 5) Group 5 (Indicate Type of Facility)	4 2 1 0.5 0.1
(G2) Distance from slope toe to facility (m) Note: For facility on the slope face, G2 = 0		
UPSLOPE AND DOWNSLOPE TOPOGRAPHY		
(J) Topography above and below rock slope.	1) Upslope angle < 35° Downslope angle < 15°	0
	2) Upslope angle ≥ 35° Downslope angle < 15°	0.3
	3) Upslope angle < 35° 15° ≤ Downslope angle < 30°	0.6
	4) Upslope angle < 35° Downslope angle ≥ 30°	1.2
	5) Upslope angle > 35° 15° ≤ Downslope angle < 30°	0.9
	6) Upslope angle > 35° Downslope angle ≥ 30°	1.5
LIKELY SCALE OF FAILURE		
(K) Size of Failure	1) Individual Blocks (Volume < 5 m^3) 2) Minor (5 m^3 ≤ Volume < 50 m^3) 3) Moderate (50 m^3 ≤ Volume < 500 m^3) 4) Major (Volume ≥ 500 m^3)	0.1 0.3 0.7 1.0
VULNERABILITY (CONSEQUENCE FACTOR)		
(V) Consequence Factor	1) The Consequence-to-life Category of the feature is "1" or "2", large volume of failure is expected, and occupied building may collapse or be covered in the event of landslip, or mass transportation is seriously affected. 2) Other cases	1.25 1.0

Figure 3.11 - Scoring Scheme of Rock Slope Priority Classification System, Hong Kong (Golder Associates, 1996) (Sheet 3 of 4)

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NEW PRIORITY CLASSIFICATION SYSTEM FOR ROCK CUT SLOPES

CALCULATION OF SCORES

Instability Score for Failure Mode i ($I.S._i$)

$$I.S._i = (A1 + A2) + B \times (C1 + C2 + C3 + D1 + D2) + (E1 + E2) + (EJ)$$

Notes: (1) For Ravelling Failure, maximum value of C2 = 10.
(2) For Toppling Failure, maximum value of C2 = 20.

Consequence Score for Failure Mode i ($C.S._i$)

$$C.S._i = K (F + G) H \times V$$

where: $F = F1 \left(\dfrac{\alpha H - F2}{\alpha H} \right)$; $G = 2\,G1 \left(\dfrac{\beta H - G2}{\beta H} \right)$;

Notes: (1) If **H** > 30 m; **H** = 30 for all the consequence formulae.
(2) If **F** or **G** is negative it will be assigned zero value.

The parameters α and β can be determined from anticipated scale of failure (K) and upslope and downslope topography (J) using the table below:

		K = 0.1	K = 0.3	K = 0.7	K = 1.0
α		0.5	0.8	1.0	1.2
β	J = 0.0	0.5	1.0	1.3	1.5
	J = 0.3	0.6	1.2	1.5	1.8
	J = 0.6	0.7	1.4	1.7	2.1
	J = 1.2	0.9	1.8	2.3	2.7
	J = 0.9	0.8	1.6	2.0	2.4
	J = 1.5	1.0	2.0	2.6	3.0

Total Score for the Feature (T.S.)

$$T.S. = \sum_{i=1}^{N} \frac{I.S._i \; C.S._i}{100}$$

where N is the number of failure modes observed for the feature.

Figure 3.11 - Scoring Scheme of Rock Slope Priority Classification System, Hong Kong (Golder Associates, 1996) (Sheet 4 of 4)

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Slope Data

Slope No. :	SIFT No. :	SIFT Class :
Slope Height, H = ______ m Slope Angle, θ = ______ °	Crest Wall Height, H_{wc} = ______ m Toe Wall Height, H_{wt} = ______ m	
SIFT Section Profile No.	Part of Larger Fill Body : Yes / No	

Instability Score (IS)

Sliding (IS_1 = a.b.c.d.e.f.g =)

(a) Geometry (From Figure C1)
S1 = 32
S2 = 16
S3 = 8
S4 = 4
S5 = 2
S6 = 1

(b) Type of Surface Cover
Bare = 4
Vegetated = 3
Chunam = 1.5
Shotcrete = 1

(c) Surface Drainage Provision
No = 2
Yes = 1

(d) Signs of Seepage
Yes = 2
No = 1

(e) Potential Leaking Services
Leaking = 2
Presence = 1.5
None = 1

(f) Past Instability
Major = 8
Minor = 2
No = 1

(g) Signs of Distress
Yes = 4
No = 1

Liquefaction (IS_2 = ¼.IS_1.h.i =)

(h) Slope Height
≥30 m = 4
≥20 - <30 = 3
≥10 - <20 = 1
<10 m = 0.5

(i) Type of Surface Cover
Bare = 1.1
Vegetated = 1.1
Chunam = 0.5
Shotcrete = 0.25

Major Washout ($IS_3 = (IS_1)^{1/3}$ .j.k.l.m.n.o.p.q =)

(j) Catchment Characteristics : Topographic Setting and Size of Catchment

Topographic Setting	Size of Catchment (m^2) ≤100	100 - 500	500 - 1000	1000 - 10000	>10000
Traverse Drainage Line	2	4	8	16	32
Adjacent Drainage Line	2	3	6	12	24
Traverse Topographic Depression	1	2	4	8	16
Adjacent Topographic Depression	1	2	3	6	12
Planar Slope	0.5	1	3	5	10
Spur	0.5	1	2	4	8

(k) Type of Crest Facility

Road	Platform & Urban development	Catch-water	Minor Development eg. Rural Footpath	Natural
1.0	0.5	0.25	0.10	0.05

(l) Volume of Fill Body (m^3)

≤100	100 - 500	500 - 1000	1000 - 10000	>10000
0.10	0.25	0.5	1	2

(m) Channelisation of Debris — Yes = 2.0, No = 0.5

(n) Erosion and Entrainment along Debris Trail — Yes = 2.0, No = 1.0

(o) Spread of Debris — Yes = 0.5, No = 1.0

(p) Unstable Terrain — Yes = 2.0, No = 1.0

(q) Masonry Wall at Crest

Wall Height ≥ 3 m	2.0
Wall Height < 3 m	1.5
No Masonry Wall	1.0

Consequence Score (CS)

Facility	Type	Group No.	Proximity			K	L	V: V_1	V_2	V_3	C = H * K * L * V / 10: C_1	C_2	C_3
Toe (1)			α =										
Toe (2)			α =										
Crest (1)			<3 m	3 - 6 m	6 - 10 m								
Crest (2)			<3 m	3 - 6 m	6 - 10 m								
										CS = ΣC			

Total Score (TS)

$S = \sum_{1}^{3} [IS_i CS_i]$	$TS = \log_{10}(S) =$

Warning Messages : W1, W2, W3, W4 & W5

Figure 3.12 - Scoring Scheme of Fill Slope Priority Classification System, Hong Kong (Wong, 1996)

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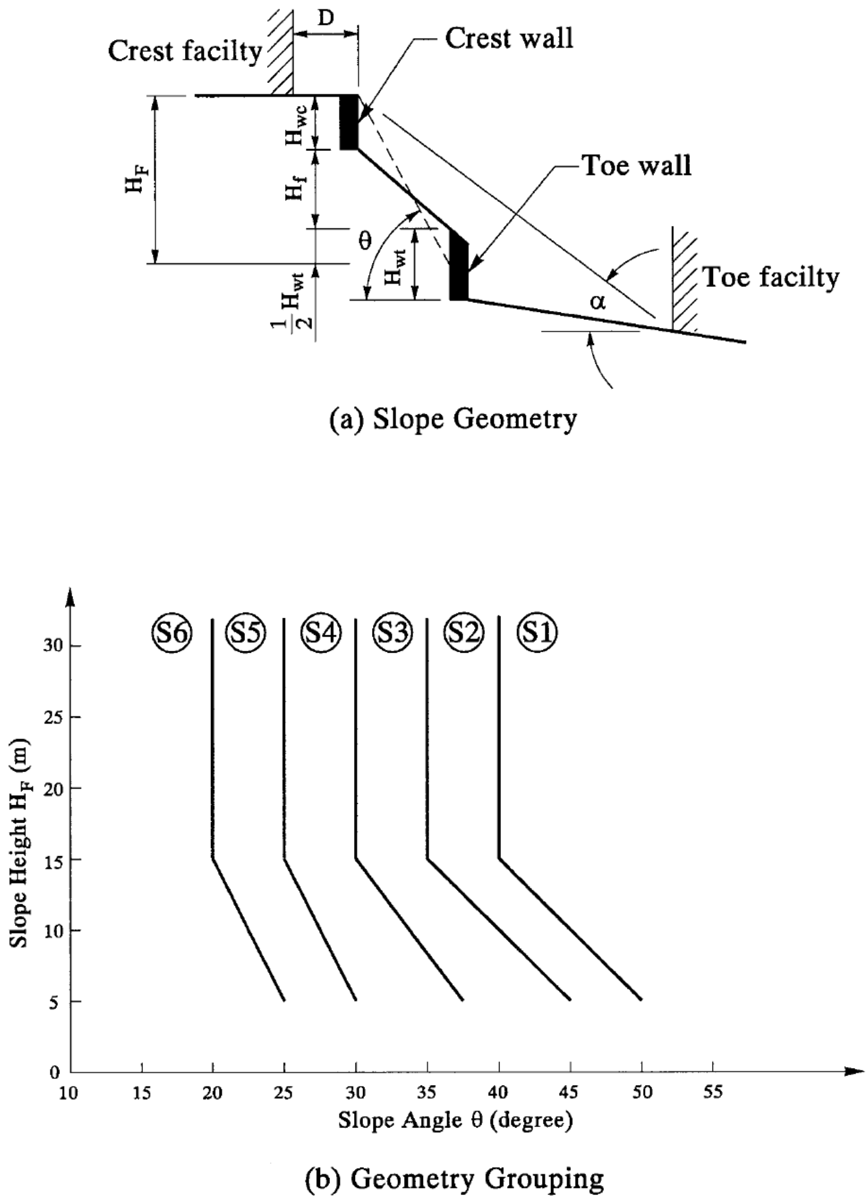

Notes : (1) For a slope with geometry at the dividing line between two categories, the slope is taken to be within the less severe cateogory.

(2) If the toe wall is not retaining the fill body, use $H_F = H_{wc} + H_f$.

Figure 3.13 - Slope Geometry Grouping for Fill Slope Priority Classification System, Hong Kong (Wong, 1996)

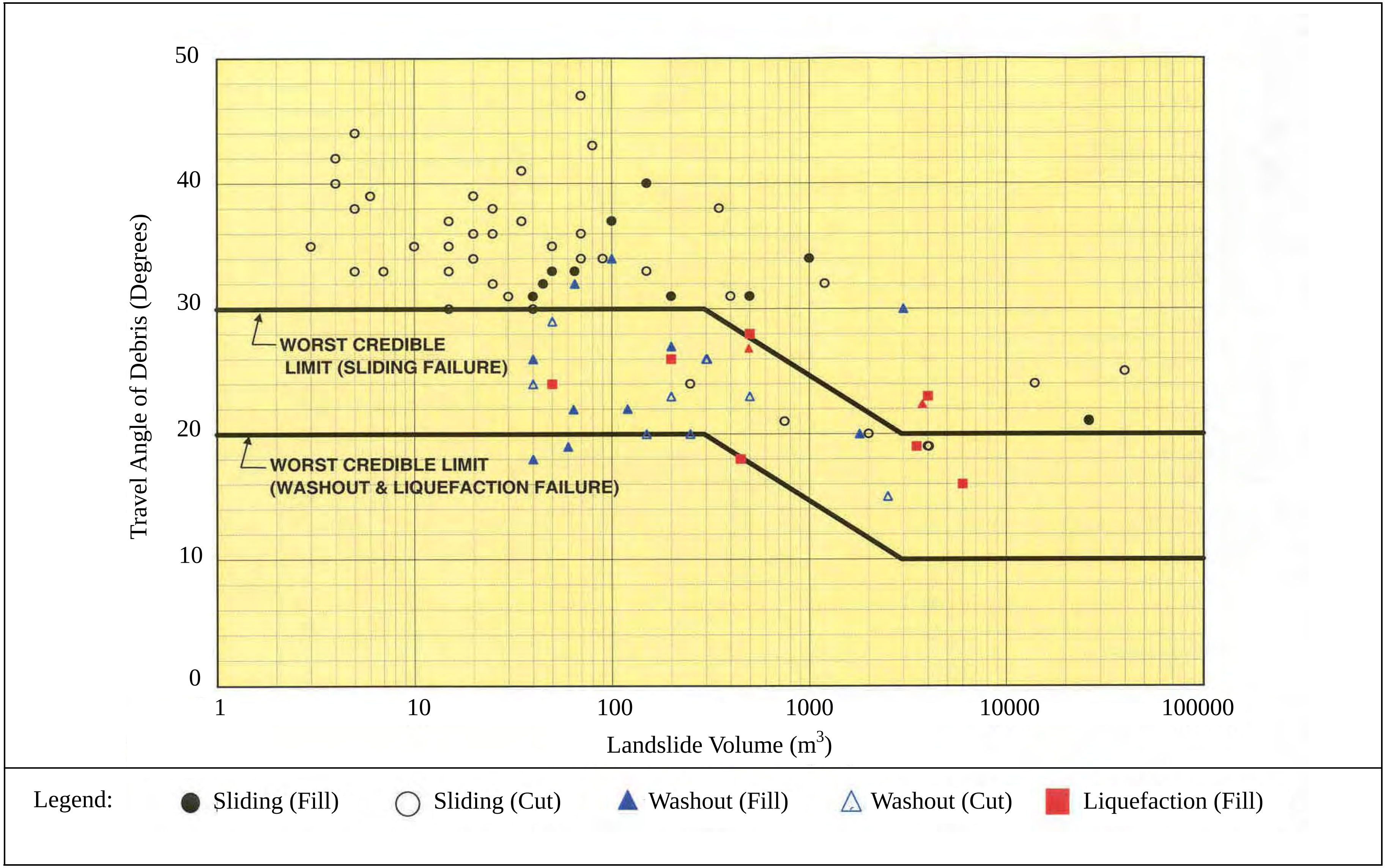

Figure 3.14 - Worst Credible Limits of Debris Mobility Adopted for Different Mechanism of Fill Slope Failure (Wong, 1996)

Wall No. ____________________ **Section :** ○ 1-1 (Most Severe Consequence)
○ 2-2 (Maximum Feature Height)

(A) GEOMETRY (Figure D1)

		1-1	2-2
(i)	H_w	m	m
(ii)	H_r	m	m
(iii)	H_s	m	m
(iv)	β	°	°
(v)	θ_f	°	°
(vi)	α	°	°
(vii)	Surcharge at crest of wall, s	kPa	kPa
(viii)	$\frac{H_e}{B_w}$ =		
(ix)	In the case of multiple walls, θ =	°	°

· Feature Height, H

$= H_s + H_r + H_w$ [m]

· Effective Height

$H_e = H_w (1 + 0.35 \tan \beta) + \frac{s}{20}$

[m]

(B) WALL SLENDERNESS RATIO ($\frac{H_e}{B_w}$)

(i)	$4.2 < \frac{H_e}{B_w} \leq 5$	○	For (i) B = 100
(ii)	$3.5 < \frac{H_e}{B_w} \leq 4.2$	○	(ii) 75
(iii)	$2.8 < \frac{H_e}{B_w} \leq 3.5$	○	(iii) 50
(iv)	$2.0 < \frac{H_e}{B_w} \leq 2.8$	○	(iv) 25
(v)	$\frac{H_e}{B_w} < 2.0$	○	(v) 0
			B [ ]
(vi)	Is $\frac{H_e}{B_w} > 5$	○	Yes/No*

(C) WALL CONDITION

(i)	Advanced stage of severe deformation and/or distress	○	For (i) C= 100
(ii)	Onset of severe deformation and/or distress	○	(ii) 70
(iii)	Moderate deformation and/or distress	○	(iii) 30
(iv)	Minimal deformation and distress	○	(iv) 0
			C [ ]

(D) NATURE OF RETAINED MATERIAL

(i)	Fill or unknown	○	For (i) D = 1.0
(ii)	Colluvium, residual soil, PW 0/30 or PW 30/50 rock mass	○	(ii) 0.7
			D [ ]

Figure 3.15 - Scoring Scheme of Retaining Wall Priority Classification System, Hong Kong (Wong, 1998) (Sheet 1 of 5)

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(E) POTENTIAL FOR WATER INGRESS		
(E1) Water Ingress through Surface		For (i) E1 = 15 (ii) 10 (iii) 0
(i) Crest area substantially unprotected	○	
(ii) Crest area partially protected	○	
(iii) Crest area substantially protected	○	E1 [ ]
(E2) Drainage Provisions for Surface Water		For (i) E2 = 15 (ii) 10 (iii) 5 (iv) 0
(i) Few or no channels above wall crest plus potential for convergent flow of surface water towards the wall	○	
(ii) Few or no channels above wall crest	○	
(iii) Some channels above wall crest but insufficient in size and/or number	○	E2 [ ]
(iv) Adequate channels above wall crest	○	
(E3) Water-carrying Services		For (i) E3 = 15 (ii) 10 (iii) 0
(i) Presence of potentially leaky services and signs of leakage noted	○	E3 [ ]
(ii) Presence of potentially leaky services but no signs of leakage noted	○	
(iii) No potentially leaky services	○	
(E4) Seepage		For (i) E4 = 15 (ii) 10 (iii) 5 (iv) 0
(i) Heavy seepage at mid-height or above	○	
(ii) Slight to moderate seepage at mid-height or above, or heavy seepage below mid-height	○	
(iii) Slight to moderate seepage below mid-height, or signs of seepage on wall face	○	
(iv) No signs of seepage	○	
Form of wall drainage [Weepholes/Horizontal drains/Nil*]		E4 [ ]

(F) TYPE OF WALL		
(i) Random rubble masonry wall (with or without pointing) with no ties or horizontal beams	○	For (i) or (ii) F = 30 (iii) or (iv) or (v) or (vi) F = 20 (vii) or (viii) F = 10 (ix) or (x) F = 0
(ii) Random rubble masonry wall (with or without pointing) with ties or horizontal beams	○	
(iii) Wall composed of lime-stabilised soil	○	
(iv) Brick wall	○	
(v) Dry packed dressed block/squared rubble wall without ties	○	
(vi) Any type of masonry wall (except for random rubble walls) with horizontal beams made of lime-stabilised soil or brick	○	F [ ]
(vii) Dry packed dressed block/squared rubble wall with ties	○	
(viii) Any type of masonry wall (except for random rubble walls) with concrete horizontal beams	○	
(ix) Masonry facing to concrete wall	○	
(x) Concrete wall	○	
(xi) Others (Please specify : ______________)	○	
Evidence of the wall having been extended upwards in the past?		Yes/No*
Is wall of dry packed random rubble > 5 m		Yes/No*

Figure 3.15 - Scoring Scheme of Retaining Wall Priority Classification System, Hong Kong (Wong, 1998) (Sheet 2 of 5)

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(G) PAST INSTABILITY

Confirmed Past Instability	G1	Confirmed Past Instability	G2	G = G1 or G2, whichever is the greater
○ Full-height failure	30	○ Full-height failure	20	
○ Multiple part-height or structural failures	25	○ Multiple part-height or structural failures	15	
○ Part-height failure	20	○ Part-height failure	10	
○ Structural failure only	20	○ Structural failure only	10	G
○ None	0	○ None	0	

(J) AVERAGE GRADIENT OF NATURAL SLOPE BELOW WALL

		For	J
(i)	$\alpha > 35°$	(i)	= 60
(ii)	$25° < \alpha \leq 35°$	(ii)	30
(iii)	$15° < \alpha \leq 25°$	(iii)	15
(iv)	$\alpha \leq 15°$	(iv)	0

If there is no natural slope below wall, take J = 0

J

(K) FACILITY BELOW CREST OF FEATURE

Type of crest facility (for roads and footpaths, give also the name)

Group No.

Distance of facility from crest of feature, K_2 m

Group	K_1
1	= 4
2	2
3	1
4	0.5
5	0.1

K_1

K_2

(L) FACILITY BELOW TOE OF FEATURE

Type of toe facility (for roads and footpaths, give also the name

Group No.

Distance of facility from toe of feature, L_2 m

Group	L_1
1	= 4
2	2
3	1
4	0.5
5	0.1

L_1

L_2

(M) UPSLOPE AND DOWNSLOPE TOPOGRAPHY

			For	M
(i)	Upslope angle β above crest $< 35°$ & downslope angle α below toe $< 15°$	○	(i)	= 0
(ii)	Upslope angle β above crest $\geq 35°$	○	(ii)	0.3
(iii)	Downslope angle α below toe : $15° \leq \alpha < 30°$	○	(iii)	0.6
(iv)	Downslope angle α below toe $\geq 30°$	○	(iv)	1.2
(v)	Conditions (ii) & (iii)	○	(v)	0.9
(vi)	Conditions (ii) & (iv)	○	(vi)	1.5

M

Figure 3.15 - Scoring Scheme of Retaining Wall Priority Classification System, Hong Kong (Wong, 1998) (Sheet 3 of 5)

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(N) CONSEQUENCE FACTOR	
Consequence-to-life category (i) '1' ○ (ii) '2' ○ (iii) '3' ○ Consequence factor is used if a large number of fatalities, say more than 10, will result from the landslip. The following conditions are typical for such situation : (a) the Consequence-to-life Category of the feature is '1' or '2', ○ (b) large volume of failure is expected, and ○ (c) occupied buildings may collapse or be covered in the event of failure, or mass transportation is seriously affected. ○	If large number of casualty will result in the event of a failure (e.g. conditions (a), (b) & (c) apply), N = 1.25 Otherwise, N = 1.0 N [ ]

CALCULATED SCORES AND WARNING MESSAGES

INSTABILITY SCORE (I.S.)

I.S. = (B X D) + C + E1 + E2 + E3 + E4 + F + G + J

Notes: (a) If $\frac{H_e}{B_w} > 5$, take [(B x D) + C] to be 200 for all wall types

(b) If wall is of dry-packed random rubble of > 5 m, take C = 100

I.S. [ ]

CONSEQUENCE SCORE (C.S.)

C.S. = 2N (K + L*)V

C.S. [ ]

where :

$$K = K_1 \left[\frac{1.2H_w - K_2}{1.2H_w}\right] \nless 0$$

$$L^* = 2L_1 \left[\frac{(2+M)H - L_2}{(2+M)H}\right] \nless 0$$

$$V = \gamma H_w$$

Notes : (1) γ = 1.0 for full-scale failure
= 0.7 for partial failure
= 0.4 for minor failure

(2) If $H_w > 20$ m, take $H_w = 20$ m in calculating V.

TOTAL SCORE (T.S.)

T.S. = (I.S.) (C.S.) / 100

T.S. [ ]

WARNING MESSAGES

W1 = Warning, if the nature of retained material is PW 50/90 or better rock mass. W1 [ ]

W2 = Warning, if θ_f is < 75° W2 [ ]

W3 = Warning, if there is evidence of the wall having been extended upwards in the past. W3 [ ]

W4 = Warning, if muddy water indicating internal erosion is observed to be flowing out of the wall face. W4 [ ]

Figure 3.15 - Scoring Scheme of Retaining Wall Priority Classification System, Hong Kong (Wong, 1998) (Sheet 4 of 5)

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W5 = Warning, if H of Section 1-1 < 75% of H of Section 2-2.	W5
W6 = Warning, if reinforcement (e.g. soil nails) or other forms of support to the wall (e.g. buttresses, propping by buildings etc.) is present.	W6
W7 = Warning, if wall is "post-GCO".	W7
W8 = Warning, if wall belongs to "other" type that is not included in Item F.	W8
W9 = Warning, if there is a natural slope below the wall.	W9
W10 = Warning, if the feature is a SIFT Class A feature.	W10
W11 = Warning, if θ < 60° and individual walls are < 3 m in the case of a series of walls retaining a number of platforms	W11
W12 = Warning if wall slenderness ratio is greater than 5	W12

* Delete where appropriate

Figure 3.15 - Scoring Scheme of Retaining Wall Priority Classification System, Hong Kong (Wong, 1998) (Sheet 5 of 5)

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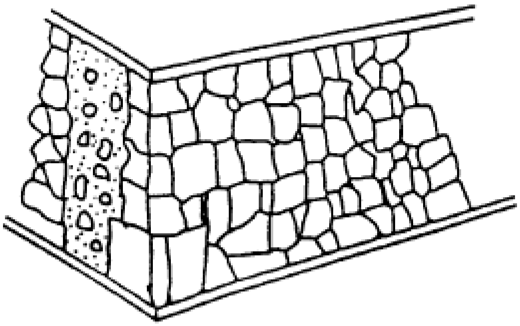
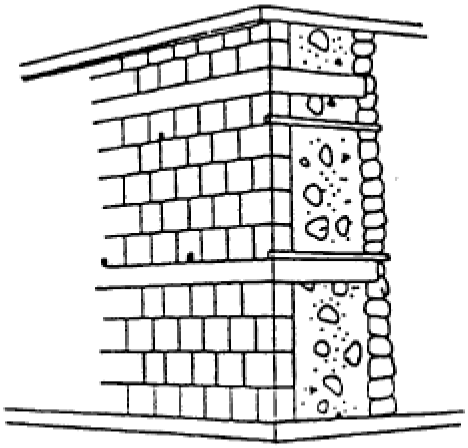
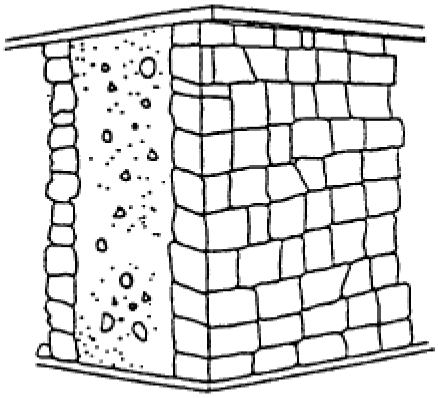


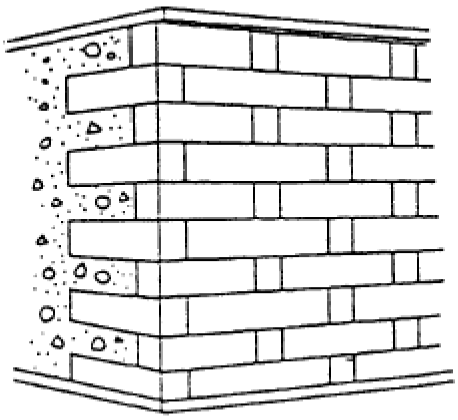
(a) Dry Packed Random Rubble Wall



(b) Dressed Block Wall with Horizontal Beams



(c) Dry Packed Squared Rubble Wall



(d) Tied Face Wall

Figure 3.16 - Typical Forms of Construction of Masonry Walls in Hong Kong (Chan, 1996)

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Plate 1 - Dry Packed Random Rubble Wall (11SW-A/R389)

Plate 2 - Pointed Random Rubble Wall (11SW-A/R116)

Plate 3 - Dry Packed Squared Rubble Wall (11SW-A/R109)

Plate 4 - Dry Packed Squared Rubble Wall with Horizontal Beams (11SW-A/R163)

Plate 5 - Pointed Squared Rubble Wall (11SW-A/R295)

Plate 6 - Pointed Squared Rubble Wall with Horizontal Beams (11SW-A/R194)

Figure 3.17 - Illustrative Examples of Different Types of Masonry Wall in Hong Kong (Chan, 1996) (Sheet 1 of 3)

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Plate 7 - Dressed Block Wall (11SW-A/R46)

Plate 8 - Dressed Block Wall with Horizontal Beams (11SW-A/R423)

Plate 9 - Tied Face Wall (11SW-A/R74)

Plate 10 - Tied Face Wall with Horizontal Beams (11SW-A/R45)

Plate 11 - Random Rubble Wall with Stone Ties

Plate 12 - Recent Masonry Walls

Figure 3.17 - Illustrative Examples of Different Types of Masonry Wall in Hong Kong (Chan, 1996) (Sheet 2 of 3)

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Plate 13 - Presence of Expansion Joints or Similar Construction Joints

Plate 14 - Special Architectural Features, such as Masonry Blocks with Irregular Pattern

Figure 3.17 - Illustrative Examples of Different Types of Masonry Wall in Hong Kong (Chan, 1996) (Sheet 3 of 3)

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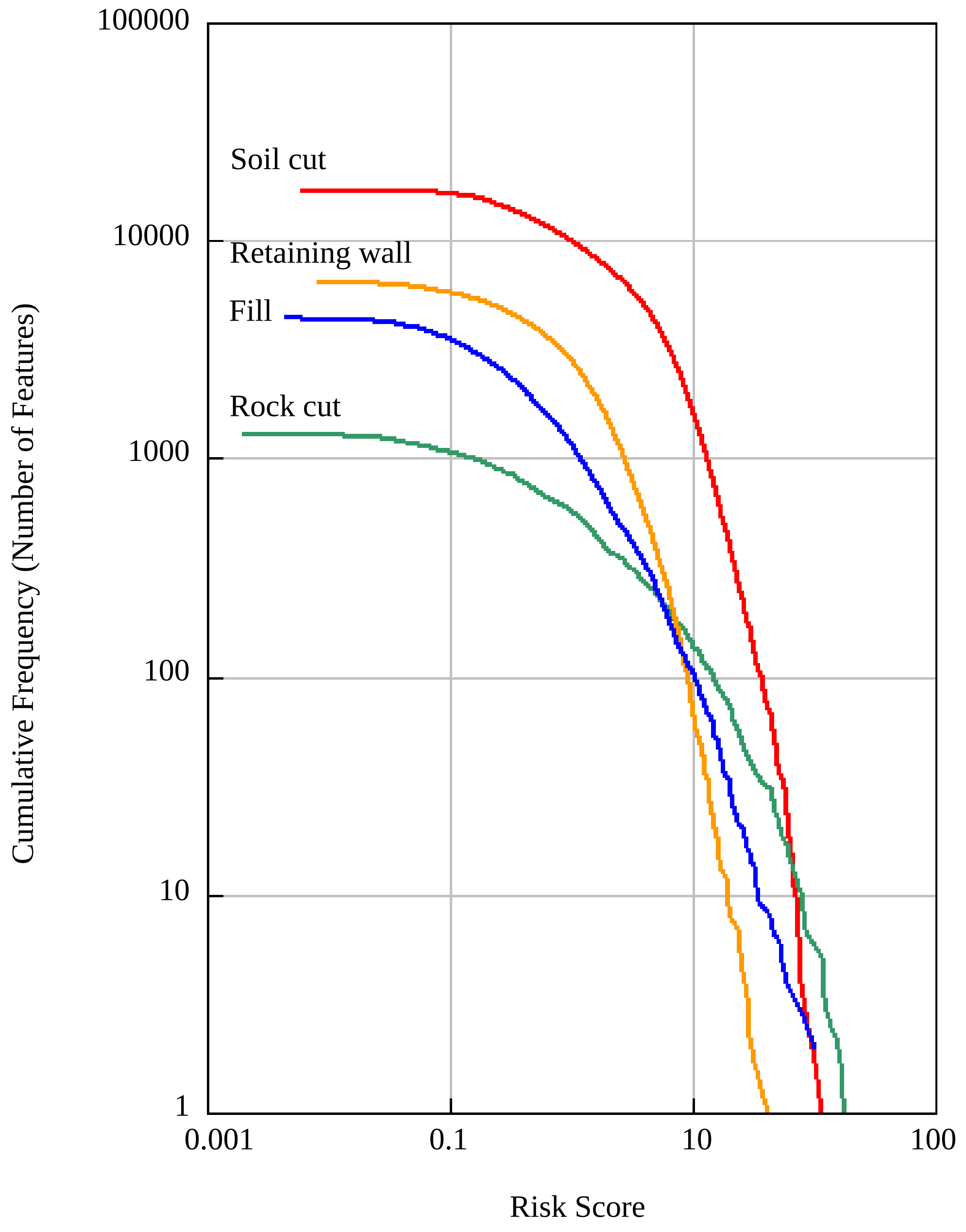

Figure 3.18 - Distribution of Risk Score of Different Slope Types in Hong Kong

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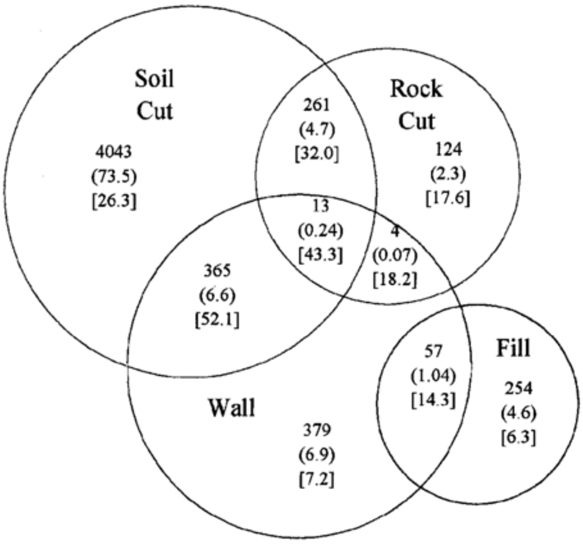

Notes: (1) Number in () denotes the percentage of the top 5,500 features, e.g. 4,043/5,500, for soil cuts.
(2) Number in [] denotes the percentage of the features of the same type, e.g. 4,043/number of soil cuts in the SIS, for soil cuts.

Figure 3.19 - Percentage of Different Slope Types within the 5,500 Top-ranking Pre-1977 Man-made Slopes in Hong Kong

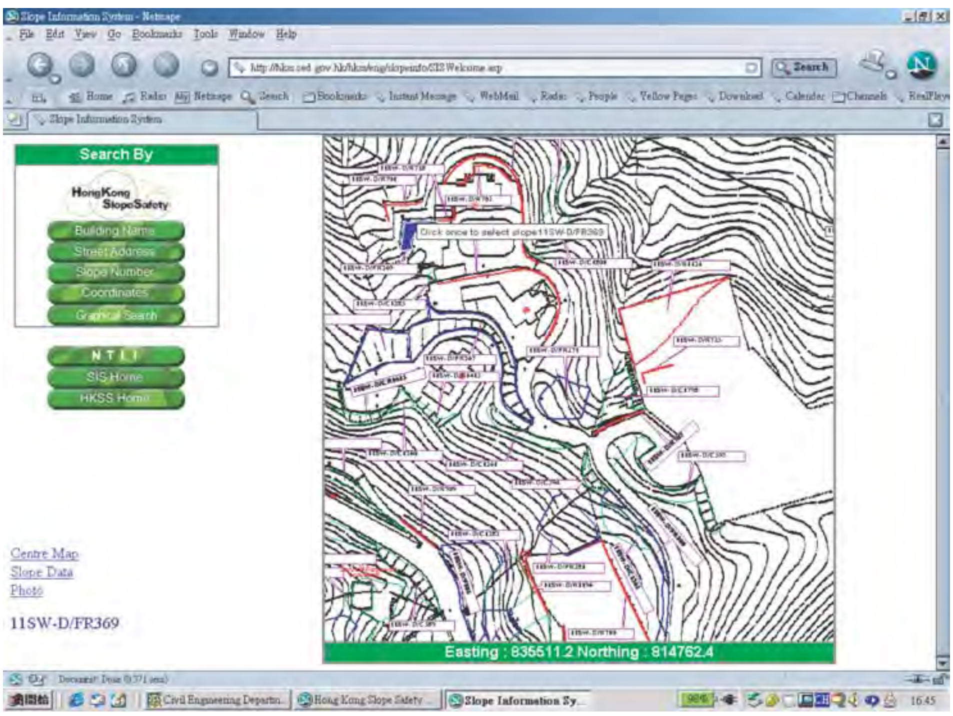

Figure 3.20 - Slope Information System Operating on a GeoMedia Platform

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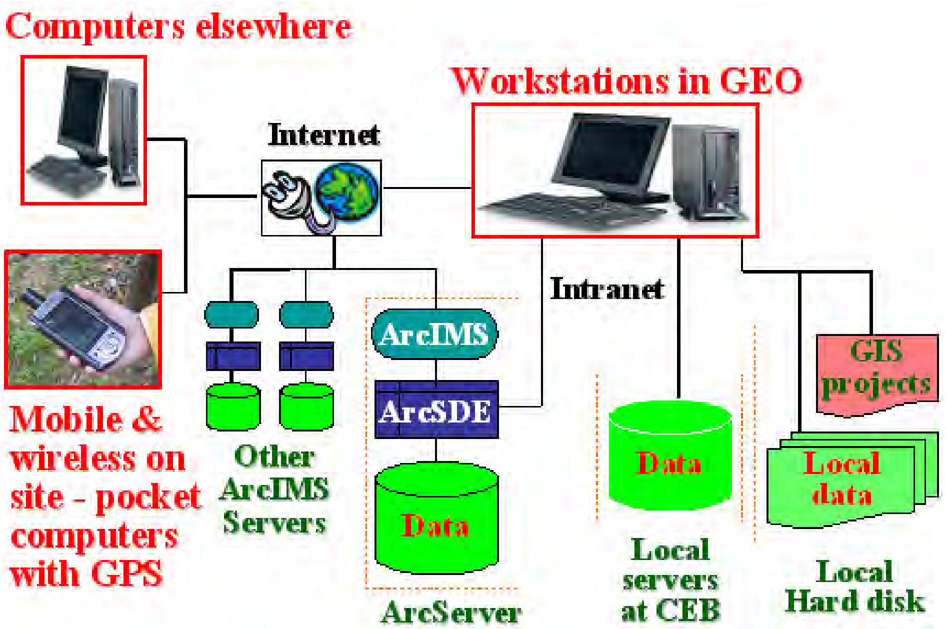

Figure 3.21 - Enterprise-based Set Up of the Geological Modeling System

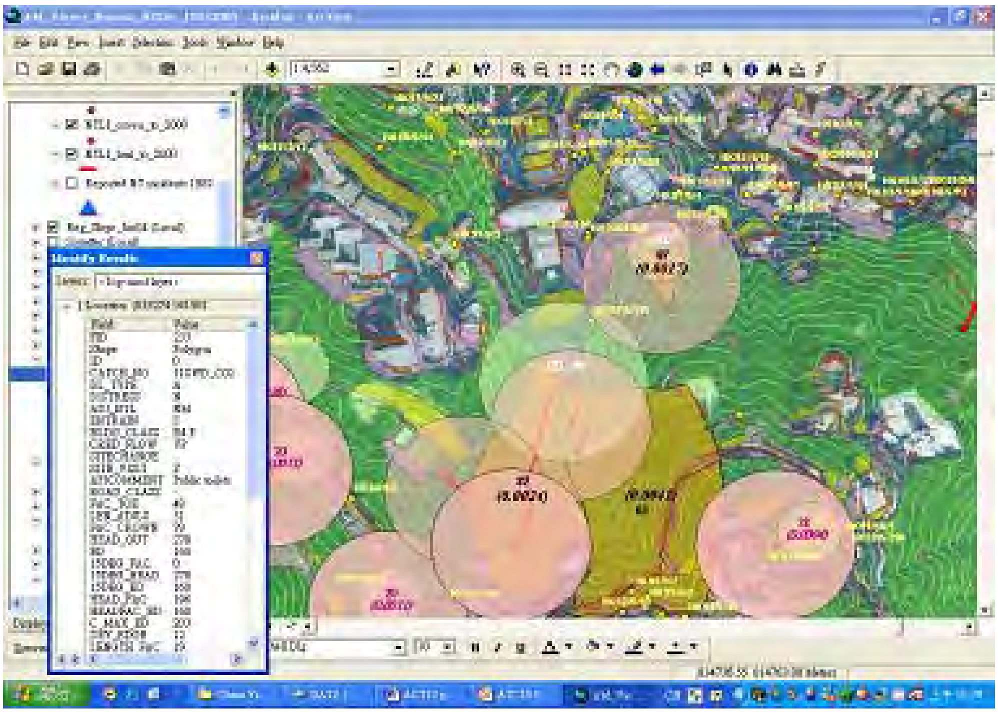

Figure 3.22 - Geological Modeling System Operating on an ArcGIS Platform

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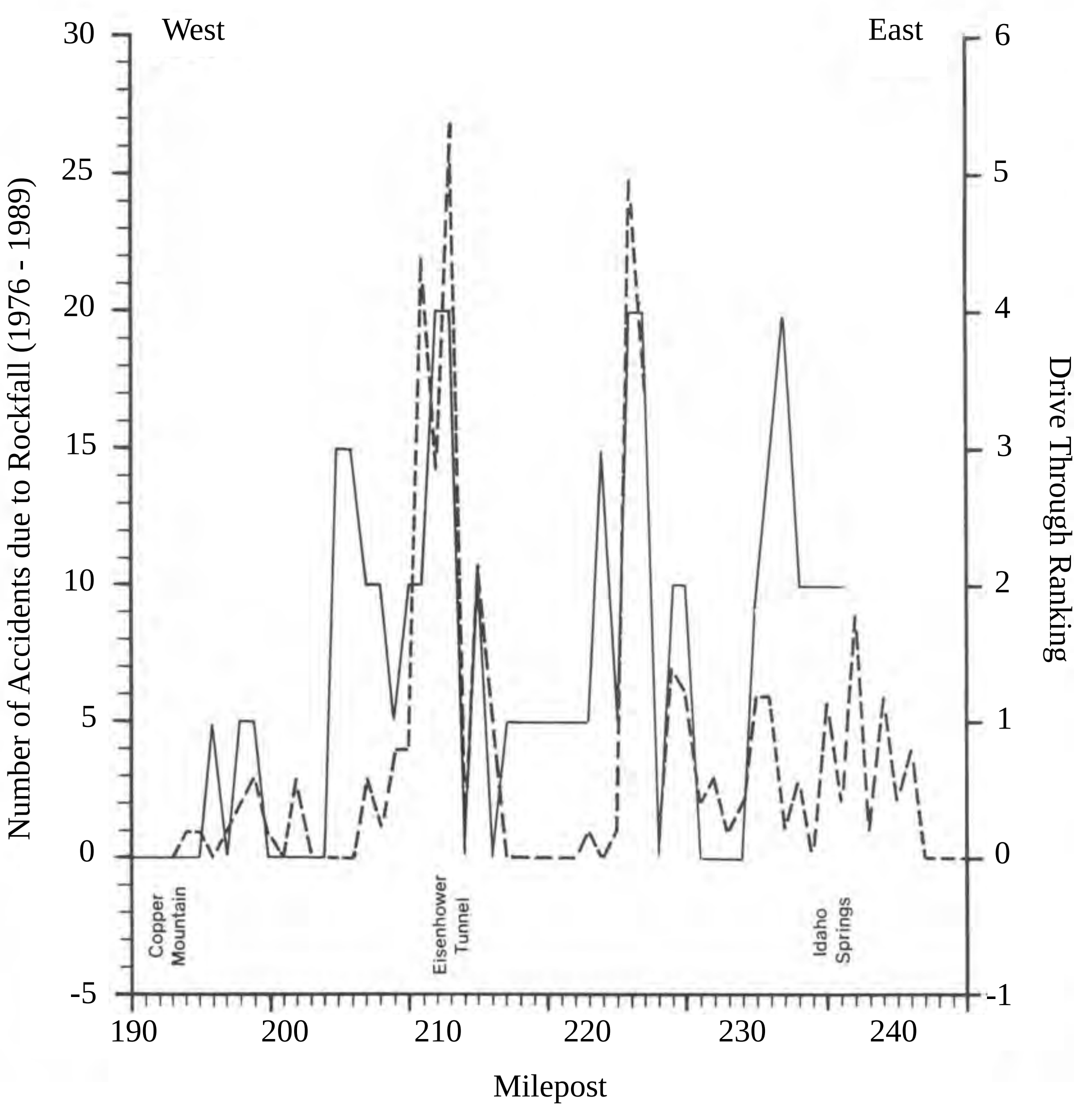

Figure 3.23 - An Example Showing the Combination of Accident Data from CRASH and Rockfall Information from Maintenance Personnel (Stover, 1992)

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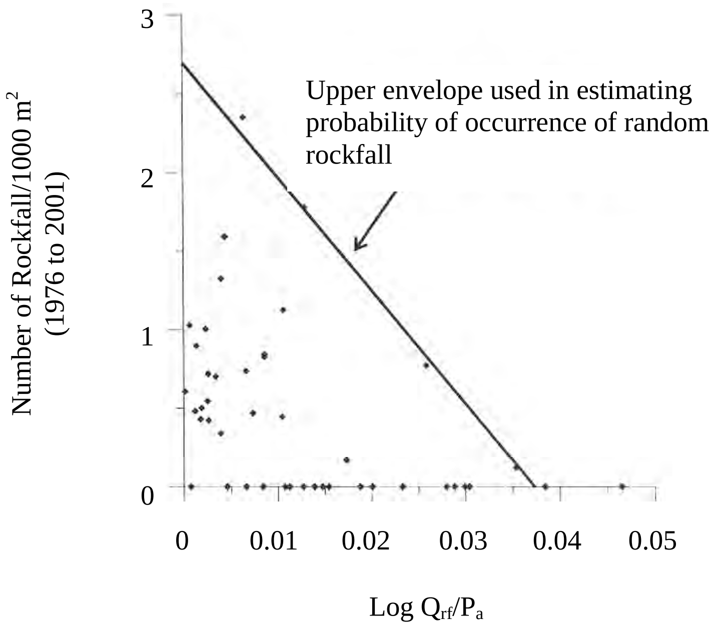

Probability Ratings

No. of Rock Falls	Rating
>13	Very high
6-13	High
2-5	Moderate
0-1	Low

Note: The values in this Table are based on a 26-year period of record (1975 to 2001)

Stabilization Rating

Definition	Rating
Stabilization measures have not been implemented.	None
Very little stabilization measures have been implemented or are deemed ineffective.	Negligible
Some stabilization measures have been undertaken but more is required.	Partial
Methods have been implemented to current standards to actively inhibit detachment.	Adequate

Evidence of Recent Activity

Definition	Rating
No evidence of recent activity.	None
Evidence of recent activity. Limited or no evidence of old activity. Recent activity does not appear to indicate continuing instability.	Moderate
Evidence of recent and old activity. Rock fall reported within previous year or change noted from previous inspection. Recent activity indicates continuing stability.	Considerable

Overburden Stability Index

Definition	Rating
Frequent ravelling over extensive areas. Precarious positioning of large boulders. Overburden is a major source of rock fall.	Very unstable
Overburden is a source of rock fall but moderate in terms of stability and extent	Unstable
Overburden is either not present or not considered a significant potential source of rock fall	Stable

Figure 3.24 - Details of Rating and Adjustments in Rock Slope Hazard Rating, Canada (Hungr et al, 2003)

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(a) Risk Rating

The Assessed Risk Level (ARL) is established based on the following risk matrix:

Likelihood	Consequence Class				
	C5	C4	C3	C2	C1
L1	ARL3	ARL2	ARL1	ARL1	ARL1
L2	ARL4	ARL3	ARL2	ARL1	ARL1
L3	ARL5	ARL4	ARL3	ARL2	ARL1
L4	ARL5	ARL5	ARL4	ARL3	ARL2
L5	ARL5	ARL5	ARL5	ARL4	ARL3
L6	ARL5	ARL5	ARL5	ARL5	ARL4

Notes:

(1) The Likelihood Rating L1 to L6 shown in Figure3.25(b)

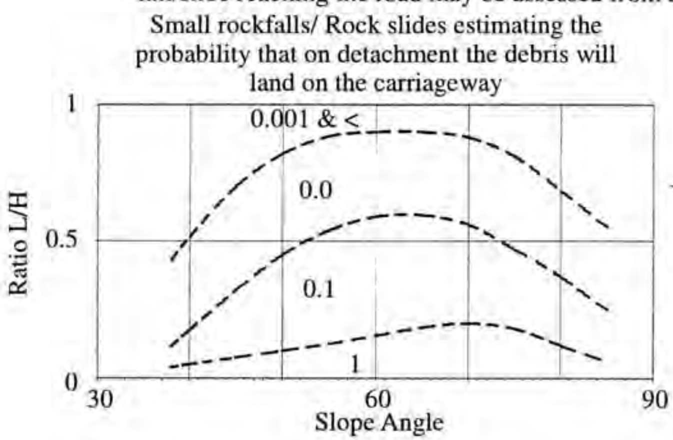
(2) The Consequence Rating C1 to C5 shown in Figure3.25(c)

(b) Likelihood Rating

– Likelihood Rating is categorized as follows:

Class	Descriptions
L1	The event may, or is expected to, occur within a short period under average circumstances, or the mechanism is active at present (depending on circumstances the "short" period could be from days to no more than two to three years). Indicative Annual Probability around 0.9.
L2	The event may, or is expected to, occur within a moderate period (from a few years to no more than about 30 years) or within the inspection period under slightly adverse circumstances. Indicative Annual Probability around 10^{-1}.
L3	The event could be expected to occur at some time over about a 100 year period in the normal course of events but would only occur within the next inspection period under adverse circumstances. Indicative Annual Probability around 10^{-2}.
L4	The event would not be expected to occur within about a 100 year period under normal conditions and is unlikely to occur within the next inspection period except under very adverse circumstances. Indicative Annual Probability around 10^{-3}.
L5	The event would not be expected to occur within about a 100 year period and is unlikely to occur within the next inspection period even under very adverse circumstances. Indicative Annual Probability around 10^{-4}.
L6	The event is unlikely to occur even under extreme circumstances. Indicative Annual Probability < around 10^{-5}.

– The likelihood Rating reflects the probability of a landslide occurring and reaching the element at risk. For failures from road-side rock cur slopes, the probability of small rock fall/slide reaching the road may be assessed from the following chart:



For the general case, L = a
Where a catch ditch is present and d > w/3, then
L = a + 2w for slope angles ≤65°
L = a + w for slope angles > 65°

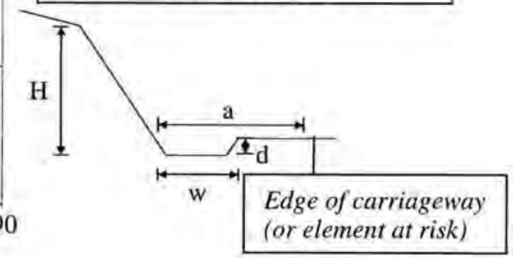


Figure 3.25 - Formulation of RTA Slope Risk Analysis Scheme (extracted from RTA, 2002) (Sheet 1 of 2)

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(c) Consequence Rating

- Consequence Rating for loss of life is categorized as follows:

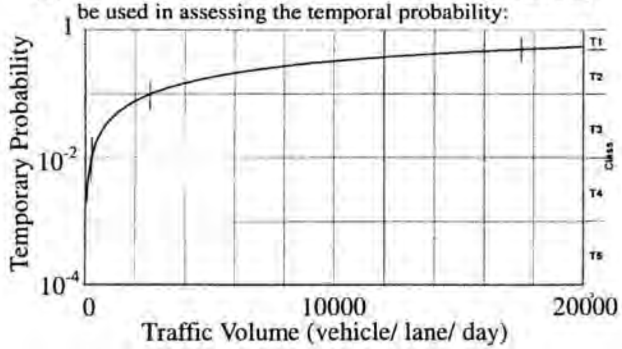
Vulnerability	Temporal Probability of an Individual Being Present at the Time of Failure				
	T5	T4	T3	T2	T1
V1	C4	C3	C2	C1	C1
V2	C4	C3	C2	C1	C1
V3	C5	C4	C3	C2	C2
V4	C5	C5	C4	C3	C3
V5	C5	C5	C5	C4	C4

Notes:

(1) Temporal probability is classified as follows:

Class	Descriptions
T1	Person usually expected to be present as part of the normal pattern of usage (eg residential buildings, some commercial buildings). Road users in the heaviest of urban traffic conditions. (p > 0.5).
T2	Person often expected to be present as part of the normal pattern of usage (eg many commercial buildings). Road users on major urban arterial roads and the most heavily trafficked rural roads. (p 0.1 – 0.5).
T3	Person may sometimes be present as part of the normal pattern of usage. Road users on many urban arterial roads and most major rural arterial roads. (p 0.01 – 0.1).
T4	Person unlikely to be present even where there is a pattern of usage. Road users on suburban roads and minor rural arterial roads. (p 0.001 – 0.01).
T5	Person is very unlikely to be present. Road users on the most lightly trafficked roads, road shoulders etc. (p < 0.001).

(2) For landslides affecting roads, the following chart may be used in assessing the temporal probability:



(3) Vulnerability is classified as follows:

Class	Descriptions
V1	Person in the open unable to evade rockfall or other debris (movement very/extremely rapid), or buried, or engulfed in a building collapse. Vehicle impacting a block > 1 m high or lost into a deep, narrow void at highway speeds. (p > 0.5).
V2	Partial building collapse. Person in open may be able to evade debris. Vehicle impacting a 0.5 – 1 m high block at highway speeds or a block > 1 m high at urban speeds or lost into a shallow void. (p 0.1 – 0.5).
V3	Building penetrated, no collapse. Emergency evacuation possible. Most people in open able to evade debris. Vehicle impacting a 0.5 – 1 m high block at urban speeds, or a block > 1 m high at low speeds. Vehicle impacting loose or wet mixed soil/rock debris (or crossing a stepped surface with c 0.1 – 0.2 m steps caused by a developing embankment failure) at highway speeds. (p 0.01 – 0.1).
V4	Building struck, damaged but not penetrated. Vehicle impacting a block around 0.2 m high at highway speeds or a 0.5 – 1 m high block at low speeds. Vehicle impacting loose or wet mixed soil/rock debris (or crossing a stepped surface with c 0.1 – 0.2 m steps caused by a developing embankment failure) at urban speeds. Vehicle interacting with a shallow void/depression where guardfence may prevent a vehicle from leaving the road. (p 0.001 – 0.01).
V5	Building struck, only minor damage etc. Vehicle impacting a block around 0.2 m high at urban speeds or a smaller block at highway speeds. Vehicle impacting loose or wet mixed soil/rock debris at low speeds. Vehicle traversing an irregular surface formed by soil or small (< 100 mm min dimension) rock, or by a developing embankment failure, at highway speeds. (p < 0.001).

- Consequence Rating for damage to property and consequential effects is categorized as follows:

Class	Descriptions
C1	Total closure of a Sub-Network Rank 5 or 6 (SN5-6) road for an extended period Major infrastructure or property damage (other than road) Very high disruption cost (other than road users) Very high repair cost (Total direct and indirect costs > $10M)
C2	Total closure of one carriageway of an SN5- 6 road or total closure of an SN3–4 road for an extended period Substantial infrastructure or property damage Large disruption costs High repair cost (Total direct and indirect costs > $2M < $10M)
C3	Partial or total closure of an SN3-4 road for a short period, longer period if reasonable alternatives are available Moderate infrastructure or property damage Moderate disruption costs Moderate repair cost (Total direct and indirect costs > $0.5M < $2M)
C4	Partial or total closure of an SN2 road for a short period Minor infrastructure or property damage Minor disruption costs Low repair cost (Total direct and indirect costs > $0.1M < $0.5M)
C5	Partial or total closure of an SN1 road for a short period Negligible infrastructure or property damage Little or no disruption costs Very low – no repair cost (Total direct and indirect costs < $0.1M)

Figure 3.25 - Formulation of RTA Slope Risk Analysis Scheme (extracted from RTA, 2002) (Sheet 2 of 2)

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Instability Score (IS) = α DS + β MC
where,
α and β are weighting factors, with $\alpha + \beta = 1$
DS = Discriminant Score which is the probability of a slope feature belonging to the failed slope group, ranging from 0 to 1 and based on the following parameters:

Cuts and Natural Slopes	Fill Embankment
(11 significant variables)	(7 significant variables)
– Vegetation cover condition – Height – Presence of corestone boulders – Measure of ground saturation – Slope angle – Cutting topography relationship – Slope shape – Exposed percentage (rock) – Rock condition profile – Plan profile – Surface Drainage rating	– Main cover type – Vegetation cover condition – Slope angle – Geology – Plan profile – Presence of structures – Upslope / downslope geometry

MC = Monte-Carlo probability score which is the probability of the Factor of Safety < 1 for the 1 in 100-year return period 24-hour rain storm, ranging from 0 to 1.

Probability of Failure (FOS<1) for 24 hour, 450mm rainfall event

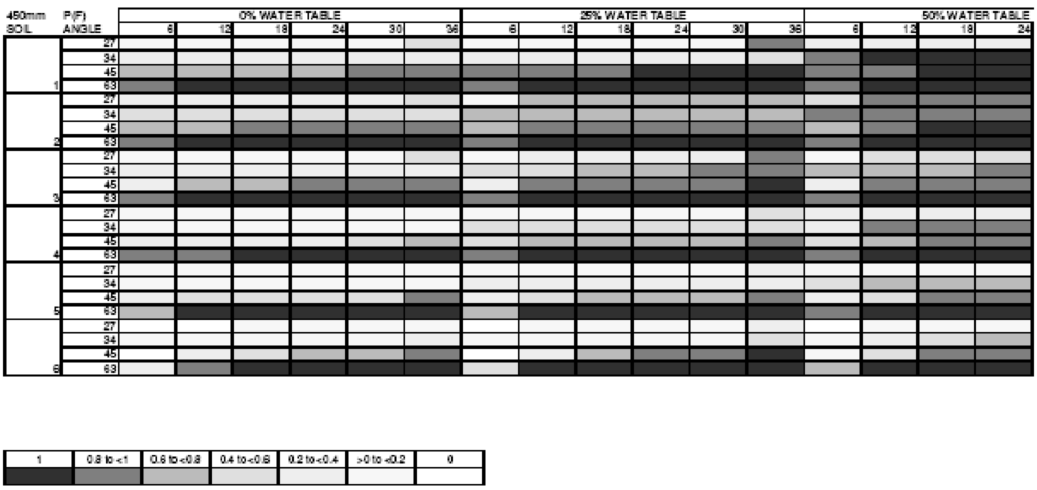


Figure 3.26 - Formulation of Instability Score, SMART
(extracted from PWD Malaysia, 2004)

The Consequence Score is calculated according to equations 2 to 6.

CS = K (F+GJ+R) V (eq. 2)

where:

F = F_1 (H-F_2/H) >0 (eq. 3)

GJ = $2G_1$ ((1.5+J) H-G_2/(1.5+J) H) (eq. 4)

R = $2R_1$ ((1.5+J) H-R_2/(1.5+J) H) (eq. 5)

V = γH (eq. 6)

Notes:

(1) γ = 1.0 for full-scale failure
0.7 for partial failure
0.4 for minor failure

(2) If H > 30 m, take H = 30 m in calculating V

where:

F = Above crest of feature component
GJ = Below crest of feature component
R = Road facility component
J = Upslope and Downslope topography
H = Slope height (m)
F1 = Above crest of feature facility score
F2 = Distance from crest of feature to the facility (m)
G1 = Below crest of feature facility score
G2 = Distance from toe of feature to the facility (m)
R1 = Road facility score
R2 = Distance from slope crest or slope toe to the road facility (m)

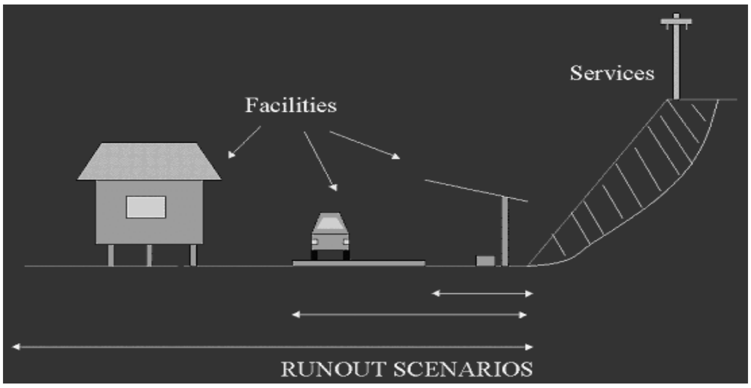
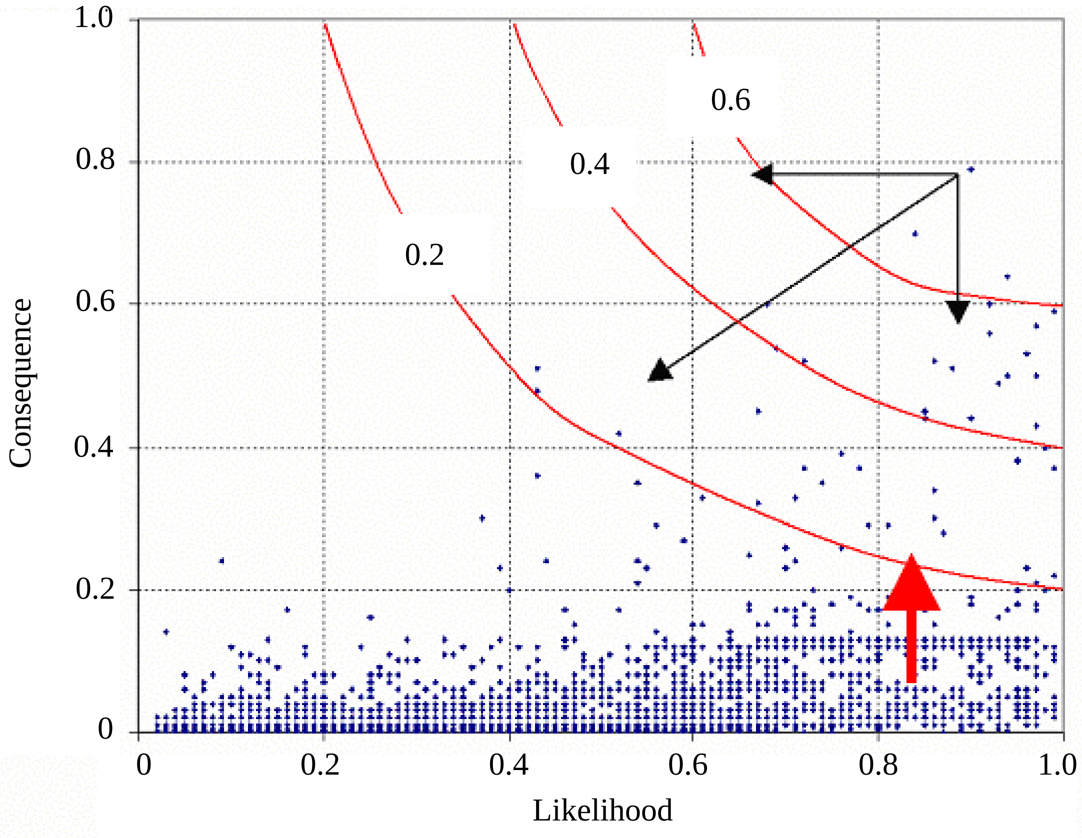


Figure 3.27 - Formulation of Consequence Score, SMART
(extracted from PWD Malaysia, 2004)



<u>Total Risk Score</u>	<u>Total Risk Category</u>
0 - 0.1	Very Low
0.1 - 0.2	Low
0.2 - 0.4	Medium
0.4 - 0.6	High
0.6 - 1.0	Very High

Figure 3.28 - Typical Instability Score and Consequence Score Ratings on the TSR Slopes and Categorization of the Calculated Total Risk Score TS (extracted from PWD Malaysia, 2004)

a) In determining the consequence-to-life category of a slope, the designer should use his own professional judgement in assessing the "severity in terms of loss of life in the event of failure" in each particular case, giving due consideration to the types of buildings and facilities that may be threatened, and how the buildings and facilities would be affected in the event of slope failure. In assessing the effects of a slope failure on buildings and facilities, account should be taken of such factors as follows:

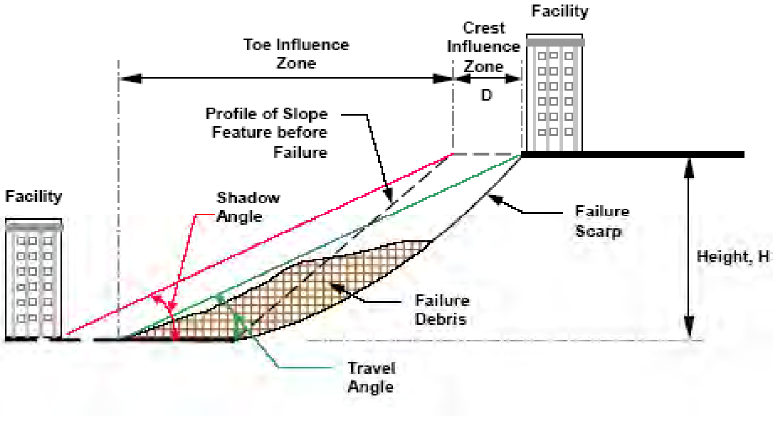
Factors to be Considered	– Possible mechanisms and scale of failure – Site conditions – Proximity of the buildings and facilities to the slope – Likely density of occupation and frequency of usage of the buildings and facilities in the event of failure – Travel distance of the landslip debris – Resistance of the buildings and facilities to debris impact – Vulnerability of occupants and users.

b) Adjustment of consequence-to-life category for proximity of the buildings and facilities can be made as follows:

Proximity of Buildings and Facilities		Adjustment on Consequence-to-Life Category
For Buildings and Facilities at Slope Toe	Beyond Expected Travel Distance of Landslide Debris	Downgrade by one category
	Beyond Possible Extreme Travel Distance of Landslide Debris	Downgrade by two category
For Buildings and Facilities at Slope Crest	Beyond Expected Crest Influence Zone	Downgrade by one category
	Beyond Extreme Limit of Crest Influence Zone	Downgrade by two category

Notes: (1) See Figure 4.2 for the estimate of travel distance of landslide debris and crest influence zone.

Figure 4.1 - Qualitative Guidelines for Consequence-to-life Category Assessment (Works Bureau, 1999)



a) Estimate of the expected travel distance of landslide debris can be made as follows:

Type of Feature	Travel Angle for Estimation of the Expected Travel Distance of Landslide Debris	
	Debris Volume $\leq 300\ m^3$	Debris Volume $> 300\ m^3$
Cut slopes and retaining walls	35°	25°
Fill slopes	25°	15°

b) Estimate of the possible extreme travel distance of landslide debris can be made as follows:

Type of Feature	Travel Angle for Estimation of the Possible Extreme Travel Distance of Landslide Debris	
	Debris Volume $\leq 300\ m^3$	Debris Volume $> 300\ m^3$
Cut slopes and retaining walls	30°	20°
Fill slopes	20°	10°

c) Estimate of crest influence zones can be made as follows:

Expected Crest Influence Zone	0.4 H
Extreme Limit of Crest Influence Zone	H

Figure 4.2 - Estimation of Expected and Possible Extreme Travel Distance of Landslide Debris (GEO, 2004a)

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Figure 4.3 - The Kwun Lung Lau Landslide, Hong Kong, on 23 July 1994

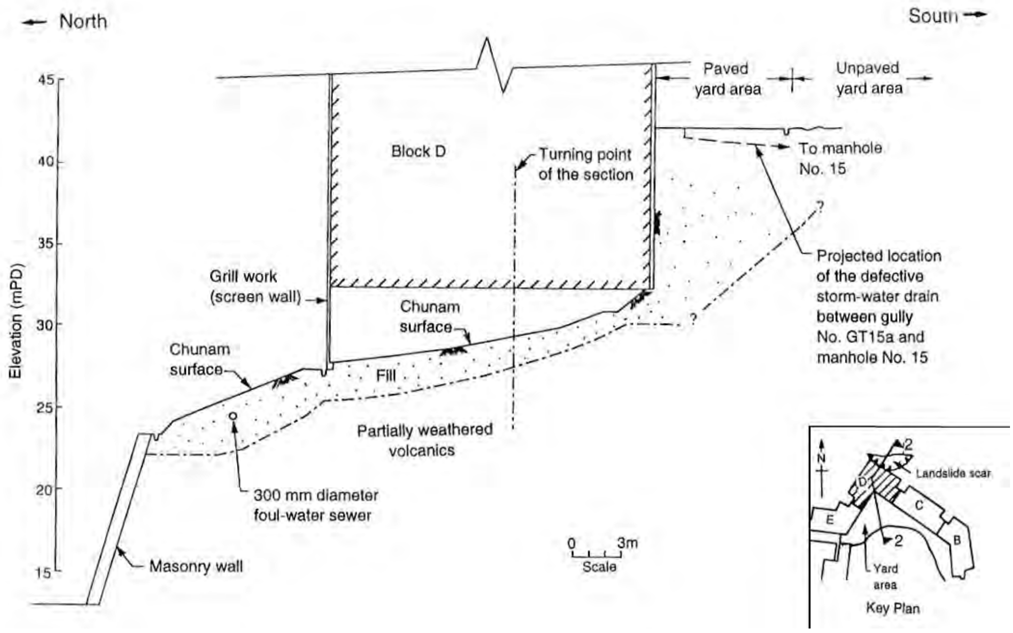

Figure 4.4 - Cross-section Traversing the 1994 Kwun Lung Lau Landslide Site (Wong & Ho, 1997)

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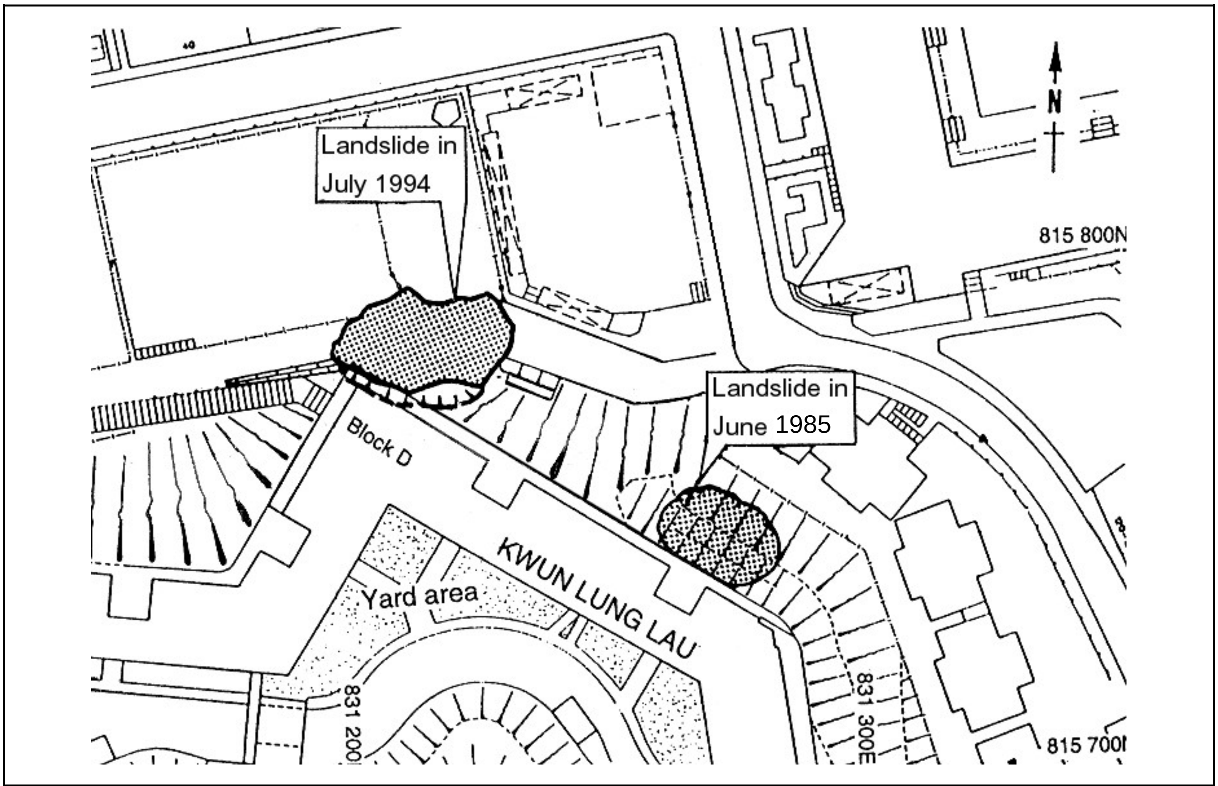

Figure 4.5 - Location of the 1984 and the 1994 Kwun Lung Lau Landslides (Wong & Ho, 1997)

Figure 4.6 - Liquefied Debris of the 1992 Kennedy Road Landslide, Hong Kong

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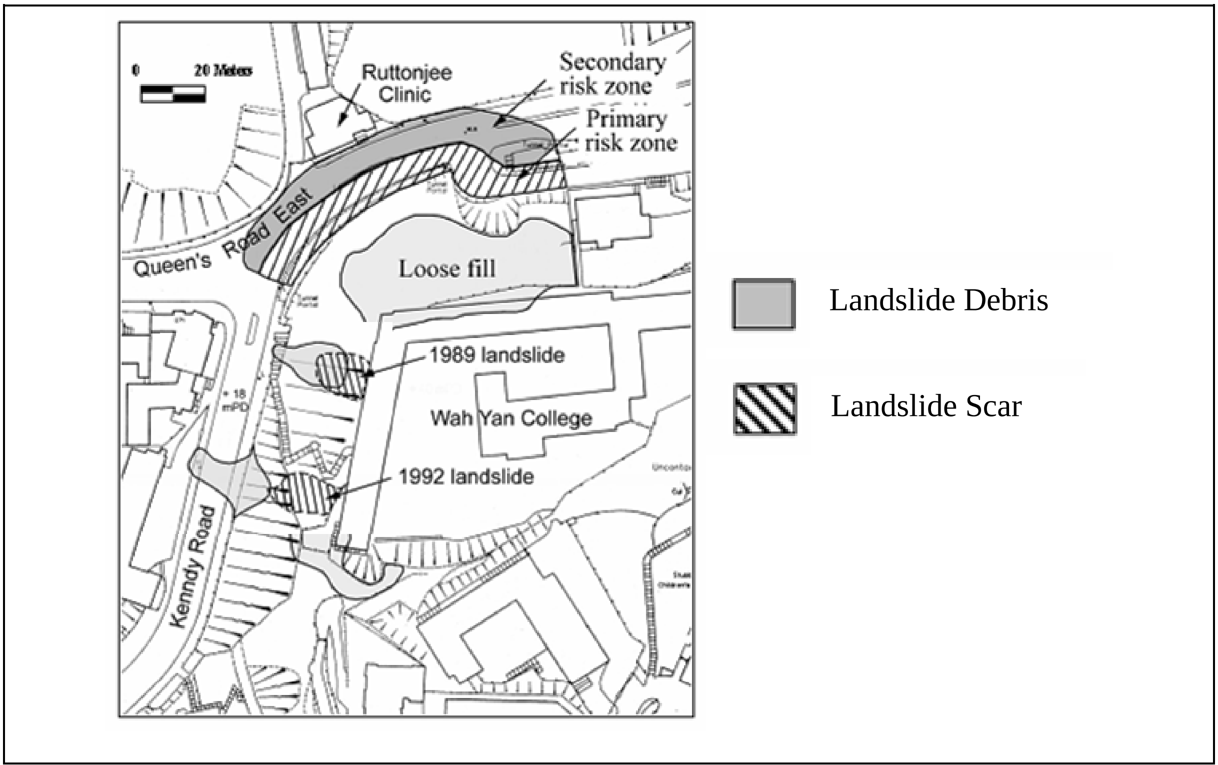

Figure 4.7 - The 1989 Kennedy Road Landslide and Qualitative Risk Assessment at Wah Yan College, Hong Kong

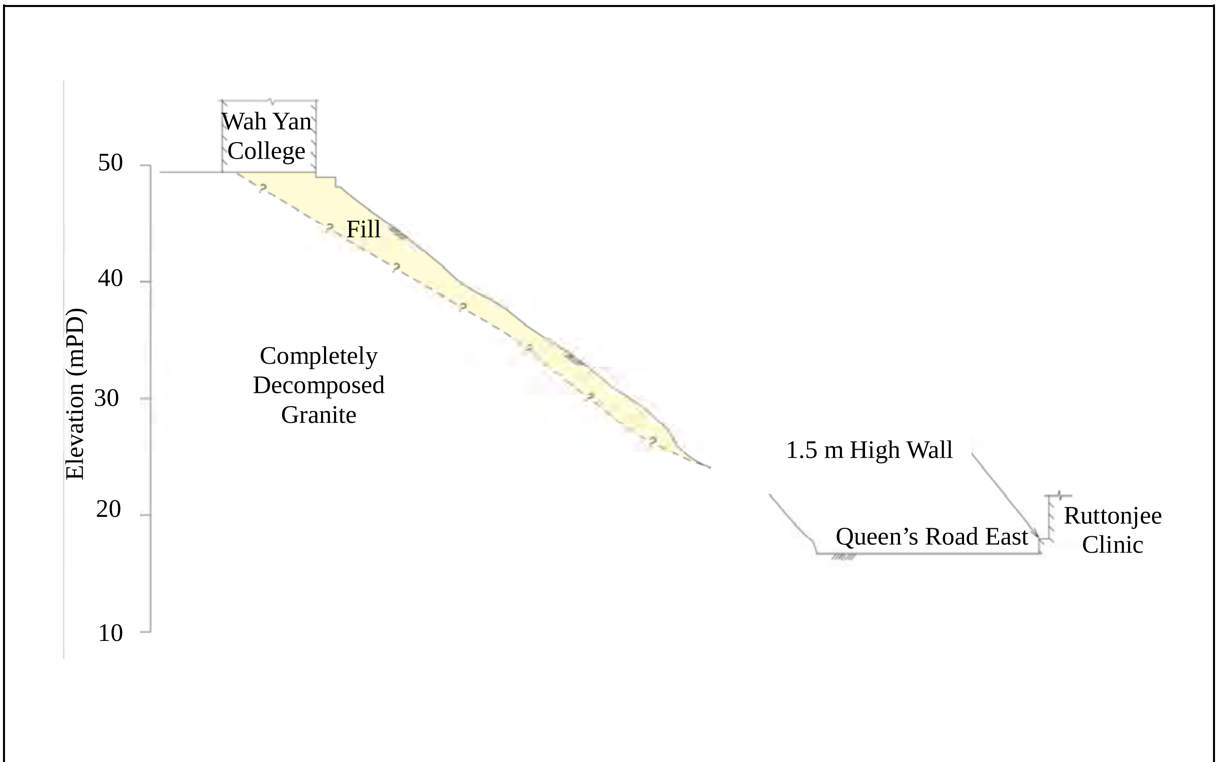

Figure 4.8 - Cross-section through the 1992 Kennedy Road Landslide Site (Wong, 1993)

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Risk Category		Risk to Life					Economic Loss				
		Loss of Life Consequence Category					Economic Loss & Disruption to Community Consequence Category				
		1	2	3	4	5	I	II	III	IV	V
Hazard Likelihood Category	A	H	H	H	H	R	H	H	M	L	R
	B	H	H	H	L	R	H	M	L	V	R
	C	H	M	L	V	R	M	L	V	R	R
	D	M	L	V	R	R	L	V	R	R	R
	E	L	V	R	R	R	V	R	R	R	R
	E-	V	R	R	R	R	R	R	R	R	R

Note: PLL is the average number of fatalities per year. Risk Category is defined as follows:

(a) Risk Category

Class	Descriptions (PLL for risk to life)	Further Study
H	High - of major concern (notional PLL > 10^{-3})	This failure mode should be examined with priority attention, to assess/verify the scale of the problem
M	Moderate - of considerable concern (notional PLL form 10^{-3} to 10^{-4})	This failure mode should be examined, to assess/verify the scale of the problem
L	Low - of some concern (notional PLL form 10^{-4} to 10^{-5})	It is advisable to examine this failure mode, to assess/ verify the scale of the problem
V	Very Low - practically not a concern (notional PLL less than 10^{-5})	Further study not warranted except in special circumstances
R	Residual risk - no indication of risk problem	Further study not warranted

(b) Likelihood Category

Class	Failure Likelihood Category
A	Very high (notionally 1 in 10 years)
B	High (notionally 1 in 10 to 100 years)
C	Moderate (notionally 1 in 100 to 1,000 years)
D	Low (notionally 1 in 1,000 to 10,000 years)
E	Very Low (notionally much less than 1 in 10,000 years)

Figure 4.9 - FMEA Categorization Scheme (Sheet 1 of 2)

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(b) Likelihood Category (Continued)

Class	Effect Likelihood Category (likelihood of occurrence of the stated effects given the failure mode)	Adjustment on Failure Likelihood Category
x	Probable (notionally 0.5 or higher)	No change
y	Quite possible (notionally 0.1 to 0.5)	Downgrade by half a category
z	Possible (notionally < 0.1)	Downgrade by one category

(c) Consequence Category

Class	Loss of Life Consequence Category
1	Very high chance of loss of life (PLL notionally > 1); multiple fatalities may occur
2	High change of loss of life (PLL notionally 0.1 to 1); low chance of multiple fatalities
3	Moderate chance of loss of life (PLL notionally 0.01 to 0.1)
4	Low chance of loss of life (PLL notionally < 0.01)
5	Very low chance of loss of life (PLL much less than 0.01)

Class	Economic Loss & Disruption to Community Consequence Category
I	Very high (severe structural damage to multi-story buildings; prolonged evacuation of multi-story building or a large number of houses; prolonged breakdown of transportation network)
II	High (severe structural damage to within a few flats or individual houses; prolonged evacuation of within a few flats or individual houses; prolonged closure of major road or important access; temporary breakdown of transportation network)
III	Moderate (some damage to properties; temporary evacuation of within a few flats or individual houses; temporary closure of major road or important access)
IV	Low (less serious than above)
V	Very low (much less serious than above)

Figure 4.9 - FMEA Categorization Scheme (Sheet 2 of 2)

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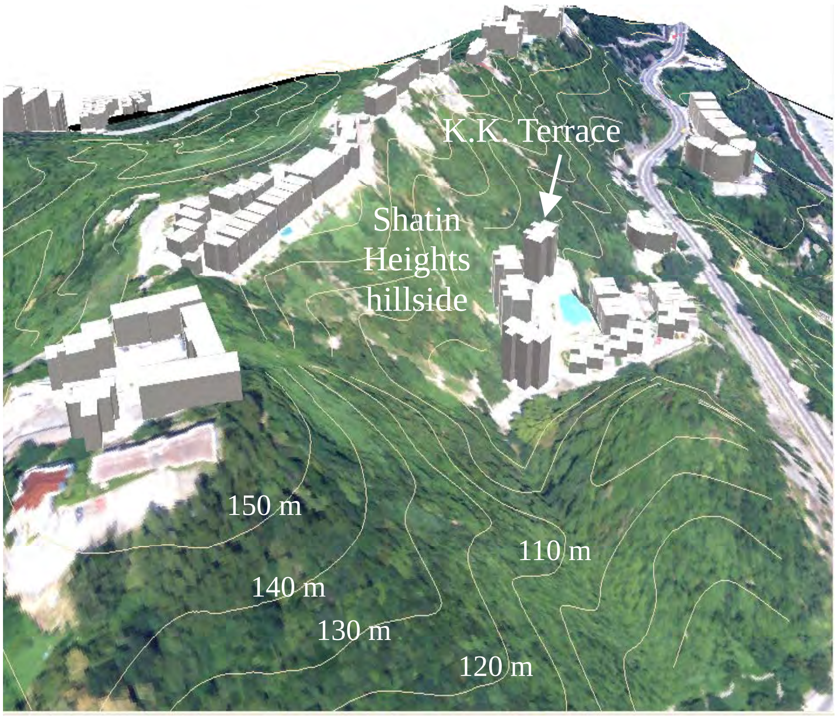

Figure 4.10 - Shatin Height, Hong Kong

Figure 4.11 - View of Debris Run-out at Toe of Hillside

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Figure 5.1 - The Fei Tsui Road Landslide, Hong Kong, on 13 August 1995

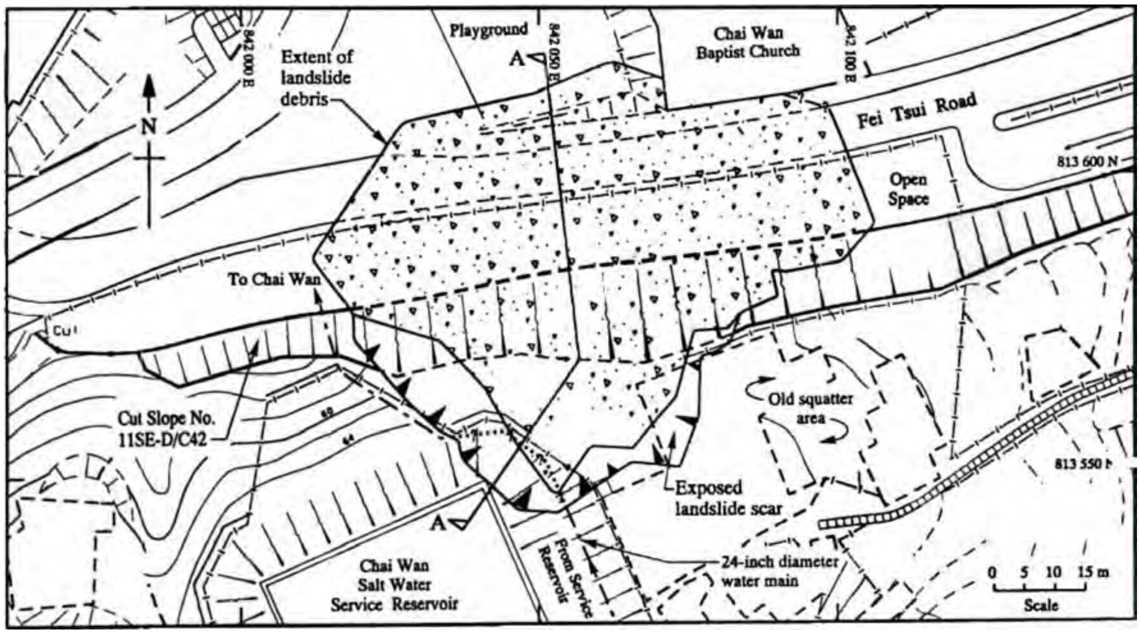

Figure 5.2 - Plan of the Fei Tsui Road Landslide (Wong et al, 1997)

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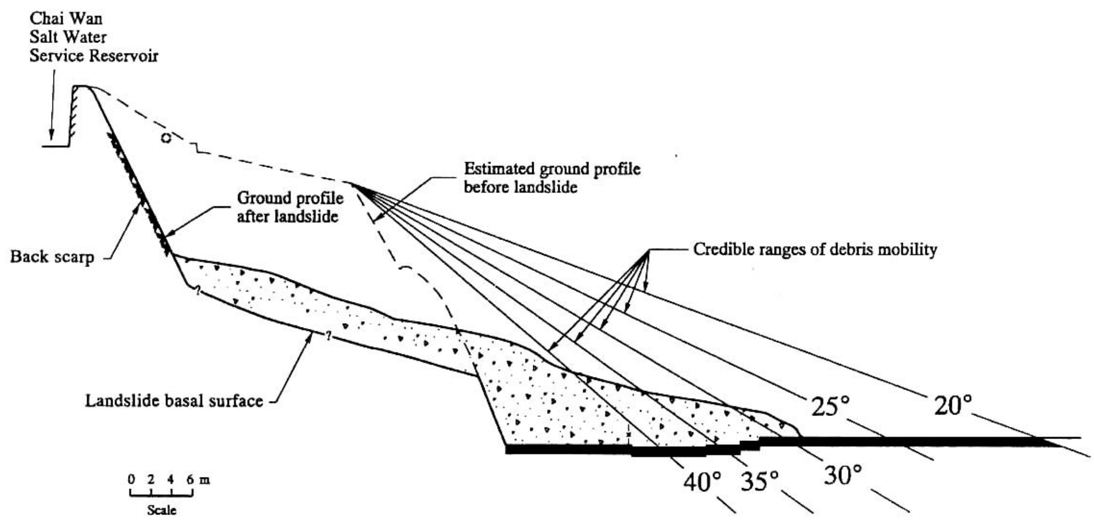

Figure 5.3 - Different Degrees of Debris Mobility for the Fei Tsui Road Landslide (Wong et al, 1997)

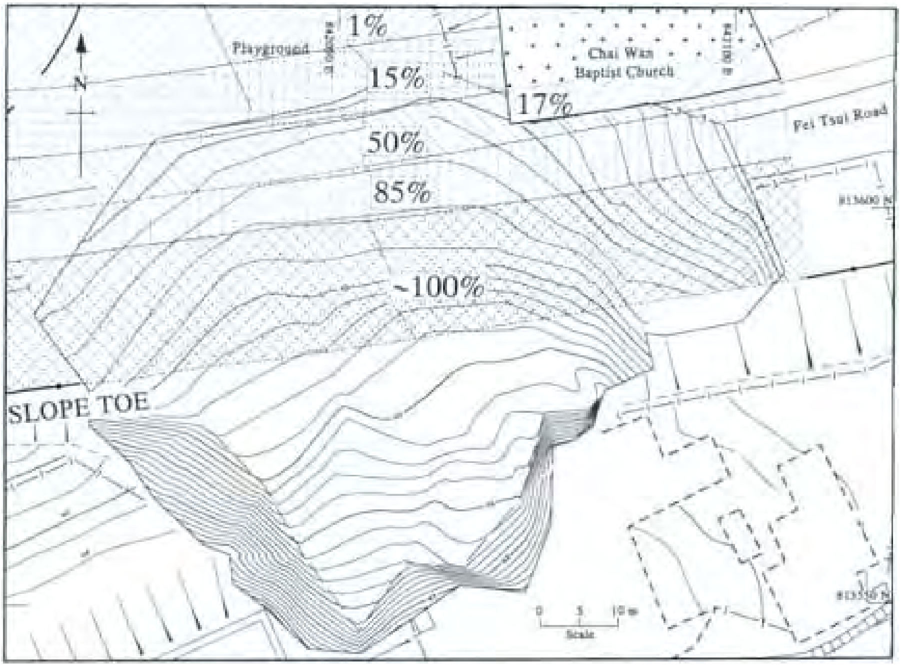

Figure 5.4 - Vulnerability Factors at Different Proximity Zones for the Fei Tsui Road Landslide (Wong et al, 1997)

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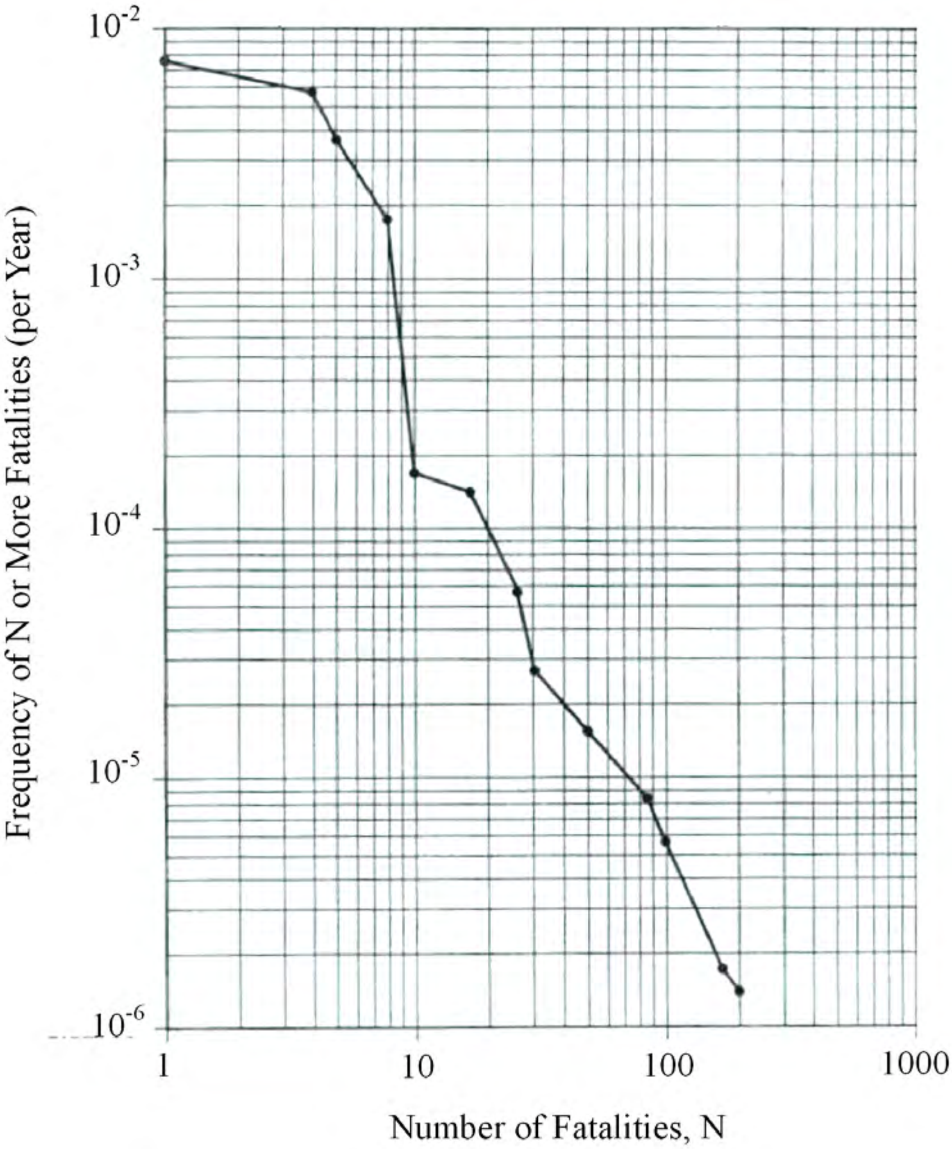

Figure 5.5 - Calculated F-N Curve for the Fei Tsui Road Landslide (Wong et al, 1997)

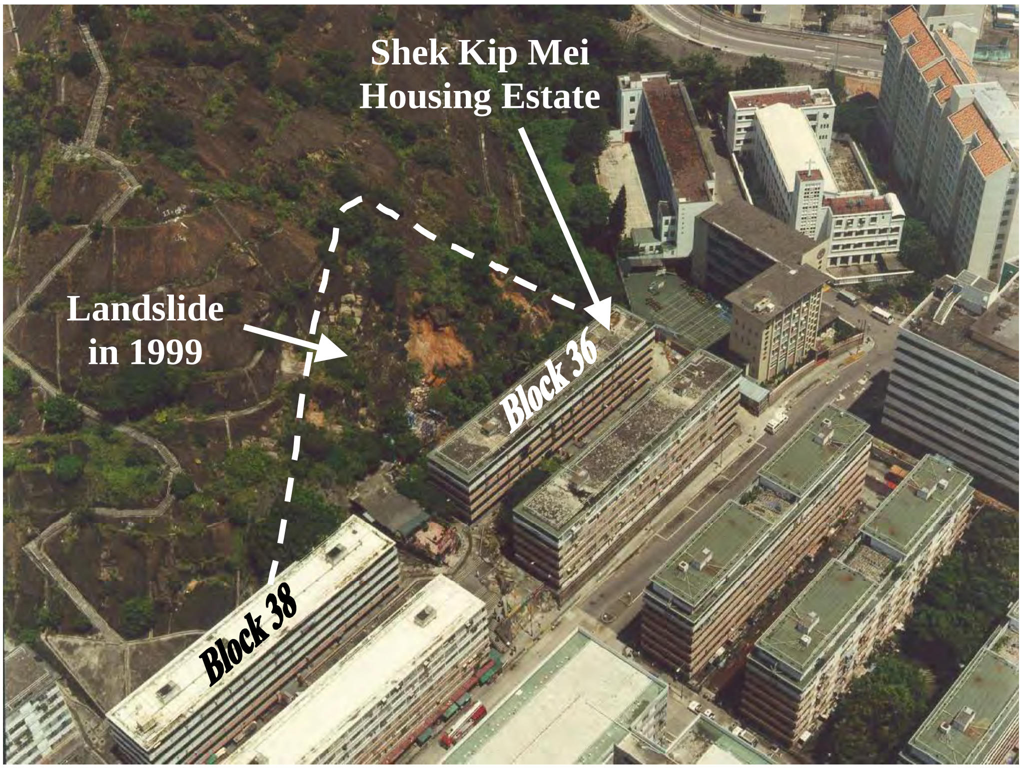

Figure 5.6 - The Shek Kip Mei Landslide, Hong Kong, on 25 August 1999

Figure 5.7 - The Displayed Mass of the Shek Kip Mei Landslide

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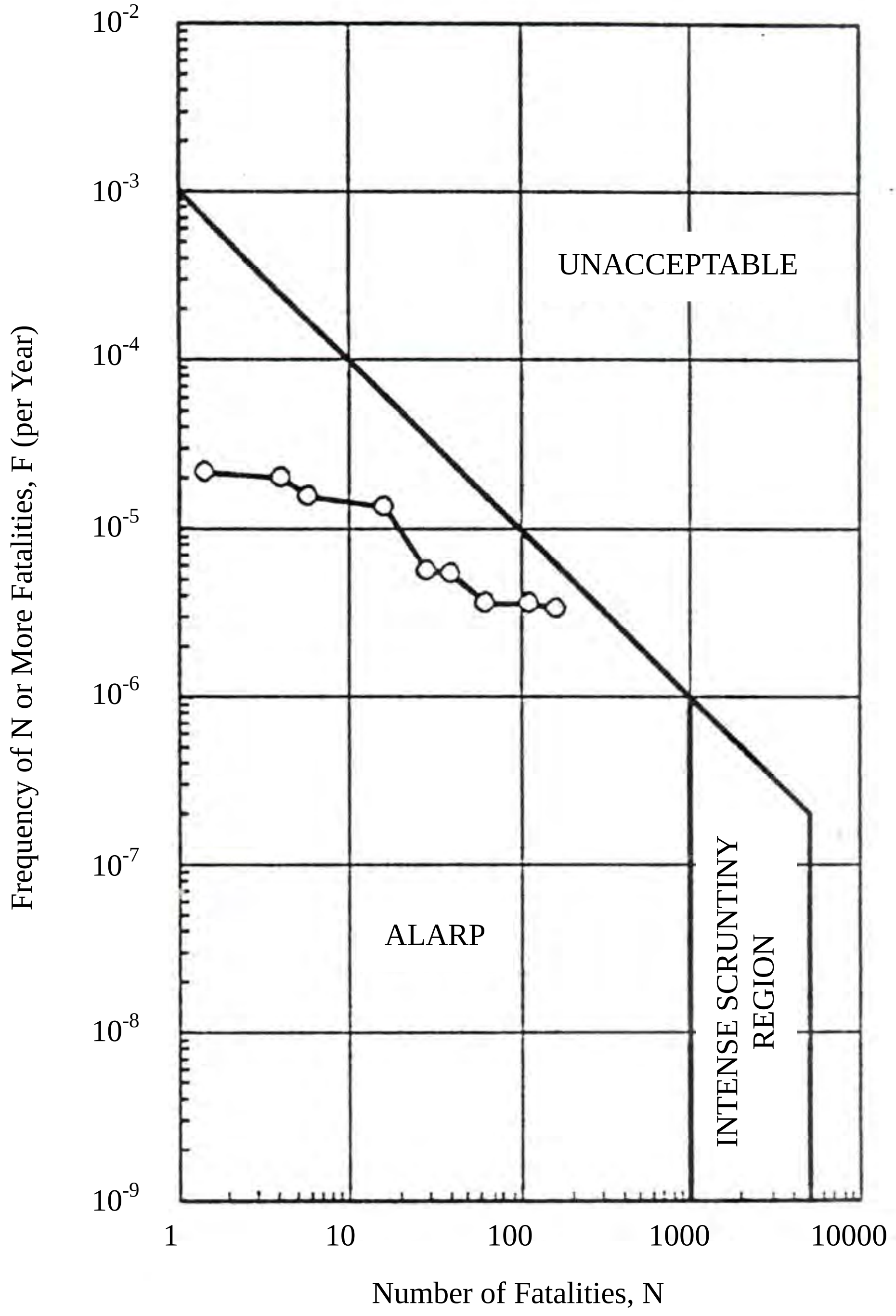

Figure 5.8 - Calculated F-N Curve for the Shek Kip Mei Landslide (El-Ramly et al, 2003)

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Figure 5.9 - Landslides in August 1995 Affecting the Lei Yue Mun Squatter Area

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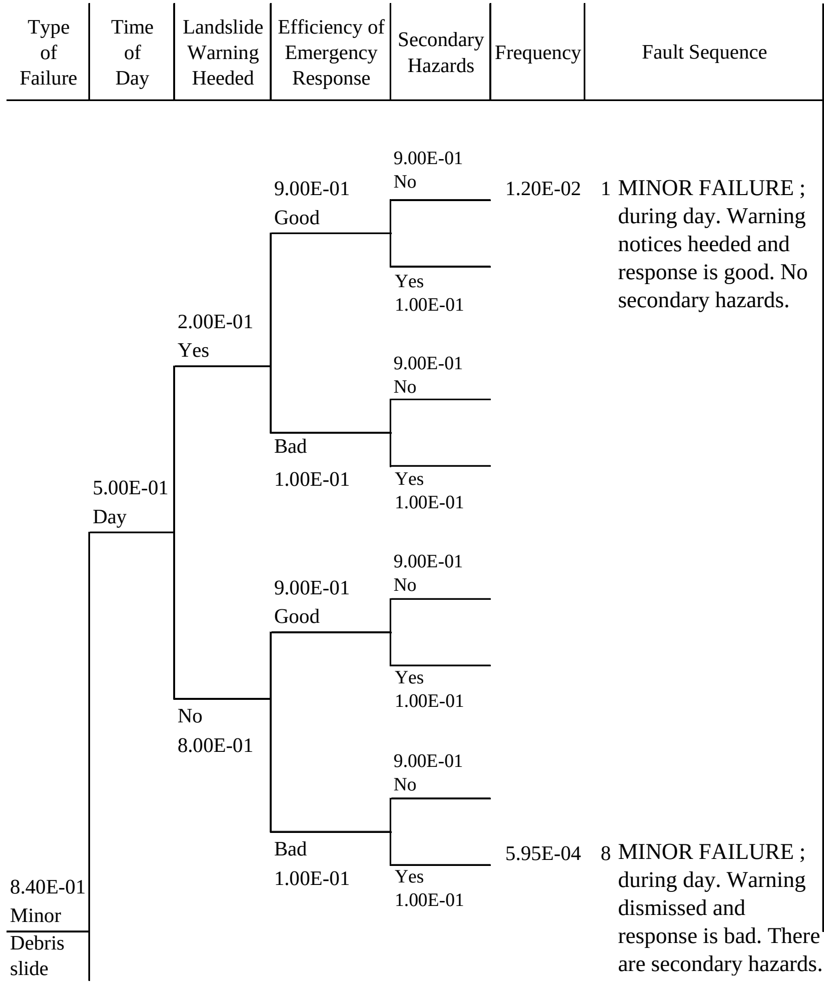

Fault Category	Minor Injuries	Major Injuries	Fatality	Equivalent Fatality	Risk
D	0.0778	0.0259	0	0.003	3.59E-05
D	0.1296	0.0259	0	0.003	4.34E-06
D	0.0518	0.0518	0	0.005	7.29E-06
D	0.1037	0.0518	0	0.006	8.48E-07
D	0.0864	0.0288	0	0.003	1.60E-04
D	0.144	0.0288	0	0.004	1.93E-05
D	0.0576	0.0576	0	0.006	3.24E-05
D	0.1152	0.0576	0	0.006	3.77E-06

Note: The following rule is assumed: Equivalent fatalities = No. of fatalities + (0.1 × No. of major injuries) + (0.005 × No. of minor injuries).

Figure 5.10 - Extract of an Event Tree for the Lei Yue Mun QRA (Hardingham et al, 1998)

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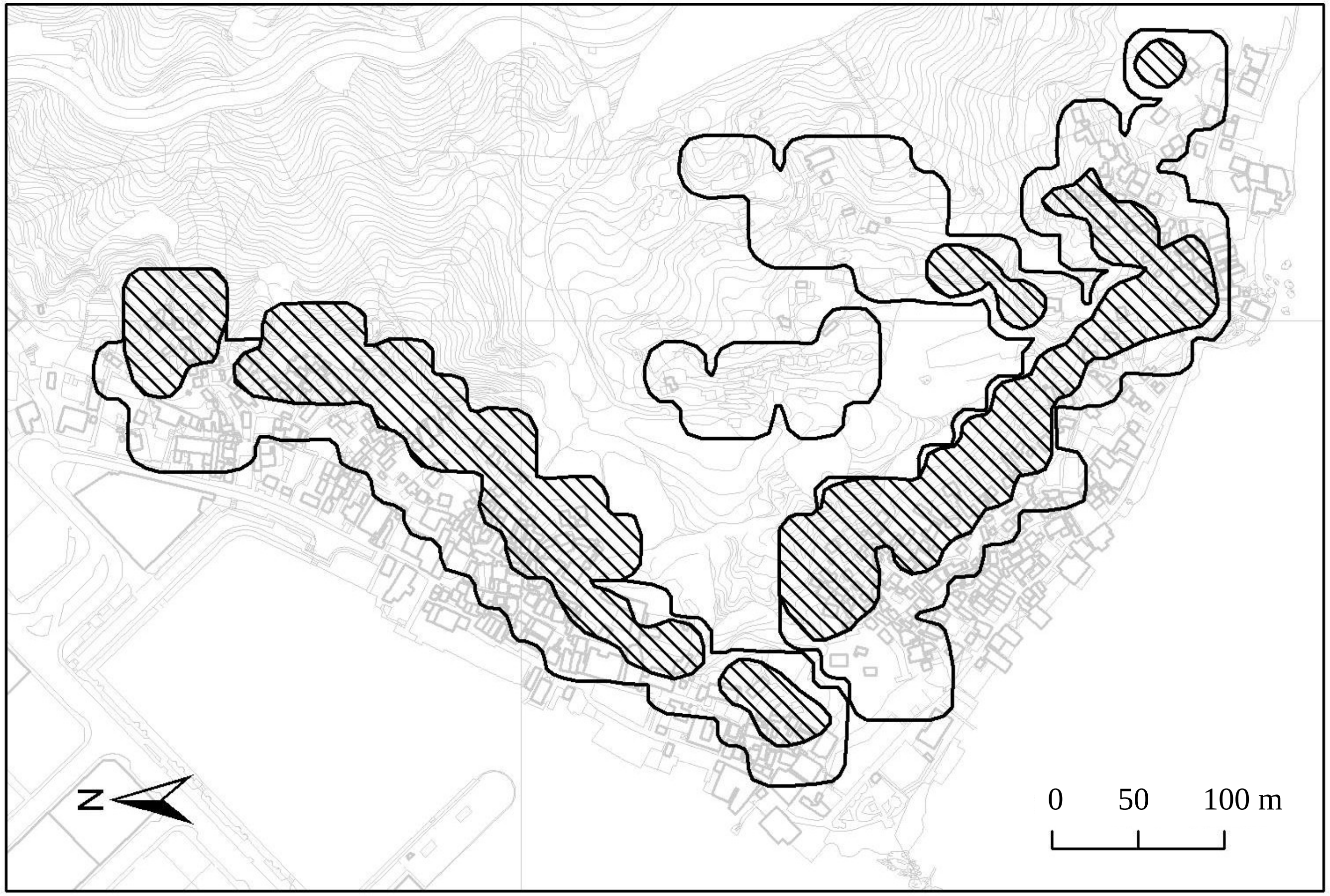

Legend:

Risk > 10^{-4}

Risk = 10^{-6}

Figure 5.11 - Individual Risk Contours for the Lei Yue Mun Squatter Area (Hardingham et al, 1998)

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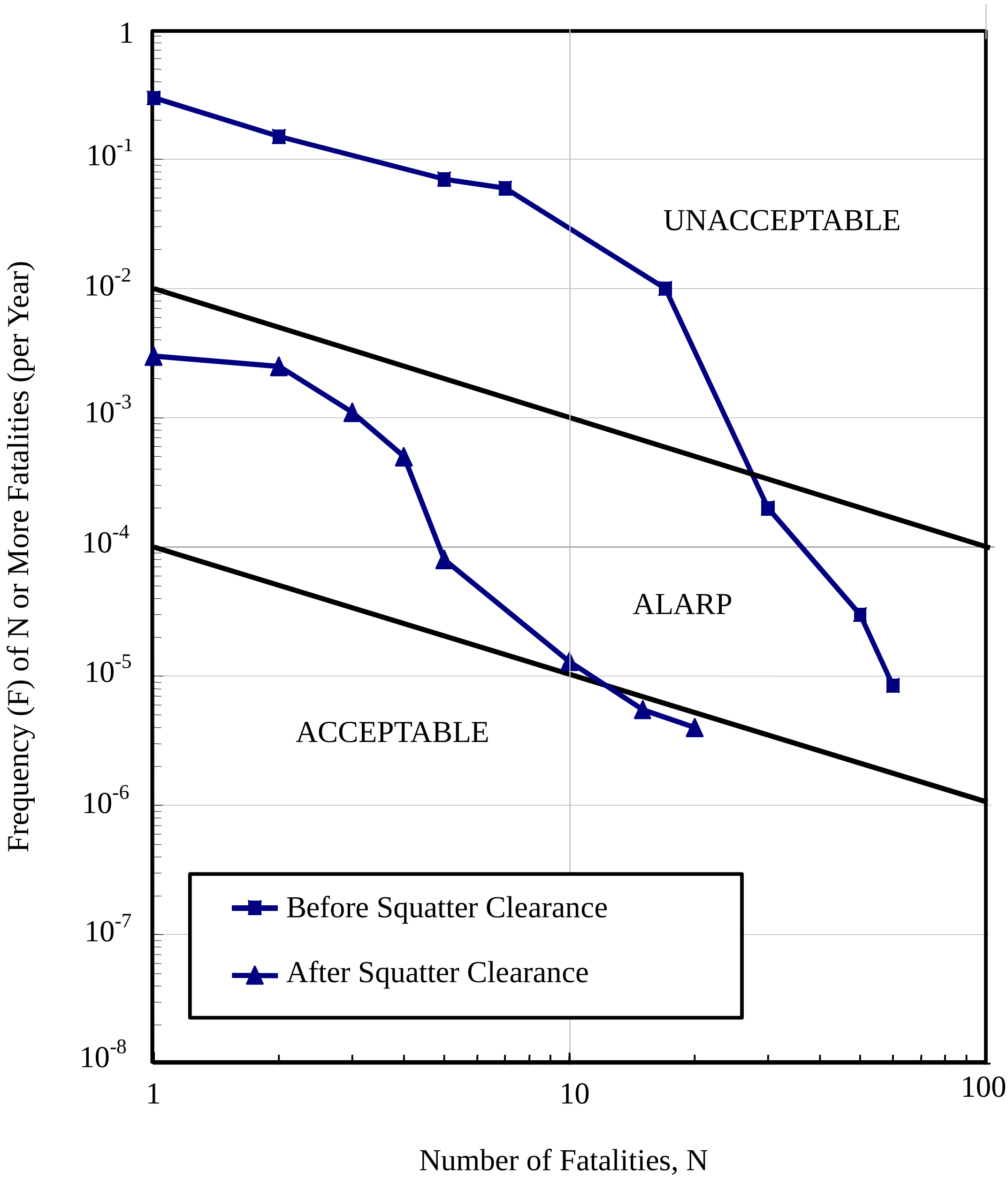

Figure 5.12 - Societal Risk for the Lei Yue Mun Squatter Area (Hardingham et al, 1998)

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Figure 5.13 - Landslide-prone Natural Terrain in Hong Kong

Figure 5.14 - A 20 m^3 Landslide in 1998 Resulted in Damage to Property

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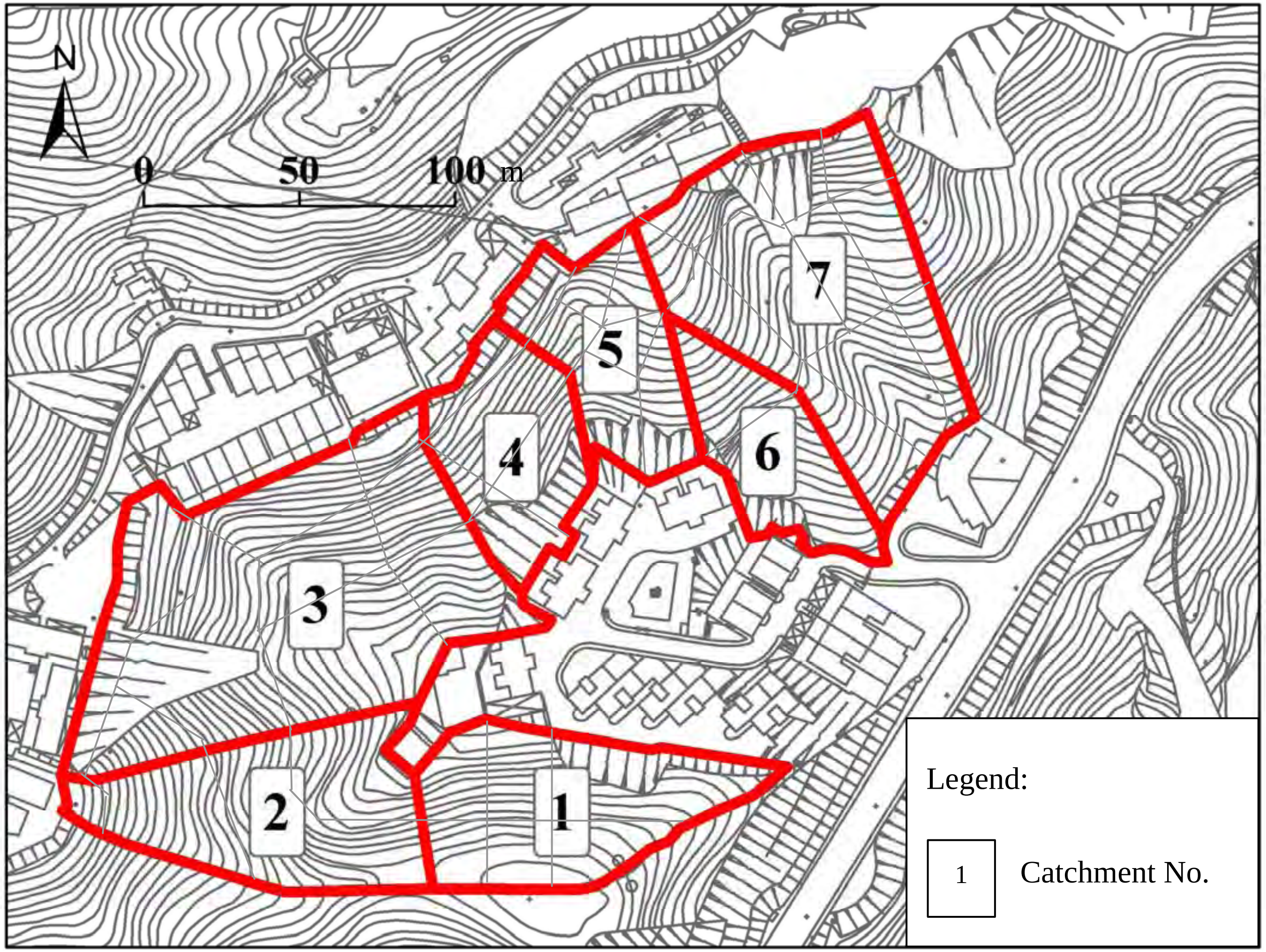

Figure 5.15 - Natural Terrain Catchments in Shatin Heights, Hong Kong

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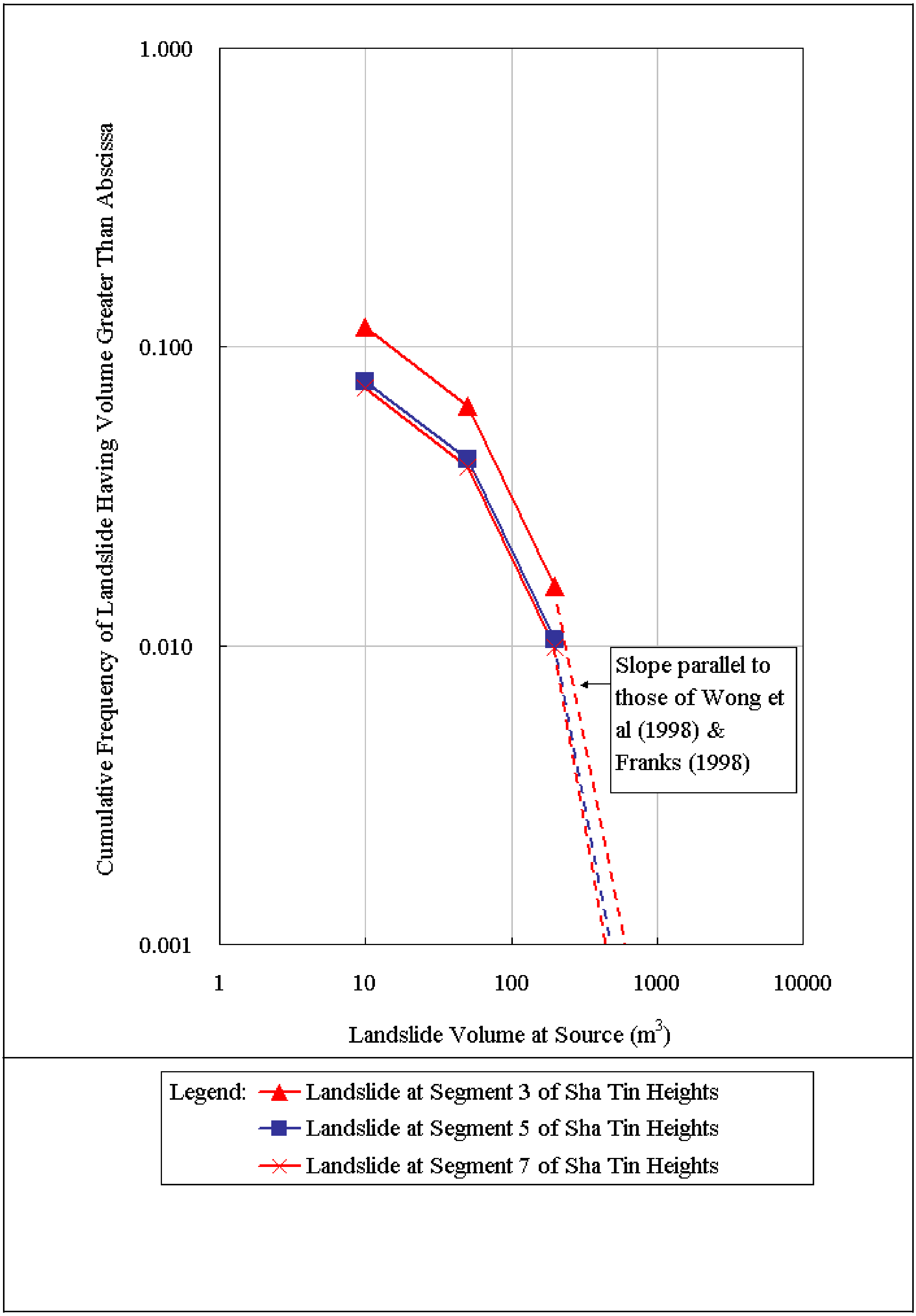

Figure 5.16 - Volume-Frequency Relationship at Shatin Heights (FMSW, 2001)

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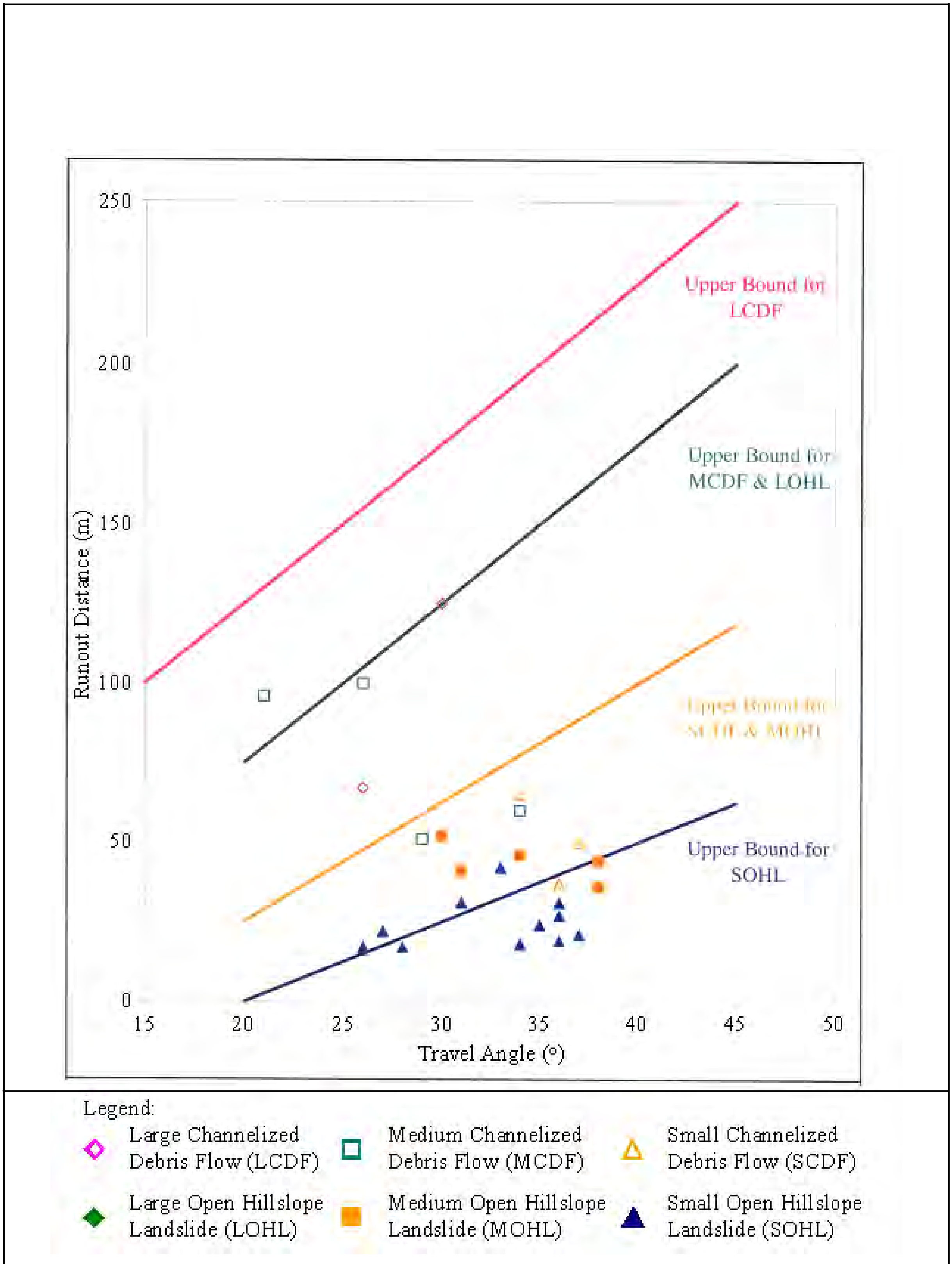

Figure 5.17 - Landslide Debris Runout Model for Shatin Heights (FMSW, 2001)

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(a) Before Risk Mitigation

(b) After Risk Mitigation

Legend:

Risk > 10^{-4} Risk >10^{-5} to <10^{-4} Risk = 10^{-6}

Figure 5.18 - Personal Individual Risk at Shatin Heights (FMSW, 2001)

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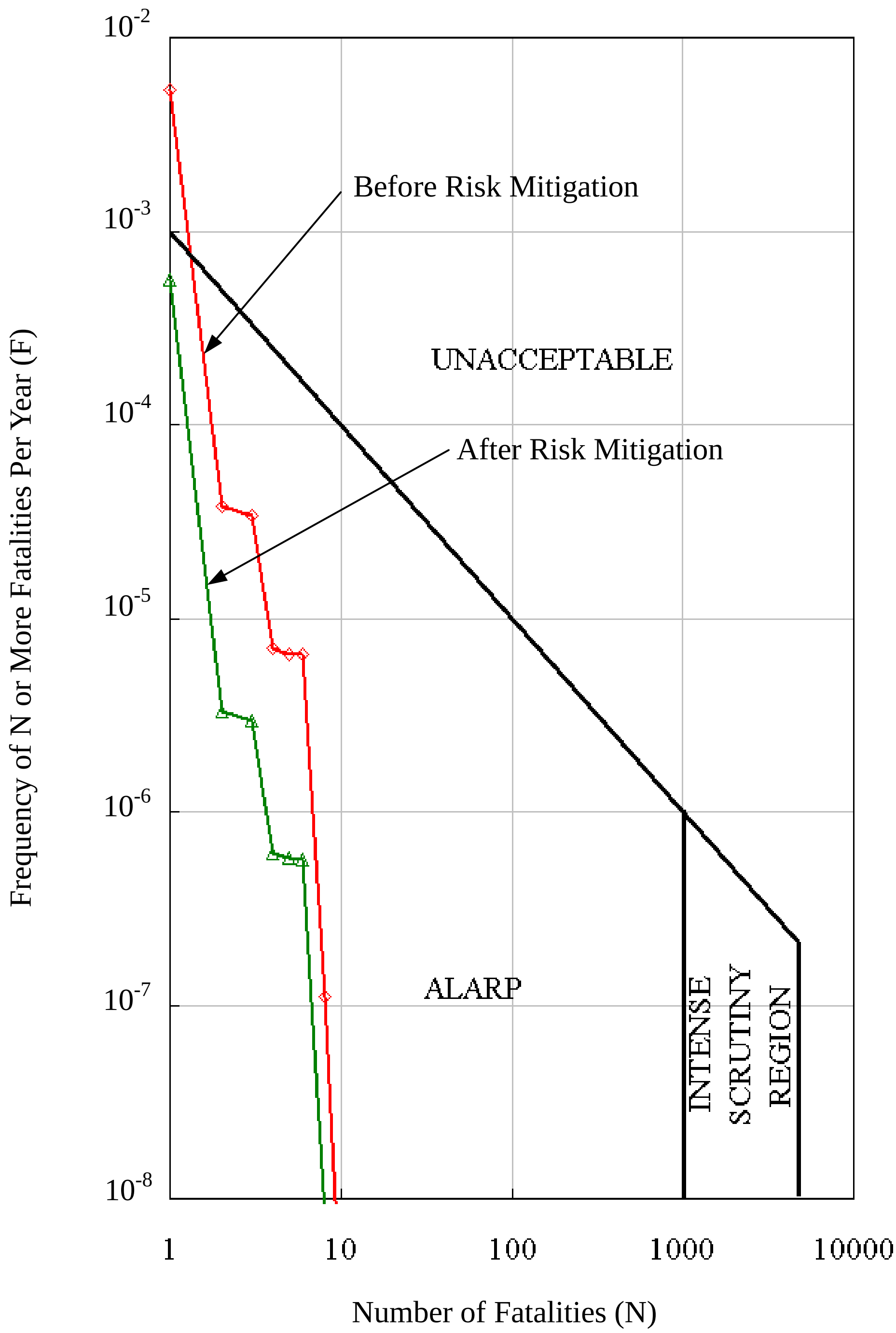

Figure 5.19 - Calculated F-N Curves for Shatin Heights (FMSW, 2001)

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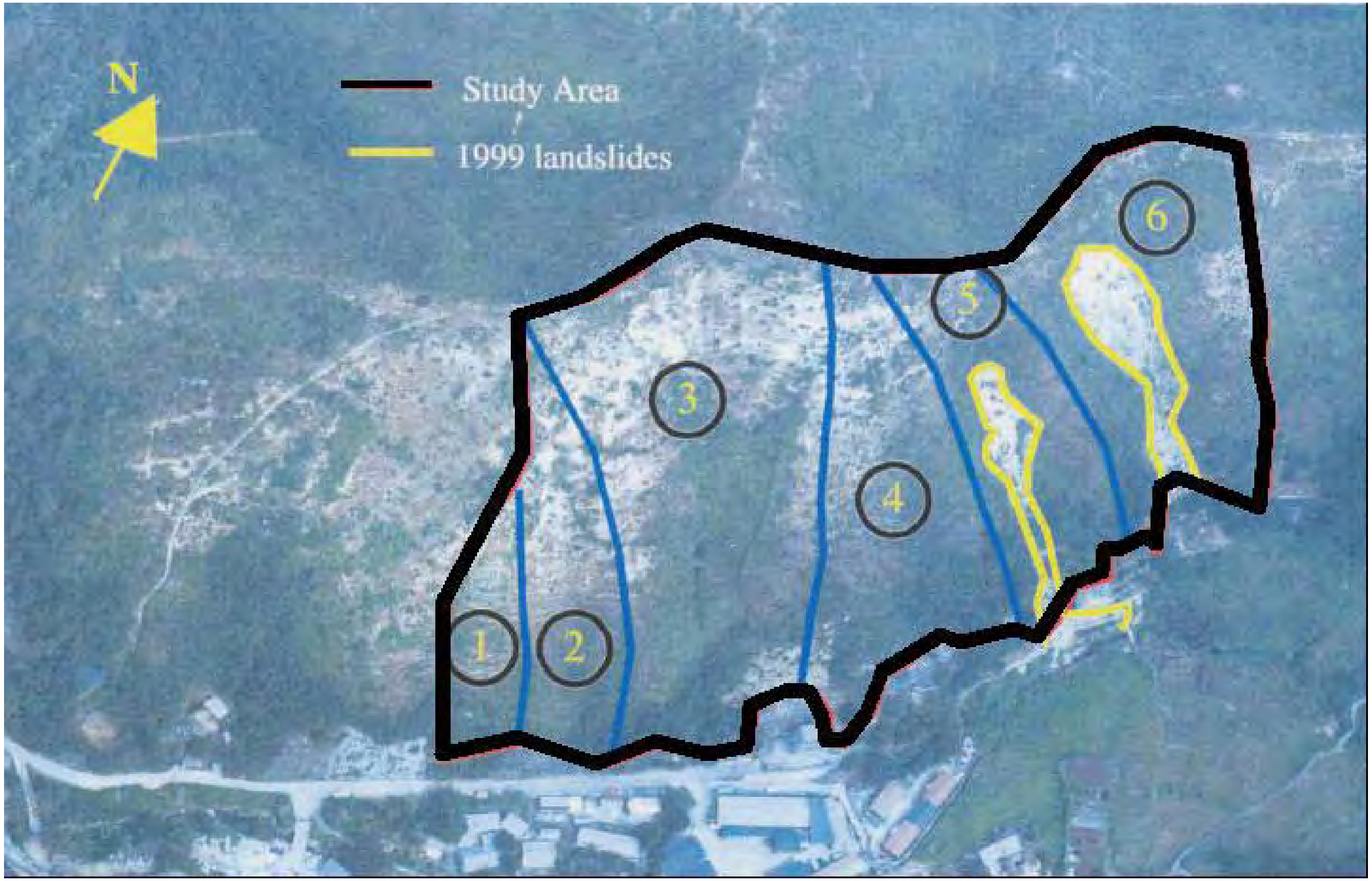

Figure 5.20 - The August 1999 Landslides at Pat Heung, Hong Kong

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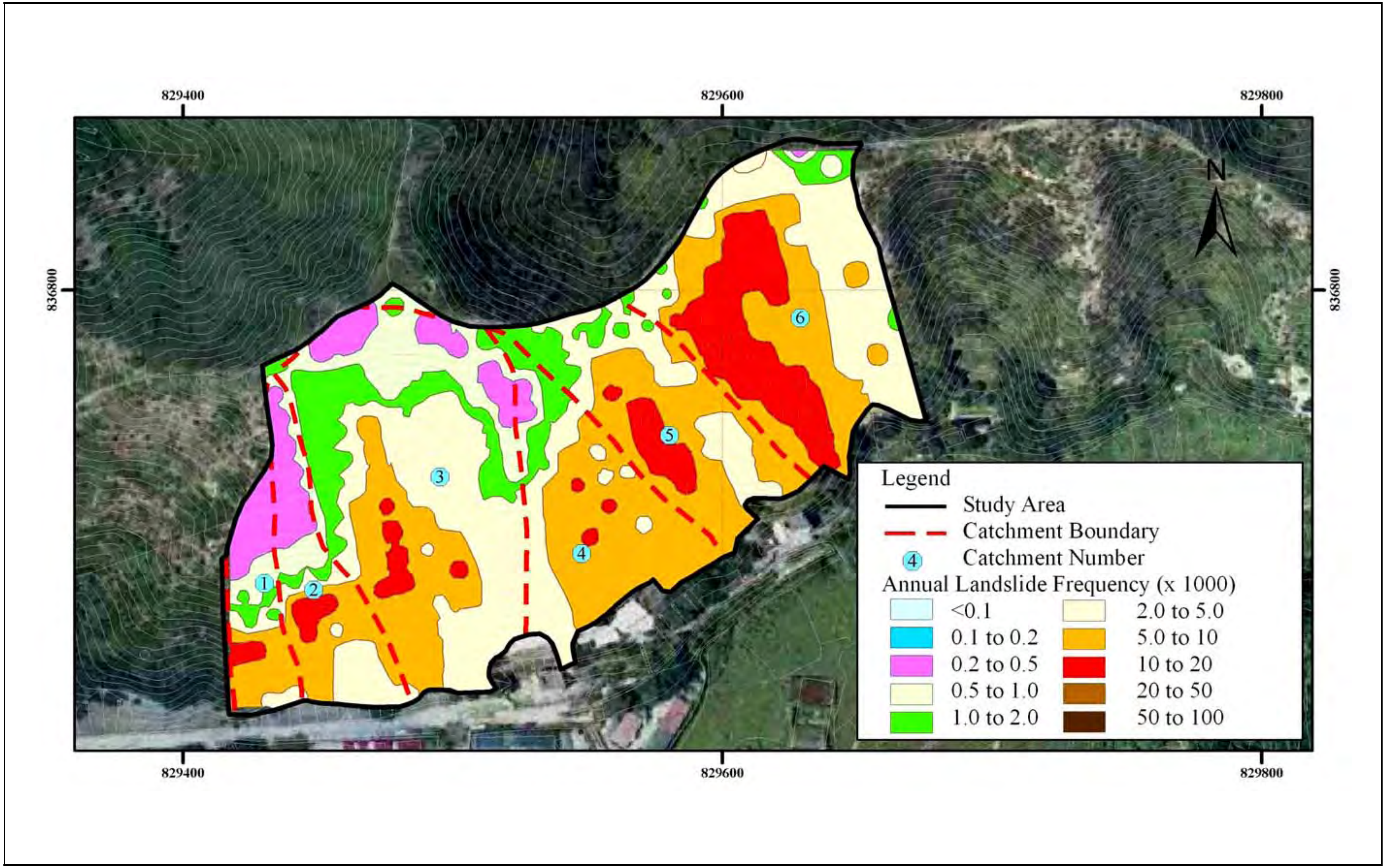

Figure 5.21 - Annual Landslide Frequency (OAP, 2003)

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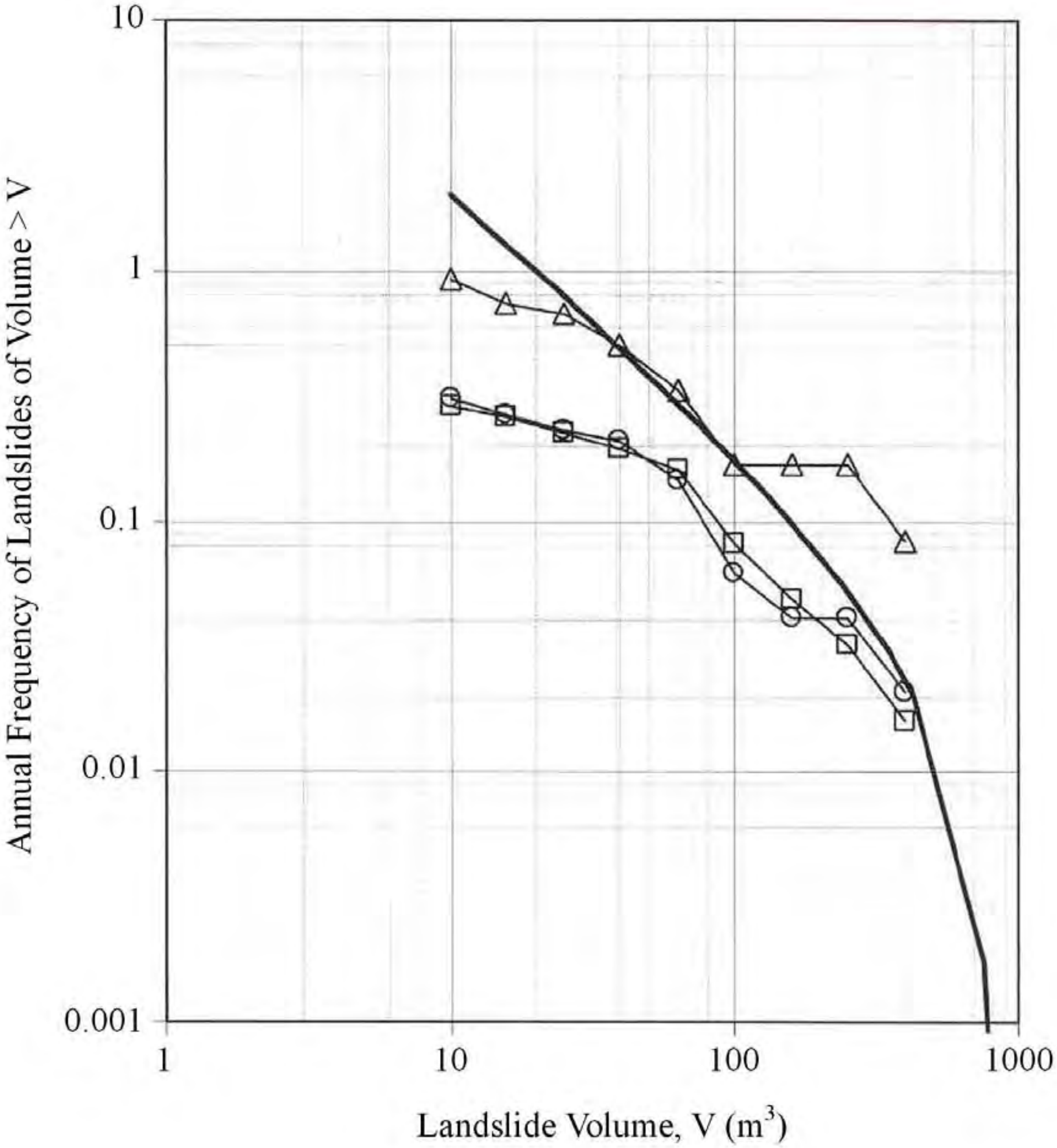

Legend:

Overall (adopted in QRA)
1939 - 2001
1953 - 2001
1989 - 2001

Figure 5.22 - Volume-Frequency Distribution for Landslides at Pat Heung (OAP, 2003)

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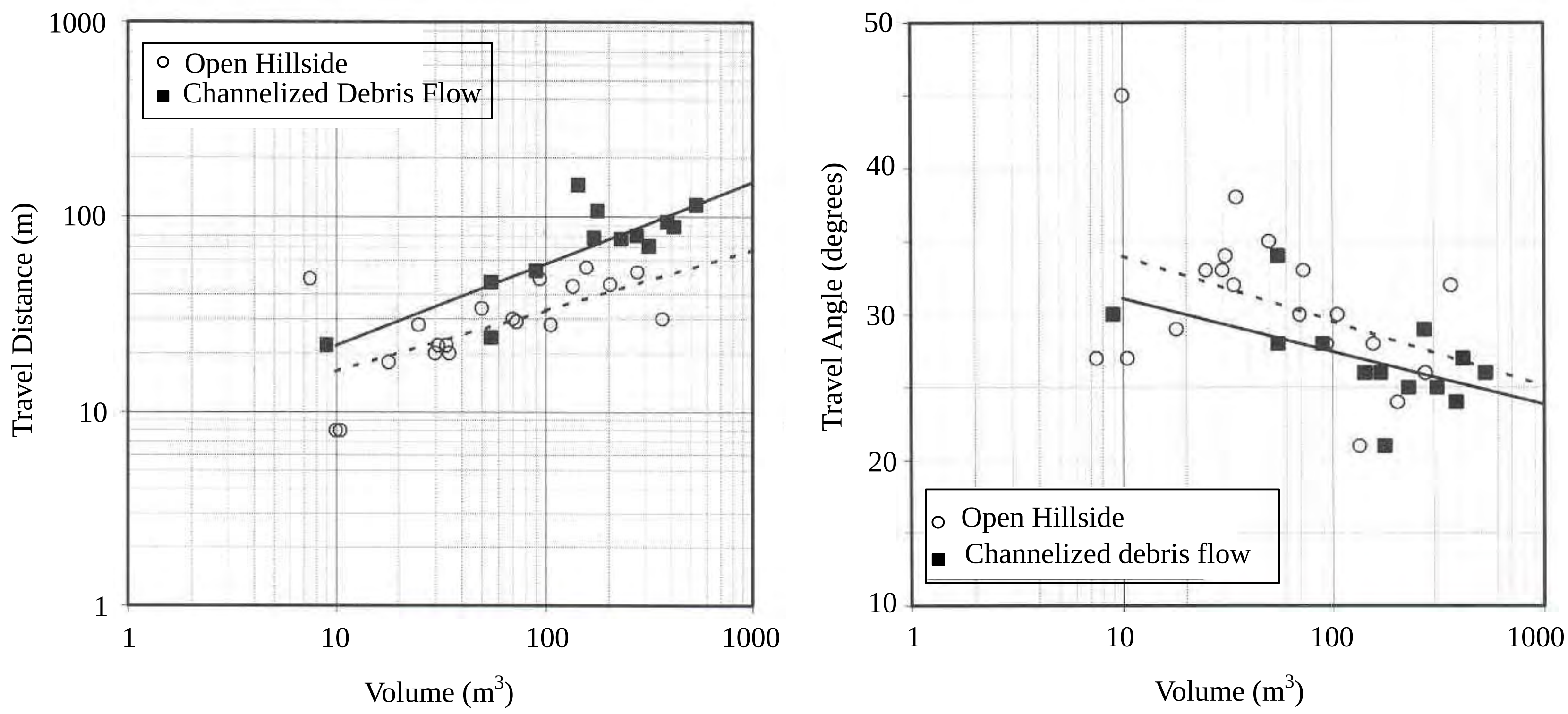

Figure 5.23 - Mobility of Landslides in Pat Heung (based on OAP, 2003)

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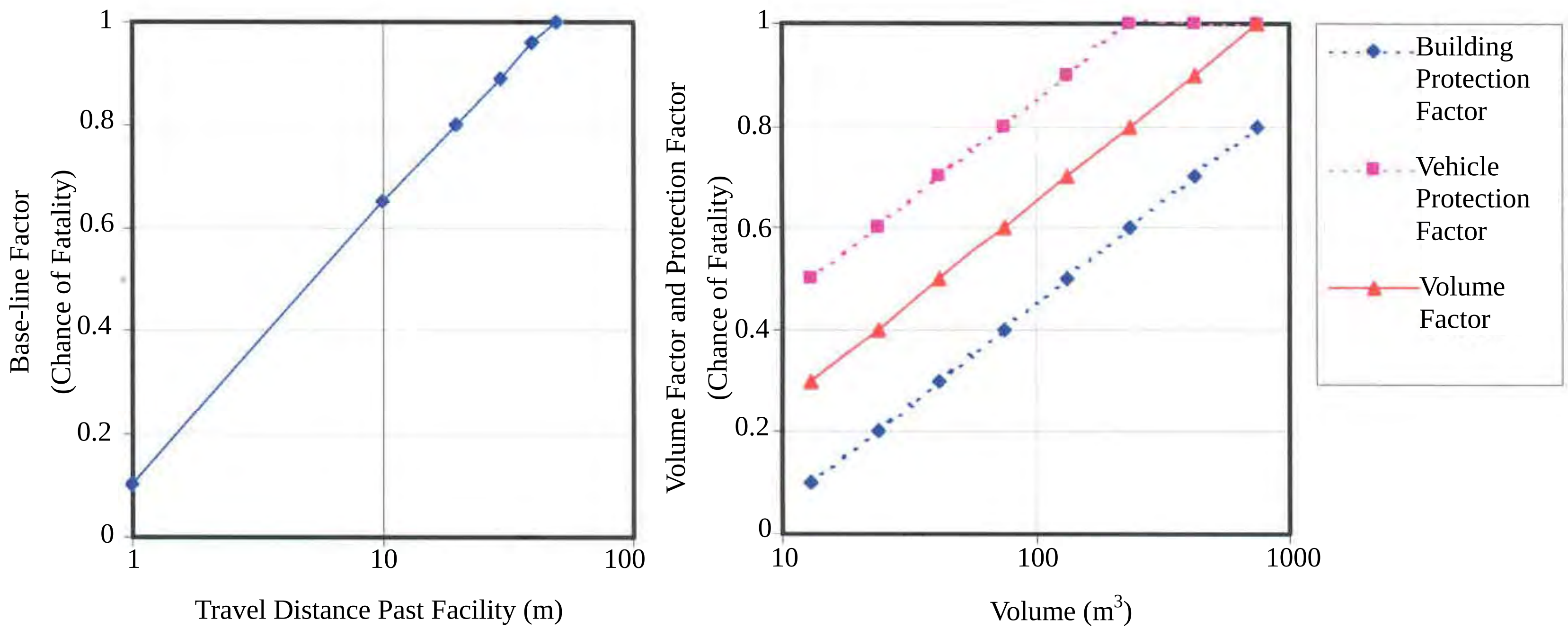

(a) Base-line Factor

(b) Volume Factor and Protection Factor

Notes: (1) The base-line factor is applied to a facility located at a given distance from the distal end of the debris runout
(2) Vulnerability factor = Base-line factor × Volume factor × Protection factor

Figure 5.24 - Vulnerability Factor adopted in Pat Heung QRA (based on OAP, 2003)

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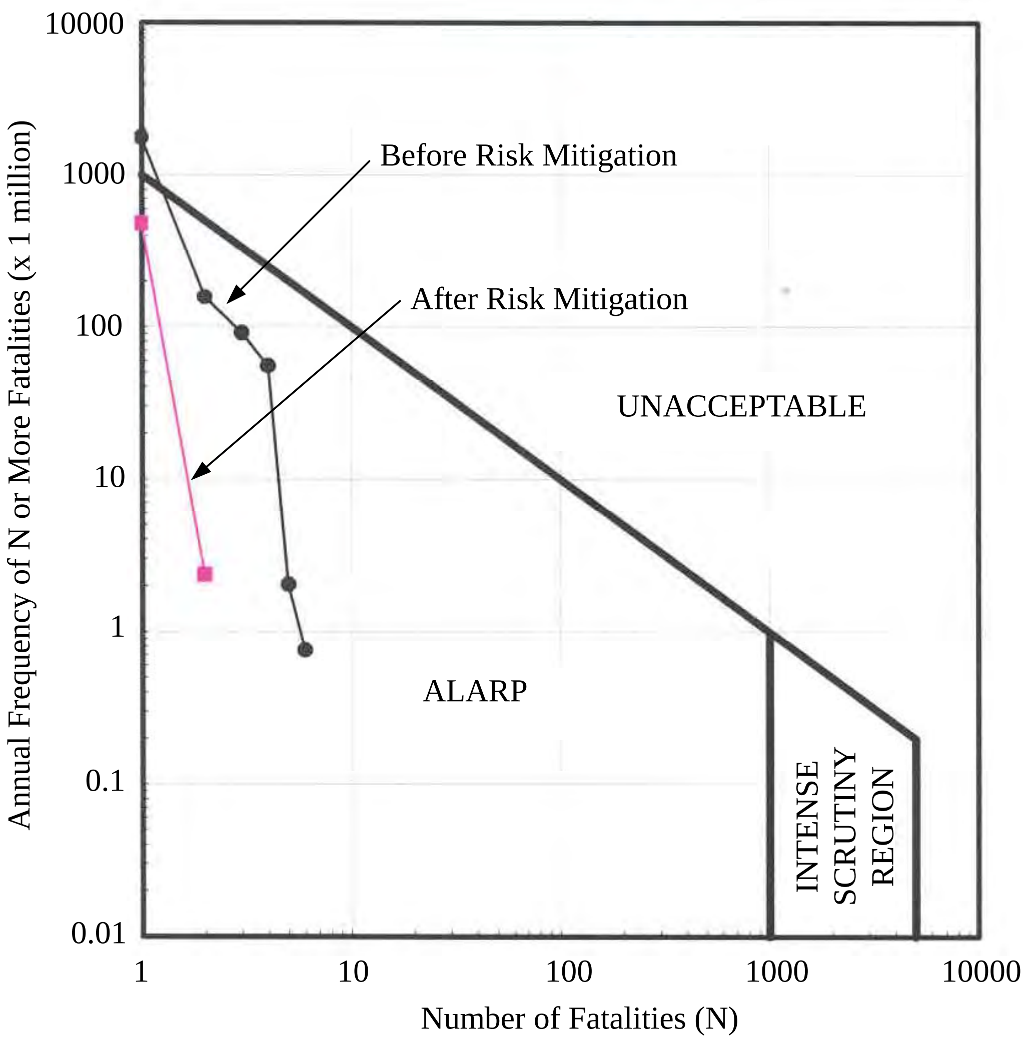

Figure 5.25 - Calculated F-N Curve for Pat Heung (OAP, 2003)

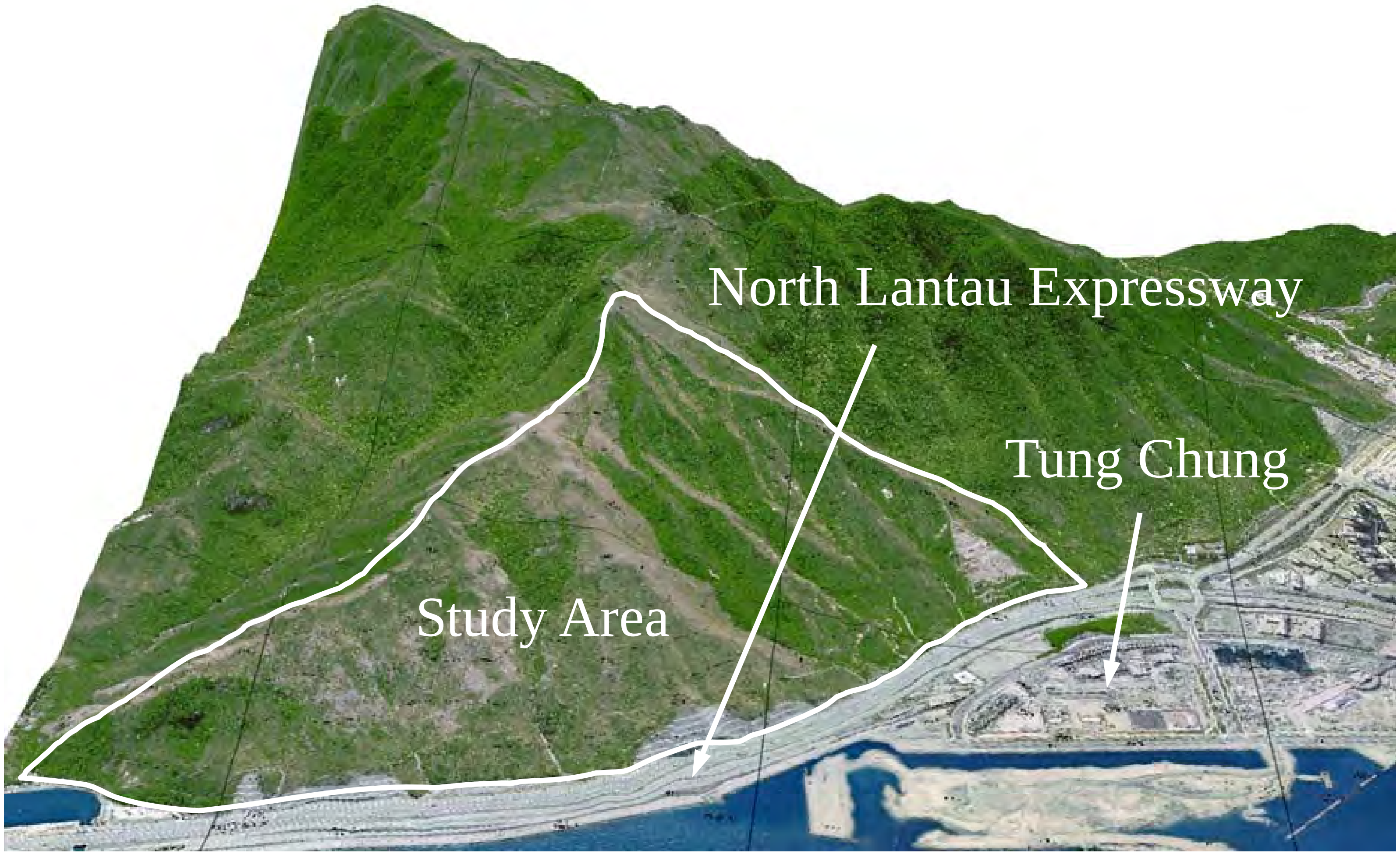

Figure 5.26 - Natural Hillside Overlooking North Lantau Expressway, Hong Kong

Legend:

- Distressed ground (with tension cracks and slow moving landslides).
- Area of landslide clustering.
- Alluvium, channelized debris flow dposit, colluvium and taluvium boulder accumulate along the drainage channels.
- Shallow landslides deposit colluvium on gully side slopes. Many landslides.
- Taluvial lobes downslope from intermittent rock outcrops.
- Rockfall debris at the toe of rock outcrops.
- Accumulation of colluvium in topographic depressions.
- Landslides occur on former steep coastal slopes.
- Open hillslope colluvium accumulates on relatively shallow hillslopes. In feldsparphyric rhyolite/ porphyritic microgranite terrain. Very few landslides.
- Open hillslope colluvium on relatively shallow hillslopes (younger terrain) in the rhyolite lava/ tuff terrain as a result of creep. Few landslides.
- Relatively steep hillslopes in the upper portion of the rhyolite lava/ tuff terrain (older terrain). Drainage channels generally have well defined convex breaks of slope at their heads but very few recent landslides.

Incised and degraded

Younger

Debris fans, comprising coalescing bodies of colluvium/ alluvium, have developed at the hillslope toe.

- Study Area Boundary
- Former Shoreline
- Former Cliffline

- Areas of saprolite along hillside spurs. Very few landslides.
- Rock outcrops

Figure 5.27 - Landslide Process Model (OAP, 2005)

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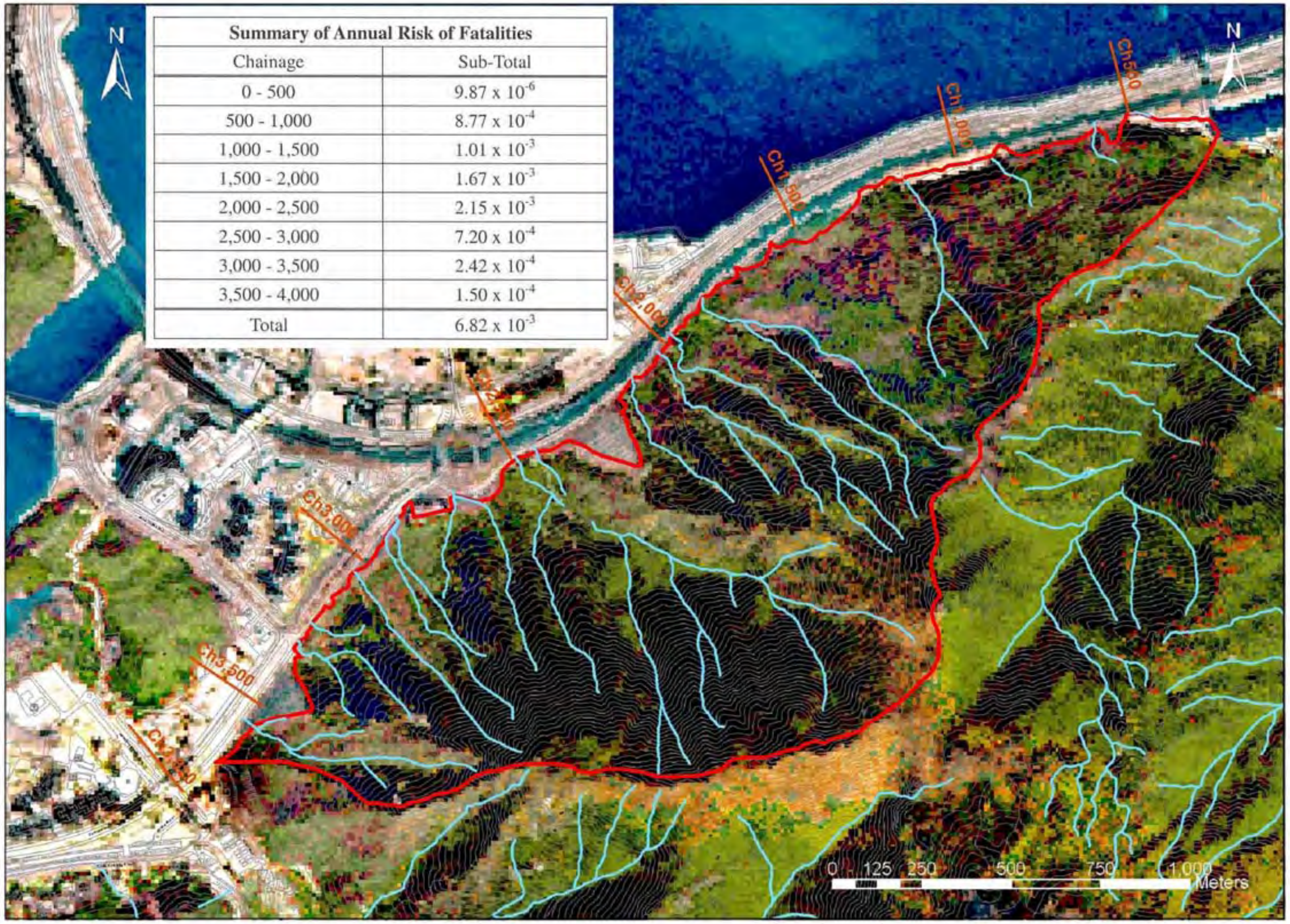

Summary of Annual Risk of Fatalities

Chainage	Sub-Total
0 - 500	9.87×10^{-6}
500 - 1,000	8.77×10^{-4}
1,000 - 1,500	1.01×10^{-3}
1,500 - 2,000	1.67×10^{-3}
2,000 - 2,500	2.15×10^{-3}
2,500 - 3,000	7.20×10^{-4}
3,000 - 3,500	2.42×10^{-4}
3,500 - 4,000	1.50×10^{-4}
Total	6.82×10^{-3}

Figure 5.28 - Spatial Distribution of Annual Risk of Fatalities at Different Sections of North Lantau Expressway (OAP, 2005)

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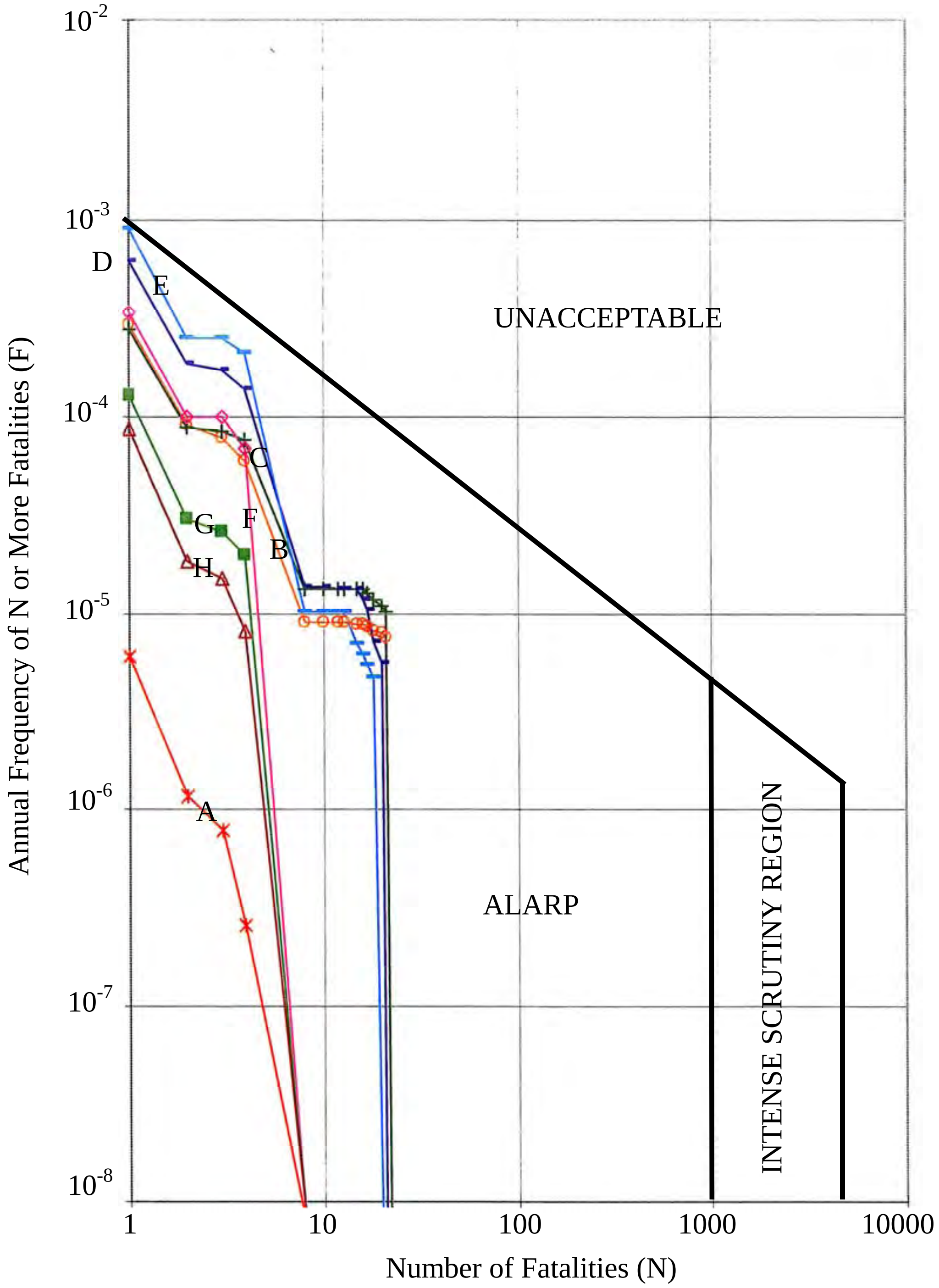

Legend:

A - Chainage 0 - 500 m
B - Chainage 501 - 1,000 m
C - Chainage 1,001 - 1,500 m
D - Chainage 1,501 - 2,000 m
E - Chainage 2,001 - 2,500 m
F - Chainage 2,501 - 3,000 m
G - Chainage 3,001 - 3,500 m
H - Chainage 3,501 - 4,000 m

Figure 5.29 - Calculated F-N Curves for North Lantau Expressway (OAP, 2005)

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Design Requirement for Risk Mitigation			
Location	Debris Volume (m^3)	Debris Velocity (m/s)	Debris Height (m)
A	500	13	2.5
B	500	13	2.5
C	1,000	15	3.0
D	1,000	15	3.0
E	1,000	15	3.0
F	1,700	16	3.5

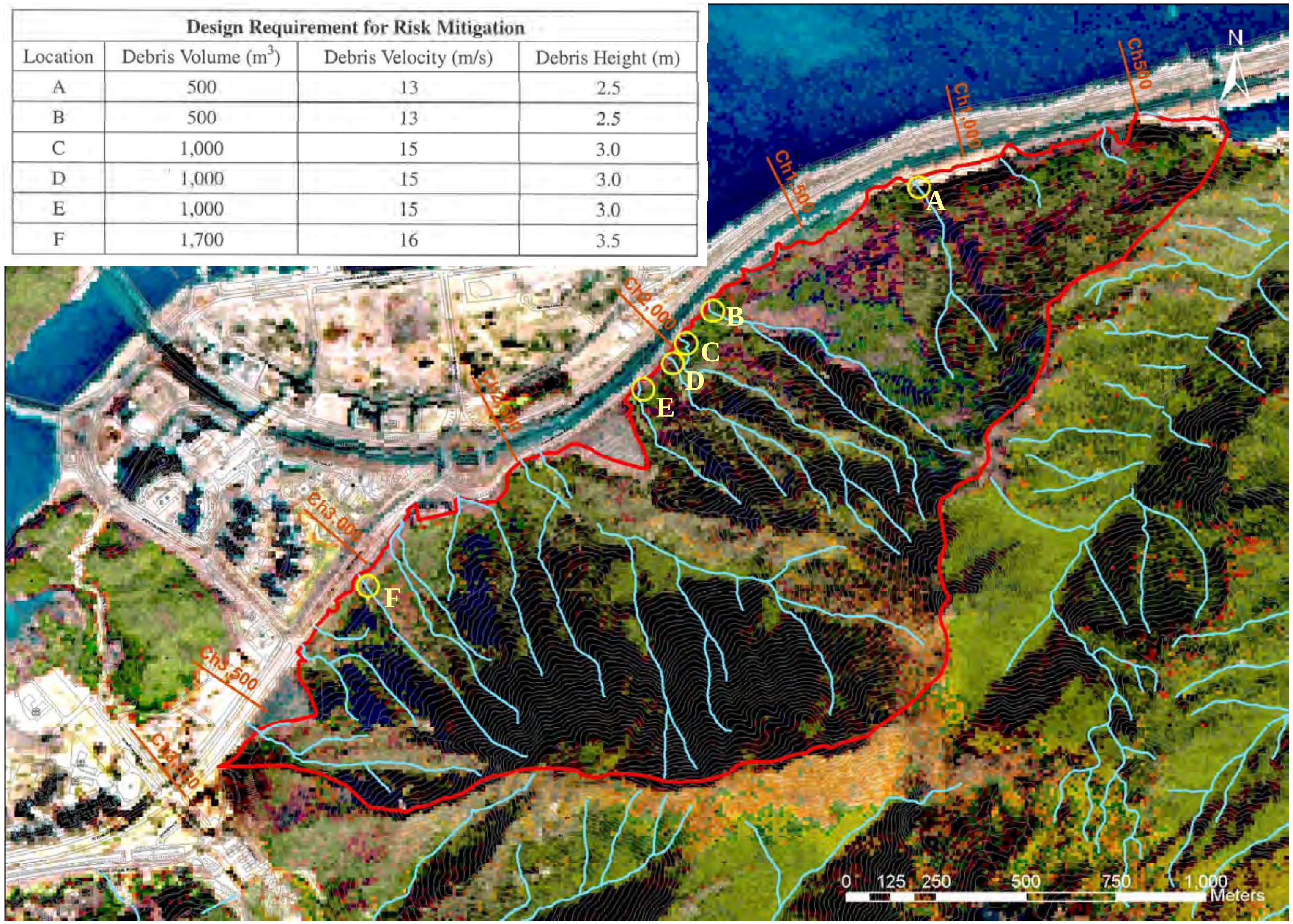

Figure 5.30 - Mitigation Strategy (OAP, 2005)

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Figure 5.31 - Catchments and Sub-catchments in Area B, Ling Pei, Hong Kong (Wong et al, 2004c)

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Figure 5.32 - Historical Landslides in Ling Pei (Wong et al, 2004c)

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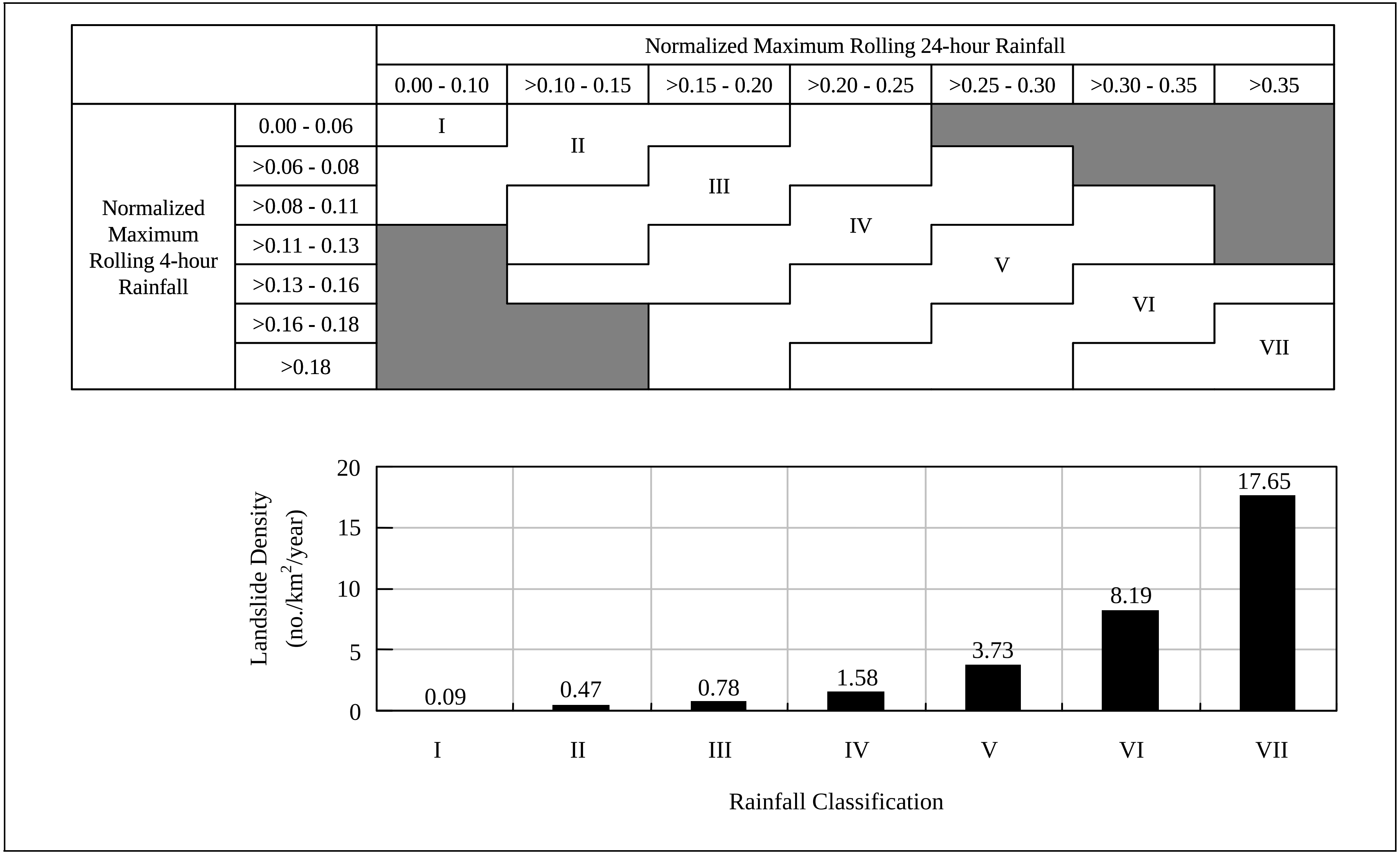

Figure 5.33 - Rainfall-Natural Terrain Landslide Density Correlation based on Combined 24-hour and 4-hour Rainfalls (Wong et al, 2004c)

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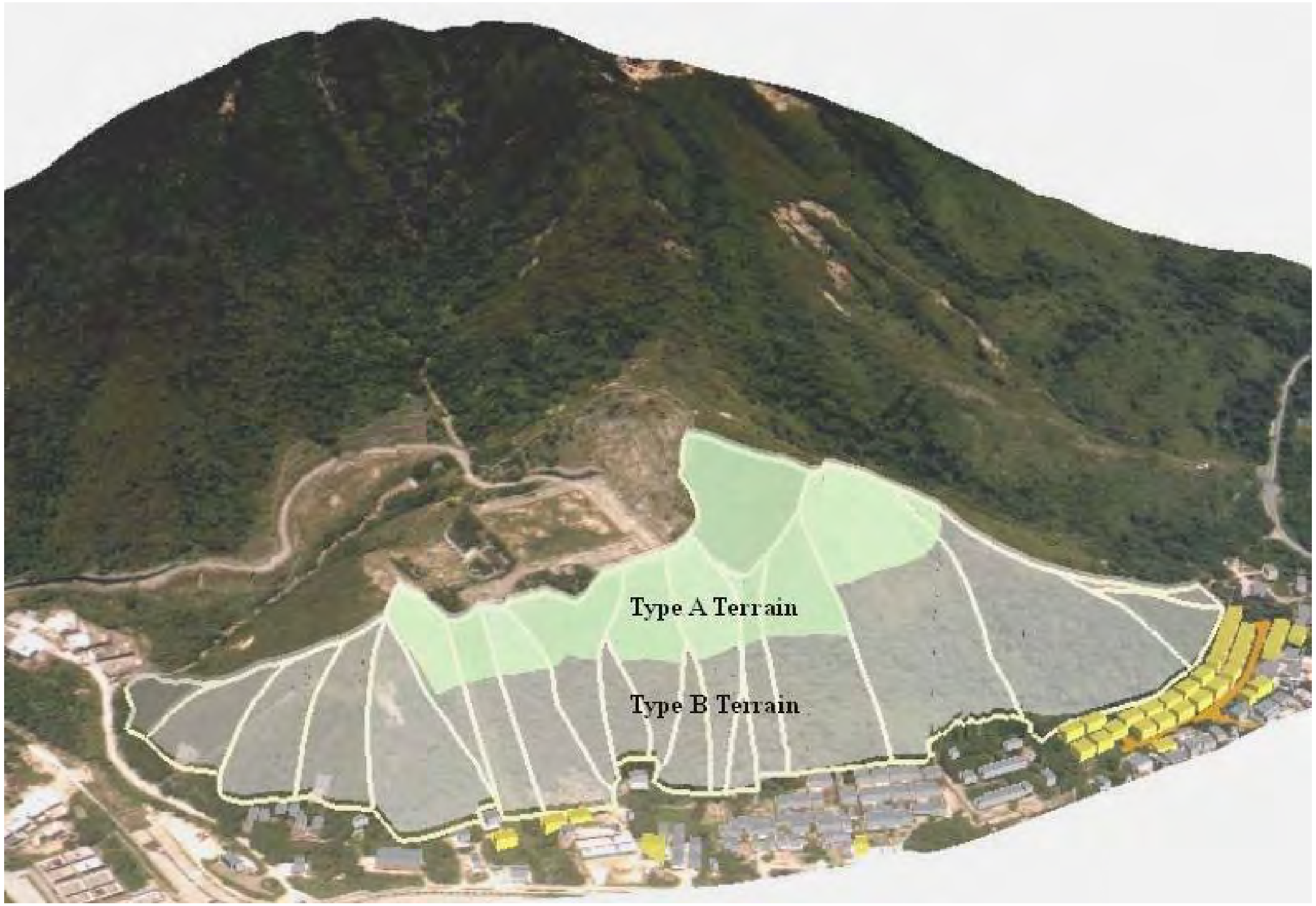

Figure 5.34 - Terrain Classification (Wong et al, 2004c)

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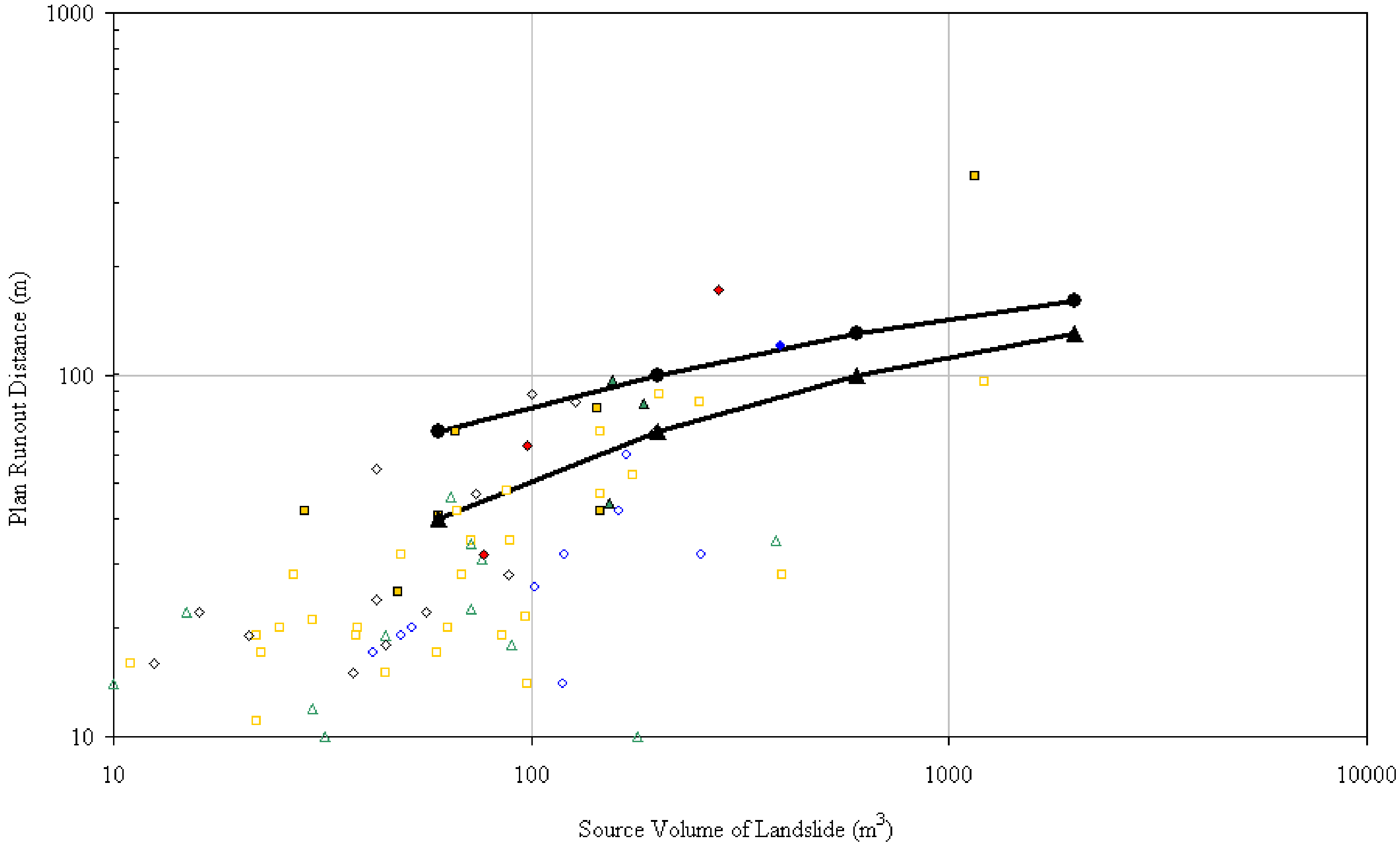

Legend:

Worst Credible Limit for Channelized Debris Flow

Worst Credible Limit for Open Hillslope Debris Slide/ Avalanche

Figure 5.35 - Worst Credible Debris Runout Distance in Ling Pei (Wong et al, 2004c)

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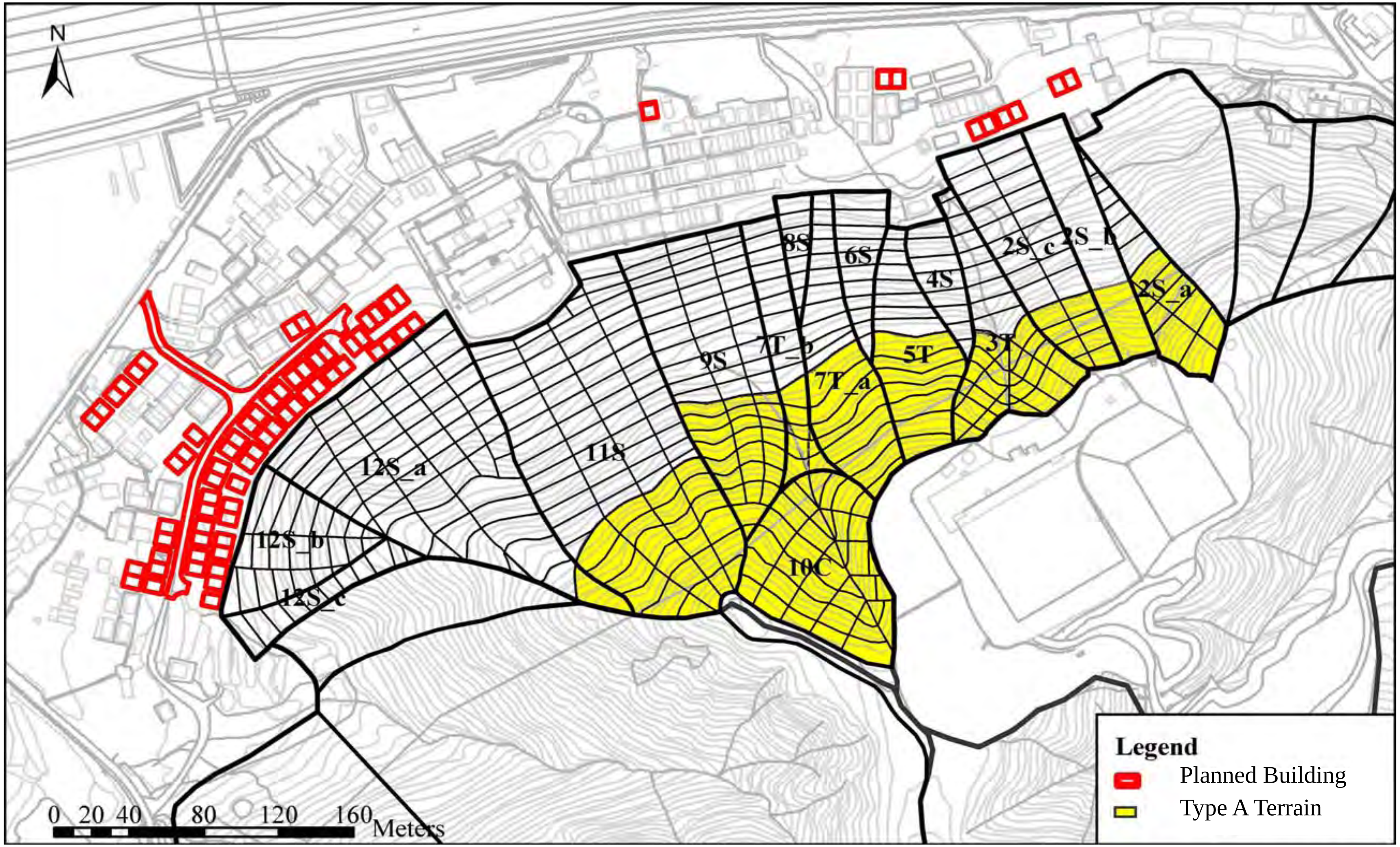


Figure 5.36 - Hillside Units (Wong et al, 2004c)

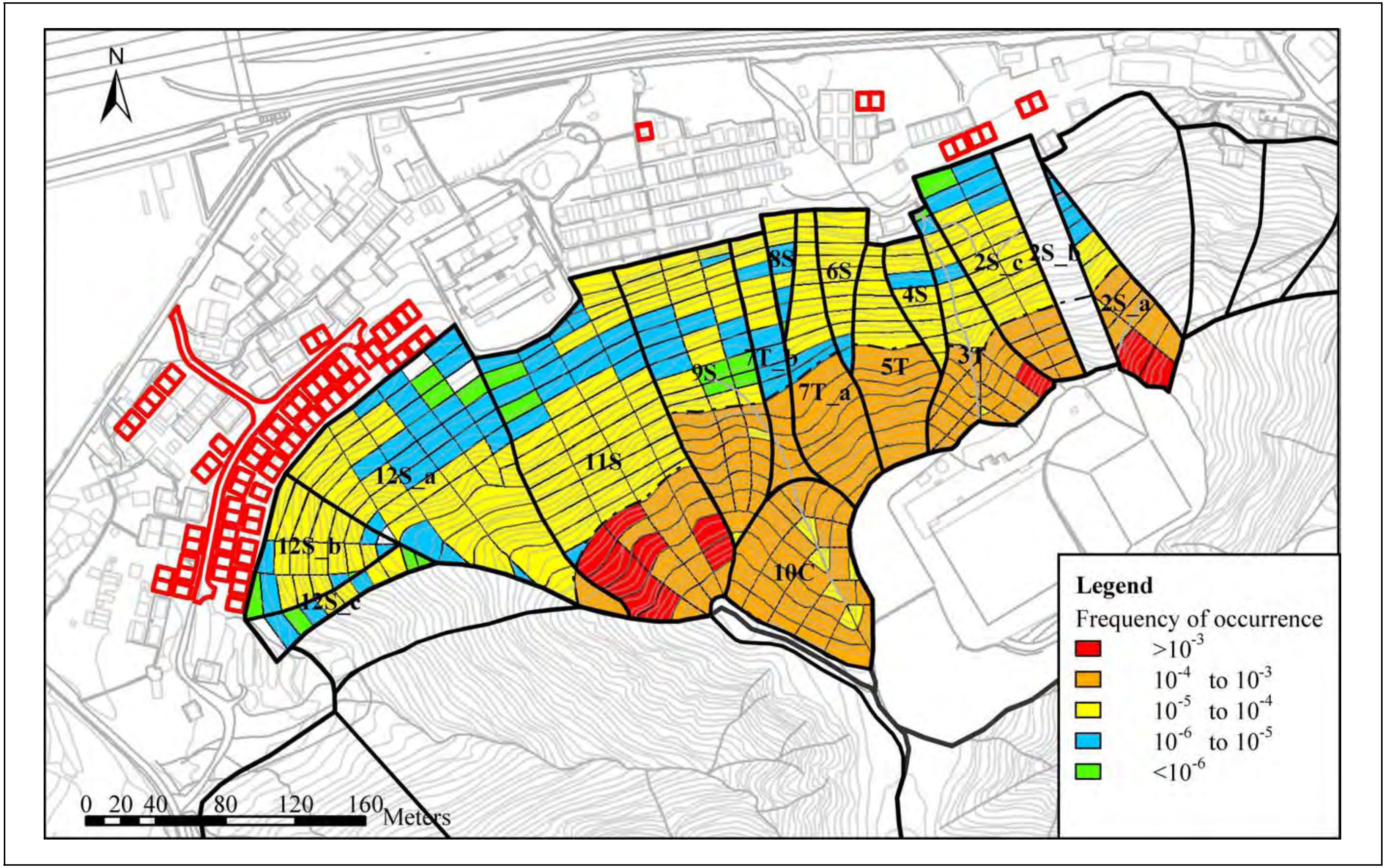
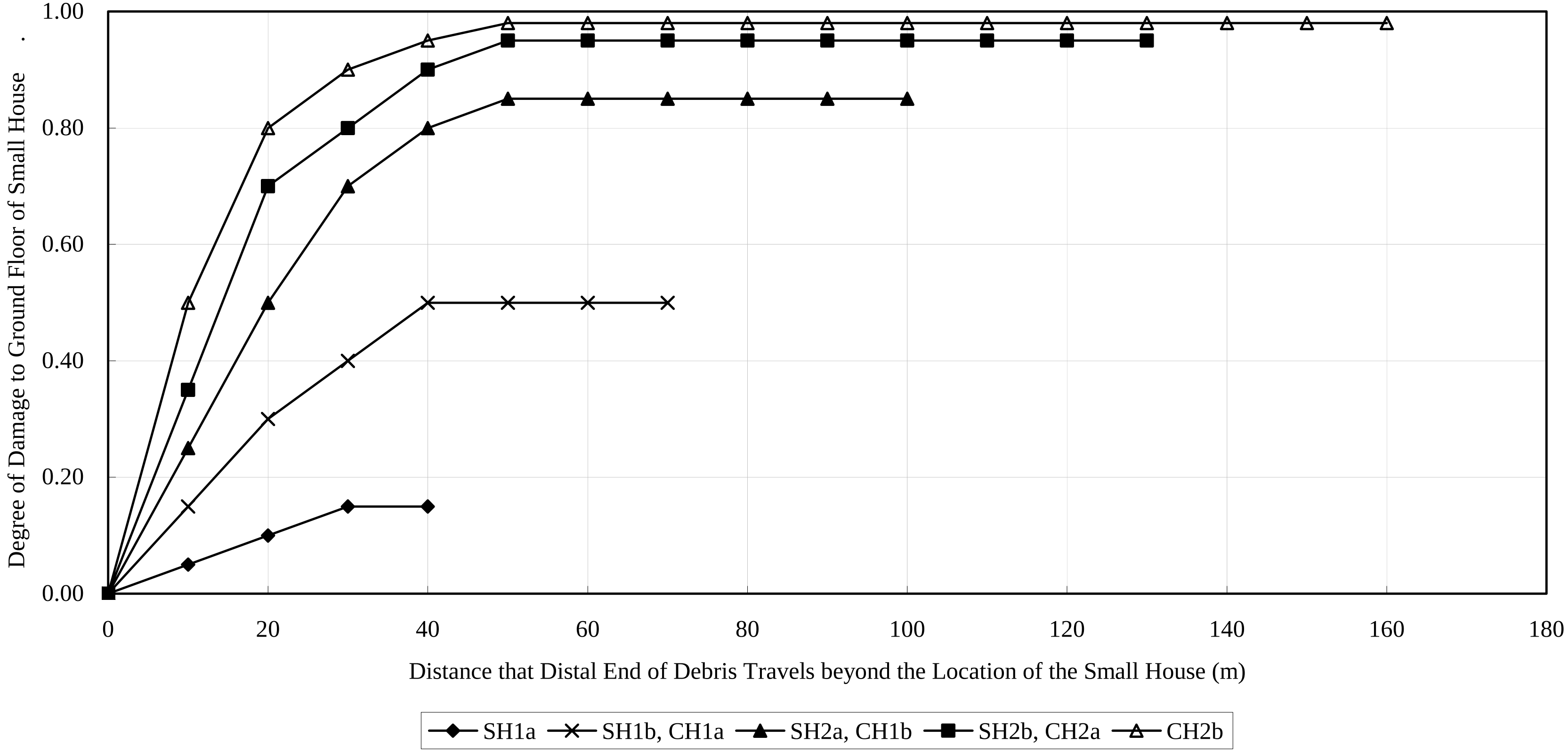


Figure 5.37 - Calculated Annual Frequency of Landslide Hazard H1a (20 m^3 to 60 m^3) (Wong et al, 2004c)



Note: SH1a, etc. as defined in Table 5.8.

Figure 5.38 - Degree of Damage to Ground Floor of Building (Wong et al, 2004c)

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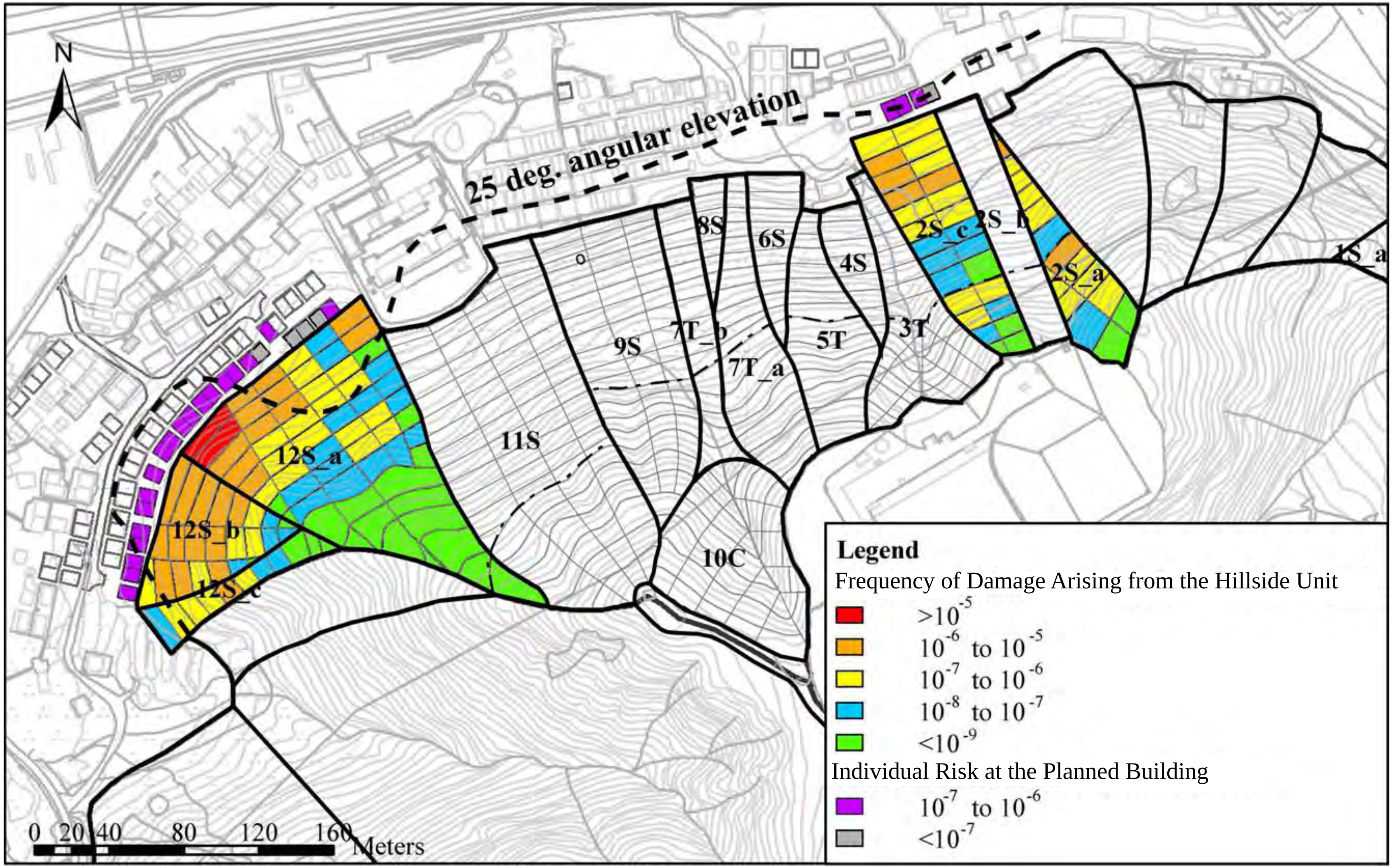
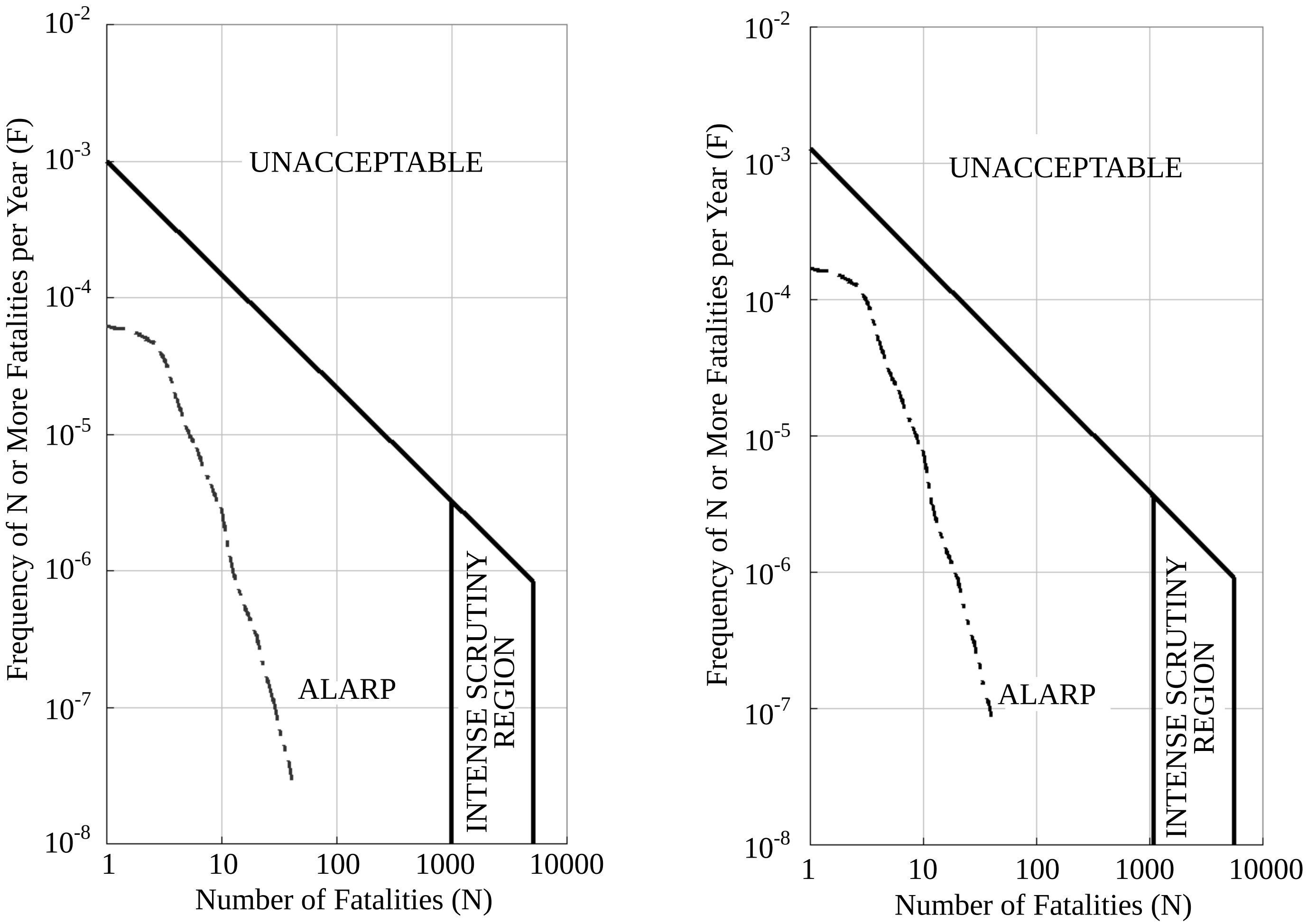


Figure 5.39 - Individual Risk at Planned Buildings (Wong et al, 2004c)



(a) For Planned Buildings

(b) For Existing and Planned Buildings
(Note: Risk criteria scaled up according to consultation boundary length = 560 m)

Figure 5.40 - Calculated F-N Curves for Ling Pei (Wong et al, 2004c)

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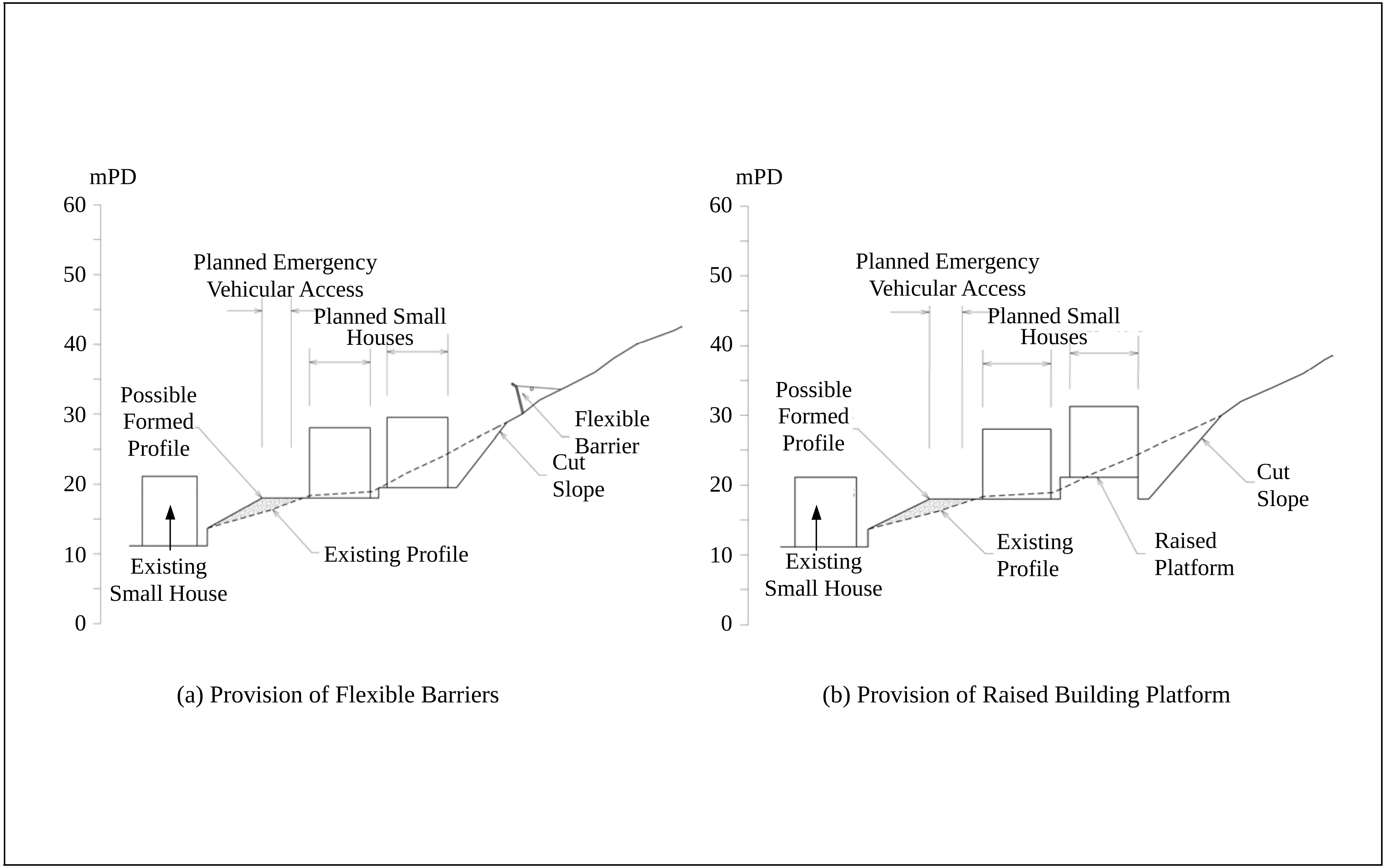

Figure 5.41 - Evaluation of Risk Mitigation Options (Wong et al, 2004c)

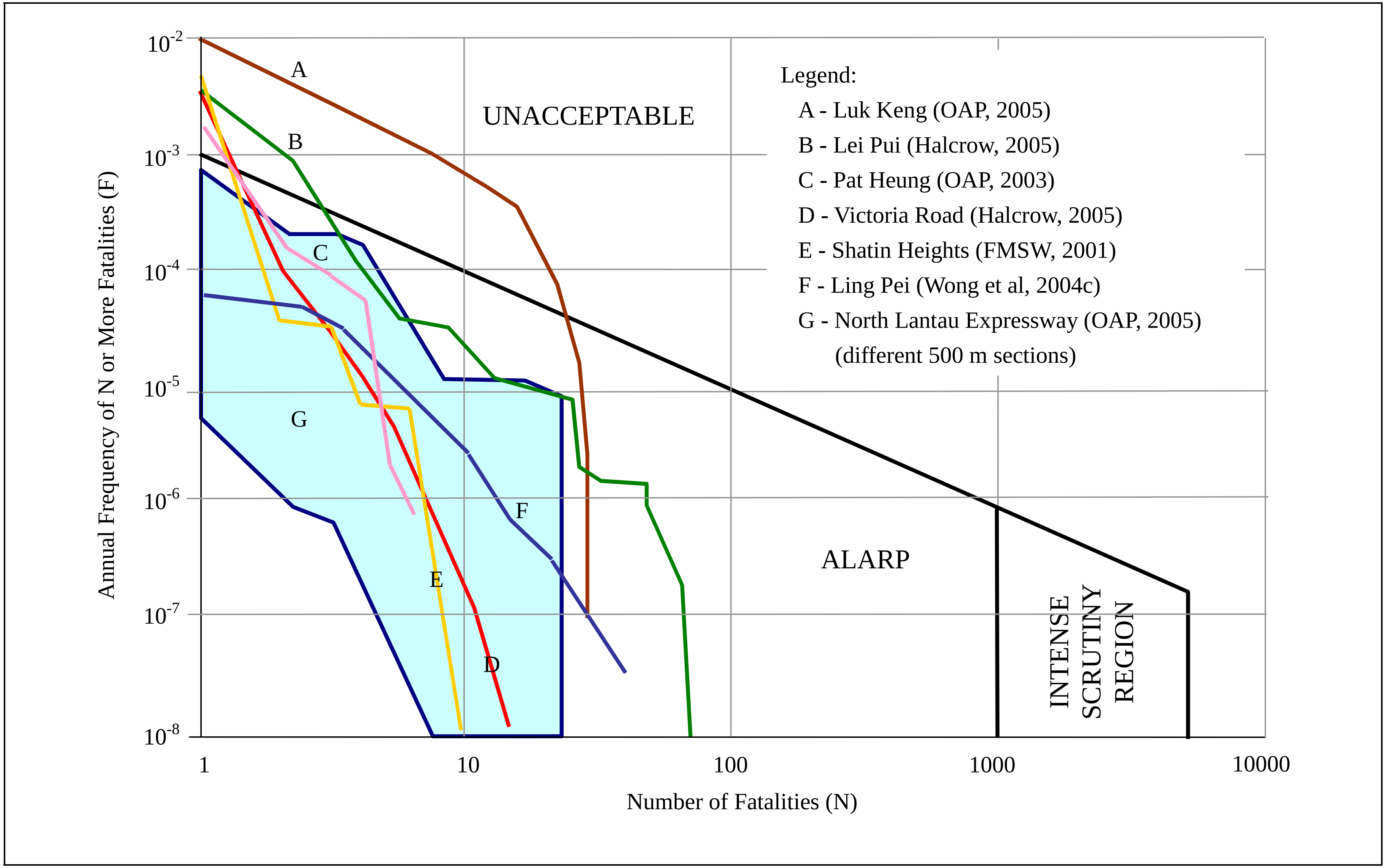

Figure 5.42 - F-N Curves of Selected Natural Terrain Landslide QRA in Hong Kong

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Figure 5.43 - The Tsing Shan Debris Flow in 2000

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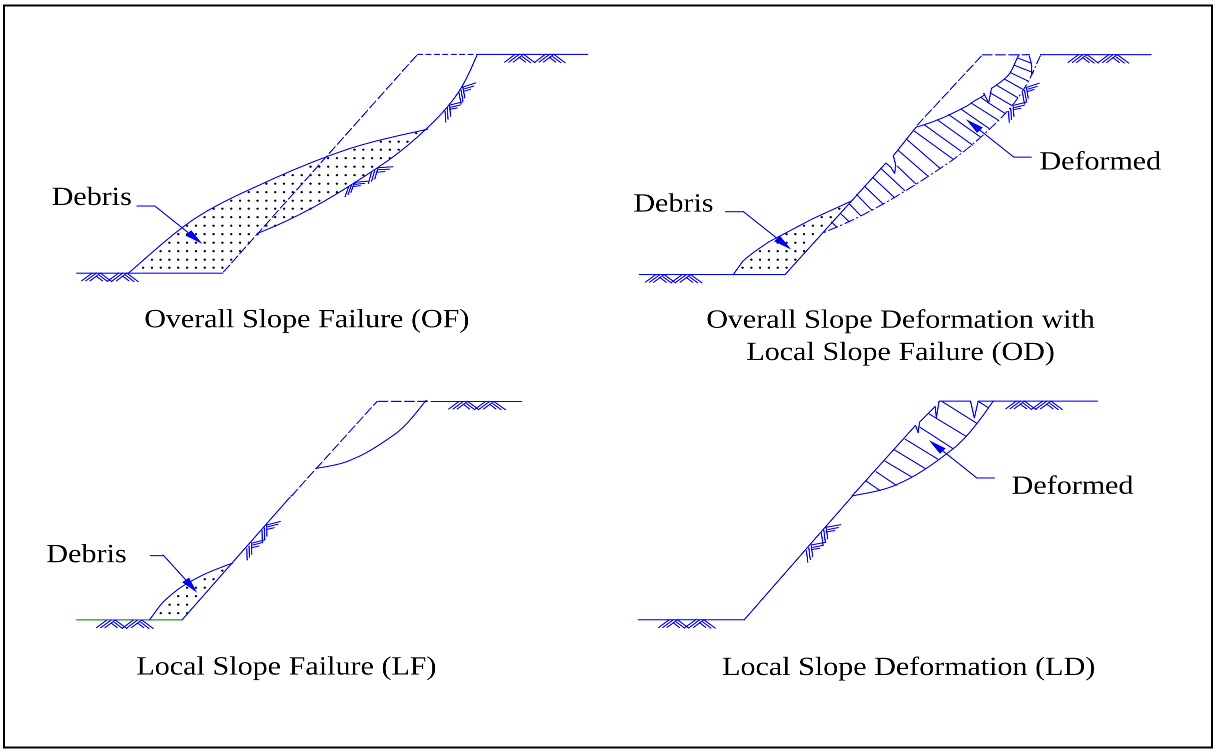

Figure 6.1 - Modes of Seismic-induced Slope Instability Adopted in QRA (Wong & Ho, 1998b)

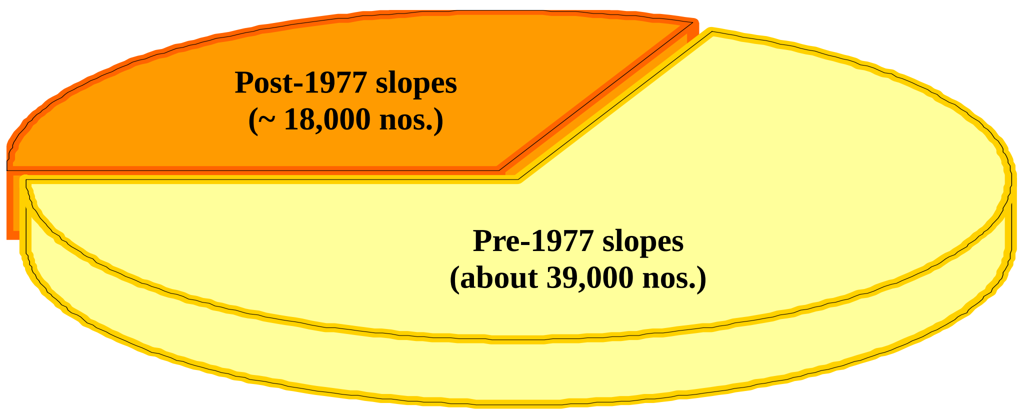

Figure 6.2 - Catalogue of Slopes Comprising 57,000 Sizeable Man-made Slopes in Hong Kong

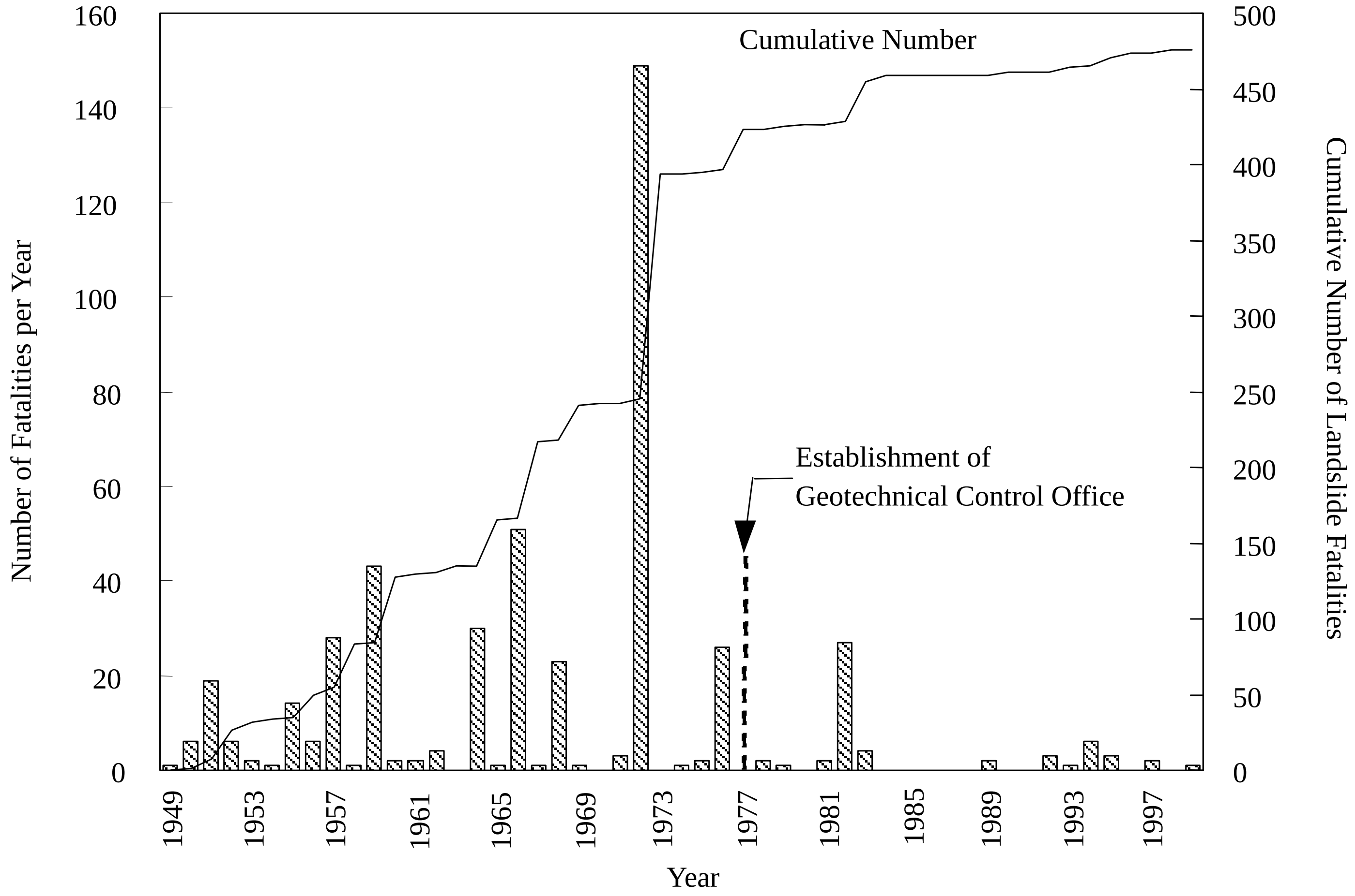

Figure 6.3 - Known Landslide Fatalities in Hong Kong (Wong & Ho, 2000)

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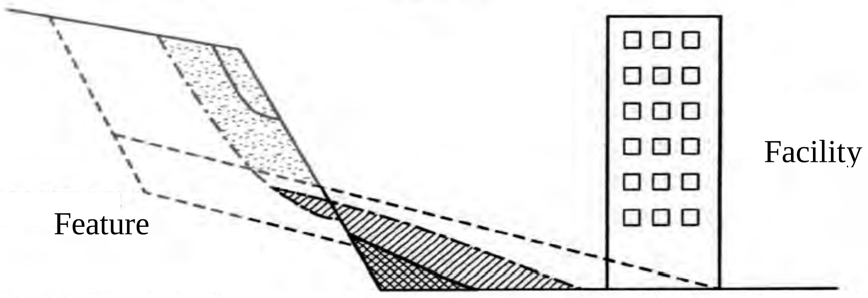
Type of Slope Feature	– Cut – Fill – Retaining wall
Mechanism of Failure	– Sliding – Wash-out – Liquefaction
Scale of Failure	– <20 m^3 – 20 - 50 m^3 – 50 - 200 m^3 – 200 - 1,000 m^3 – 1,000 - 10,000 m^3 – >10,000 m^3
Facility Affected	– Consequence model

$$H_1 \longrightarrow F_1, C_1$$
$$H_2 \longrightarrow F_2, C_2$$
$$H_3 \longrightarrow F_3, C_3$$



$$[\text{Hazard}]_{ij} = [\text{Mechanism}]_i\ [\text{Scale}]_j$$

Figure 6.4 - Hazard and Frequency Model (Wong et al, 1997)

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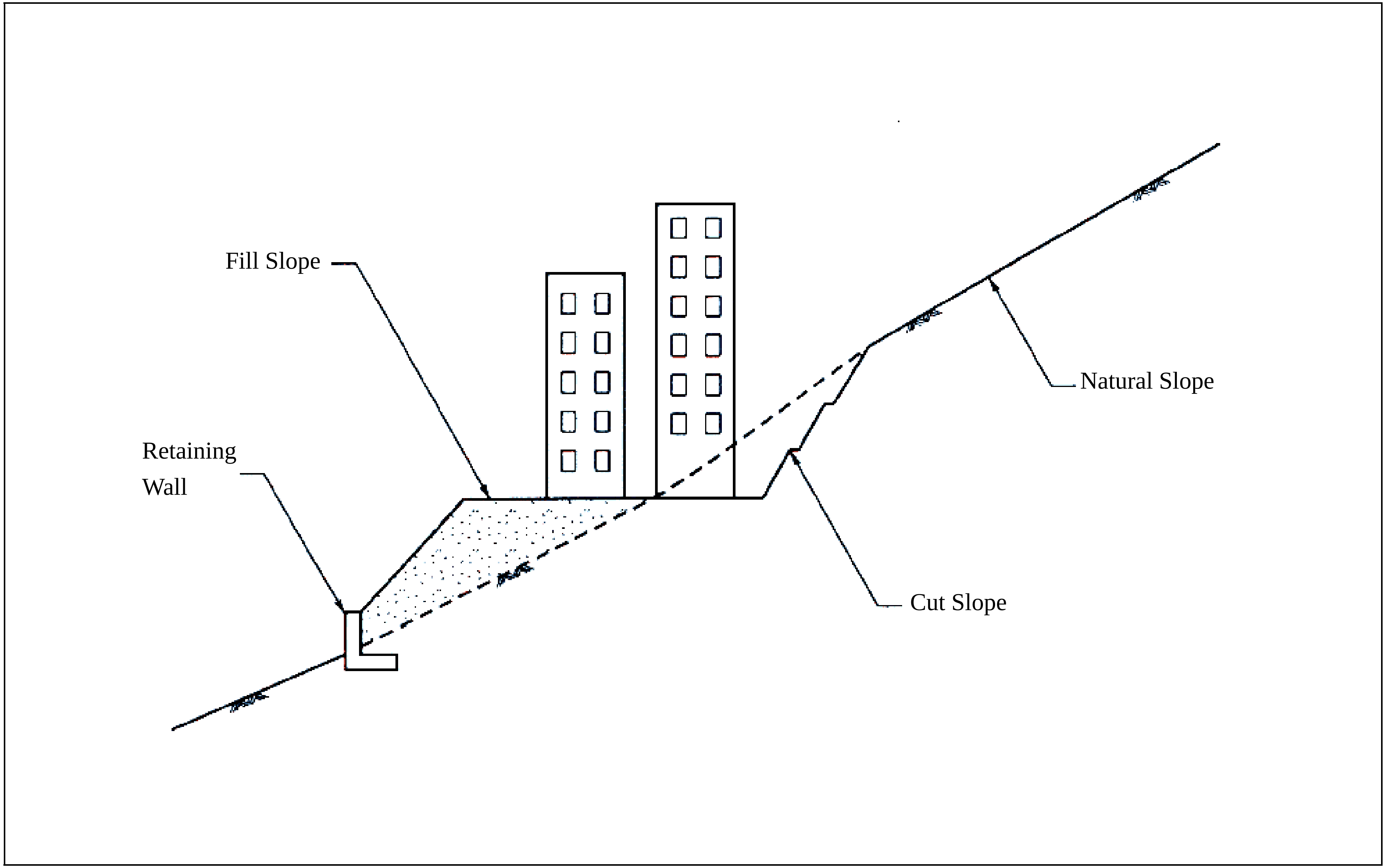

Figure 6.5 - Types of Slope Features

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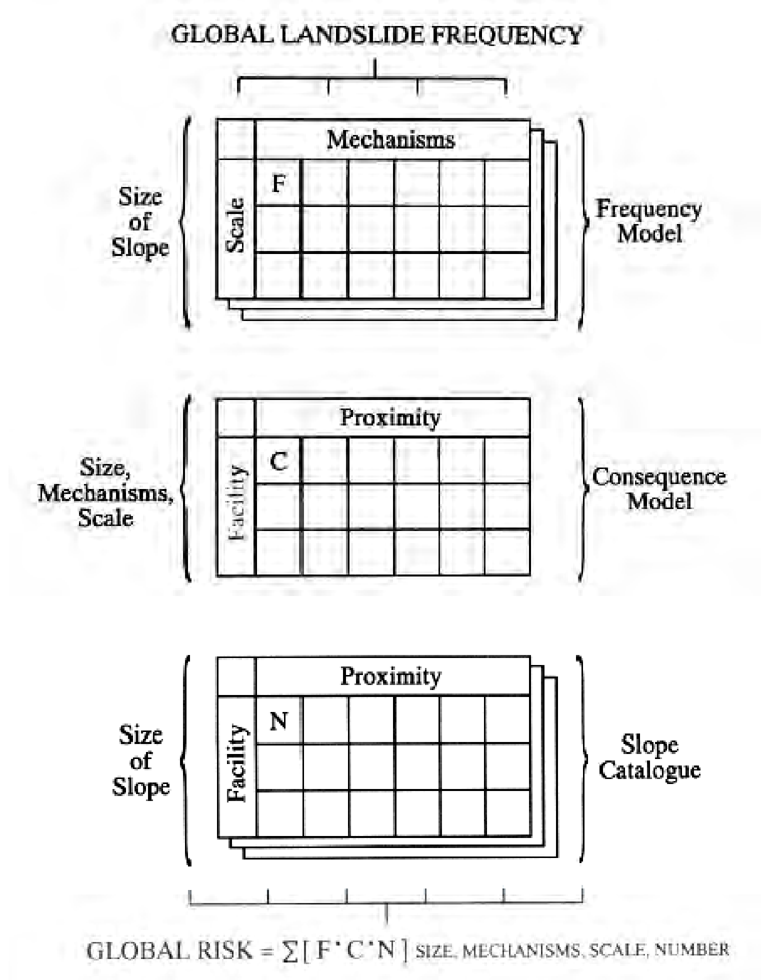

<u>FOR A GIVEN SLOPE FEATURE</u>

SITE-SPECIFIC RISK = ∑[FREQUENCY][CONSEQUENCE]

ALL HAZARDS: MECHANISM & SCALE

<u>FOR ALL 37,000 SLOPE FEATURES</u>

GLOBAL RISK = ∑SITE-SPECIFIC RISK

ALL FEATURES: TYPE (CUT, FILL, WALL)
SIZE
NATURE & PROXIMITY OF FACILITIES

'SLOPE DATA'

Figure 6.6 - Global Risk Summation by Integration of Frequency and Consequence Model (Wong et al, 1997)

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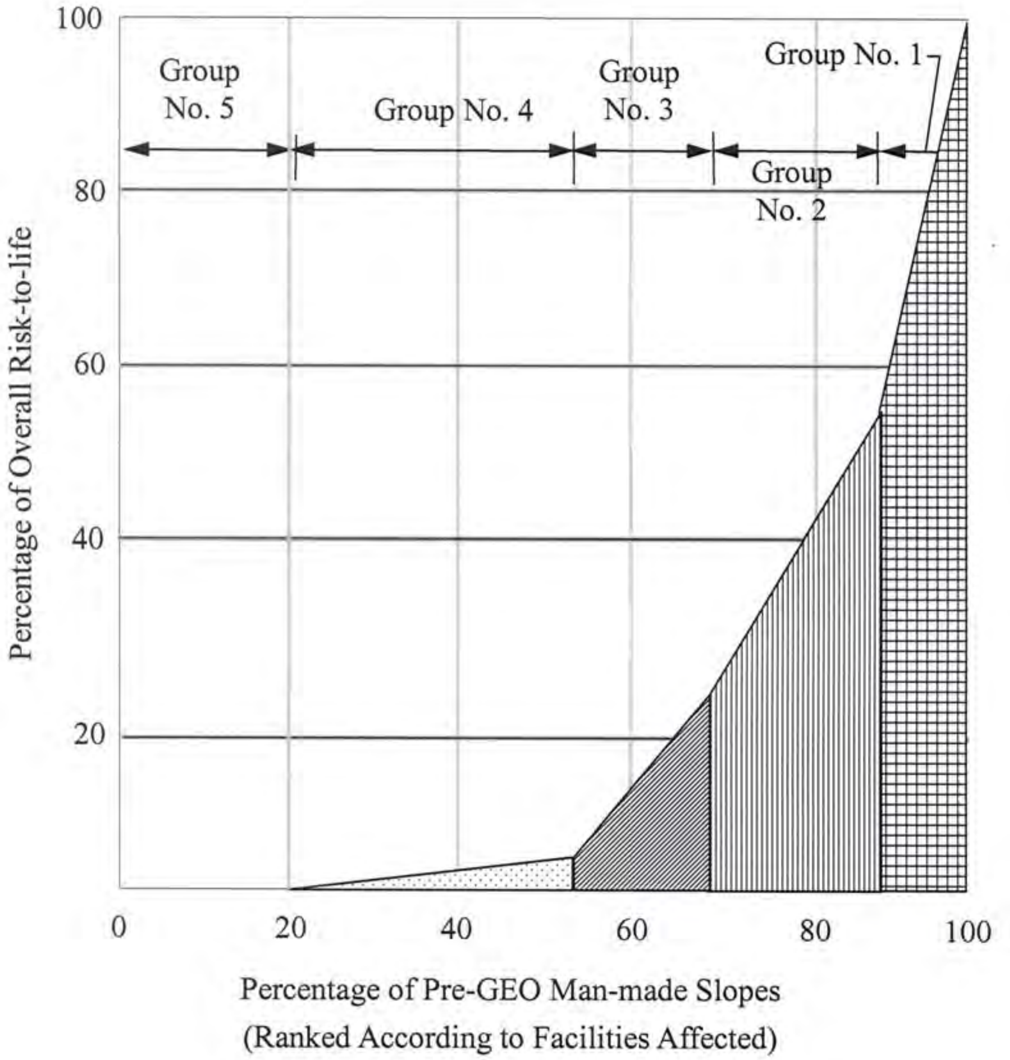
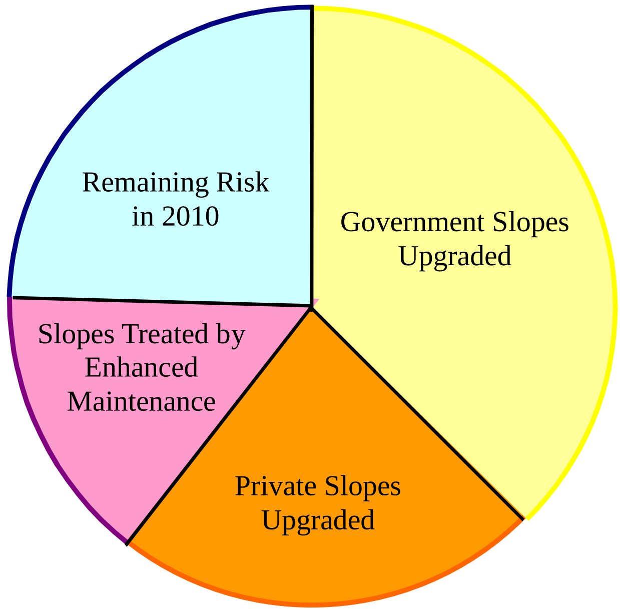


Figure 6.7 - Risk Profile of Un-engineered Man-made Slopes in Hong Kong in 1977 (Wong & Ho, 1998a)



Note: Remaining risk of un-engineered slopes in 2010 is about 25% of the risk in 2000.

Figure 6.8 - Reduction of Risk of Un-engineered Man-made Slopes from 2000 to 2010 (based on Lo & Cheung, 2004)

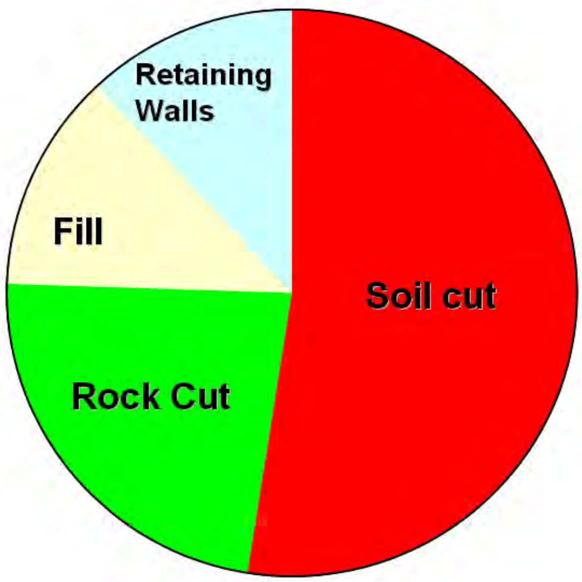


Figure 6.9 - Distribution of Risk among Un-engineered Man-made Slopes in 2010 (based on Lo & Cheung, 2004)

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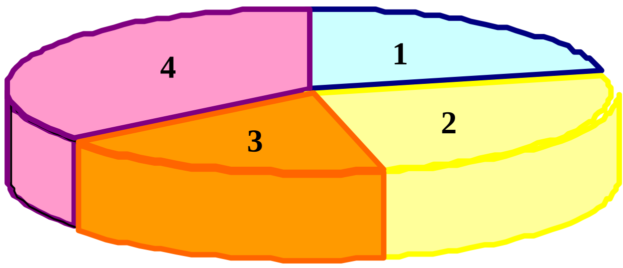
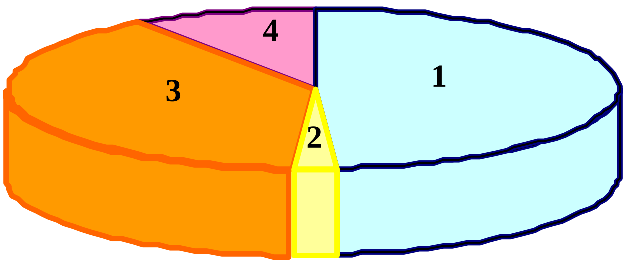


(a) Proportion by Slope Number (total 57,000 nos)



(b) Proportion by Risk (total 5 PLL per year)

Legend:

1	=	Un-engineered slopes affecting Groups No. 2(b) & 3 facilities and unplanned structures
2	=	Un-engineered slopes affecting Groups No. 4 & 5 facilities
3	=	Engineered slopes treated by old technology (see Note (4) of Table 6.12)
4	=	Engineered slopes treated by robust technology (see Note (4) of Table 6.12)

Figure 6.10 - Breakdown of Risk of 57,000 Man-made Slopes in the Catalogue of Slopes by 2010 (based on Lo & Cheung, 2004)

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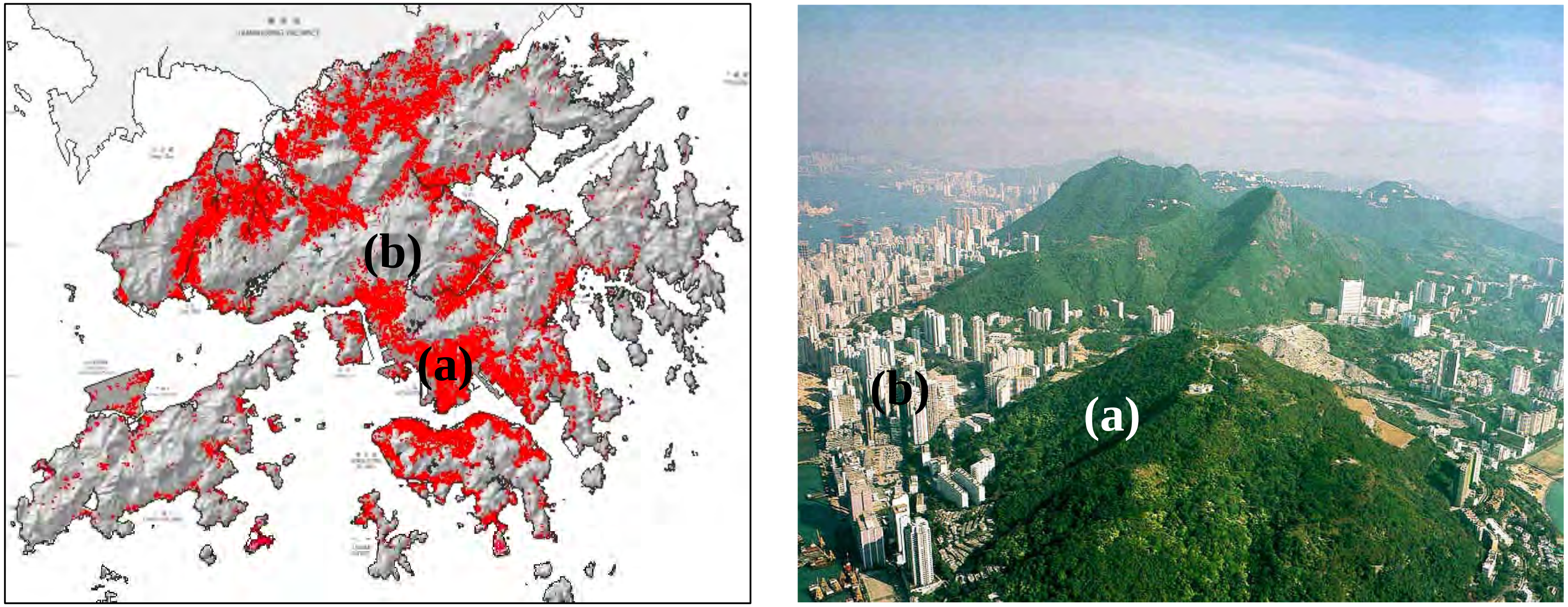

Figure 6.11 - Hong Kong, with (a) Urban Development Fringing (b) Steep Natural Hillsides

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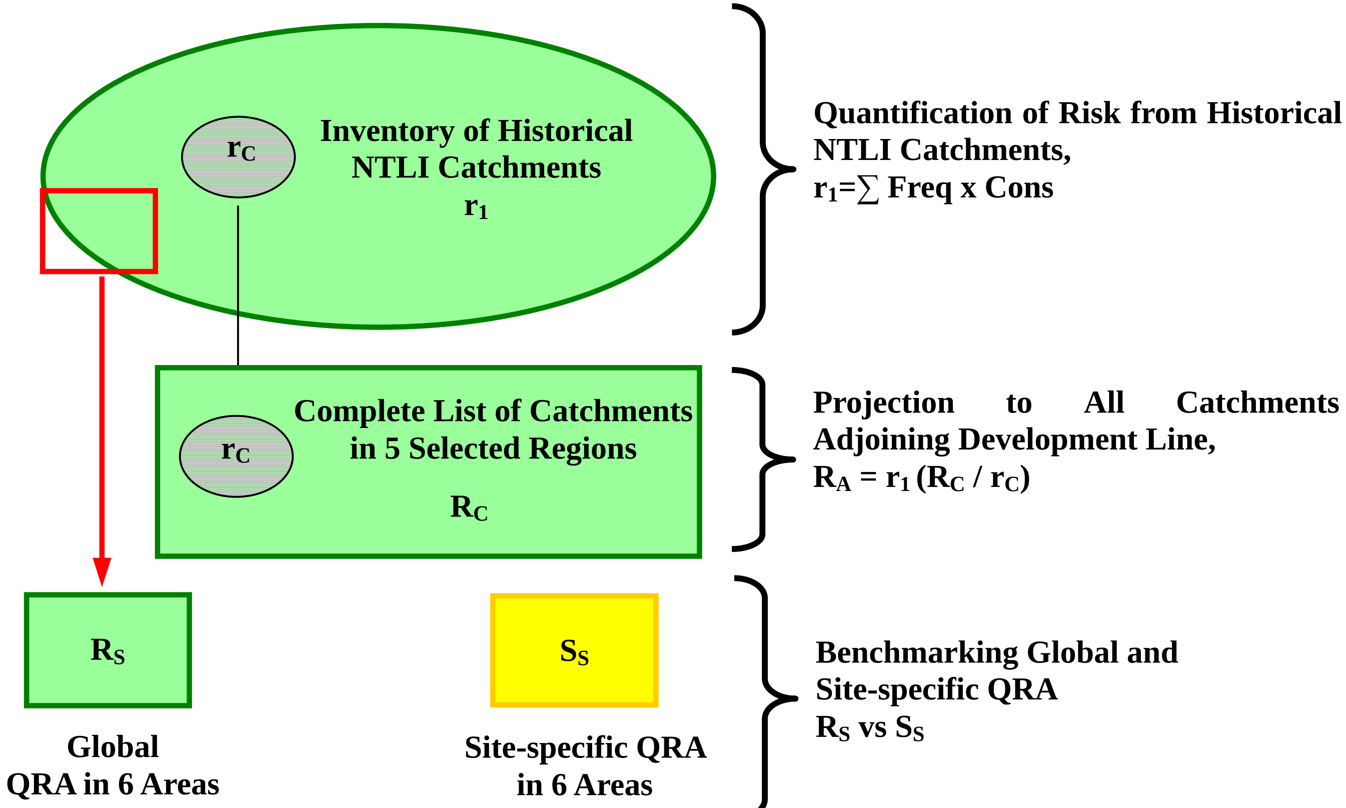

Figure 6.12 - Risk Model of Global QRA for Natural Terrain Landslides in Hong Kong

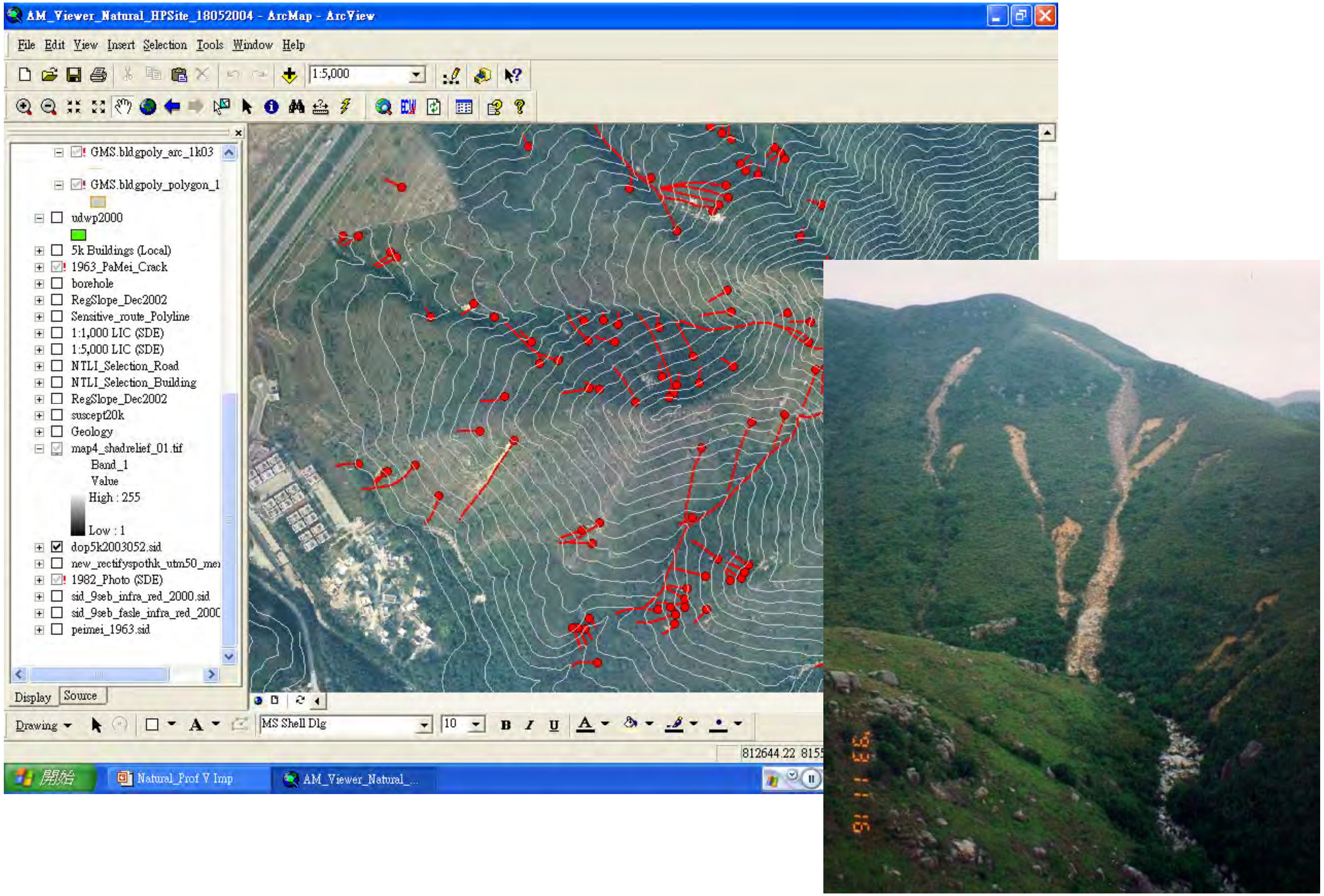

Figure 6.13 - Natural Terrain Landslide Inventory, Hong Kong (Comprising over 30,000 Historical Natural Terrain Landslides)

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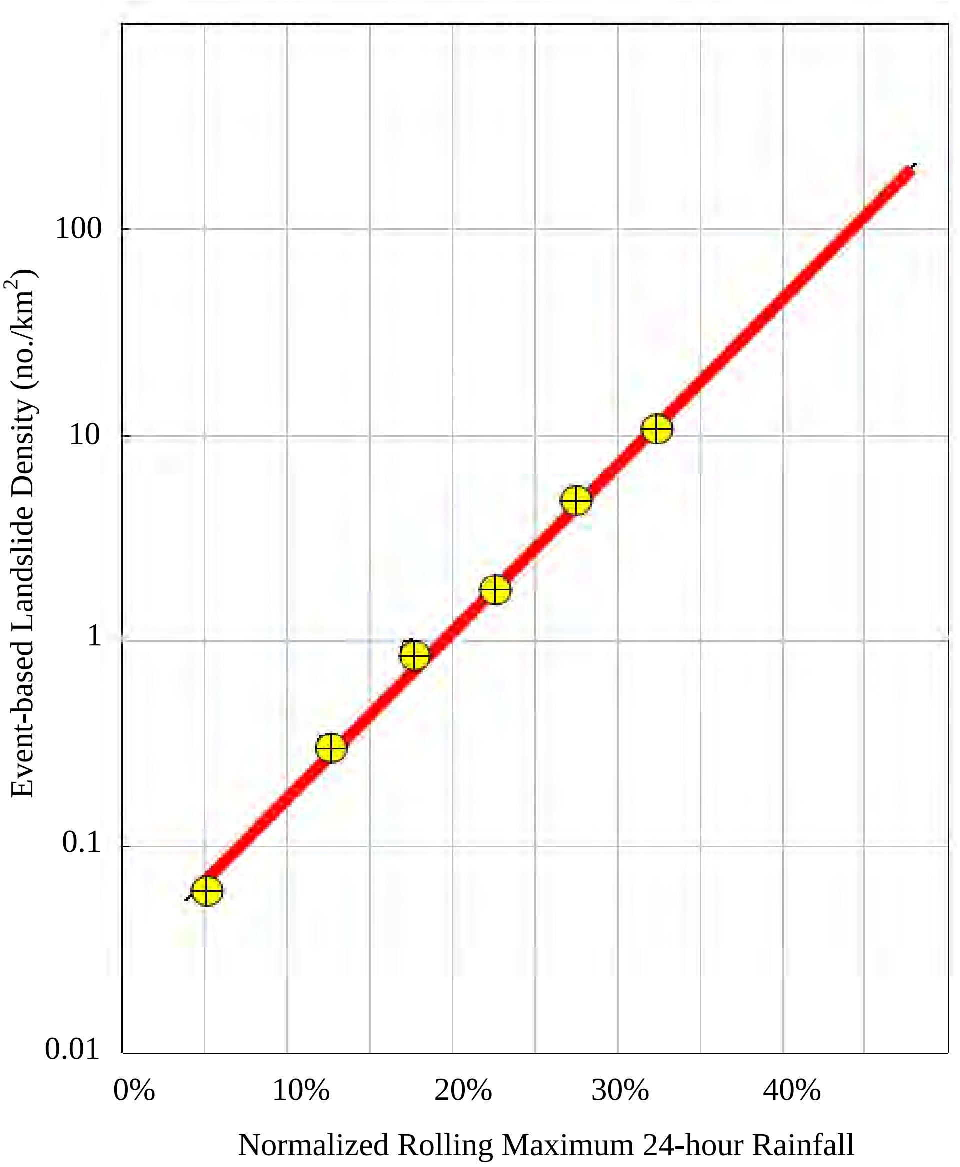

Figure 6.14 - Rainfall-Natural Terrain Landslide Correlation
(based on Ko, 2003; Wong et al, 2004b)

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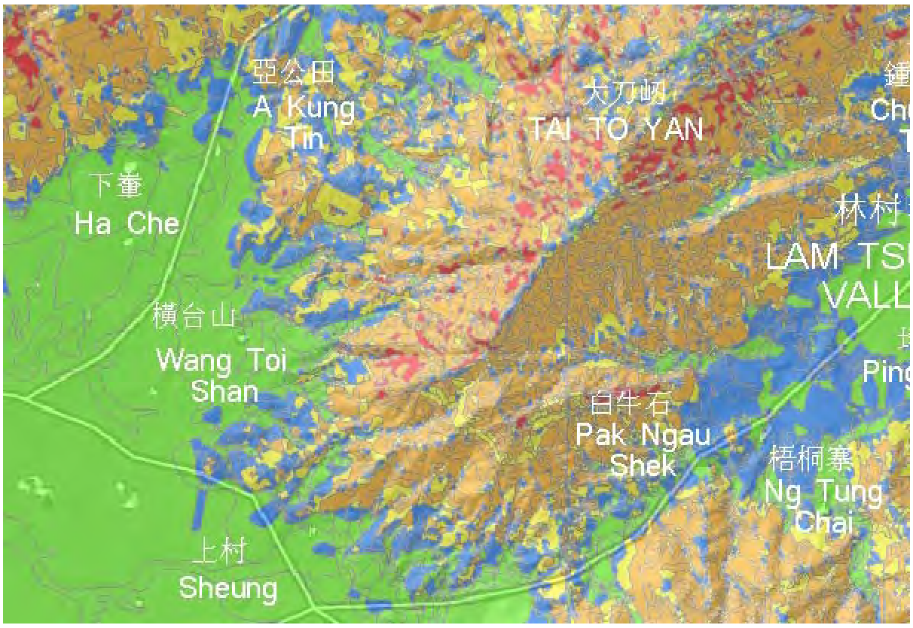

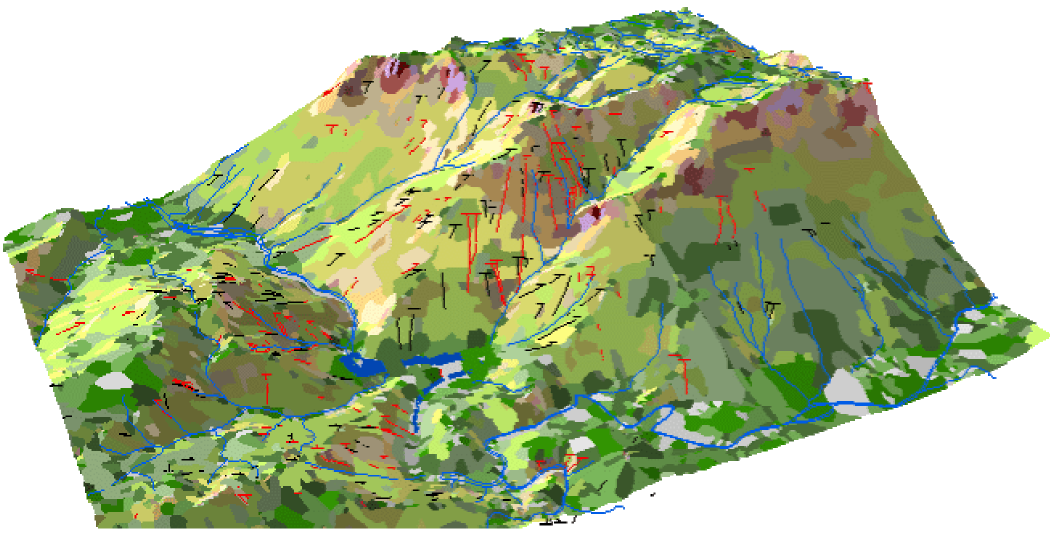

Figure 6.15 - Susceptibility Analysis

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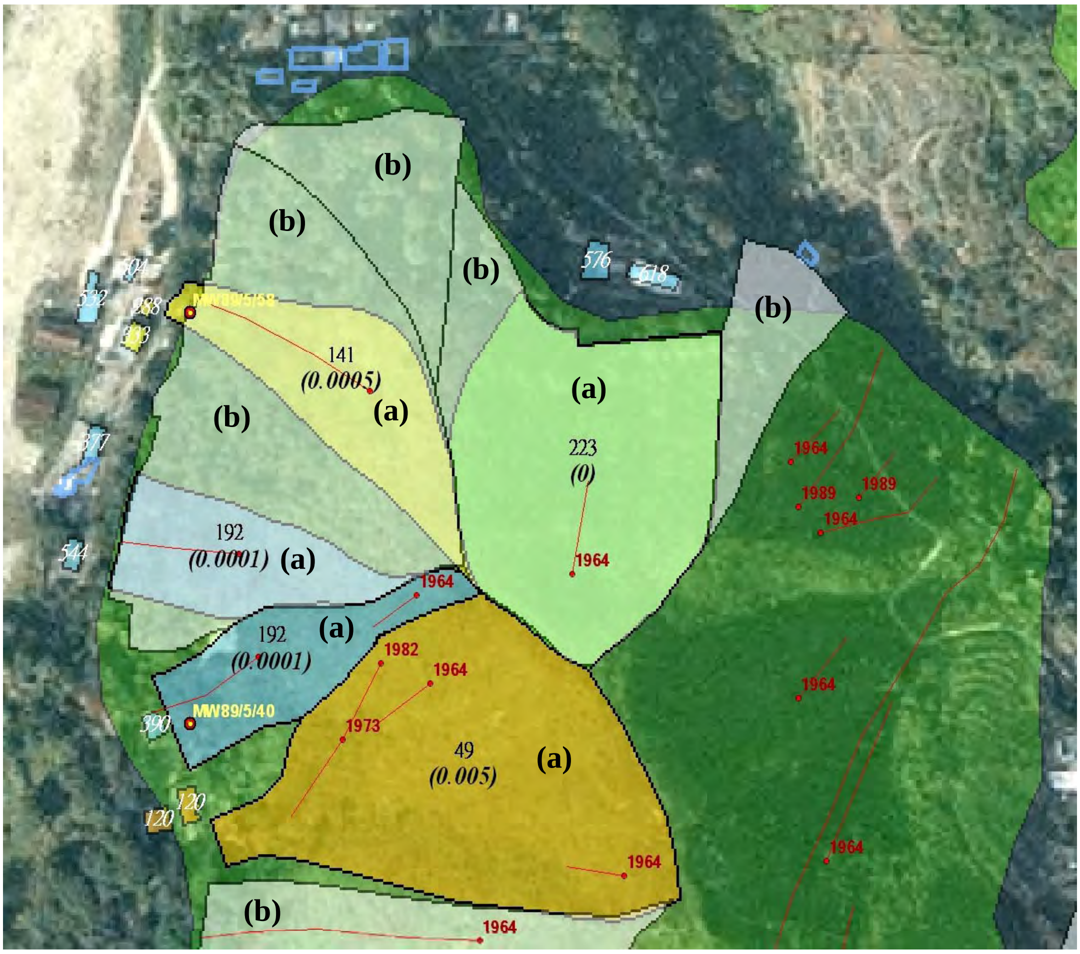

Figure 6.16 - GIS Inventory of (a) Historical Landslide Catchments
and (b) Supplementary Catchments

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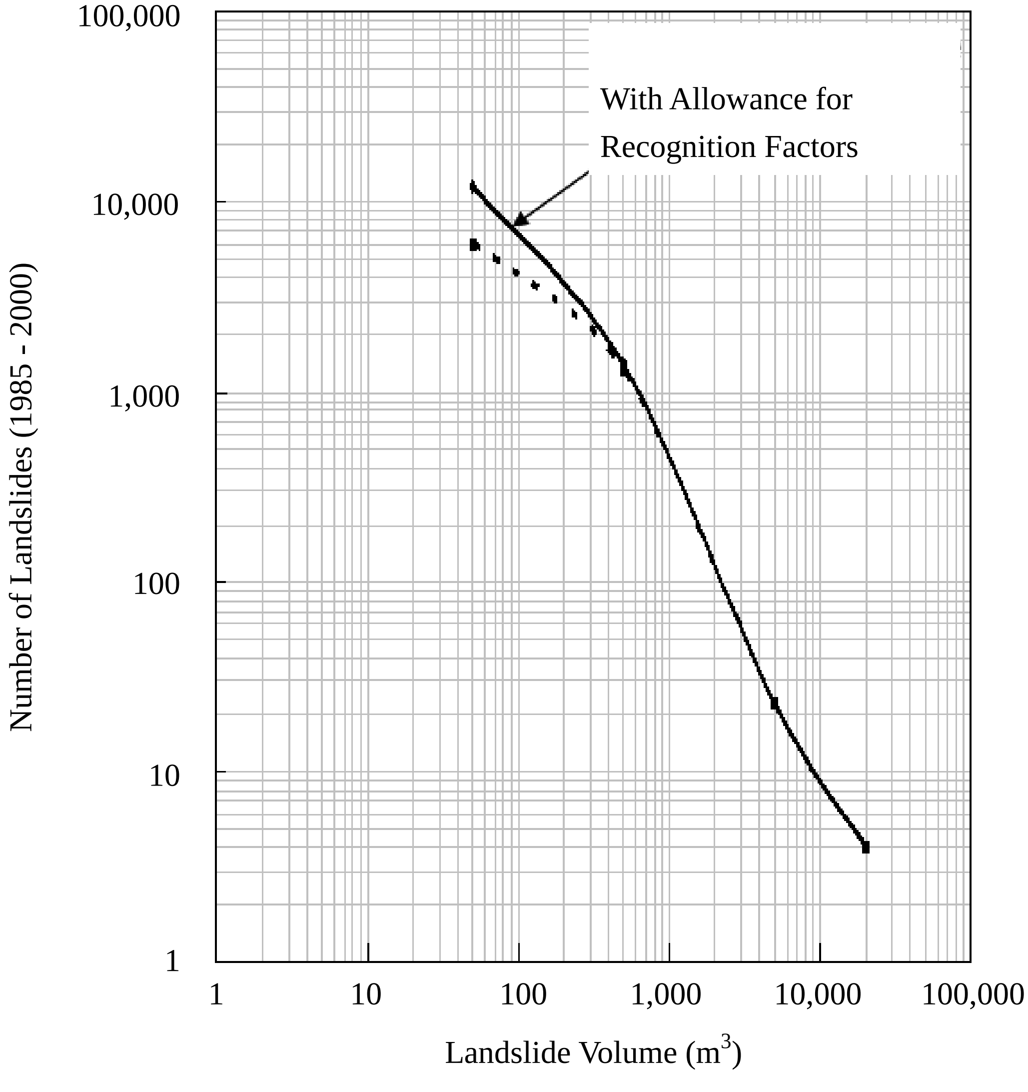

Figure 6.17 - Global Volume-Frequency Relationship (based on Wong et al, 2004b)

$$\text{Consequence} = \text{CON1} + \text{CON2}$$

(No. of fatality) = *(Without building collapse)* + *(Additional due to building collapse)*

$$\text{CON1} = Pn \times Vn \times Sn \times Ln$$

$$\text{CON2} = Pc \times Vc \times Sc \times Lc$$

Population at risk of 10-m wide direct hit

Vulnerability factor (0 to 1.0)

Scale factor (0.5 to 10)

Location factor (0.25 to 1.25)

Figure 6.18 - Generalized Consequence Model for Natural Terrain Landslides (Wong et al, 2004b)

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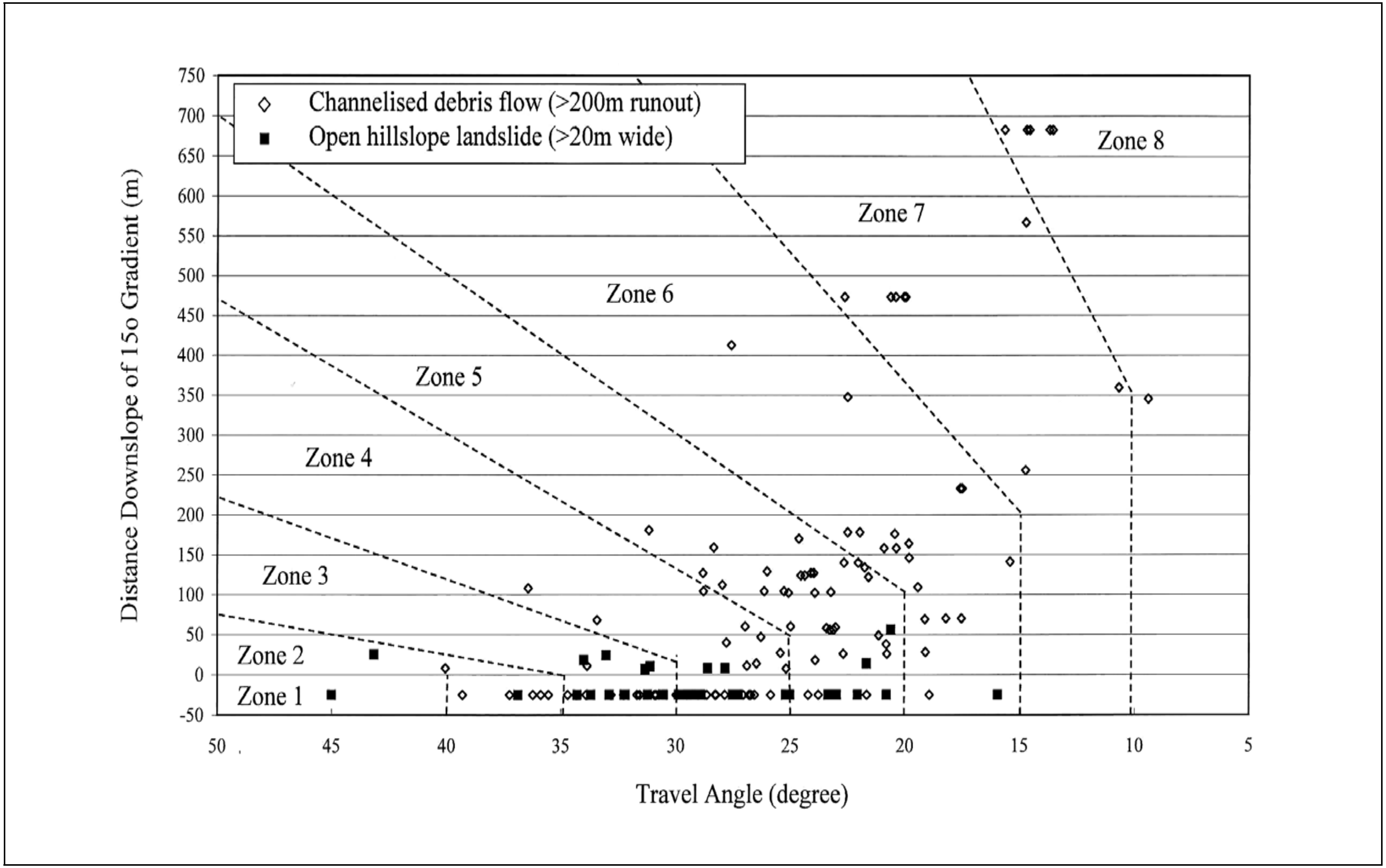

Figure 6.19 - Empirical Runout Zones Adopted in Consequence Model (Wong et al, 2004b)

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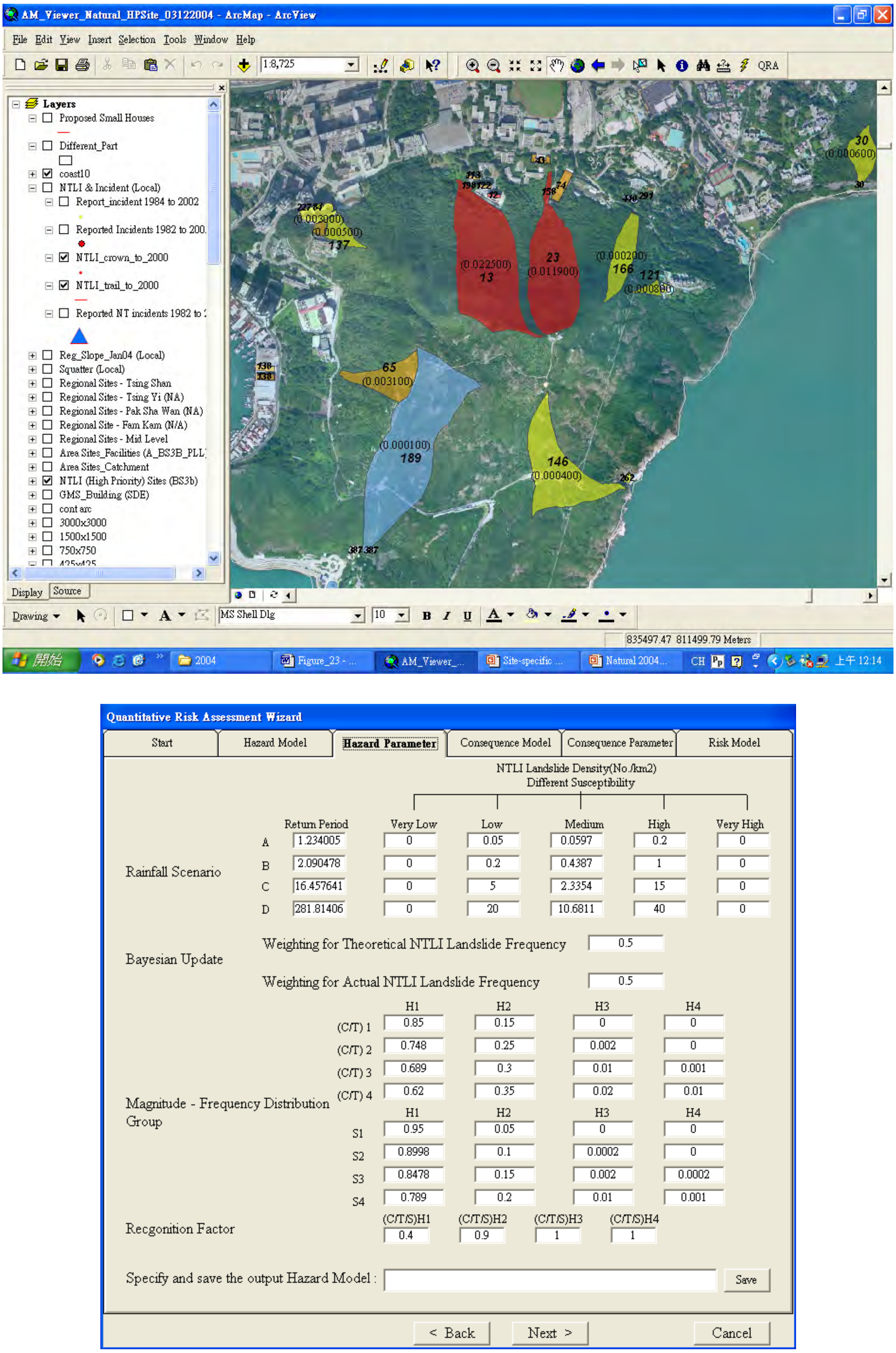

Figure 6.20 - Global QRA Undertaken on a GIS Platform

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	Historical Landslide Catchments	All Catchments
Global QRA	6.2×10^{-3} (Building data validated)	-
	6.6×10^{-3} (Building data not validated)	9.6×10^{-3} (Building data not validated)
Site-specific QRA	-	5.7×10^{-3} (Building data validated)

Figure 6.21 - Calibration with Site-specific QRA Results (Wong et al, 2004b)

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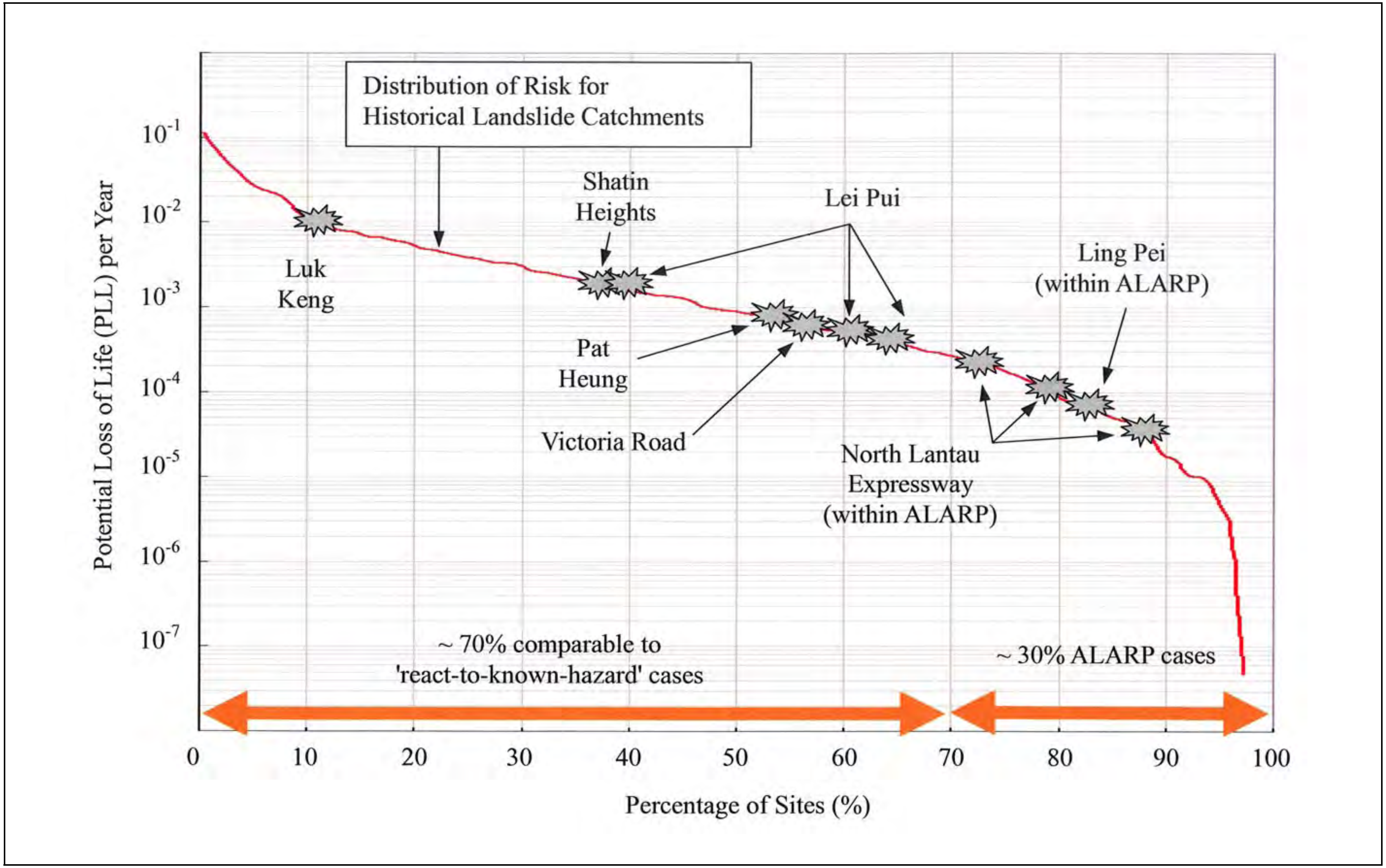

Figure 6.22 - Risk Profile of Historical Landslide Catchments

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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

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