ASSESSMENT OF GLOBAL LANDSLIDE RISK POSED BY PRE-1978 MAN-MADE SLOPE FEATURES: RISK REDUCTION FROM 1977 TO 2000 ACHIEVED BY THE LPM PROGRAMME

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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. A charge is made to cover the cost of printing.

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FOREWORD

This Report presents the findings of an assessment of the global landslide risk posed by pre-1978 man-made slope features. Only the risk reduction from 1977 to 2000 achieved by the LPM Programme is considered.

In this study, the historical data on landslides reported to the GEO during the period from 1984 to 1998 have been used to calculate the average annual failure frequencies for different types of man-made slope features. Data in the Slope Information System have been used to estimate the potential landslide consequences. Databases provided by the Landslip Investigation Division and the three District Divisions have been used to estimate the landslide risk reduction attributed to the actions taken under the LPM Programme. Various uncertainties have been identified and sensitivity analysis has been carried out as part of the risk assessment. Readers should note that the global landslide risk results presented in this Report are for comparative purposes. They should not be taken as true risk values in the absolute sense.

This study was carried out by Mr W.M. Cheung and Mr Y.K. Shiu of the Special Projects Division, with much of the data collection and analyses performed by the four technical officers, Mr C.H. Chan, Mr C.K. Lee, Mr K.C. Chan and Mr T.F. Wong. Valuable assistance was also provided by the database controllers of the Landslip Investigation Division, the Slope Safety Division and the three District Divisions. A number of colleagues gave useful comments on the draft version of this Report and suggestions for improvement. All contributions, which have made this pilot study a thought-provoking and interesting exercise, are gratefully acknowledged.

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ABSTRACT

The technique of Quantitative Risk Assessment has been applied to evaluate the performance of the Government's Landslip Preventive Measures (LPM) Programme since the establishment of the Geotechnical Control Office (renamed as the Geotechnical Engineering Office (GEO) in 1991) in 1977. The components of this study are:

- determination of the global landslide risk in 1977 arising from pre-1978 man-made slope features registered in the GEO's New Catalogue of Slopes;
- determination of the reduction in global landslide risk from 1977 up to the end of September 2000 attributed to LPM action on the selected slope features;
- determination of the percentage risk reduction from 1977 to 2000 attributed to the LPM Programme.

This study deals with landslide risk reduction and risk minimisation attributed to the LPM Programme only. Risk reduction and risk minimisation due to other actions such as squatter clearance under the Non-development Clearance Programme, issue of Landslip Warning, slope removal or upgrading under public works and private development projects, advisory services on land-use planning and checking of new slopes, etc, are not examined. Also, this study focuses only on risk-to-life. Other types of risk such as economic risk and social impact are not considered.

The approach of global landslide risk assessment adopted in this study includes the determination of the frequencies of landslides and analysis of the potential consequences of landslides in terms of fatalities. The frequencies of landslides are estimated from historical records on failures of man-made slopes reported to the GEO during the period from 1984 to 1998. The consequence analysis considers the characteristics of the slope feature, the distance of the affected facilities from the slope feature, the size of the landslide and the vulnerability of the affected facilities. In assessing the global landslide risk, the residual risk of those slope features that have been upgraded under LPM Programme and confirmed to meet the required safety standards is accounted for. Sensitivity analysis is also carried out.

The results of the risk assessment are expressed in terms of Potential Loss of Life (PLL). F-N curves have also been derived. The risk assessment indicates that about 90% of the landslide risk is attributed to 'major' failures (i.e. failure with a volume $\geq 50\ m^3$). The results of this study also show that the LPM Programme has been effective in reducing landslide risk in Hong Kong. Up to the end of September 2000, it is estimated that the global landslide risk has been reduced to about 50% of the level in 1977.

The landslide risk results (both PLL and F-N curves) presented in this Report are not true risk values in the absolute sense due to a number of uncertainties. As such, they should only be used for comparative purposes. The uncertainties affecting the calculated risk values can be divided into two categories, viz. parameter uncertainty and model uncertainty. These uncertainties are briefly discussed in the Report.

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1. INTRODUCTION

In 1995, the Geotechnical Engineering Office (GEO) embarked on a 5-year accelerated Landslip Preventive Measures (LPM) Programme. This is one of the components of the long-term LPM Programme. Thus, the end of the accelerated LPM Programme (2000) marks a suitable point in time for evaluating the performance of the Programme since the establishment of the Geotechnical Control Office (renamed as the Geotechnical Engineering (GEO) Office in 1991) in 1977.

Quantitative Risk Assessment (QRA) is a useful tool for such an evaluation. The components of this study are:

(a) determination of the global landslide risk in 1977 arising from pre-1978 man-made slope features (features) registered in the GEO's New Catalogue of Slopes;

(b) determination of the reduction in global landslide risk from 1977 up to the end of September 2000 attributed to LPM action on the selected slope features; and

(c) determination of the percentage risk reduction from 1977 to 2000 attributed to the LPM Programme.

The locations of the pre-1978 man-made slope features are shown in Figure 1.

This study deals with landslide risk reduction and risk minimisation attributed to the LPM Programme only. The risk reduction/minimisation measures include upgrading of Government features, and upgrading of private features through the issue and discharging of statutory orders. Risk reduction and risk minimisation due to other actions such as squatter clearance under the Non-development Clearance Programme, issue of Landslip Warning, slope removal or upgrading under public works and private development projects, advisory services on land-use planning and checking of new slopes, etc, are not examined. Also, this study focuses only on risk-to-life. Other types of risk such as economic risk and social impact are not considered.

The landslide risk results presented in this Report are for comparative purposes. They should not be taken as absolute risk values.

2. LANDSLIDE RISK ASSESSMENT

QRA provides a mathematical tool for determining the landslide risk. In the context of QRA, the landslide risk of an individual feature is defined as the product of the probability of a landslide and the consequence of its occurrence. The global landslide risk is the summation of individual landslide risks as given below:

$$\text{Global Landslide Risk} = \sum_{\text{all slopes}} \left\{\text{Probability of Landslide}\right\} \left\{\text{Consequence}\right\}$$

3. METHODOLOGY

3.1 General

The methodology for the landslide risk assessment is based on previous work carried out by DNV Technica (1996) and Wong et al (1997). Slope features have been classified into four feature types, viz. soil cut slopes, rock cut slopes, fill slopes and retaining walls. In practice, there are different combinations of feature types. For the sake of simplicity, mixed features are classified under one of the four feature types in accordance with the approach outlined in Appendix A.

The basic components of the landslide risk assessment are:

(a) landslide hazard identification;

(b) failure frequency analysis;

(c) consequence analysis; and

(d) risk estimation.

Figure 2 shows the relationship between each step of the landslide risk assessment. A brief description of each step of the QRA process is given below.

3.2 Landslide Hazard Identification

In landslide risk assessment, the first step is to identify the hazards. Hazard is defined as "a condition with the potential for causing an undesirable consequence" (Canadian Standards Association, 1991). In this study, the hazards are those resulting from failures of pre-1978 registered man-made slope features in Hong Kong.

3.3 Failure Frequency Analysis

Average annual failure frequencies have been estimated for the following three categories of slope features:

Category 1 - All pre-1978 features except those which have been found to meet the required safety standard by Old Studies (see GEO Circular No.19) and Stage 2 Studies.

Category 2 - Pre-1978 features that have been found to meet the required safety standard through Stage 2 Studies.

Category 3 - Pre-1978 features that have been found to meet the required safety standard through Old Studies.

The average annual failure frequencies for Categories 1 to 3 features have been derived from a review and analysis of GEO landslide records for the period from 1984 to 1998

(15 years). They are presented in Tables 1a to 1d, 2a to 2d and 3a to 3d respectively for the four slope feature types. These failure frequencies have been used to calculate the global landslide risks in 1977.

3.4 Consequence Analysis

Consequence analysis considers the persons at risk, i.e. those who could be impacted by the landslide. The landslide consequence model proposed by Wong et al (1998) has been adopted in the analysis. The model considers the characteristics of the slope feature (e.g. feature type, angle and height, etc), the distance of the affected facilities from the slope feature, the size of the landslide and the vulnerability of the affected facilities. The facility is assumed to be located at the worst location and its degree of occupation is taken to be under average condition. The expected failure consequence is scaled according to the actual size of failure and the actual location of the facility. The expected failure consequence is expressed in terms of Potential Loss of Life (PLL) given the occurrence of a landslide:

$$\text{Expected Failure Consequence (PLL)} = \sum \left\{ \begin{array}{l} \text{Expected no. of fatalities} \\ \text{for facilities directly} \\ \text{affected by a reference} \\ \text{landslide} \end{array} \right\} \left\{ \frac{\text{Actual size of landslide}}{\text{Size of reference landslide}} \right\} \left\{ \begin{array}{c} \text{Vulnerability} \\ \text{factor} \end{array} \right\}$$

In the above expression, the vulnerability factor indicates the estimated probability of death in the event of a reference landslide affecting a facility. It is a function of various factors including the nature, proximity and spatial distribution of the affected facilities, mobility of the landslide debris, size of failure and the degree of protection offered to persons by the facilities, etc. The expected number of fatalities for a facility directly affected by a reference landslide is based on the estimated loss of life derived for different facility groups as defined in the New Priority Classification Systems for slopes and retaining walls (Wong, 1998), as reproduced in Table 4 (with minor modifications on the notes).

3.5 Estimation of Global Landslide Risk

3.5.1 General

The global landslide risk is determined by the summation of the products of failure frequency and the respective consequence for all features. It must be emphasised that due to a number of uncertainties (see Section 6) involved in the calculation of landslide risk, the results as determined from this study should not be taken as absolute risk values. They should only be used for comparative purposes.

A worked example demonstrating the method for calculating the landslide risk for a soil cut slope is given in Appendix B.

3.5.2 Global Landslide Risk in 1977

For features that have been upgraded under the LPM Programme, a file search has been conducted to determine the actual facilities that were affected by these features in 1977. For the other features, because of the large number of such features, no file search was carried out. The affected facilities in 1977 are based on information collected in the period 1994 to 1998, when the data collection was carried out for the Slope Information System (SIS). Upon compilation of databases on slope feature type groupings, average annual failure frequencies and vulnerability factors, the distribution of global landslide risks in 1977 with respect to different groups of facilities being affected for the four types of features examined (i.e. soil cuts, rock cuts, fill slopes and retaining walls) are determined. The global landslide risk in 1977 is determined by the summation of the respective risks from Categories 1 to 3 features.

The landslide risks are expressed in terms of Potential Loss of Life (PLL).

3.5.3 Global Landslide Risk in 2000

The reduction in landslide risk posed by the pre-1978 slope features is primarily due to the execution of the LPM Programme which includes upgrading of Government features and upgrading of privates features through the issue and discharge of statutory orders. Similar to the procedure stated in Section 3.5.2 above, databases of slope feature type groupings, average annual failure frequencies and vulnerability factors are prepared for the estimation of the global landslide risk in 2000.

For features that have been upgraded to the required safety standard, some landslide risk still remains. In this study, this remaining risk of landsliding is called ‘residual risk’. Average annual failure frequencies before and after the implementation of the upgrading works have been established for these features. The residual landslide risk is calculated using these failure frequencies and the expected consequence of failure of these features (see Section 5.1 and Appendix C).

4. ASSUMPTIONS AND DATABASES USED IN THE LANDSLIDE RISK ASSESSMENT

The following assumptions have been made in the landslide risk assessment:

(a) The number of pre-1978 slope features is as given in the New Catalogue of Slopes. The slope features classification has been established based on the “Systematic Identification of Features in the Territory (SIFT)” project. Features assigned with SIFT Classes A, B1 and C1 correspond to pre-1978 slope features, i.e. features formed before 30 June 1978. Slope features without a SIFT class are assumed to be post-1978 features and they have been excluded from the risk assessment. There are about 950 features without data on SIFT classes and they have been disregarded due to lack of information for the risk assessment.

(b) To facilitate reference to the slope data in the New

Catalogue of Slopes, the boundaries of those slope features in the Old Slope Catalogue for which actions have been taken by the GEO or other parties have been compared with those for features in the New Slope Catalogue. It is assumed that an old feature is the same as a new feature if the percentage overlapping area of the old and new features on plan is greater than or equal to 80%, see Figure 3. Otherwise, the slopes will be considered individually.

(c) Dangerous Hillside Orders (DHOs) have been served on 1,202 features. Up to the end of July 2000, 457 of these features have their DHOs officially discharged. The other DHOs are at various stages of implementation. Based on past records, the average time between the serving and discharging of a DHO is approximately 30 months. There are about 320 features which have DHOs served on them for more than 30 months but still not yet discharged.

Landslide risk posed to New Territories Exempted Houses (NTEH) has not been assessed in this study. This is because this study only deals with pre-1978 slope features, and features affecting NTEH have only been formed after 1978 in association with developments.

For this study, relevant information has been obtained from a number of databases compiled by different divisions of the GEO. A summary of the databases used is given in Appendix D.

5. ANALYSIS AND RESULTS

5.1 Residual Landslide Risk

As mentioned in Section 3.5.3, residual risk is accounted for in the landslide risk assessment. In calculating the residual landslide risk for features that have been upgraded to the required safety standard under the LPM Programme, the average annual frequencies for major failures (failure volume $\geq$ 50 m^3) before and after the implementation of upgrading works have been established. The residual landslide risk (PLL) for these features is estimated to be 1.8 per year. This represents approximately 15% of the landslide risk (PLL of 12.2 per year) that would exist for such features before the upgrading works were carried out. The approach for calculation of the residual risk is given in Appendix C.

5.2 Landslide Risk in 1977

5.2.1 Potential Loss of Life

From the database provided by Slope Safety Division of the GEO, 33,510 out of 49,932 features have been identified as pre-1978 features, and there are 1,610 pre-1978 features with squatters situated at the slope toe and/or the slope crest. Among these 1,610 features, 327 features have squatters situated both at the slope toe and the slope crest, and they have been excluded from this study. The landslide risk posed on facilities other than squatters for the remaining 1,283 (i.e. 1,610 - 327) features have been considered in the study. Thus, the number of pre-1978 features under consideration becomes 33,510 - 327 = 33,183.

Based on the SIS database, there are 51,396 features in the New Catalogue of Slopes (excluding Disturbed Terrain features). Therefore, a projection from 49,932 to 51,396 features has been made. From this, the number of pre-1978 features is estimated to be 34,493. By excluding the 327 features that affect squatters only, the number of pre-1978 features considered in the landslide risk assessment is 34,493 - 327 = 34,166. Among these pre-1998 features, 32,103 are Category 1 features, 375 are Category 2 features and 1,688 are Category 3 features.

An assessment has been carried out to estimate the landslide risk in 1977 contributed by features in each of the three categories. The results of the assessment indicate that the landslide risk (PLL) from Categories 1, 2 and 3 features are 14.7 per year, 0.1 per year and 1.1 per year respectively. The total landslide risk (PLL) in 1977 is 14.7 + 0.1 + 1.1 = 15.9 per year. The distributions of landslide risk among different types of features are given in Tables 5a and 5b.

The results of the analyses show that the ratio of the landslide risk affecting toe facilities to that affecting crest facilities is on average about 6:1.

An assessment has also been made of the global landslide risk attributed to major landslides only. The estimated risk (PLL) is 14.2 per year (based on 34,166 pre-1978 features). This indicates that major landslides contribute to about 90% of the global landslide risk.

5.2.2 F-N Curves

F-N curves can be derived from the same set of data for estimating the PLL. The PLL is a summation of the risks attributed to different facility groups. The expected number of fatalities and the multiple fatality factors for a reference (standard) landslide for each facility group is given in Table 4. The number of fatalities (N) associated with a particular landslide at any of the features of a certain slope height range can be calculated by (i) multiplying the expected number of fatalities for a reference landslide by the respective vulnerability factors; and (ii) multiplying the result from (i) by the ratio of the expected width of landslides for that particular group of features to the width of the reference landslide. The frequency of occurrence (f) of that landslide with the calculated number of fatalities is equal to the failure frequency for that particular group of features multiplied by the number of features under consideration. By adding together the calculated frequencies of occurrence for N or more fatalities from different affected facility groups and sub-groups, the respective cumulative frequency of occurrence (F) can be determined. The approach used for constructing the F-N curve is given in Appendix E.

The F-N curves for the pre-1978 man-made features in 1977 (for both major failures only and all failures) are shown in Figure 4. The shapes of the F-N curves depend on the assumptions made and the model used in the assessment. There are a number of uncertainties associated with this study (see Section 6), the curves should not be regarded as true representation of risk but rather, they should be used for comparative purposes only.

5.3 Landslide Risk Reduction Up to in 2000

5.3.1 General

Reduction in landslide risk through the LPM Programme can be achieved mainly through two means: (i) by undertaking upgrading works on sub-standard features; and (ii) by changing the types of facilities affected by the features (e.g. facility changed from group 1 to group 5).

Sections 5.3.2 and 5.3.3 below describe the landslide risk reduction arising from various actions taken by the GEO and other parties under the LPM Programme.

5.3.2 Landslide Risk Reduction through LPM Upgrading Works

Up to September 2000, 1,435 features have been upgraded under the LPM Programme. The resulting reduction in landslide risk (PLL) is 4.1 per year (after accounting for the residual risk, see Section 5.1). The distribution of landslide risk reduction among the various feature types is shown in Table 6a.

Out of the PLL of 4.1 per year, 3.9 (i.e. about 95%) is attributed to risk reduction associated with major slope failures.

Since the risk reductions are calculated using the average annual failure frequencies derived for Category 1 features (see Section 3.3), they represent the lower bound of the risk reduction. It is because the failure frequencies for the features included in the LPM Programme should be much higher than those for Category 1 features. Tables 7a and 7b show that the average annual failure frequency for the population of features included in the LPM Programme but before the implementation of upgrading works (1.34% per year) is about 3 times of that for features not included in the LPM Programme (0.46% per year). These failure frequencies are based on all failures. If only the major failures are considered, the difference between the two failure frequencies is even larger (0.14% per year for the population of features included in the LPM Programme but before the implementation of upgrading works and 0.03% for features not included in the LPM Programme). Section 7.2 below will further elaborate the effect of the distribution of the average annual frequencies among Category 1 features on the results.

5.3.3 Landslide Risk Reduction through Implementation of Upgrading Works under the DH Orders

In accordance with the District Divisions' database in July 2000, 457 out of 1,202 slope features have their DH Orders (DHOs) discharged. However, upgrading works for more DHO features may have been completed while the administrative procedures have not been completed for the DHOs to be discharged. From past records, the average time between serving and discharging of a DHO is approximately 30 months.

Reduction in landslide risk due to the implementation of upgrading works under the DHO Orders has been assessed for the following three cases:

Case 1 - Only features which have their DHOs officially discharged are considered. There are 457 such features.

Case 2 - In addition to the features under Case 1, features on which DHOs have been served for more than 30 months but still not yet been officially discharged are also considered, i.e. the upgrading works under the DHOs served on these features are assumed to have been implemented. There are 320 such features. Thus, there are 457 + 320 = 777 features in this case.

Case 3 - In addition to the features under Case 1, all the features on which DHOs have been served but still not yet been officially discharged are also considered, i.e. the upgrading works are assumed to have been fully implemented. There are 745 such features. Thus, there are 457 + 745 = 1,202 features in this case.

Case 1 is the lower bound estimate of risk reduction whereas Case 2 represents the best estimate of the probable upper bound situation. Inclusion of Case 3 is to show the situation in which the upgrading works under all the DHOs have been implemented. Risk reductions (PLL) associated with Cases 1, 2 and 3 have been calculated to be 0.9, 1.5, and 2.4 per year respectively (with residual risk accounted for). In all the three cases, over 90% of the risk reduction is attributed to major slope failures. The distribution of landslide risk among the various feature types is shown in Table 6b.

5.4 Global Landslide Risk Reduction

The global landslide risk reduction (PLL) resulting from the LPM Programme (see Sections 5.3.2 and 5.3.3 above) for Case 2 is (1.5 + 4.1) = 5.6 per year, which represents 5.6/15.9 = 35% of the risk that existed in 1977. This is the lower bound value because the estimation of landslide risk reductions has been based on the average annual failure frequency for Category 1 features. Some sensitivity analyses on this have been carried out to examine the bounds of results (see Section 7.2).

6. UNCERTAINTIES

6.1 General

The assessment in this study involves a number of uncertainties. Many of the uncertainties cannot be measured or quantified. They should, however, be borne in mind when interpreting the results of the global risk assessments.

There are two main sources of uncertainties. They are (i) parameter uncertainty; and (ii) model uncertainty.

6.2 Parameter Uncertainty

(a) The identification of pre-1978 features is primarily based on the SIFT classification in the SIS database. Thus, the results of the global landslide risk assessment are dependent on the accuracy of the SIFT classes assigned. There are cases of mis-classification of features.

(b) The global landslide risk in 1977 attributed to features that have not been included in the LPM Programme has been calculated based on information collected in the period 1994 to 1998 on facilities affected by the slope features, when the data collection was carried out for the SIS. This is likely to have overestimated the landslide risk in 1977 and hence underestimated the landslide risk reduction due to the LPM Programme. It is because the potential consequence of landslides in 1977 is most likely to be smaller than that assumed in the present calculation.

(c) The failure frequencies used in the residual landslide risk assessment are based on failure records covering relatively short periods of time. They are to some extent governed by the rainstorms encountered in the periods. Also, the failure frequencies of reinforced (i.e. soil-nailed) slopes could be different from unreinforced slopes. However, the period of observation is too short for any firm conclusions to be drawn on the difference in failure rate.

(d) With the information currently available, the failure frequencies of the Category 1 features included and those not included in the LPM Programme cannot be accurately determined. Thus the estimation of global landslide risk in 1977 has been based on the assumption that the failure frequencies are uniformly distributed among the Category 1 features. Since the uniformly distributed failure frequencies are used for estimating the landslide risk in 1977 attributed to the features included in the LPM Programme, it will result in underestimating the landslide risk reductions (see Sections 5.3.2 and 7.2).

(e) Similar to paragraphs (d) above, the uniformly distributed failure frequencies assumed among the features signed off by Old Studies and Stage 2 Studies have introduced uncertainties in the estimation of global landslide risk in 1977. However, given the relatively small number of features involved, the effect is considered insignificant.

(f) The database on squatter slopes does not contain adequate information about squatter slopes. Features affecting squatter areas cannot be differentiated from those affecting licensed areas. Also, the exact number of squatter features is uncertain.

(g) In calculating the landslide risk level in 1977, historical failure records after 1984 have been used to estimate the failure frequencies of the slope features. As a number of the features were upgraded under LPM before this time (a total of about 180 features between 1977 and 1983), it is possible that the failure frequencies so calculated are lower than the actual ones. Furthermore, as the upgrading works between 1977 and 1983 were concentrated on fill slopes in that period, the failure frequency of fill slopes could have been underestimated.

6.3 Model Uncertainty

(a) The consequence model used in this risk landslide risk assessment has not been subjected to calibrations against observations. Its use results in a calculated risk level for year 2000 higher than the current expected annual fatality rate, indicating that there is some pessimism in the model.

(b) The global risk assessment assumes that failure would involve the top of the slope feature in evaluating the travel distance of landslide debris. This is a conservative assumption and will over-predict the risk.

7. SENSITIVITY ANALYSIS

7.1 Consequence Model

As the assessment of landslide risk is based on the consequence model that has not been subjected to field calibrations, the calculated risks (PLL) do not necessarily represent the expected annual fatality rate. Considering the equation presented in Section 2, global landslide risk is directly proportional to the expected number of fatalities for facilities affected by a reference landslide, i.e. consequence. Any change in the consequence will proportionally induce a change in the global landslide risk. In other words, if the reduction in global landslide risk is expressed as a percentage of the 1977 global landslide risk, its value is not sensitive to any change to the number of fatalities in each facility group assumed in the consequence model. This conclusion has been verified by calculation.

7.2 Average Annual Failure Frequency for the Population of Slope Features Included in the LPM Programme But before the Implementation of Upgrading Works

Sensitivity analyses have been carried out in which the ratio (R) of the average annual failure frequency for the population of features included in the LPM Programme but before the implementation of upgrading works to that for the population of features not included in the LPM Programme is increased from 1 to 4 (i.e. the average annual failure frequencies of the Category 1 features are re-distributed among the group of features that has been included in the LPM Programme and the group of features that has not been included in the LPM Programme). Figure 6a summarises the results of the analyses. The results indicate that if the ratio (R) is increased from 1 to 4, the corresponding global landslide risk reductions for Case 2 features and features upgraded by LPM works would increase from 35% to 58%. Based on statistical data, the ratio is about 3 (1.34/0.46) for all failures and about 4.5 (0.14/0.03) for major failures only (see Section 5.3.2). Taking the probable range of the ratio to be between 2.5 and 3.5, the range of risk reduction is shown in the shaded portion in Figure 6. For the probable upper bound case (Case 2 features and features upgraded by LPM works), the landslide risk reduction lies between 51% and 56%. Thus, up to the end of September 2000, the global landslide risk has been reduced to the range between (100% - 51%) = 49% and (100% - 56%) = 44% of the level in 1977.

Figure 4 shows the F-N curves for the global landslide risk in 1997 due to the pre-1978 slope features (for both major failures only and all failures). The curves cover the two situations of R = 1 and R = 3. A comparison between the F-N curves of the 1977 global landslide risk and that of 2000 (for Case 2 features and features upgraded by LPM works, with R = 3) is shown in Figure 5.

The landslide risk results presented should not be taken as absolute values. They should only be used for comparative purposes.

7.3 Residual Landslide Risk

As indicated in Section 5.1 above, for features that have been upgraded to the required safety standard, the residual landslide risk is taken to be 15% of the risk that exists for such features before the implementation of upgrading works. Sensitivity analyses were carried out in which the residual landslide risk was varied between 5% and 15%. Results of the analyses, which are summarised in Figure 6b, indicate that for every 5% increase in the residual landslide risk, there is a decrease of about 3% in the global landslide risk reduction.

7.4 Failure Frequency of Fill Slopes

Slope upgrading works were carried out mainly on fill slopes during the period 1977 to 1984. In estimating the failure frequency of fill slopes, only failures in the period 1984 to 1998 are considered. This might have resulted in underestimating the failure frequency (Section 6.2(g)). Sensitivity analyses were carried out in which the average annual failure frequency for fill slopes was increased by an amount ranging from 10% to 50%. The results as presented in Figure 6c indicate that the global landslide risk reduction is insensitive to changes in the failure frequency of fill slopes.

8. HISTORICAL LANDSLIDE FATALITY DATA

A review of historical landslide fatalities has been carried out in order to compare with the calculated global landslide risk reductions. Information on fatalities from landslides is available between 1917 and 2000 (up to September). The information is reasonably comprehensive from 1963 onwards.

Figure 7a shows the historical annual fatalities (excluding boulder falls from natural terrain) for the period from 1963 to September 2000. The fatalities include those due to landslides affecting buildings, roads, squatters/licensed areas and other facilities. Figure 7b shows the fatalities excluding those from squatters/licensed areas.

The historical fatalities cannot truly reflect the annual landslide risk because they are influenced by factors such as yearly variations in rainfall, population growth and increase in developments. As a simple but crude attempt to minimise the influence of variations in rainfall, 15-year rolling average annual fatalities are calculated.

Figure 7c shows the historical landslide fatalities (excluding those from squatters/licensed areas) between 1963 and September 2000 expressed as 15-year rolling averages. The population in Hong Kong over the same period is also plotted in the same figure. There is a marked drop in the 15-year rolling average loss of life in 1987. This is partly due to the fact that the fatalities in the two disasters in 1972 have become discounted by that year and partly due to the risk reduction actions of the GEO. There is a trend of overall risk reduction since early 1980's despite a steady rise in population. The 15-year rolling average landslide fatalities is about 1 per year in 1990s compared to about 9 per year in 1977.

Figure 7d shows the 15-year rolling average landslide fatalities per capita. The trend is similar to that in Figure 7c with the 15-year rolling average loss of life being about 0.16×10^{-6} per year in the 1990s compared to about 2×10^{-6} per year in 1977.

The historical data indicates that the fatality rate has decreased significantly since 1977. However, it is not possible to separate out the contribution due to the LPM Programme alone from other GEO landslide risk reduction actions.

9. DISCUSSION

Based on the analytical results given in Table 5a, most (over 80%) of the global landslide risk comes from soil cut slopes. This can be explained by the fact that the number of such slopes and their average failure frequencies are higher. Retaining walls contribute the least amount of risk, whereas the risk from fill slopes is higher than that from rock cut slopes. Furthermore, Tables 6a and 6b show that most of the landslide risk reduction is attributed to the various actions taken on soil cut slopes.

'Probability of landsliding' and 'consequence' are the two components that make up the landslide risk. The LPM Programme is effective in reducing the former component (probability of failure), but the actions may not reduce the latter. Indeed, the continual increase in population and the growing pressure on forming less land by reclamation will collectively increase the potential consequence of landsliding. Such an increase can, to a certain extent, negate the efforts being made under LPM to reduce the global landslide risk. An example is given below to illustrate this point.

Figure 8 shows the location and profile of a slope feature before LPM works. The toe facility affected by the feature at that time was a road. The landslide risk (PLL) before the works was assessed to be about 10^{-4} per year. The residual risk (PLL) of the feature after the LPM works could be an order of magnitude lower. Figure 9 shows the extent of the feature upon completion of the LPM works. It can be noted from this Figure that a new building has been constructed on the other side of the road. While the LPM works have reduced the probability of landsliding of the feature, the construction of the new building could have increased the potential consequence of failure. Assuming that no risk mitigation measures have been taken as part of the development, the present landslide risk (PLL) of the feature is estimated to be about 10^{-3} per year, which is an order of magnitude higher than that calculated for the condition that existed before the LPM works. This example illustrates the point that the results of global landslide risk assessments may not entirely reflect the effectiveness of the LPM action.

The work carried out in this study is a preliminary assessment. Further improvements may be made to refine the calculation model. Also, it is expected that with the Engineer Inspections being undertaken, the quality of the input data will improve with time. It is important that data collected at different times be properly kept and time-stamped, so that the risk trend can be assessed later if required.

This study has put into perspective the relative distribution of risk among different feature types in 1977 and 2000. It could assist in the consideration of allocation of resources in the 10-year Extended LPM Programme. It must be stressed that this is the first time that the technique of QRA has been applied to assess the performance of the LPM Programme. The main benefit of this study is to gain experience, to identify more clearly the requirements on input data and to highlight areas requiring further improvements.

10. CONCLUSIONS

Notwithstanding the limitations of the QRA approach and the data available, the work done is sufficient to indicate that the LPM Programme has been effective in reducing landslide risk in Hong Kong. Up to the end of September 2000, it is estimated that the global landslide risk has been reduced to about 50% of the level in 1977.

The landslide risk results presented in this Report are not true risk values in the absolute sense. As such, they should only be used for comparative purposes.

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Table 1a - Average Annual Failure Frequency for Pre-1978 Soil Cut Slopes

Slope Height (m)	No. of Slopes	No of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 10	15,981	1,471 (54)	0.61 (0.02)
> 10 - ≤ 20	2,558	389 (50)	1.01 (0.13)
> 20	592	137 (26)	1.54 (0.29)
Total	19,131	1,997 (130)	0.70 (0.05)

Table 1b - Average Annual Failure Frequency for Pre-1978 Rock Cut Slopes

Slope Height (m)	No. of Slopes	No. of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 10	825	108 (6)	0.87 (0.05)
> 10 - ≤ 20	225	59 (5)	1.75 (0.15)
> 20	87	30 (2)	2.30 (0.15)
Total	1,137	197 (13)	1.16 (0.08)

Table 1c - Average Annual Failure Frequency for Pre-1978 Retaining Walls

Wall Height (m)	No. of Walls	No. of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 5	4,634	101 (0)	0.15 (0)
> 5 - ≤ 10	1,873	32 (1)	0.11 (4E-03)
> 10	368	3 (0)	0.05 (0)
Total	6,875	136 (1)	0.13 (1E-03)

Table 1d - Average Annual Failure Frequency for Pre-1978 Fill Slopes

Slope Height (m)	No. of Slopes	No. of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 10	3,043	156 (19)	0.34 (0.04)
> 10 - ≤ 20	1,528	51 (11)	0.22 (0.05)
> 20	388	11 (3)	0.19 (0.05)
Total	4,959	218 (33)	0.29 (0.04)

Note: In Tables 1a to 1d, the features signed off by Stage 2 Studies and Old Studies and failures involving such features have been excluded. The figures in brackets are numbers for major failure (failure volume ≥ 50 m^3).

Table 2a - Average Annual Failure Frequency for Pre-1978 Soil Cut Slopes That Have Been Signed Off By Stage 2 Studies

Slope Height (m)	No. of Slopes	No of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 10	81	8 (2)	0.66 (0.16)
> 10 - ≤ 20	39	1 (0)	0.17 (0)
> 20	15	3 (0)	1.33 (0)
Total	135	12 (2)	0.59 (0.10)

Table 2b - Average Annual Failure Frequency for Pre-1978 Rock Cut Slopes That Have Been Signed Off By Stage 2 Studies

Slope Height (m)	No. of Slopes	No. of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 10	6	1 (0)	1.11 (0)
> 10 - ≤ 20	3	0 (0)	0 (0)
> 20	0	0 (0)	0 (0)
Total	9	1 (0)	0.74 (0)

Table 2c - Average Annual Failure Frequency for Pre-1978 Retaining Walls That Have Been Signed Off By Stage 2 Studies

Wall Height (m)	No. of Walls	No. of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 5	76	0 (0)	0 (0)
> 5 - ≤ 10	121	0 (0)	0 (0)
> 10	10	0 (0)	0 (0)
Total	207	0 (0)	0 (0)

Table 2d - Average Annual Failure Frequency for Pre-1978 Fill Slopes That Have Been Signed Off By Stage 2 Studies

Slope Height (m)	No. of Slopes	No. of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 10	15	0 (0)	0 (0)
> 10 - ≤ 20	11	0 (0)	0 (0)
> 20	0	0 (0)	0 (0)
Total	26	0 (0)	0 (0)

Note: The figures in brackets are numbers for major failure (failure volume ≥ 50 m^3).

Table 3a - Average Annual Failure Frequency for Pre-1978 Soil Cut Slopes That Have Been Signed Off By Old Studies

Slope Height (m)	No. of Slopes	No of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 10	274	23 (0)	0.56 (0)
> 10 - ≤ 20	376	26 (1)	0.46 (0.02)
> 20	239	21 (2)	0.59 (0.06)
Total	889	70 (3)	0.52 (0.02)

Table 3b - Average Annual Failure Frequency for Pre-1978 Rock Cut Slopes That Have Been Signed Off By Old Studies

Slope Height (m)	No. of Slopes	No. of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 10	32	11 (0)	2.29 (0)
> 10 - ≤ 20	28	6 (0)	1.41 (0)
> 20	17	10 (1)	3.92 (0.39)
Total	77	27 (1)	2.31 (0.09)

Table 3c - Average Annual Failure Frequency for Pre-1978 Retaining Walls That Have Been Signed Off By Old Studies

Wall Height (m)	No. of Walls	No. of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 5	191	0 (0)	0 (0)
> 5 - ≤ 10	277	1 (0)	0.02 (0)
> 10	118	0 (0)	0 (0)
Total	586	1 (0)	0.01 (0)

Table 3d - Average Annual Failure Frequency for Pre-1978 Fill Slopes That Have Been Signed Off By Old Studies

Slope Height (m)	No. of Slopes	No. of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 10	66	2 (0)	0.20 (0)
> 10 - ≤ 20	47	0 (0)	0 (0)
> 20	23	1 (0)	0.29 (0)
Total	136	3 (0)	0.15 (0)

Note: The figures in brackets are numbers for major failure (failure volume ≥ 50 m^3).

Table 4 - Expected Number of Fatalities for Affected Facilities Used in the Analysis (Wong, 1998)

Facility Group No.	Facilities	Expected No. of Fatalities (Note 3)
1	(a) Building with a high density of occupation or heavily used (Notes 1 and 2) - residential building, commercial office, store and shop, hotel, factory, school, power station, ambulance depot, market, hospital/polyclinic/clinic, welfare centre	3
	(b) Others - bus shelter, railway platform and other sheltered public waiting area - cottage, licensed and squatter area - dangerous goods storage site - road with very heavy vehicular or pedestrian traffic density	3
2	(a) Building (Note 2) - built-up area (e.g. indoor car park, building within barracks, abattoir, incinerator, indoor game's sport hall, sewage treatment plant, refuse transfer station, church, temple, monastery, civic centre, manned substation)	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	1
3	Roads & Open Space - densely-used open space and public waiting are - quarry - road with moderate vehicular or pedestrian traffic density	0.25
4	Roads & Open Space - lightly-used open-aired recreation area - non-dangerous goods storage site - road with low vehicular or pedestrian traffic density	0.03
5	Roads & Open Space - remote area - road with very low vehicular or pedestrian traffic density	0.001

Notes:

(1) To account for different types of building structure with different detailing of windows and other perforations, etc, multiple fatality factors of 1, 2, 3, 4 and 5 in proportions of 10%, 20%, 40%, 20% and 10% respectively are considered appropriate for Group No. 1(a) facilities. The multiple fatality factor accounts for the possibility that some incidents may result in a disproportionately larger number of fatalities than that envisaged. Thus, the expected number of fatalities for Group No. 1(a) facilities becomes 3x multiple fatality factors, i.e. 3x1 = 3, 6, 9, 12 and 15 in proportions of 10%, 20%, 40%, 20% and 10% respectively. The multiple fatality factors for the other Facility Groups are 1.

(2) For a failure involving collapse of buildings (slope height exceeds 20 m and failure volume exceeds 10,000 m^3), an additional number of fatalities of 100 is assumed.

(3) The expected number of fatalities refers to the occurrence of a reference landslide of 10 m wide with a volume of 50 m^3.

Table 5a - Distribution of Landslide Risk in 1977 among Different Types of Slope Features

Slope Feature Type	Landslide Risk (PLL)	Proportion of Risk (%)
Soil Cut Slopes	13.45	84.8
Rock Cut Slopes	0.86	5.5
Retaining Walls	0.45	2.8
Fill Slopes	1.10	6.9
Total	15.86	100

Table 5b - Distribution of Landslide Risk in 1977 among Different Facility Groups

Facility Group No.	Landslide Risk (PLL)	Proportion of Risk (%)
1	13.25	83.6
2	1.73	10.9
3	0.75	4.7
4	0.12	0.7
5	0.01	0.1
Total	15.86	100

Table 6a - Distribution of Landslide Risk Reduction (from 1977 to 2000) due to Upgrading of Pre-1978 Features through LPM Upgrading Works

Slope Feature Type	Landslide Risk Reduction (PLL)	Proportion of Risk Reduction (%)
Soil Cut Slopes	3.53	87.4
Rock Cut Slopes	0.07	1.7
Retaining Walls	0.01	0.2
Fill Slopes	0.43	10.7
Total	4.04	100

Table 6b - Distribution of Landslide Risk Reduction (from 1977 to 2000) due to Implementation of Upgrading Works under DH Orders on Pre-1978 Features

Slope Feature Type	Landslide Risk Reduction (PLL)	Proportion of Risk Reduction (%)
Soil Cut Slopes	1.41	91.5
Rock Cut Slopes	0.05	3.2
Retaining Walls	0.03	2.1
Fill Slopes	0.05	3.2
Total	1.54	100

Note: The figures in Table 6b correspond to Case 2 (see Section 5.3.3). The figures for Case 1 and Case 3 are similar.

Table 7a - Average Annual Failure Frequency for Pre-1978 Features Included in the LPM Programme But before the Implementation of Upgrading Works

Feature Height (m)	No. of Features	No of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 10	1,042	281 (20)	1.80 (0.13)
> 10 - ≤ 20	1,119	170 (20)	1.01 (0.12)
> 20	476	79 (14)	1.11 (0.20)
Total	2,637	530 (54)	1.34 (0.14)

Table 7b - Average Annual Failure Frequency for Pre-1978 Features Not Included in the LPM Programme

Slope Height (m)	No. of Slopes	No. of Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 10	23,441	1,555 (59)	0.44 (0.02)
> 10 - ≤ 20	5,065	361 (47)	0.48 (0.06)
> 20	959	102 (17)	0.71 (0.12)
Total	29,465	2,018 (123)	0.46 (0.03)

Note: In Tables 7a and 7b, the features signed off by Stage 2 Studies and Old Studies have been excluded. The figures in brackets are numbers for major failure (failure volume ≥ 50 m^3).

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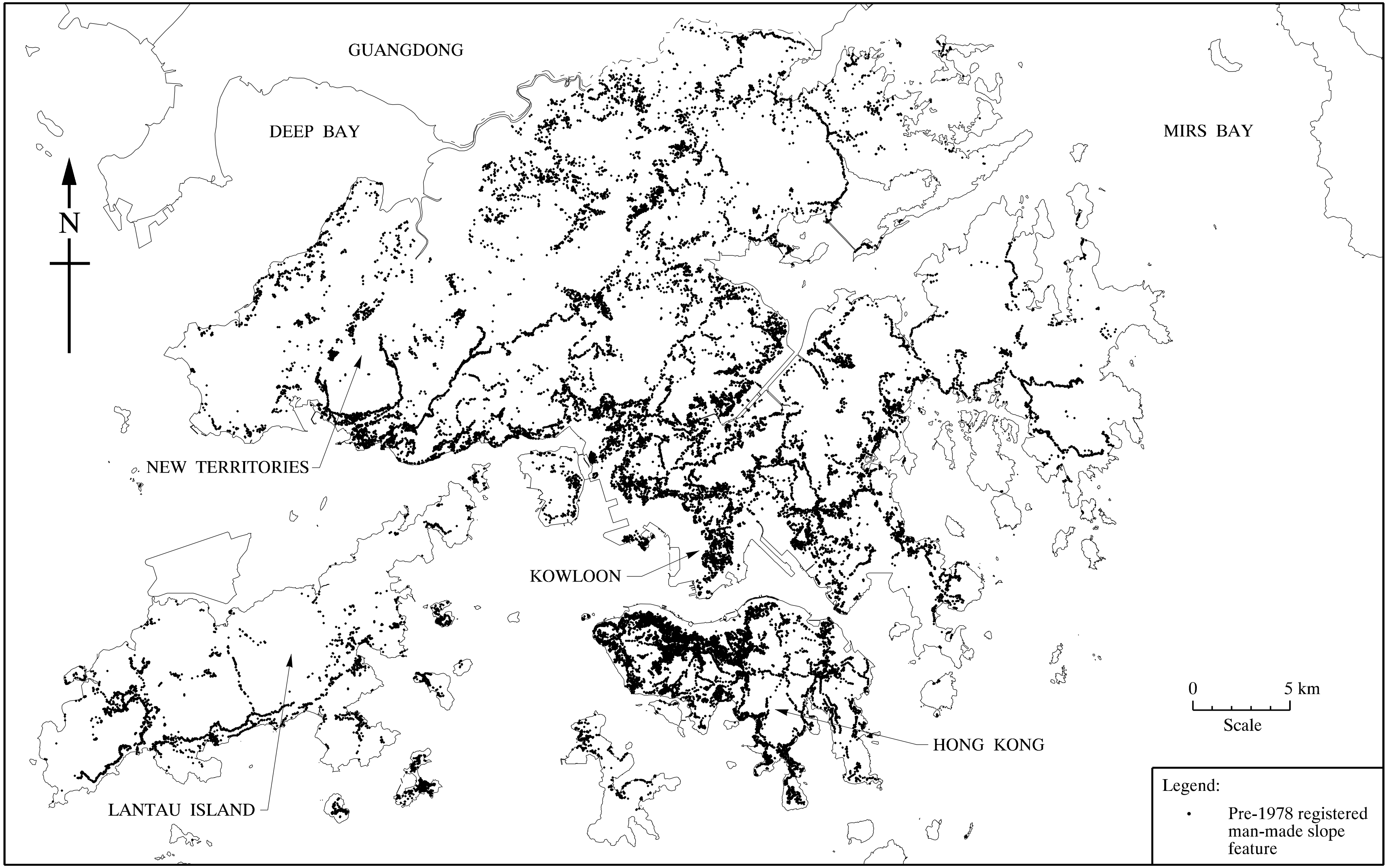


Figure 1 - Locations of Pre-1978 Registered Man-made Slope Features

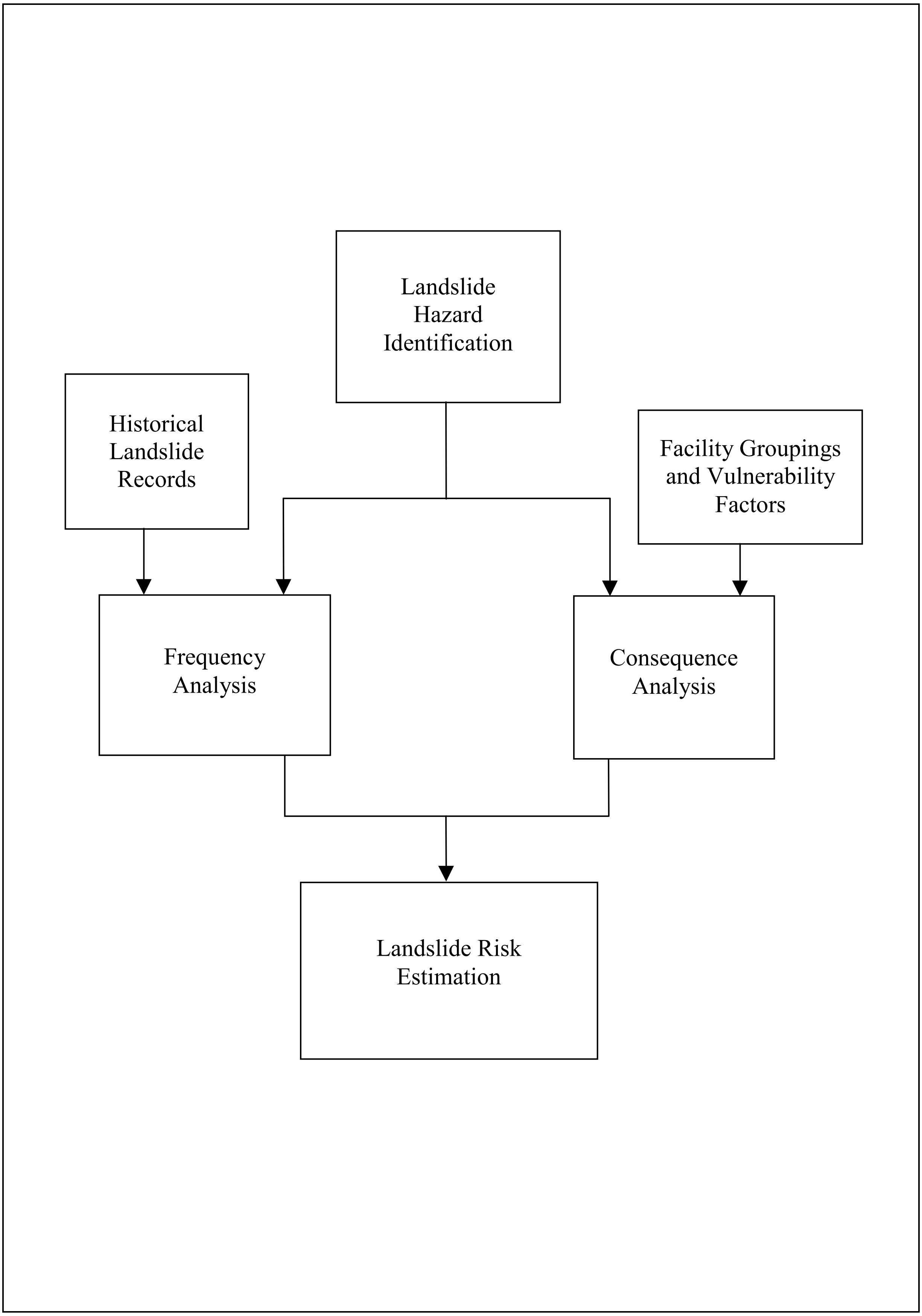
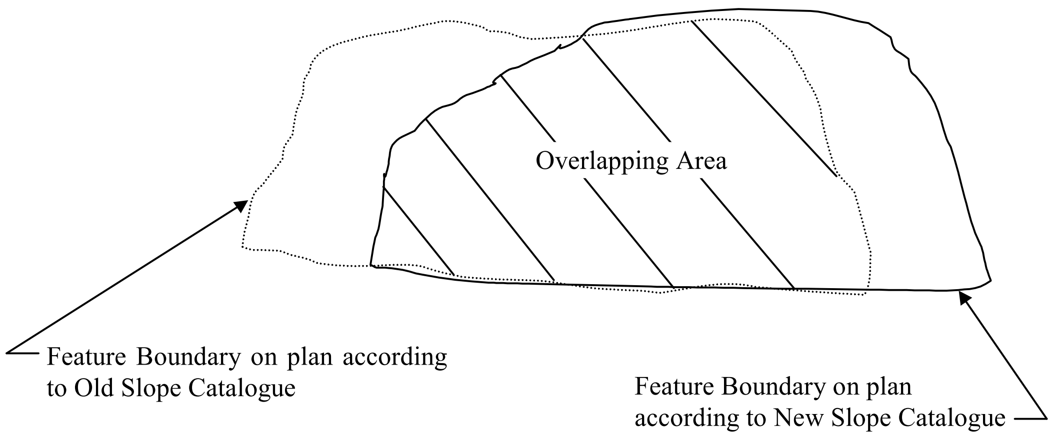
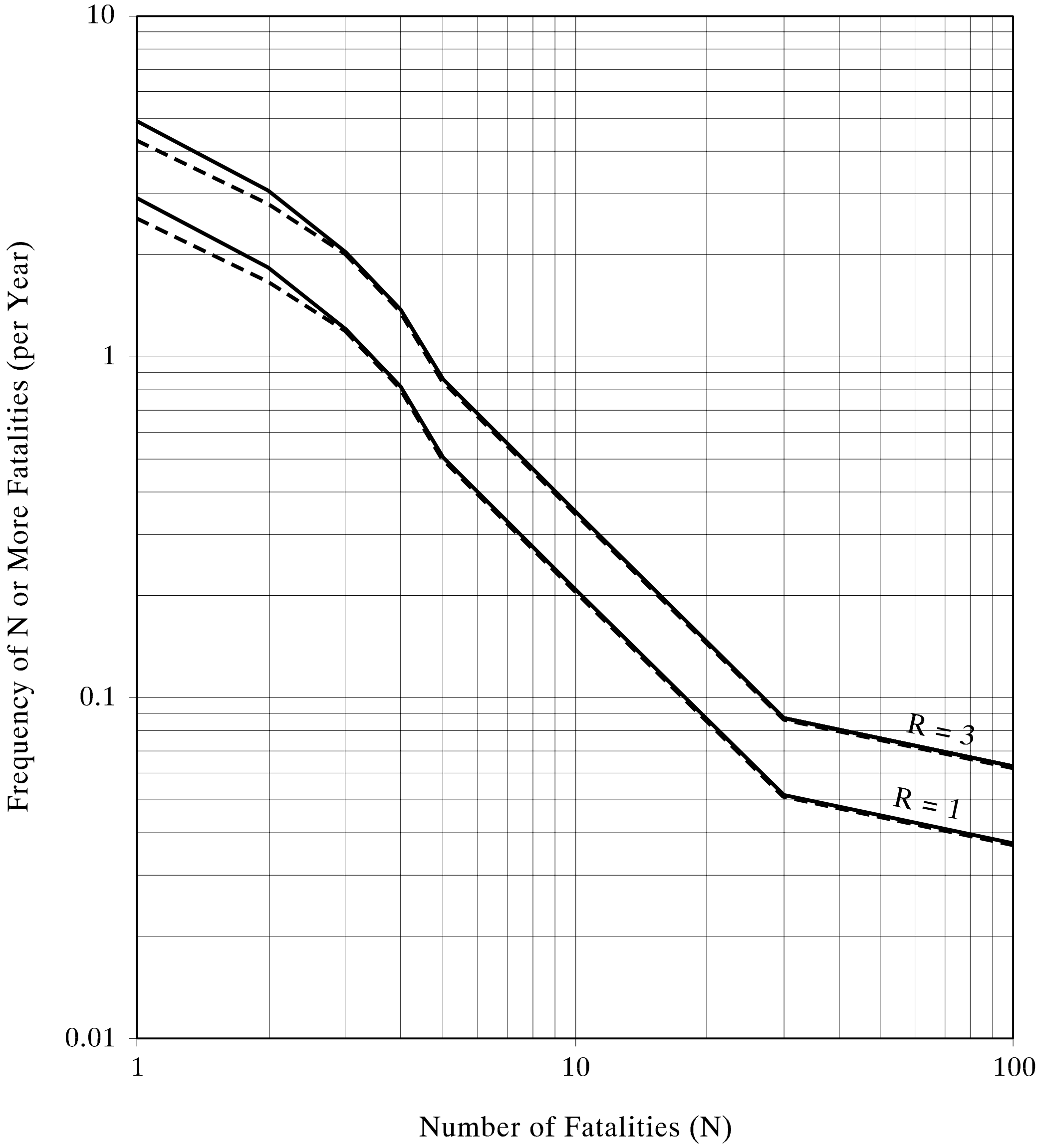


Figure 2 - Framework of Landslide Risk Assessment



$$\text{If } \frac{\text{Overlapping area}}{\text{Area bounded by new slope boundary}} \geq 80\%, \text{ then the old slope feature = the new slope feature.}$$

Figure 3 - Mapping between Old and New Slope Features



Legend:

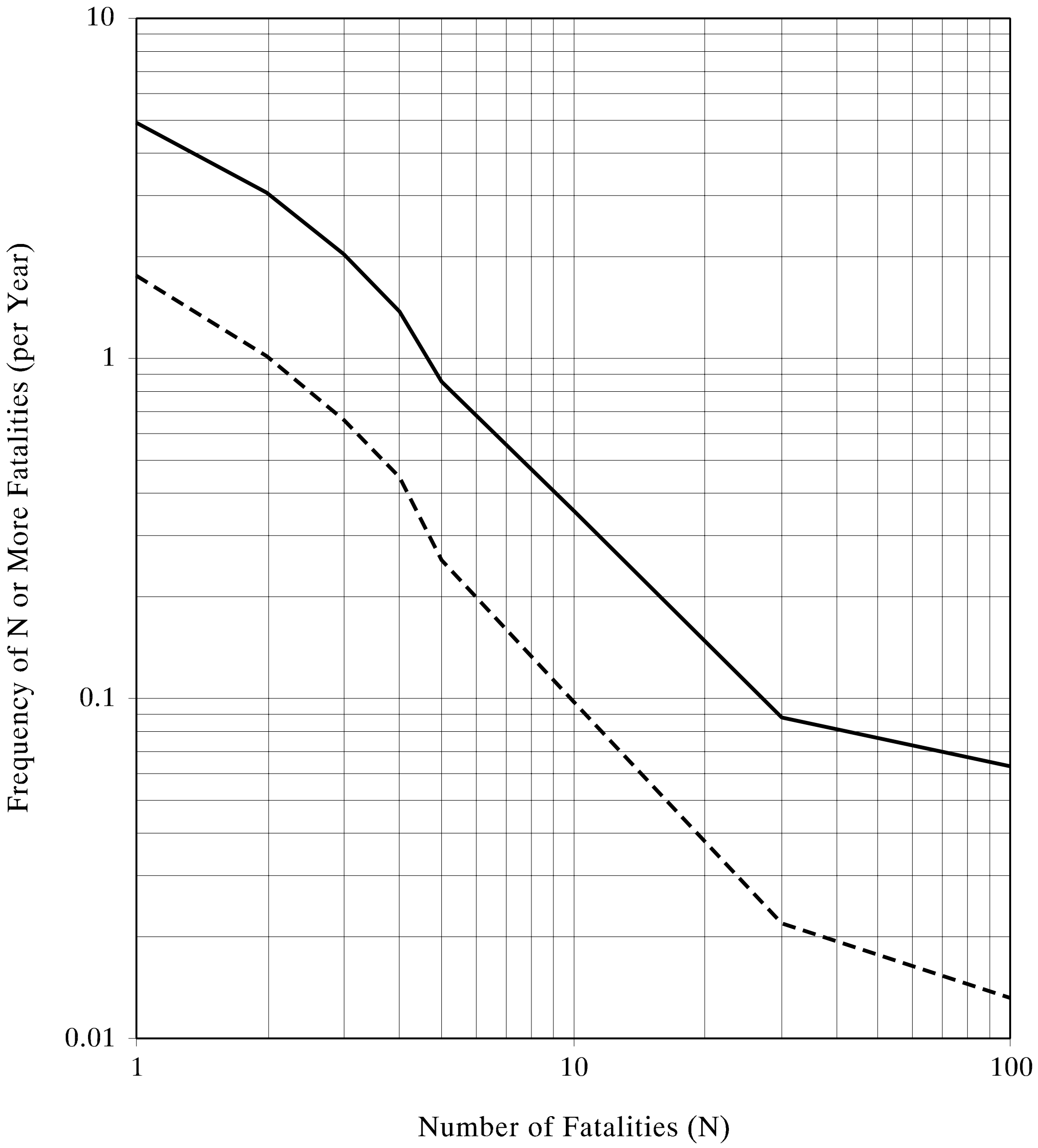
—— 1977 all failures

- - - - 1977 major failures (i.e. volume $\geqslant$ 50 m^3)

Note:

$$R = \frac{\text{The average annual failure frequency for the population of features included in the LPM programme but before the implementation of upgrading works}}{\text{The average annual failure frequency for the population of features not included in the LPM programme}}$$

Figure 4 - F-N Curves Representing the Global Landslide Risk in 1977 due to Pre-1978 Slope Features



Legend:

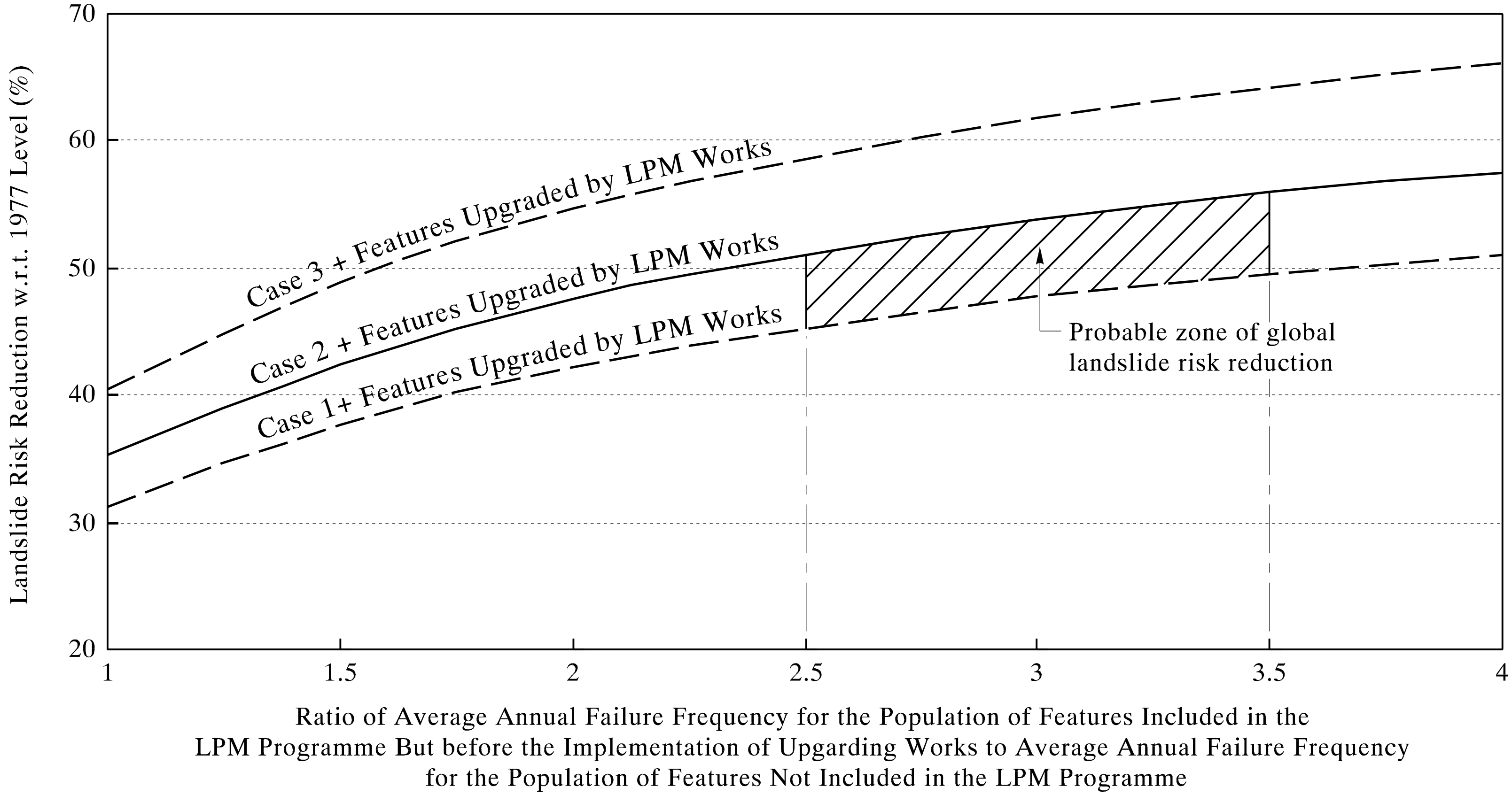
1977 (R = 3)
2000 (Case 2 features and features upgraded by LPM works, and R = 3)

} All failures

Note:

$$R = \frac{\text{The average annual failure frequency for the population of features included in the LPM programme but before the implementation of upgrading works}}{\text{The average annual failure frequency for the population of features not included in the LPM programme}}$$

Figure 5 - F-N Curves Representing the Global Landslide Risk in 1977 and in 2000 due to Pre-1978 Slope Features



Legend:

Case 1	Only features which have their DHOs officially discharged are considered
Case 2	In addition to the features under Case 1, features on which DHOs have been served for more than 30 months but still not yet been officially discharged are also considered (more probable case)
Case 3	In addition to the features under Case 1, all features on which DHOs have been served but still not yet been officially discharged are also considered

Figure 6a - Effect of Distribution of Failure Frequency on Global Landslide Risk Reduction

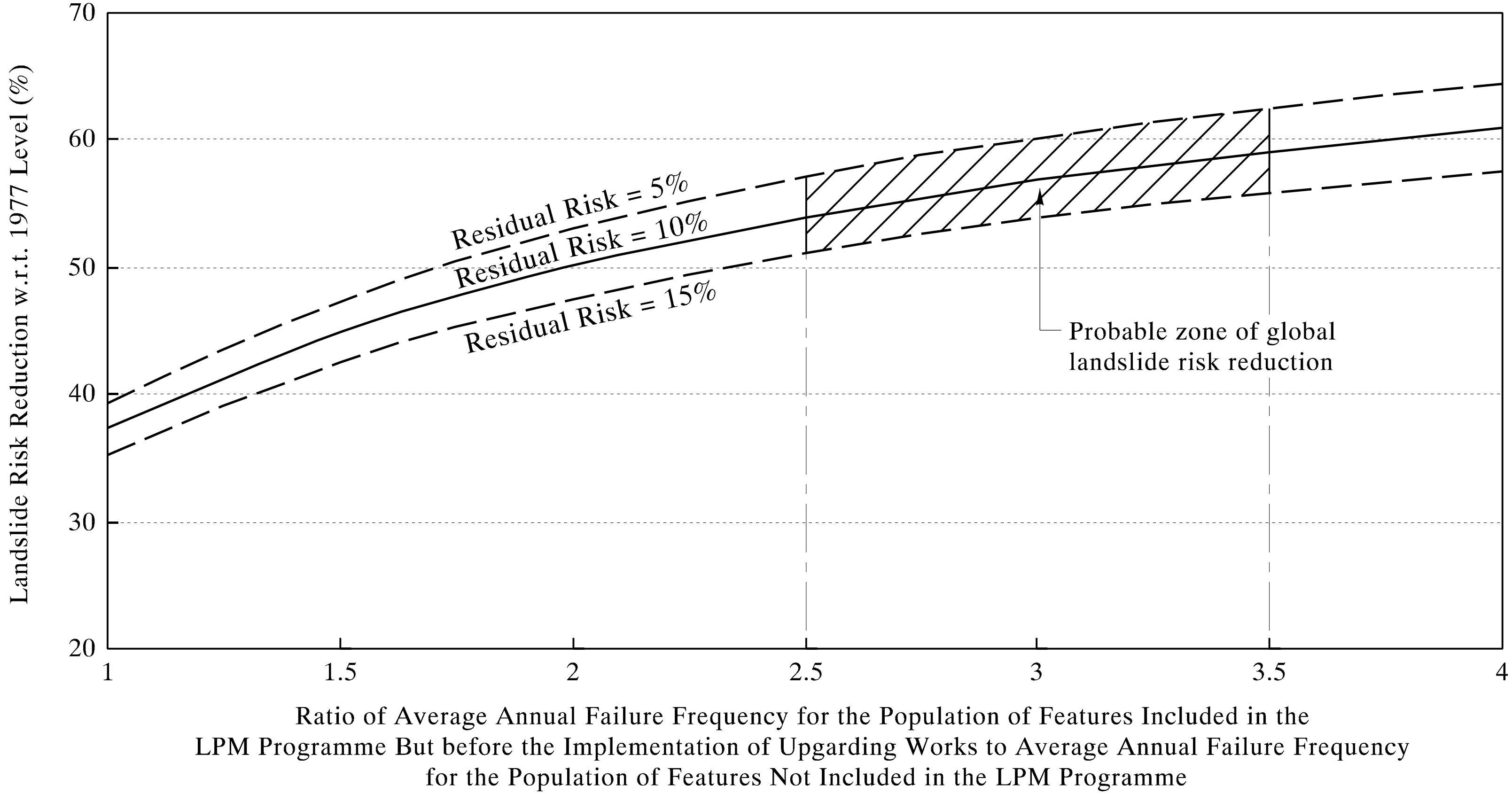


Figure 6b - Effect of Residual Risk on Global Landslide Risk Reduction (Case 2 Features + Features Upgraded by LPM Works)

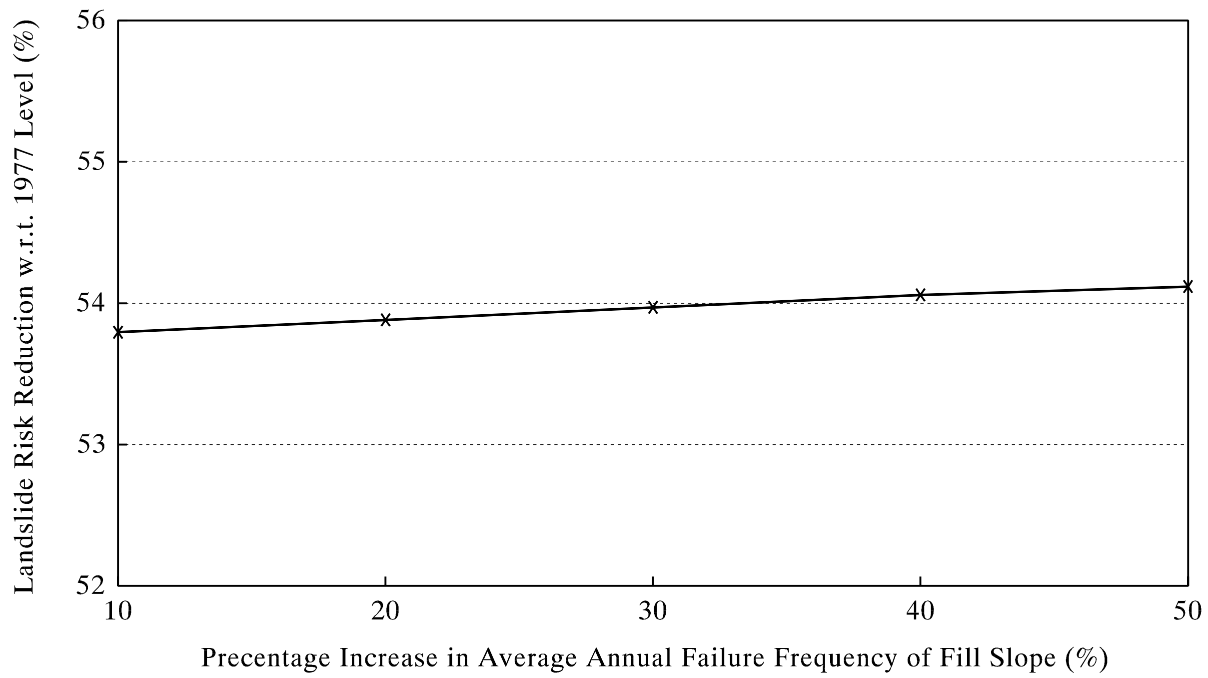


Figure 6c - Effect of Changes in Failure Frequency of Fill Slopes on Global Landslide Risk Reduction (Case 2 Features and Features Upgraded by LPM Works, and R = 3)

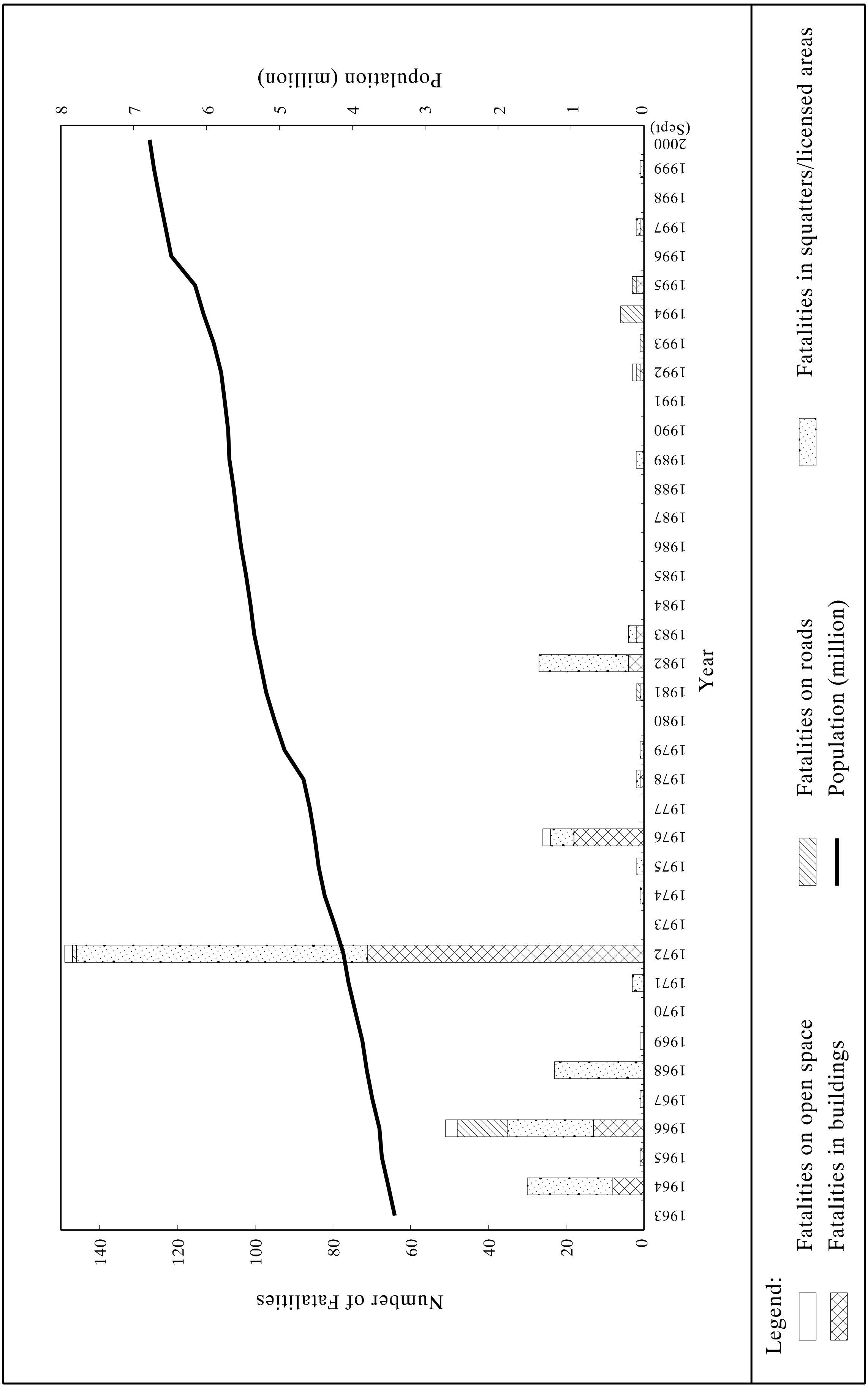


Figure 7a - Historical Annual Landslide Fatalities

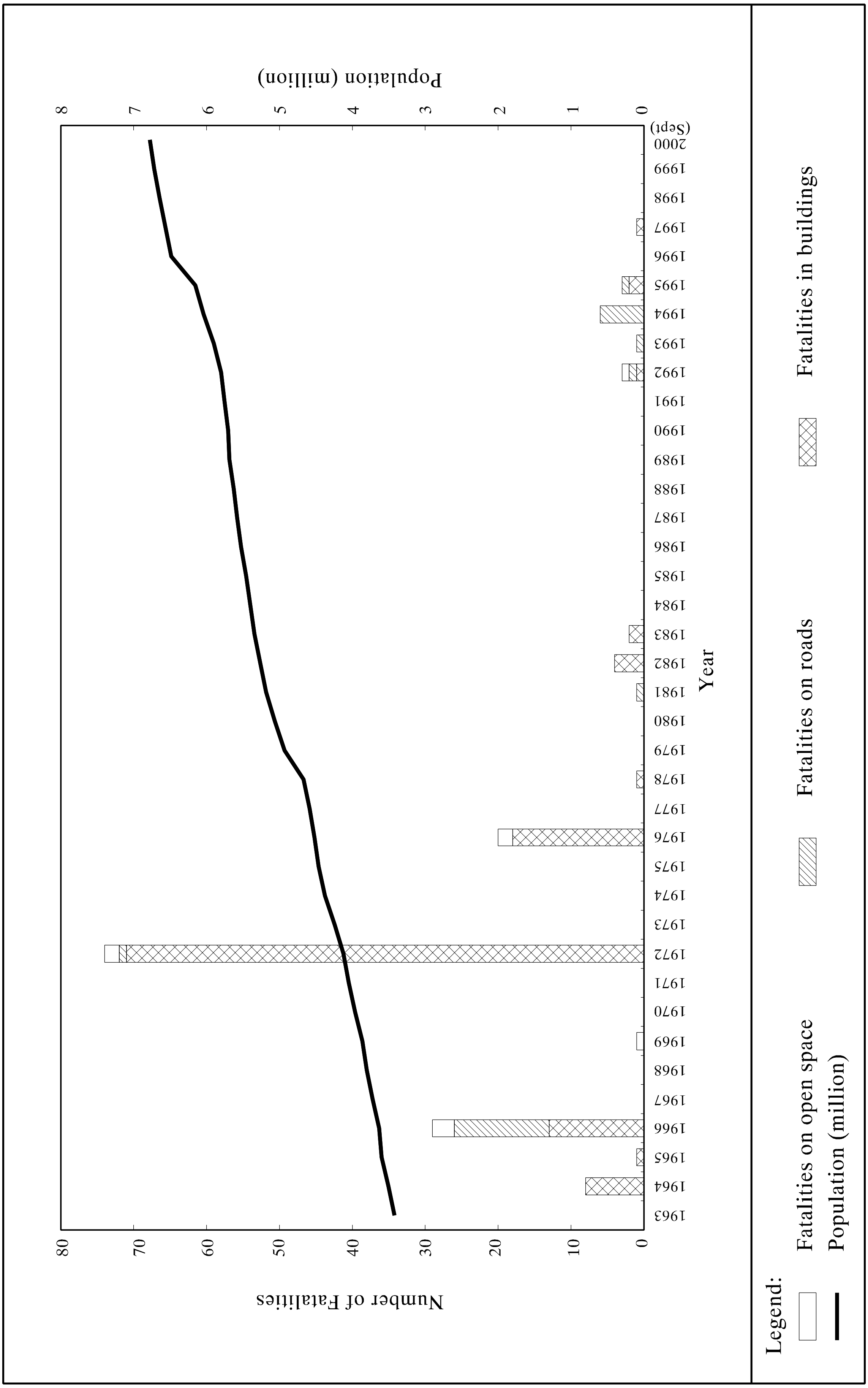
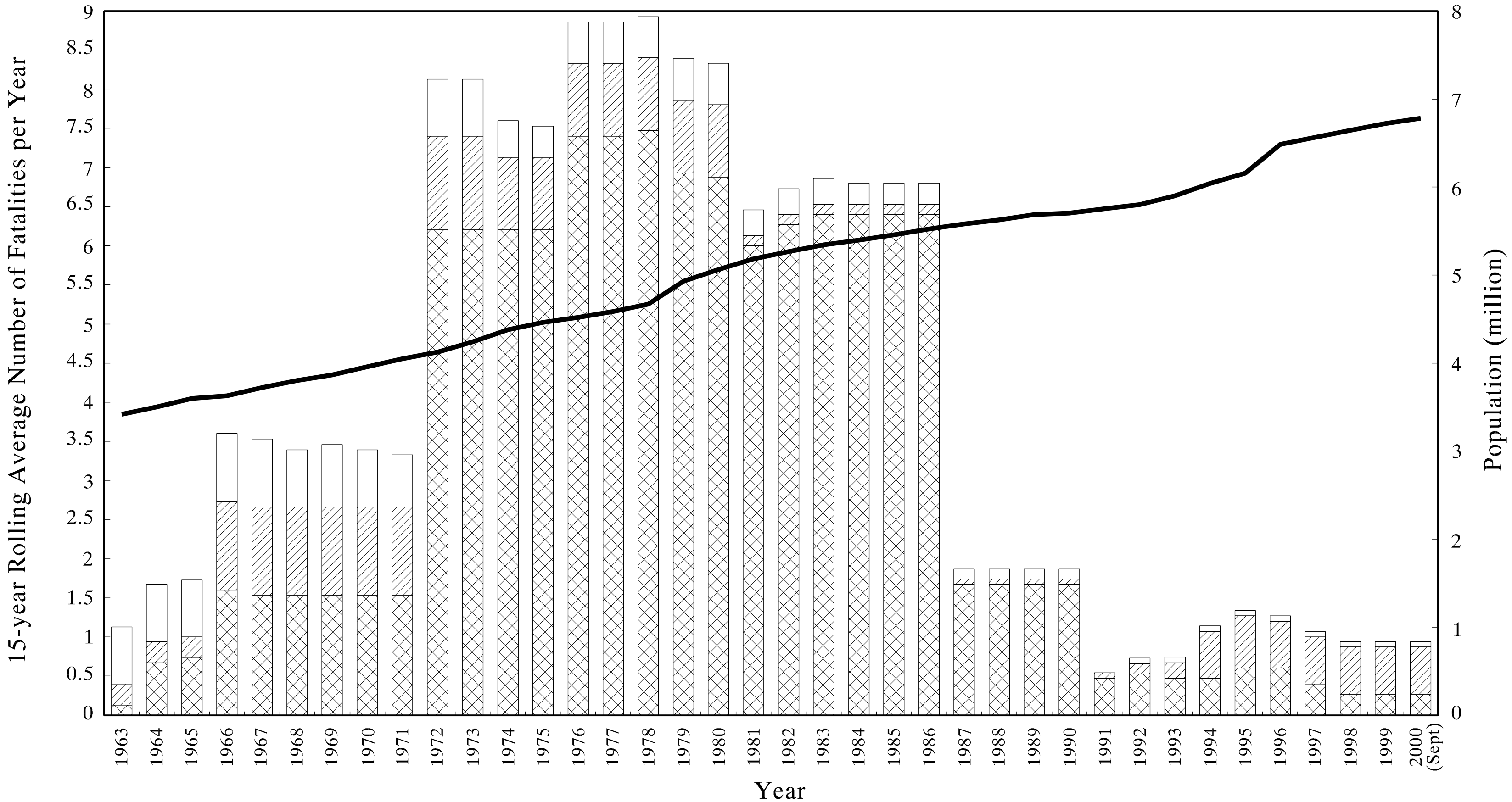


Figure 7b - Historical Annual Landslide Fatalities Excluding Those from Squatters/Licensed Areas



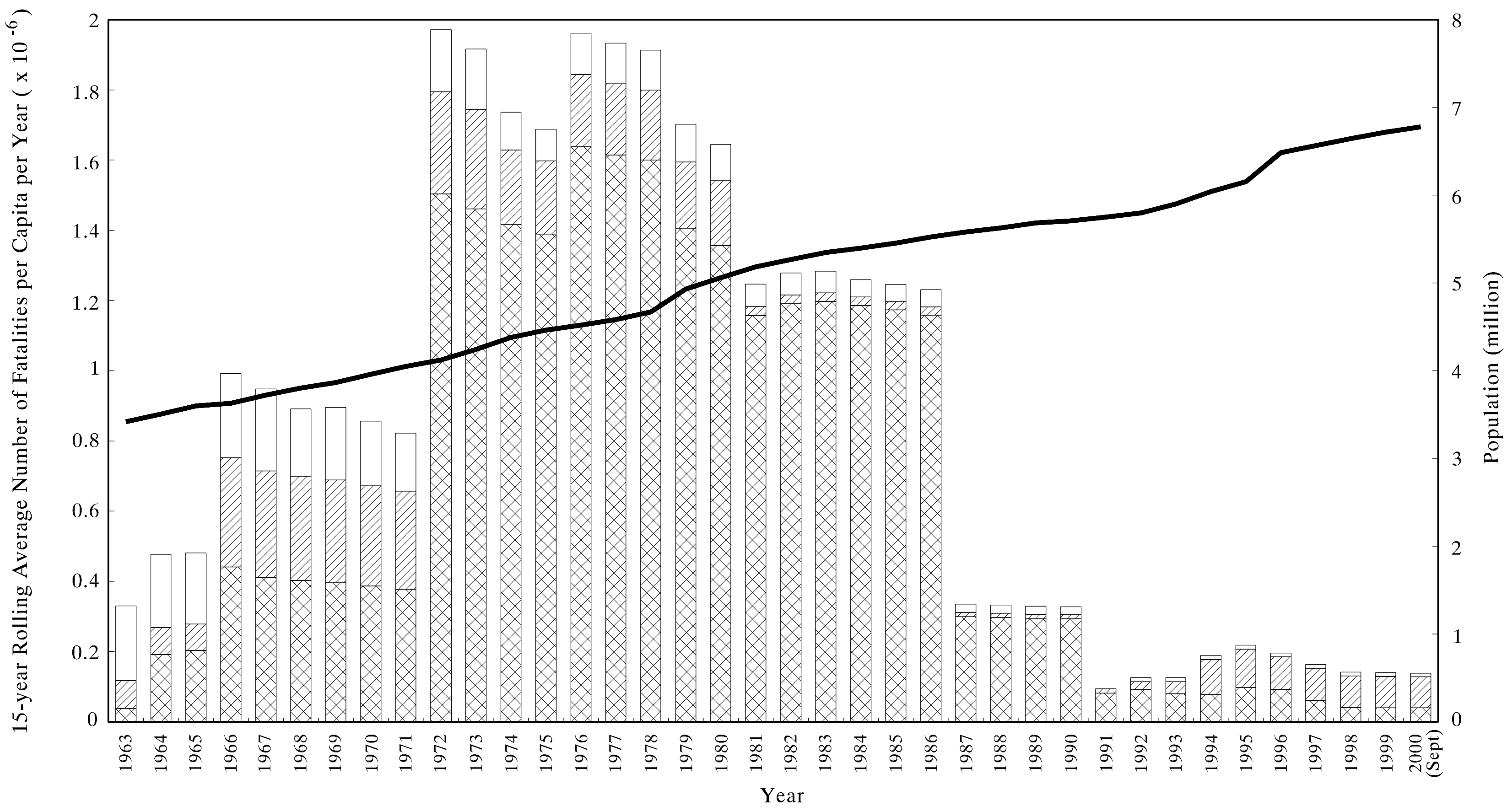
Legend:

Fatalities on open space | Fatalities on roads | Fatalities in buildings

Population (million)

Note: Fatalities on squatters/licensed areas have been excluded.

Figure 7c - Historical 15-year Rolling Average Landslide Fatalities



Legend:

Fatalities on open space

Fatalities on roads

Fatalities in buildings

Population (million)

Note: Fatalities on squatters/licensed areas have been excluded.

Figure 7d - Historical 15-year Rolling Average Landslide Fatalities per Capita

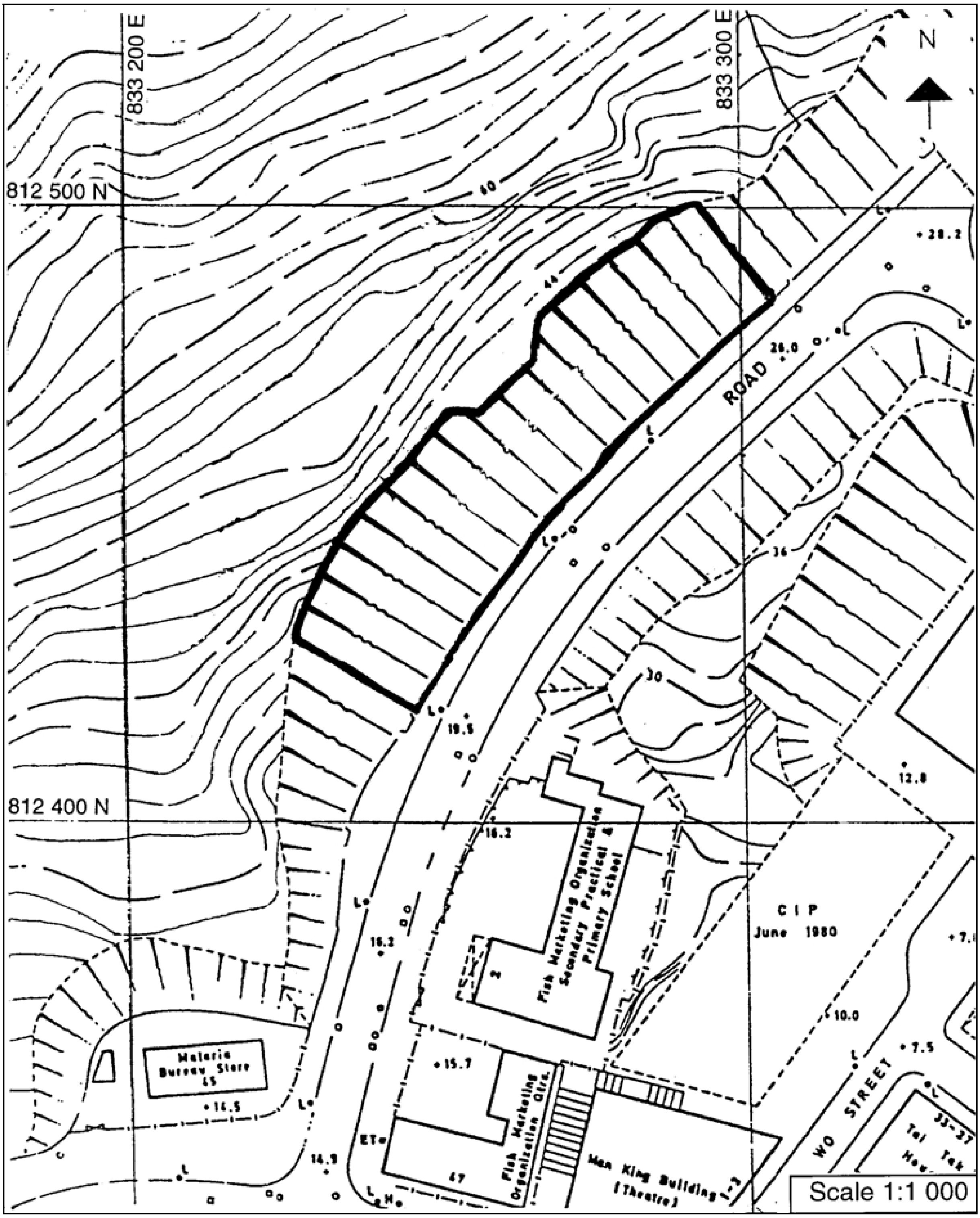


Figure 8 - Extent of Feature before the Carrying out of Upgrading Works

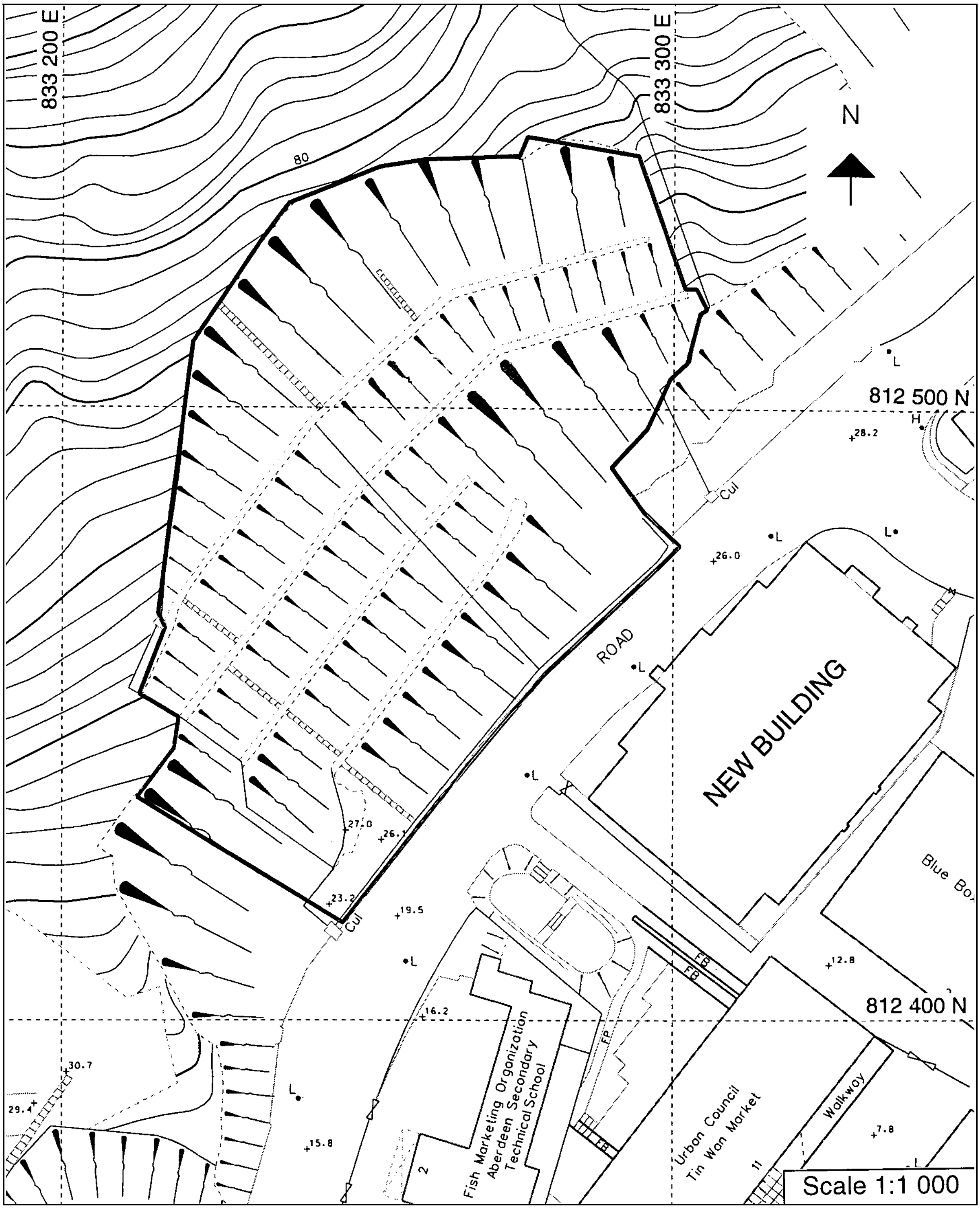
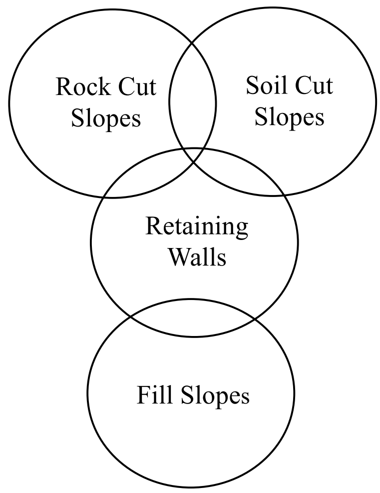


Figure 9 - Extent of Feature upon Completion of Upgrading Works

APPENDIX A

APPROACH FOR CLASSIFYING MIXED FEATURES

The following steps show the approach of classifying mixed features under one of the four basic feature types, namely soil cut slopes, rock cut slopes, fill slopes and retaining walls.



Note: The overlapping areas correspond to the respective mixed feature types. For example, the overlapping area between retaining walls and fill slopes comprise "FR" features.

Figure A1 - Venn Diagram Illustrating the Original Distribution of Slope Features

Step 1: Separation into soil cut and rock cut slopes

For a cut slope, if the height of the soil portion is < 3 m and the height of the rock portion ≥ 3 m, the cut slope is regarded as a rock cut slope, otherwise it is classified as a soil cut slope.

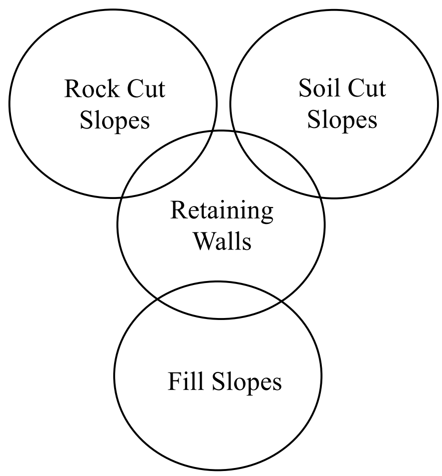


Figure A2 - Venn Diagram Illustrating the Distribution of Slope Features after Separation into Soil Cut and Rock Cut Slopes

Step 2: Separation into retaining walls and other slope feature types

(a) For a soil cut slope and retaining wall

If the ratio of wall height to total feature height is < 0.5, the feature is regarded as a soil cut slope. Otherwise, it is classified as a retaining wall.

(b) For a rock cut slope and retaining wall

If the ratio of wall height to total feature height is < 0.5, the feature is regarded as a rock cut slope. Otherwise, it is classified as a retaining wall.

(c) For a fill slope and retaining wall

If the ratio of wall height to total feature height is < 0.5, the feature is regarded as a fill slope. Otherwise, it is classified as a retaining wall.

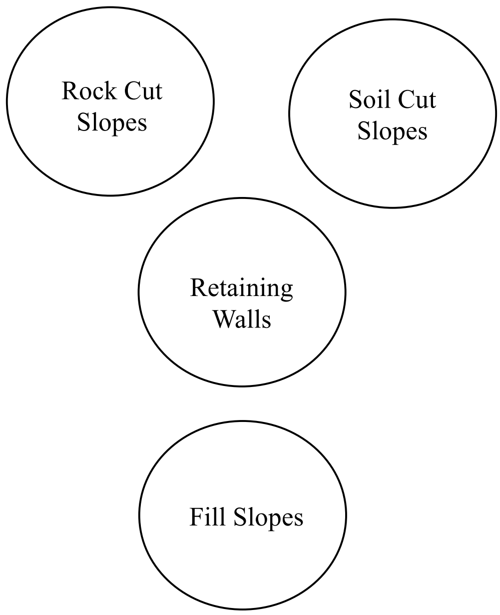


Figure A3 - Venn Diagram Illustrating the Distribution of Slope Features after Total Separation

APPENDIX B

WORKED EXAMPLE ON ASSESSMENT OF LANDSLIDE RISK

A road of moderate vehicular density is situated at a certain distance away from the toe of a pre-1978 soil cut slope with a shadow angle of 27° as shown in Figure B1. The shadow angle, which reflects the proximity of the toe facility from the slope, is defined as the angle to the horizontal of a line joining the toe facility to the slope crest. The height and length of the cut slope are 20 m and 15 m respectively.

The procedure for determining the average annual landslide risk posed by the cut slope on the toe facility (i.e. the road) is illustrated below.

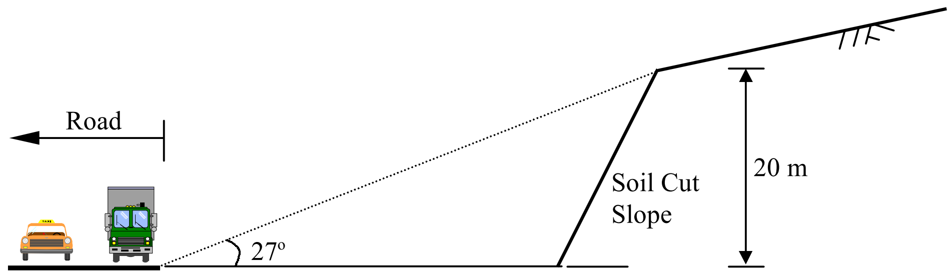


Figure B1 - Cross-section of a Hypothetical Soil Cut Slope

Step 1: Determine the characteristics of the slope and toe facility

Slope:

(i) Slope height = 20 m

(ii) Slope length = 15 m

(iii) Slope type = soil cut slope

Toe facility:

(i) Grouping of facility (road) = 3 (the grouping is based on the actual Annual Average Daily Traffic and the number of road lanes, see GEO Report No. 68)

(ii) Expected no. of fatalities if a reference landslide (a 10 m-wide landslide with failure volume of 50 m^3) occurs = 0.25 (see Table 4 of this report)

(iii) Shadow angle = 27°

Step 2: Determine the distribution of possible failure debris volume

The distribution of failure debris volume and slope height as shown in Table B1 has been determined based on data in the GEO landslide database (spanning from 1984 to 1998).

Table B1 - Distribution of Failure Debris Volume for Soil Cut Slopes of Different Heights

Slope Height (m)	Failure Debris Volume (m^3)					
	≤ 20	> 20 - ≤ 50	> 50 - ≤ 500	> 500 - ≤ 2,000	> 2,000 - ≤ 10,000	> 10,000
≤ 10	80.16%	16.11%	3.46%	0.27%	0.00%	0.00%
> 10 - ≤ 20	69.71%	18.03%	10.58%	1.44%	0.24%	0.00%
> 20	65.84%	16.77%	14.29%	2.48%	0.00%	0.62%

For the subject cut slope, the relevant distribution of failure debris volume is highlighted in the above Table. The Table shows that if a landslide occurs, the probability for a slope of a height between 10 m and 20 m to have a failure debris volume less than 50 m^3 is about 0.88 (i.e. 0.70 + 0.18).

Step 3: Determine the vulnerability factor for the toe facility

The vulnerability factors (defined as the probability of death in the event of a landslide) for a soil cut slope affecting toe facilities have been developed by Wong et al (1997). Table B2a below shows the distribution of vulnerability factors for different toe facilities (other than buildings) with different failure debris volumes and ranges of shadow angle. For the purpose of reference, Table 2b shows the distribution of vulnerability factors for a soil cut slope affecting buildings at the slope toe. In deriving the vulnerability factors, due regard has been given to the likely distribution of landslide travel distance, the location of the toe facilities relative to the slope and the likely degree of damage upon impact of the facility by the landslide debris.

Table B2a - Distribution of Vulnerability Factors for a Soil Cut Slope Affecting Roads and Other Facilities (Except Buildings) at the Toe (Wong et al, 1997)

Failure Volume (m^3)	Shadow Angle									
	0°-20°	20°-25°	25°-30°	30°-35°	35°-40°	40°-45°	45°-50°	50°-55°	55°-60°	> 60°
< 20	0	0	0	0.0002	0.0012	0.0046	0.0170	0.0340	0.0650	0.1000
20-50	0	0	0	0.0100	0.0400	0.1100	0.2300	0.3500	0.4600	0.5000
50-500	0	0	0.0225	0.0090	0.2150	0.3825	0.5450	0.6350	0.6650	0.7000
500-2,000	0	0.0600	0.2400	0.5250	0.7700	0.9150	0.9500	0.9500	0.9500	0.9500
2,000-10,000	0	0.1500	0.4400	0.7450	0.9000	0.9500	0.9500	0.9500	0.9500	0.9500
> 10,000	0	0.2000	0.5200	0.7950	0.9200	0.9500	0.9500	0.9500	0.9500	0.9500

Table B2b - Distribution of Vulnerability Factors for a Soil Cut Slope Affecting Buildings at the Toe (Wong et al, 1997)

Failure Volume (m^3)	Shadow Angle									
	0°-20°	20°-25°	25°-30°	30°-35°	35°-40°	40°-45°	45°-50°	50°-55°	55°-60°	> 60°
< 20	0	0	0	1E-06	1E-05	7E-05	3E-04	0.0075	0.0013	0.0020
20-50	0	0	0	5E-05	6E-04	0.0022	0.0057	0.0110	0.0160	0.0200
50-500	0	0	0.0030	0.0190	0.0560	0.1145	0.1825	0.2325	0.2500	0.2500
500-2,000	0	0.0150	0.0075	0.2550	0.5300	0.7700	0.9150	0.9500	0.9500	0.9500
2,000-10,000	0	0.0500	0.1800	0.4600	0.7450	0.9000	0.9500	0.9500	0.9500	0.9500
> 10,000	0	0.1000	0.2600	0.5600	0.7950	0.9200	0.9500	0.9500	0.9500	0.9500

As aforementioned, the expected number of fatalities has been calculated to be 0.25, based on a 10 m-wide reference landslide with a failure volume of 50 m^3. The actual expected number of fatalities is determined by scaling up or down this figure with respect to the expected width of failure. Table B3 shows the distribution of expected width of failure against failure volume derived from the landslide records from 1984 to 1998.

Table B3 - Distribution of Width of Landslide

	Failure Debris Volume (m^3)					
	≤ 20	> 20 - ≤ 50	> 50 - ≤ 500	> 500 - ≤ 2,000	> 2,000 - ≤ 10,000	> 10,000
Expected Width of Landslide (m)	4	7	15	20	25	30

Using the distribution of failure debris volume as highlighted in Table B1 for the 20 m high soil cut slope and the expected failure widths in Table B3, the equivalent vulnerability factor for the road concerned can be calculated as follows, taking into account the probability of the failure belonging to each class of failure volume:

(69.71%)(0)(4/10) + (18.03%)(0)(7/10) + (10.58%)(0.0225)(15/10) + (1.44%)(0.24)(15/10) + (0.24%)(0.44)(15/10) + (0%)(0.52)(15/10) = 0.01034

Note that the width of the subject slope is 15 m and so failure widths greater than this value are not used.

Step 4: Determine the landslide consequence and risk

The consequence of a reference landslide on the slope expressed in terms of Potential Loss of Life (PLL) = 0.25 x 0.01034 = 2.58E-03.

The average annual landslide risk in terms of PLL posed by the soil cut slope on the road is therefore given by:

$$\text{Landslide Risk} = \left\{\text{Probability of Landslide}\right\}\left\{\text{Consequence}\right\}$$

$= (1.01\%)(2.58\text{E-}03)$ - see Table 1a for average annual Failure Frequency value

$= 2.61\text{E-}05$

APPENDIX C

APPROACH FOR CALCULATING RESIDUAL LANDSLIDE RISK

The following steps show the approach adopted for calculating the ratio of landslide risk left upon implementation of the LPM upgrading works to that before the carrying out of the works. The remaining risk of landsliding is called 'residual risk'. The failure frequencies have been estimated based on records of 'major' landslides (i.e. failure volume ≥ 50 m^3). This is because well-documented failure records for features subject to LPM upgrading works are available for major failures for the period from 1992 to 1998 (see Special Projects Division's detailed records for 1992 to 1996 and the LSR report by Wong & Ho (1999) for 1997 to 1998).

Step 1: The average annual failure frequencies for the features included in the LPM Programme before the implementation of upgrading works are determined, as shown in Table C1:

Table C1 - Average Annual Major Failure Frequency for Pre-1978 Features Included in the LPM Programme Before the Implementation of Upgrading Works

Feature Height (m)	No. of Features	No of Major Failures (1984 - 1998)	Annual Failure Frequency (% per year)
≤ 10	1,042	20	0.13
> 10 - ≤ 20	1,119	20	0.12
> 20	476	14	0.20
Total	2,637	54	0.14

Step 2: The average annual failure frequencies for the features included in the LPM Programme and have upgrading works completed are determined, as shown in Table C2:

Table C2 - Average Annual Major Failure Frequency for Pre-1978 Features Included in the LPM Programme After the Implementation of Upgrading Works

Feature Height (m)	No. of Features	No of Major Failures (1992 - 1998)	Annual Failure Frequency (% per year)
≤ 10	712	0	0
> 10 - ≤ 20	800	2	0.04
> 20	384	6	0.22
Total	1,896	8	0.06

Step 3: Based on the failure frequencies established in Steps 1 and 2, the respective landslide risk (PLL) attributed to the 1,896 features before and after the implementation of upgrading works are estimated to be 12.2 per year and 1.8 per year respectively. In other words, the residual landslide risk is about 15% (1.8/12.2) of the landslide risk before the implementation of upgrading words.

APPENDIX D

DATABASES USED

As part of this study, a number of databases compiled by different divisions in the GEO have been used to obtain relevant information for the risk assessment. The information that has been extracted from these databases is described briefly in this Appendix:

(a) A database containing information on a total of 49,932 features was obtained from the Slope Safety (SS) Division in May 2000, in which 33,510 are identified as pre-1978 slope features according to the SIFT classification (i.e. SIFT Class A, B1 and C1). Out of these 33,510 features, 1,610 features were identified with squatters situated at the slope toe and/or at the slope crest. 327 of them have squatters situated both at the slope toe and slope crest. These 327 features have been excluded from the study. For the remaining 1,283 (i.e. 1,610 - 327) features, only the landslide risks posed on facilities other than squatters have been considered. Excluding features that affect only squatters, the total number of pre-1978 features to be considered in the risk assessment is (33,510 - 327) = 33,183. An examination of the database indicates that 30,510 features (i.e. about 91%) have adequate information for analysis.

    Apart from screening the squatter slopes from the database provided by SS Division, another database which contains about 5,400 Government features of untraceable records has been obtained from the Lands Department. An examination of the databases shows that about 1,400 of them affect facilities in Facility Group Nos. 1 and 2a. In other words, 1,400 features at the most were found to be affecting squatters during the period of information collection for the SIS database (1994 to 1998). Thus, the use of SIS information for assessing landslide risk posed to squatters should not introduce significant errors when compared with the use of the Lands Department's database.

    Based on the Slope Information System (SIS), which is also maintained by the SS Division, there are totally 51,396 features in the New Catalogue of Slopes (excluding Disturbed Terrain (DT) features). A projection of the distribution of features (from 49,932 to 51,396) has been carried out, as shown in Figure D1. Accordingly, the number of pre-1978 slope features is estimated to be 34,493 (33,510 x 51,396 / 49,932).

(b) A Dangerous Hillside Order (DHO) database was obtained from the three District Divisions in July 2000. This contains 1,065 pre-1978 features with feature numbers and 137 features without feature numbers. For those features without feature numbers, they include statutory orders served in the late 70s and early 80s, and the features were not registered in the Old Catalogue of Slopes. Thus, the total number of features with DHO served is 1,202. It has been found that 457 out of the 1,202 features have their DHOs already discharged.

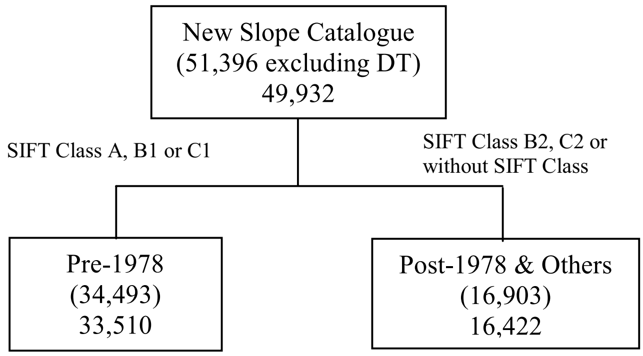
(c) A database of the Landslip Preventive Measures Information System (LPMIS) was provided by the Landslip Investigation (LI) Division in May 2000. This indicates that 375 pre-1978 features have been assessed to be up to current safety standard via Stage 2 Studies. From the same database, it has been found that 1,435 pre-1978 government features have been upgraded to current safety standard through the LPM Programme.

(d) An Old Studies database was obtained from the LI Division in April 2000. "Old Studies" are defined in GEO Circular No. 19 and they include the Planning Division Stage 1 Studies, Mid-levels Studies and Existing Slopes Division Stage 1 Studies, etc. According to this database, 1,688 pre-1978 features were signed off through Old Studies.

Figure D2 provides a schematic presentation of the databases available for this study and various actions taken by the GEO and other parties on the pre-1978 features.

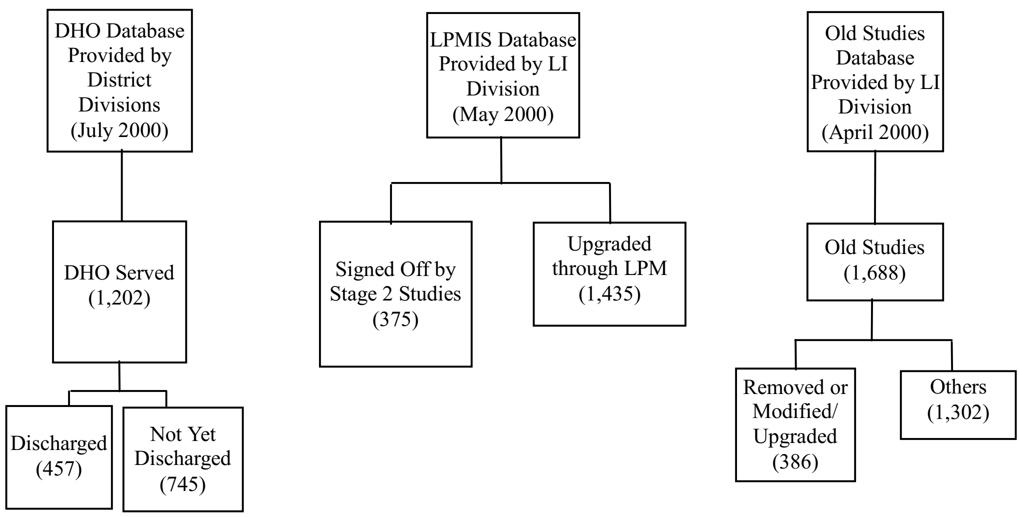
Basic information on each feature (including slope angle and height, facility groups affected, etc) is determined from NPCS data in the SIS. For those features which do not have any NPCS data (33,510 - 327 - 30,510 = 2,673), a file search was carried out to obtain the necessary information. The file search also covered features which were upgraded after 1978 so as to establish the profiles of the features and the facilities affected by the features, both before and after the upgrading works.

For this study, a new database which contains information for 33,183 features (33,510 - 327) has been created for assessing the 1977 global landslide risk.



Note: ( ) - projected number of slope features based on a total of 51,396 slope features.

Figure D1 - Distribution of Slope Features in the SIS Database



Note: "Signed off" means confirmed to be up to current safety standard by a detailed stability assessment, and checked and accepted by the GEO.

Figure D2 - Databases on Pre-1978 Slope Features and Various Actions Taken by the GEO and Other Parties on These Features

APPENDIX E

APPROACH FOR CONSTRUCTING F-N CURVE

The following steps illustrate the approach for constructing an F-N curve:

Consider an event of failure of debris volume in the range of 500 m^3 to 2,000 m^3 at soil cut slopes with heights greater than 20 m. The facilities at the slope toes affected by the event are roads with very heavy vehicular traffic density (i.e. Facility Group No. 1b) situated at a location with a shadow angle in the range of 30° to 35°. The shadow angle, which reflects the proximity of the toe facility from the slope, is defined as the angle to the horizontal of a line joining the toe facility to the slope crest. Steps 1 to 4 below show the logic of calculating the expected number of fatalities (N) of the failure event, whereas Steps 5 to 7 show the logic of calculating the corresponding frequency of occurrence (f).

Step 1: Determine the expected number of fatalities corresponding to a reference landslide affecting Facility Group No. 1b

According to Table E1, the expected number of fatalities arising from a reference landslide affecting Facility Group No. 1b is 3 x 1 (as hatched in the Table) = 3.

Table E1 - Expected Number of Fatalities Arising From a Reference Landslide (Wong et al, 1997)

Facility Group No.	Expected No. of Fatalities Arising From a Reference Landslide	Multiple Fatality Factor	Proportion
1a	3	1	0.1
1a	3	2	0.2
1a	3	3	0.4
1a	3	4	0.2
1a	3	5	0.1
1b	3	1	1
2a	2	1	1
2b	1	1	1
3	0.25	1	1
4	0.03	1	1
5	0.001	1	1
Building Collapse	50	2	1

Step 2: Determine the vulnerability factor for a reference landslide affecting the toe facility

The vulnerability factors (defined as the probability of death in the event of a landslide) for a soil cut slope affecting toe facilities have been developed by Wong et al (1997). Table E2 below shows the distribution of vulnerability factors for roads and other toe facilities (except buildings) with different ranges of failure debris volume and shadow angle. The vulnerability factor which corresponds to the failure of debris volume in the range of 500 m^3 to 2,000 m^3 and shadow angle in the range of 30° to 35° is 0.525 (as hatched in the Table).

Table E2 - Distribution of Vulnerability Factors for a Soil Cut Slope Affecting Roads and Other Facilities (Except Buildings) at the Toe (Wong et al, 1997)

Failure Volume (m^3)	Shadow Angle									
	0º-20º	20º-25º	25º-30º	30º-35º	35º-40º	40º-45º	45º-50º	50º-55º	55º-60º	> 60º
< 20	0	0	0	0.0002	0.0012	0.0046	0.0170	0.0340	0.0650	0.1000
20-50	0	0	0	0.0100	0.0400	0.1100	0.2300	0.3500	0.4600	0.5000
50-500	0	0	0.0225	0.0090	0.2150	0.3825	0.5450	0.6350	0.6650	0.7000
500-2,000	0	0.0600	0.2400	0.5250	0.7700	0.9150	0.9500	0.9500	0.9500	0.9500
2,000-10,000	0	0.1500	0.4400	0.7450	0.9000	0.9500	0.9500	0.9500	0.9500	0.9500
> 10,000	0	0.2000	0.5200	0.7950	0.9200	0.9500	0.9500	0.9500	0.9500	0.9500

Step 3: Determine the expected width of failure corresponding to a failure debris volume in the range of 500 m^3 to 2,000 m^3

The expected widths of failure corresponding to various failure volumes are shown in Table E3. The expected width of failure for a landslide with debris volume in the range of 500 m^3 to 2,000 m^3 is 20 m (as hatched in the Table).

Table E3 - Expected Width of Landslide With Respect To Failure Debris Volume (Wong et al, 1997)

Failure Volume (m^3)	Expected Width of Landslide (m)
< 20	4
20-50	7
50-500	15
500-2,000	20
2,000-10,000	25
> 10,000	30

Step 4: Determine the expected number of fatalities of the failure event

The expected number of fatalities (N) arising from the failure event at soil cut slopes with heights greater than 20 m, with a failure debris volume in the range of 500 m^3 to 2,000 m^3 and shadow angle in the range of 30º to 35º is obtained by the multiplying values determined from steps 1 to 3 and dividing the result by the width of a reference landslide, i.e. N = 3 x 1 x 0.525 x 20 / 10 = 3.15.

Step 5: Determine the number of soil cut slopes of heights greater than 20 m affecting Facility Group No. 1b with a shadow angle in the range of 30º to 35º

The distribution of number of soil cut slopes with respect to slope height and shadow angle affecting Facility Group No. 1b is given in Table E4. The corresponding number of slope is 100 (as hatched in the Table).

Table E4 - Distribution of Number of Soil Cut Slopes Affecting Facility Group No. 1b

Slope Height (m)	Shadow Angle									
	0°-20°	20°-25°	25°-30°	30°-35°	35°-40°	40°-45°	45°-50°	50°-55°	55°-60°	> 60°
≤ 10	200	200	400	400	600	700	600	400	600	600
> 10 - ≤ 20	60	140	140	100	200	200	250	300	500	600
> 20	20	30	50	100	100	100	150	150	150	180

Step 6: Determine the average annual frequency of the failure event

The distribution of failure debris volume and slope height is shown in Table E5 (see Table 1a of this Report). The corresponding average annual failure frequency is given by 0.0154 x 2.48% (as hatched in the Table) = 0.0382% per year.

Table E5 - Distribution of Failure Debris Volume for Soil Cut Slopes of Different Heights

Slope Height (m)	Average Annual Failure Frequency	Failure Debris Volume (m^3)					
		≤ 20	> 20 - ≤ 50	> 50 - ≤ 500	> 500 - ≤ 2,000	> 2,000 - ≤ 10,000	> 10,000
≤ 10	0.0061	80.16%	16.11%	3.46%	0.27%	0.00%	0.00%
> 10 - ≤ 20	0.0101	69.71%	18.03%	10.58%	1.44%	0.24%	0.00%
> 20	0.0154	65.84%	16.77%	14.29%	2.48%	0.00%	0.62%

Step 7: Determine the frequency of occurrence (f) of events corresponding to the expected number of fatalities as calculated from Step 4 above

The frequency of occurrence (f) is determined by the multiplying the results obtained in Steps 5 and 6 above by the proportion in respect to Facility Group No. 1b given in Table E1. Thus f = 100 x 0.0382% x 1 = 3.82% per year.

Steps 1 to 7 are repeated until all failure events with respect to all the four feature types, range of failure volumes and range of shadow angles are covered. For each calculated number of fatalities (N), there is a corresponding frequency of occurrence (f). Thus, by adding together the calculated frequencies of occurrence for N or more fatalities from all failure events, the respective cumulative frequency of occurrence (F) can be determined.