DIAGNOSTIC REPORT ON THE NOVEMBER 1993 NATURAL TERRAIN LANDSLIDES ON LANTAU ISLAND

GEO REPORT No. 69

H.N. Wong, K.C. Lam & K.K.S. Ho

GEOTECHNICAL ENGINEERING OFFICE
CIVIL ENGINEERING DEPARTMENT
THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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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.

The Geotechnical Engineering Office also publishes guidance documents as GEO Publications. These publications and the GEO Reports may be obtained from the Government's Information Services Department. Information on how to purchase these documents is given on the last page of this report.

J.B. Massey
Ag. Principal Government Geotechnical Engineer
August 1998

FOREWORD

Over 800 landslides occurred on the natural terrain on Lantau Island during the severe rainstorm of 4 and 5 November 1993. Thirty-three groups of a total of 56 landslides in three selected areas were systematically studied by the Special Projects Division as a project under the GEO R&D Theme Landslide Field Studies. Field works were carried out between March 1994 and June 1994 by Drs P.Y.M. Chen and A.C.O. Li. Supplementary field works were undertaken by Mr K.C. Lam and Mr A.C.W. Wong in October and November 1995. To study the spatial distribution of the landslides, aerial photographs interpretation was also undertaken by Mr K.C. Lam in October and November 1995.

The characteristics of the landslides in the three study areas were documented in the factual report by Wong et al (1996).

This Report, prepared by Mr H.N. Wong, Mr K.C. Lam and Mr K.K.S. Ho, presents the detailed diagnosis of the landslides and analyses of the data collected. Dr R.P. Martin and Mr S.W.C. Au reviewed the Report and provided valuable comments.

The Report documents the diagnosis of the Lantau landslides using the geotechnical data available at the time of the study, which was carried out before the work on the Natural Terrain Landslide Study (NTLS). Further analyses using the presently available Natural Terrain Landslide Inventory (NTLI) may be useful and the results may be compared with the present diagnosis to explore if there are major differences due to the use of different sets of geotechnical data.

P. L. R. Pang
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ABSTRACT

In the severe rainstorm of 4 and 5 November 1993, over 800 landslides occurred on the natural terrain on Lantau Island. A systematic study of the natural terrain failures in three selected areas on Lantau was carried out by the Special Projects Division of the Geotechnical Engineering Office as a project under the R&D Theme on Landslide Field Studies. A factual documentation of the investigations and observations of the landslides in the three study areas is given by Wong et al (1996).

This Report analyses the data collected and diagnoses the landslides in the three study areas. The study has highlighted the importance of having a rational classification of the different types of failure and modes of debris movement for a detailed assessment of the risk posed by landslides.

The field inspections have shown that the majority of the landslides inspected were shallow failures involving loose bouldery colluvium. The mobility of the landslide debris varied greatly and was dependent on the mechanisms of the debris movement.

It has not been able to reliably assess from the November 1993 rainstorm the effects of rainfall on landslide propensity of comparable land units because the potential local variability in rainfall intensities is not known with sufficient accuracy. The difficulty in the assessment is further exacerbated by the lack of information on the times of occurrence of the landslides.

Correlations between landslide propensity and characteristics of natural terrain components based on the GASP data, including geology, slope gradient, signs of past instability and erosion and landform, have been examined. However, it is likely that the accuracy of the correlations is limited by the resolution of the GASP data and the way the parameters were collected, as well as possible interdependence of the factors. Nevertheless, such broad correlations may be useful for general zoning purposes or global risk assessment, provided that due consideration is given to the limits of applicability of the correlations.

CONTENTS

1. INTRODUCTION

On 4 and 5 November 1993, Lantau Island was subjected to a severe rainstorm, which resulted in over 800 landslides on the natural terrain there. These landslides have provided valuable data for a systematic examination of the characteristics and mechanisms of natural terrain failures in Hong Kong. The data collated and experience gained are useful to the assessment of the propensity and risk of similar landslides in Hong Kong.

In early 1994, the Special Projects Division of the Geotechnical Engineering Office (GEO) commenced a study on the natural terrain landslides on Lantau induced by the rainstorm. The objectives of the study are :

(a) to collect information on the landslides,

(b) to assess the characteristics and mechanisms of the failures, and

(c) to examine the mobility of debris movement.

The study has included the following two major tasks :

(a) examination of the spatial distribution of the natural terrain landslides on Lantau induced by the severe rainstorm and evaluation of the characteristics of the failures by means of aerial photographs and by reference to available geotechnical information, and

(b) field inspections of the landslides in three selected study areas, viz. Areas A, B & C as shown in Figure 1.

A factual documentation of the investigations and observations of the landslides in the three selected study areas is given by Wong et al (1996). This Report presents the findings of a diagnosis of the landslides and analysis of the data collected in the study.

It should be noted that the diagnosis given in this Report is based on the geotechnical data available at the time of the study, which was carried out before the work on the Natural Terrain Landslide Study (NTLS). Further analyses using the presently available Natural Terrain Landslide Inventory (NTLI) may be useful and the results may be compared with the present diagnosis to explore if there are major differences due to the use of different sets of geotechnical data.

The terminology adopted in this Report for describing landslides, which follows that used in Wong et al (1996), is summarised in Appendix A.

2. BACKGROUND GEOTECHNICAL INFORMATION AND STUDY AREAS

2.1 Geotechnical Area Studies Programme

Geotechnical data on Lantau at 1:20 000 scale were compiled as part of the territory-wide Geotechnical Area Studies Programme (GASP) carried out by the Geotechnical Control Office (renamed as GEO in 1991) between 1979 and 1985. In GASP, Lantau Island was divided into two regions, viz. North Lantau and South Lantau (Figure 1), along the main east-west watershed associated with Lantau Peak and Sunset Peak. The GASP findings of the geotechnical area studies of North Lantau and South Lantau are documented in GASP Reports VI (GCO, 1988a) and XI (GCO, 1988b) respectively. Together with Hong Kong Geological Survey 1:20 000-scale Map Sheets no. 9, 10, 13 and 14, these contain the most comprehensive geotechnical data of the area available at the time of the present study, and the data have been used here to examine possible correlations between landslide propensity and the characteristics of the natural terrain.

A summary of the available geotechnical information on Lantau as extracted from the above GASP Reports is given in Appendix B.

2.2 Study Areas

A total of 56 natural terrain landslides in three study areas (Figure 1) in South Lantau were selected for field studies. Data on the landslides, materials involved, modes of failure and debris movement, etc. were collated and documented by Wong et al (1996).

The data collected from the field studies have provided useful information on the characteristics and mechanisms of the landslides. They also give supplementary geotechnical information on the study areas.

3. THE 4-5 NOVEMBER 1993 RAINSTORM

3.1 Typhoon Ira

The month of November in 1993 was unusually wet, with very heavy rain on 4 and 5 November brought to the western part of Hong Kong by the late-season passage of Typhoon Ira. The monthly rainfall recorded at the Royal Observatory (RO, renamed Hong Kong Observatory (HKO) in July 1997) headquarters in Tsim Sha Tsui was 144.6 mm, about four times the average recorded rainfall (viz. 35.1 mm) in November at the HKO. It was described in the weather summary prepared by the HKO for 1993 that "rain associated with Typhoon Ira was quite exceptional as intense convection embedded within one of its trailing rainbands brought concentrated heavy rain of more than 700 millimetres to the western part of the territory on 4 and 5 November" (Chan, 1995).

3.2 Rainfall over Lantau Island

Two GEO automatic raingauges (Nos. N17 and N18), three HKO automatic raingauges (Nos. R11, R12 and R33) together with two other HKO raingauges (Nos. 68 and 126), each of which comprising an autographic and a manual raingauge, were located on Lantau (Figure 1). The hourly and cumulative rainfalls recorded at the raingauges are shown in Figure 2. The rainfall was heaviest at raingauge No. N17 at Tung Chung and was most intense from the early morning to about 10 a.m. of 5 November 1993.

The return periods of different rainfall profiles (viz. duration and intensity) of this rainstorm were assessed, by reference to the historical rainfall data recorded at the HKO in Tsim Sha Tsui (Table 1). It can be seen from the Table that :

(a) the 5-minute to 60-minute recorded rainfalls (rolling maximum rainfall of about 60 mm to 110 mm) were moderately heavy but not exceptionally severe, with a return period of less than 20 years, and

(b) the 6-hour to 24-hour recorded rainfalls were extremely heavy and the 12-hour rainfall recorded at raingauge No. N17 was most severe, with an intensity of 575.5 mm and a corresponding return period of over 900 years.

The above return periods are indicative of the rarity of the storm only. There is significant limitation due to the difference in location and geographical setting between where the statistics of return periods were established (HKO at Tsim Sha Tsui) and where the rainfall was measured (Tung Chung in Lantau). The two locations are about 25 km apart.

The rolling 24-hour rainfall distribution ending at 10 a.m. on 5 November 1993 is shown in Figure 1. The recorded 24-hour rainfall was over 400 mm for most parts of Lantau and it exceeded 700 mm in the Tung Chung area, where the rainfall was most intense. The rainfall over North Lantau was heavier than that for South Lantau.

The maximum rolling 1-hour, 6-hour and 12-hour rainfall distributions are shown in Figures 3 to 5 respectively, which illustrate the development of the severe rainstorm.

Whilst there seems to be no evidence of significant orographic effects on the intensity of the rainfall in this rainstorm, firm conclusions cannot be drawn because of the sparsity of raingauges at different elevations.

3.3 Comparison with Other Major Rainstorms

The pattern of the rainfalls recorded at raingauges No. N17, R11 and N18 in the November 1995 rainstorm has been compared with major rainstorms recorded elsewhere in Hong Kong (Table 2 and Figure 6). It is evident that the medium-duration rainfall intensities, in particular those between 4 hours and 12 hours, of the November 1993 rainstorm significantly exceed those recorded in other major rainstorms. However, the short-duration (i.e. less than 2-hour) and long-duration (i.e. over 7-day) rainfalls were not as severe as those recorded in other major rainstorms examined here.

It is noted that the 24-hour rainfall of 954 mm recorded at Tai Mo Shan on 22 July 1994 was the highest 24-hour rainfall ever recorded by any of the automatic raingauges in

Hong Kong.

4. CHARACTERISTICS OF THE NATURAL TERRAIN LANDSLIDES

4.1 Locations of the Landslides

The locations of all observable natural terrain landslides on Lantau in the November 1993 rainstorm were identified with the use of aerial photographs (Table 3). The vast majority of the landslides were identified from the set of aerial photographs taken from a height of 6 000 feet on 5 December 1993, which covers most parts of Lantau. Chi Ma Wan Peninsular is not covered by this set of aerial photographs, and the locations of the landslides there were assessed from aerial photographs taken on 9 January 1995. Earlier aerial photographs were used to eliminate those landslides that occurred before the November 1993 rainstorm.

Based on aerial photograph interpretation, a total of 838 landslides were identified as having occurred on the natural terrain on Lantau as a result of the November 1993 rainstorm. The locations of the landslide crowns are shown in Drawing GCSP1. A total of 73 landslides identified in the set of aerial photographs taken on 5 December 1993 was assessed to have occurred before the November 1993 rainstorm by reference to earlier aerial photographs as noted above. The locations of the crowns of these landslides are also shown in Drawing No. GCSP-LAN-1.

4.2 Natural Terrain Landslides Reported to the GEO

Statistics on rainfall and landslides in Hong Kong for the year 1993 were described by Chan (1995). A total of 113 landslides on Lantau was reported to the GEO following the November 1993 rainstorm. Twenty of these reported landslides were classified as "natural slope failures" by the inspecting geotechnical engineers of the GEO emergency teams. These amount to about 17% of all the reported landslides and is only a small percentage (about 2%) of the population of natural terrain landslides that actually occurred on Lantau in the rainstorm.

Details of the above twenty "natural slope failures" are summarised in Table 4. The landslides had a failure volume ranging from 10 m^3 to 400 m^3, mostly affecting footpaths, access roads, catchwaters and open spaces, and were of relatively minor consequences. Given that landslides reported to the GEO are normally those of the more serious consequence, it may be inferred that the other natural terrain landslides that occurred on Lantau during the severe rainstorm probably involved insignificant consequences.

It is noteworthy that thirteen of the reported "natural slope failures" (i.e. about 65%) occurred on terrain that had been modified by human activities, including minor cutting and filling. Accordingly, these should not be taken as genuine "natural terrain landslides" with respect to the terminology adopted in this Report (see Appendix A).

4.3 Characteristics of the Natural Terrain Landslides

4.3.1 Description of Landslides in the Three Study Areas

Out of the 838 landslides identified in Lantau, eighteen groups of 28 landslides in Area A, fourteen groups of 27 landslides in Area B and one landslide in Area C were studied in more detail. The three study areas were selected based on the following considerations :

(a) a large number of natural terrain landslides were observed to have taken place in the areas (except for Area C), and

(b) hiking trails were present across the areas and hence facilitating access to the landslide sites.

Area A comprises eighteen groups of 28 landslides along a two-kilometre stretch of hiking trail between Tung Chung Au and Nam Shan. Fourteen groups of 27 landslides in Area B were studied. They are located along a one-kilometre stretch of hiking trail to the east of Keung Shan Road along the northern side of Shek Pik Reservoir. A landslide in Area C, located about 400 m southwest of Tung Chung Au, was studied. This landslide was studied because of its unusual debris mobility.

Given that ease of access is one of the major considerations in the selection of study areas, it is possible that in terms of the 838 landslides the study areas may involve lower altitude areas with more gently sloping terrain, where there may be a correspondingly higher probability of encountering colluvium.

The characteristics of landslides in the three study areas, based on information collected from desk and field studies, are summarised in Tables 5 and 6.

The above landslides had an unbulked failure volume that varied from several tens of cubic metres to over one thousand cubic metres.

With the exception of landslide B4 which involved a toppling failure of a set of sub-vertical joints in volcanic rock, all the landslides involved shallow failures, with the base of the failure being less than 3 m from the ground surface.

Forty-seven out of the 56 landslides (i.e. about 84%) occurred on a thin layer of bouldery colluvium that covered the natural terrain. The colluvium typically consists of a loose to medium dense, brown to greyish brown, sandy gravel or gravelly sand with many sub-angular to angular cobbles and boulders. The very coarse fragments generally range between 20% and 60% of the colluvium (based on volume estimated visually), and they comprise very strong to moderately strong, slightly to highly decomposed volcanic rock. The colluvium generally varies from about 0.5 m to 3 m in thickness and is underlain by either weathered volcanics or an older and denser layer of colluvium.

The loose bouldery colluvium is highly permeable given its porous structure and possible existence of preferential subsurface flow channels. In 30 out of the 56 landslides inspected, erosion pipe holes, usually near the interface of the colluvium and the underlying less permeable material, were observed in the loose colluvium exposed at the back scarps of the landslides. An example of pipe holes encountered is shown in Plate No. 1.

It is noteworthy that in the study of natural terrain landslides reported by Franks (1996), all the landslides examined involved failure of colluvium which made up at least 40% of the material composition at the landslide source.

The relationship between the source length and source width of the landslides is shown in Figure 7. The source lengths of the landslides vary between 6 m and 40 m, with a mean value of about 15 m. The source widths range from 3 m to 20 m, with a mean value of about 9.5 m. The average value of the source length-to-width ratio of the landslides is 1.7, with a standard deviation of 0.82.

The distribution of landslides for different ranges of slope gradients at the source of the failure as assessed during the field studies is shown in Figure 8.

In terms of the characteristics of the failure and debris movement, the landslides can be grouped into one of the following three broad categories :

(a) Landslides with scarps along or adjoining drainage lines. These landslides generally had a long debris trail. The debris was likely to have been subject to significant influence by surface water flow and may have travelled in a "mixed" or "hydraulic" mode, depending on the extent of the influence of surface water. Examples of such landslides include : landslides A2, A4, A10B, A12, A17, A18, B1, B2, B4 and B5.

(b) Landslides with scarps on a relatively planar sloping terrain. The debris was generally not significantly influenced by the action of surface water and it was usually deposited by a "gravitational" (principally sliding) mode. Examples of such landslides include : landslides A1A, A3, A5B, A6, A7, A8, A11, A13A, A13B, A14, A15, B9, B10, B12 and B14.

(c) Landslides with scarps on the sideslope of a drainage valley. In these landslides, part of the debris was deposited on the sideslope while the rest of the debris ran into the drainage course and may have travelled further downslope in a "mixed" or "hydraulic" mode. Examples of such landslides include : landslides A1B, A5A, A10C, A10D, A16, B3, B7 and B11.

The landslide in Area C appears to be an exception to the observations of landslides involving a "sliding" movement in that the debris travelled a long distance of about 120 m along a comparatively gentle sloping surface (which is at about 20° to the horizontal). The debris apparently moved along the ground surface downslope of the failure source area, stripping off only the vegetation but most of the top soil was left more or less intact. There were no signs of any hydraulic sorting or significant action due to surface water flow having affected debris movement, either during initial runout of the debris or after its deposition.

4.3.2 Natural Terrain Attributes Obtained from the GASP Reports

The terrain attributes at the locations of the landslide crowns of the 838 landslides have been extracted from terrain classification maps given in GASP Reports.

The distribution of landslides on terrain units of different average gradients is shown in Figure 9.

The distribution of landslides with respect to the different types of solid geology is shown in Figure 10.

Some of the landslides occurred in areas assessed by GASP as having been affected by erosion and past instability. The distribution of landslides within and outside such areas are shown in Figure 11.

5. DIAGNOSIS OF THE NATURAL TERRAIN LANDSLIDES

5.1 Mechanisms and Causes of Failure

5.1.1 General

It was established from the landslides inspected in the three study areas that the initiation of failure at the source of the landslides could involve a range of different mechanisms. The contributory factors and the likely failure mechanisms are discussed in the Sections 5.1. to 5.5. Section 5.6 assesses terrain effects for the 838 landslides identified as having occurred on the natural terrain on Lantau as a result of the November 1993 rainstorm.

5.1.2 Perched Water Table in Thin Colluvium

This is considered a likely major factor involved in many of the Lantau natural terrain landslides in the November 1993 rainstorm. Over 80% of the landslides examined involved the failure of a thin surface layer of bouldery colluvium. These landslides were triggered by wetting of the colluvium (possibly leading to destruction of suction that may exist in the finer matrix) due to direct surface infiltration and subsurface seepage, together with probable development of a transient water table perching above the interface between the colluvium and the less permeable underlying material. Given the heterogeneous nature of the colluvium layer and the likely presence of preferential flow paths in the layer, subsurface seepage flows leading to a build-up of seepage pressures acting within selected zones in the layer might also have contributed to triggering the landslides.

The abundance of such landslides in the rainstorm may be related to the rainfall pattern being most severe over the medium duration range, which is likely to be a favourable factor to support the development of perched water pressures in the colluvium.

It is possible that hydrogeological conditions that are conducive to the development of perched water table in a thin surface layer of weak material may also prevail in saprolite. However, experience from landslide studies suggests that whilst failure of saprolites can also occur due to development of perched water table, such mechanism is comparatively less common, especially where deeply weathered saprolite is involved.

5.1.3 Local Steepening/Surcharge of Ground

Some landslides involved small cut and fill slopes alongside the hiking trail that traversed the natural terrain (e.g. landslides B10, B13 and B14). Local ground steepening due to cutting (increasing the shear stresses in the natural terrain above due to removal of toe support) and surcharge due to filling (increasing the shear stresses in the natural terrain below due to additional imposed weight) might have contributed to these landslides.

Past landslides could also have resulted in local steepening and surcharging of the natural terrain.

5.1.4 Changes in Infiltration and Flow Pattern of Surface Water

Past landslides could have resulted in a local increase in surface infiltration via exposed scars and tension cracks, as well as concentration of surface water flow due to changes in topography in the vicinity of the previous failures (e.g. landslides A9 and B1). These changes might contribute to the potential for triggering further landslides in subsequent rainstorms.

5.1.5 Sliding and Toppling of Rock Blocks

Failures might involve a rock face or cliff by way of sliding or toppling of rock blocks (e.g. landslide B4). Slope degradation, prolonged erosion, opening up of rock joints and ingress of surface water are possible factors contributing to such failures. The probability of such failures is difficult to assess with any certainty.

5.1.6 Removal of Toe Support or Ground Steepening on the Sideslope of a Stream Course

Removal of ground at the toe of the sideslope of a stream course may occur due to prolonged erosion or ground depletion through previous landslides near the toe that run into the stream course. The above processes will have resulted in steepening of the slope, loss of support to the sideslope, reduction of margin of safety and failure prone to rainfall. An example of such a landslide is landslide No. B3.

5.1.7 Failure Due to Knock-on Effects

There are indications that some of the natural terrain landslides could have been the result of knock-on effects. For example, a small landslide above a hiking trail might have led to deposition of debris on the trail and resulted in subsequent concentrated discharge of surface water onto the terrain below the trail leading to failure (landslide No. B6).

Apart from being affected by changes in the surface water flow pattern, subsequent landslides might also be induced by other knock-on effects arising from an initial failure, such as local steepening of the failure scar and surcharge of the ground below, increase in surface infiltration through the exposed scar and ground vibrations due to the initial landslide. It is possible that some of the multiple-source natural terrain landslides could have been due to knock-on effects. Examples of these are landslides No. A17, A18, B1 and B5.

5.2 Slope Stability Analyses

A series of infinite slope analyses with seepage flow parallel to the ground profile has been carried out. The scenario considered involves a thin surface colluvium, or a relatively weak and permeable saprolitic soil of limited thickness overlying stronger less permeable partially weathered rock where there is sufficient permeability contrasts for the development of perched water table.

A range of values of soil shear strength parameters (ϕ' = 35° for the soil matrix, c' = 2 kPa to 5 kPa, together with allowance made for an increase in ϕ' due to boulder inclusions in accordance with the recommendations given by Irfan & Tang, 1993), thickness of colluvium layer and depth of perched water table that resemble the mechanism of failures involving a thin surface weak soil layer was considered (Appendix C).

The purpose of the analyses is to examine how different combinations of parameters could theoretically affect the occurrence of this mechanism of failure, which was the most common one involving thin surface colluvium in the November 1993 Lantau natural terrain landslides.

The main observations from this set of preliminary analyses are summarised below :

(a) Terrain having a gradient between 35° and 40° has a relatively low margin of safety against failure, and instability is predicted even with a modest build-up of perched water pressure.

(b) Colluvial terrain that is below 25°, the development of perched water pressure over the full depth of a thin colluvium layer ($\leq$ 2m thick) up to the ground surface may not be sufficient to induce failure. Other factors, such as a low mass shear strength (e.g. due to very loose zones or altered materials in the colluvium layer), localised elevated seepage pressure (e.g. due to presence of soil pipes), a thicker layer of colluvium (e.g. > 2 m thick, where the contribution of the c' component to shear strength is reduced), a local steep gradient, wash-out action by surface water, etc, singly or in combination, might have been involved in contributing to the failures in such shallow terrain.

(c) The commonly perceived trend that steep terrain (e.g. gradient > 35°) tends to be less stable given a thicker colluvium layer overlying stronger, less permeable ground is confirmed by the analyses. This suggests that the thickness of colluvium might reduce with the gradient of natural terrain steeper than 35° where the terrain has been subjected to a sizeable rainstorm (which is in fact a 'load test' on the terrain).

(d) For a loose colluvium layer of 2 m thick which is the common situation in the study areas, the layer is theoretically unstable for terrain having a gradient > 40° when the soil becomes saturated. Hence, slopes steeper than 40° are likely to be composed of a stronger soil or rock mass, e.g. partially weathered rock. This means that the mechanism and material involved in landslides on terrain steeper than 40° could be different from those on less steep terrain. It is therefore possible that terrain steeper than 40° may not be more vulnerable to landslide than less steep terrain due to presence of stronger material and different failure mechanism involved.

(e) Given the same thickness of colluvium, failure is predicted on a 35° terrain under lower perched water pressure than that for 30° or 25° terrain, which means that the likelihood of failure on 35° terrain would be higher than that of more gentle terrain, as expected and observed in the November 1993 landslides.

5.3 Threshold Rainfall Characteristics

Extremely heavy rainfall was recorded on 4 and 5 November 1993. The distribution of the 24-hour rainfall (from 10 a.m. on 4 November 1993) over Lantau is shown in Figure 1. It can be seen that the rainfall was concentrated over Tung Chung (raingauge No. N17) and Ngong Ping (raingauge No. R11) which have a maximum 24-hour rainfall of 742 mm and 602 mm respectively. This may be compared with only 107 mm of rain recorded by the Royal Observatory at Tsim Sha Tsui (raingauge No. R01) over the same period. As can be seen from Figure 2, the rainfall was most intense in the morning of 5 November 1993.

The maximum rainfall intensity was recorded in the Tung Chung area (raingauge No. N17) with the rolling maximum 12-hour and 24-hour rainfall being 575 mm and 742 mm and corresponding return periods of 904 years and 857 years respectively derived on the basis of historical rainfall data recorded by the Royal Observatory raingauge at Tsim Sha Tsui. The difficulties of assessing reliable return periods for extreme rainstorms are discussed by Wong & Ho (1996). The actual return periods for the November 1993 rainfall are likely to be much lower than those estimated above.

The rainfall profile recorded at raingauge No. N17 is compared with the characteristics of other major rainstorms recorded in Hong Kong (Figure 12). It can be seen that the 1993 rainstorm at Lantau was extremely heavy, particularly over the medium duration (viz. several hours to a few days).

It is evident that the natural terrain landslides at Lantau were induced by extreme rainfall. However, it has not been possible to reliably assess the effects of rainfall intensity on landslide propensity of comparable land units from this rainstorm alone because the potential local variability in rainfall intensity and the actual timings of the landslides are not known with sufficient accuracy.

5.4 Volume of Failure

The original failure volume (i.e. volume at the source of the landslide) and the total volume (i.e. source volume plus the increase in volume during the downhill motion of the displaced material) estimated for the landslides in the pilot areas based on the field inspections are shown in Figure 13. It should be noted that although the volume assessment is considered to be consistent, it is possible that the likely systematic error is of the order of 50% to 100%.

The volumes of the landslides generally ranged from several tens of cubic metres to over a thousand cubic metres. For failures in a planar slope (viz. Type 1), the degree of accumulation of additional debris is negligible (i.e. the source volume is approximately equal to the total volume). The degree of accumulation increased for failures that ran into stream courses (viz. Types 2 & 3), with a ratio of total volume to source volume (i.e. V_t/V_s) of up to about 3 to 4. There is a weak trend that the V_t/V_s ratio reduces with increase in source volume.

The plots of landslide frequency against volume for different types of failure are shown in Figures 14 and 15 for landslide volume at source and total landslide volume respectively. The corresponding cumulative frequency plots are shown in Figures 16 and 17 respectively. Such data will be of great value in the prediction of the frequency of landslides of different volumes for quantitative risk assessments.

It should be cautioned that the above observations are only applicable to natural terrain of a comparable nature and similar landslide mechanisms to that in this study and should not be extrapolated to other types of natural terrain landslides. For example, very large-scale failures may be controlled by specific geological weaknesses and their mechanisms of initiation may be different (e.g. may be due to slope degradation triggered by relatively light rain).

Those landslides with a large failure volume and/or a high degree of accumulation during the downslope path are worthy of further studies to better identify the factors that cause their initiation and mobility.

5.5 Travel Distance of Landslide Debris

The study of natural terrain landslides on Lantau has reinforced the observation that the mobility of landslide debris can be significantly affected by the mechanisms of debris movement. Information on the characteristics of the flow paths or debris trails of the landslide debris is summarised in Tables 7 to 9.

The travel angle, defined as the inclination to the horizontal of the line joining the distal end of the debris to the crown of the landslide scar, is a useful parameter to denote debris mobility. The available data are plotted in Figure 18. Data on the volumes of landslides are summarised in Table 10.

For debris movement without a significant influence from the action of surface water, i.e. 'gravity' (or 'sliding') mode, the travel angle generally ranged from 30° to 40°, with a mean value of about 35°. This is comparable to that of landslides having similar failure mechanisms and debris volumes on soil cut slopes Hong Kong (Wong & Ho, 1996), and suggests that the fundamental mechanics of movement and operational interface friction and the operational rate of energy dissipation may be similar.

There is, however, one landslide of the 'sliding' mode in study area C in which the landslide debris was apparently much more mobile, with a debris travel angle of 20° (landslide No. C1). This is indicative of possible special phenomena, such as liquefaction, undrained loading or presence of a high perched water level, and the case deserves further examination.

Landslide debris that ran into stream courses and was subsequently subjected to significant action of surface running water (i.e. 'hydraulic mode') was more mobile with a large travel distance or a low travel angle. The travel angle (corresponding to the distal end of the debris trail where the vegetation on the surface has been stripped) generally ranged from 20° to 30°.

The travel angles for the 'mixed mode' are generally intermediate of that for the 'gravity' and 'hydraulic' modes, generally between 25° and 35°. This further highlights the differing extent of influence of surface water on debris mobility.

The catchment sizes have been systematically assessed from the topographical maps by judgement (Table 10), and these are plotted against travel angles of landslide debris in Figure 19. For the 'hydraulic' and 'mixed' failure modes, debris mobility generally shows an increasing trend with the catchment size. The corresponding trend for landslides of the 'sliding' mode is comparatively less clear for the range of failure volumes involved.

The above observations highlight the importance of giving due regard to the mechanism of debris movement in assessing the travel distance of the displaced material. Classification of failure mechanisms, modes of debris movement and consideration of possible effect of volume of failure on debris mobility are all important in the assessment of debris travel. Where due regard is given to the above effects, it is noteworthy that the observations on debris travel of natural terrain landslides follow similar trends as that for cut and fill slopes (Wong & Ho, 1996).

The travel angle is considered the most suitable and practical parameter for use in assessing debris mobility in view of its close modelling of the parameters for characterising the rate of energy loss during debris movement and its consideration of the effect of downslope gradient. In the case of man-made slopes where the downslope gradient is usually flat, the travel angle correlation obtained from a landslide database is generally sufficient to give a good prediction of debris travel distance with a relatively small uncertainty. Natural terrain landslides however usually involve a comparatively steep downslope profile and the use of the travel angle alone may not be sufficient. This is due to the comparatively poor resolution of the correlation in predicting the debris travel distance because of the small difference between the downslope angle and the travel angle. The surface morphology and condition of the downslope terrain are also possible important factors. Further work is required in this area.

5.6 Correlations between Landslide Propensity and Natural Terrain Attributes

5.6.1 General

A number of factors could conceivably affect the likelihood of natural slope failure. Based on the locations of the 838 landslides identified from aerial photographs, the correlations between the propensity of failure and the attributes of the natural terrain given in the GASP Reports and the latest geological maps have been examined. The findings are summarised in the following Sections.

5.6.2 Geology

It may be reasonably expected that the properties of the slope-forming materials (e.g. strength and permeability) that are involved in the failure are related to the geology, which should in theory affect the likelihood of failure.

An assessment of the possible influence of solid geology was made from the available global data on the 838 landslides and the results are shown in Figure 20. It can be seen that the landslide propensity in areas indicated as being of volcanic bedrock of the Lantau Formation (viz. rhyolite lava and tuff) was about six times of that in areas indicated as of granitic bedrock.

However, the above observation should be interpreted with caution. The solid geological maps do not include, or are unable to identify, thin colluvium. For instance, the three study areas where many failures involving thin colluvium occurred have been classified as volcanics rather than colluvial terrain.

As noted previously, the available evidence tends to suggest that surface colluvium may have played an important role in many of the natural terrain landslides in this rainstorm. Extreme caution therefore needs to be exercised with regard to correlations between landslide propensity and the underlying solid geology.

It is not possible to reliably diagnose from the available information as to whether the apparently higher landslide propensity in the volcanics area examined is related to the nature of the colluvium of volcanic origin being more vulnerable to landslide, or whether it is related to the possibility that a larger proportion of this volcanics area tend to have a thin layer of colluvium compared to the granitic area covered in the study, or whether the colluvium in the volcanics area is less bouldery. Also, the spatial distribution of rainfall involving more intense rain on the volcanic area than that on the granite area will also influence the landslide propensity.

Out of the 56 landslides in the three study areas, about 84% involved the failure of colluvium alone and not the underlying insitu volcanic rock, and 9% involved both colluvium and weathered volcanic rock. However, if one takes the information given in the relevant geological maps, only about 12% of the 56 landslides are identified as having occurred in areas with colluvial deposits. For the remaining areas, i.e. those shown to be of volcanics solid geology, 93% of the landslides in these areas actually involved failure of the surface colluvium layer which is evidently the controlling factor in such cases. This is clearly not meaningful, at least for the three study areas.

Therefore, the correlations developed between the frequency of failure and the solid geology in this study should not be applied to other areas with differences in the extent and properties of colluvium. As a corollary, any such correlations developed without field verification of the material type and mechanism of the failure may not be reliable and should be treated with caution.

5.6.3 Terrain Gradient

The relationship between landslide propensity and different ranges of terrain gradients is shown in Figure 21. It can be seen that the landslide propensity is the highest for moderately steep terrain with gradients ranging from 30° to 40°, which is about seven times that of terrain with gradients ranging from 5° to 15°.

For more gentle terrain, the landslide propensity is lower. This is likely to be due to a corresponding increase in the initial margin of safety and hence higher perched water pressures will be required to initiate failure (see Section 5.3 above). Steep slopes with a gradient ranging from 40° to 60° is, however, found to have a lower landslide propensity than slopes between 30° and 40°. This is probably because the slope-forming materials where the slopes are relatively steep are stronger (e.g. less weathered rock), while the moderately steep slopes in Lantau may be covered by a thin layer of colluvium which is comparatively more vulnerable to rain-induced failure. This is supported by the theoretical analyses presented in Section 5.3 above.

While the overall relationship between landslide propensity and slope gradient is similar in both South and North Lantau, it can be seen from Figure 9 that the landslide frequency in North Lantau is generally lower than South Lantau despite that the fact that the recorded rainfall intensity was higher in North Lantau. This may be a result of the differences in solid geology and possibly other factors, such as the presence and nature of the underlying colluvium layer which may be related to the solid geology in the two areas. It is noteworthy that South Lantau has a comparatively higher proportion of area underlain by volcanics (Figure 10).

For the purposes of assessing the effects of geology and slope gradient on landslide initiation, the relationship between landslide propensity and slope gradient is shown for different solid geology in Figure 22. It can be seen that in areas with granitic rocks and with other rocks (including, for example, sedimentary rocks), the correlation between frequency of landslide and slope gradient is consistent with the overall relationship described above, viz. the landslide propensity is the highest for moderately steep slopes with gradient ranging from 30° to 40°.

For the volcanics areas, some abnormalities are noted. In South Lantau, there was a relatively high landslide propensity in terrain with a gradient ranging from 5° and 15°. Twenty landslides were involved, six of which were adjacent to drainage areas. In North Lantau, the maximum landslide propensity in volcanics terrain corresponds to areas with a gradient ranging from 15° to 30°; a total of 138 landslides were involved, 36 of which were adjacent to drainage lines and the adjoining side slopes. These abnormalities may be related to locally steeper ground profiles that are not reflected in the overall gradient classification given in GASP. Also, it is possible that there are others factors that govern the landslide propensity, e.g. site topography, the degree of susceptibility of the terrain to the destabilising effects of water, soil strength, rainfall characteristics on a local scale, vegetation, etc.

5.6.4 Signs of Past Instability and Erosion

With respect to the information on past instability and erosion shown on the GASP maps, the landslide propensity in areas with signs of past instability or erosion is about 2 to 3 times of that in areas without signs of past instability and erosion. In terms of the overall landslide propensity, it can be seen from Figure 23 that there is a decreasing trend for areas with 'past instability', 'erosion' and no such influences respectively. The same trend is exhibited by landslides within South and North Lantau.

The differences in the landslide propensity in areas with and without signs of instability and erosion are not great. It is possible that the natural terrain was especially vulnerable to failure given the heavy rain in this rainstorm to the extent that the resolution of GASP's data on past instability and erosion is not sufficient to differentiate their effects.

For slopes with a gradient ranging from 15° to 30°, the available data cannot differentiate between the relative influence of past instability and erosion. However, the landslide propensity in areas with signs of past instability or erosion is higher than that where there is no recorded past instability and erosion.

For slope gradients of 5° to 15°, there are insufficient data for any reliable observations to be made.

It is interesting to note that for areas with a solid geology in granitic rock and over the range of slope gradients with sufficient data (15° to 40°), the relative landslide propensity in areas with erosion, past instability and none of them shows a decreasing trend. Further work is required to explore the apparently low frequency of failure in area with past instability, with particular reference to assessing the effect of spatial distribution of rainfall.

It is also noteworthy that the proportion of areas classified as having past instability in North Lantau is only about half of that in South Lantau.

5.6.5 Landform

The landslide propensity for terrain with different gradients and comprising different types of landform on South Lantau, where the relevant terrain information is available, is shown in Figure 24. It can be noted that :

(a) the landslide propensity is generally higher for convex sideslopes (i.e. GASP Category 'D'), for crest or ridge areas (i.e. Category 'A') with the exception of steep terrain (viz. gradient over 40°), and for concave sideslopes (Category 'C') with the exception of gentle terrain (less than 15° steep), and

(b) steep cliff/rock outcrop (Category 'M' with a gradient from 30° to 60°) and moderately steep straight sideslopes (Category 'B' with a gradient from 30° to 40°) also have a relatively high likelihood of failure.

5.6.6 Discussion

The analyses of correlations between landslide propensity and natural terrain attributes were done by reference to the GASP Reports and the geological maps published in 1995, prior to completion of Phases 1 and 2 of the Natural Terrain Landslide Study (NTLS). The results are generally consistent with the findings reported by Evans et al (1997). Given similar trends as those established by the NTLS and the relatively coarse nature of the different datasets, it is not considered necessary to repeat the analyses using information that has since become available for the present purposes.

It should be borne in mind that the effects of rainfall pattern (e.g. duration, intensity, area of land affected, etc) on the correlations have not been considered in the present assessment. Further work on this aspect is needed.

5.7 Nature of the November 1993 Natural Terrain Landslides

Although only selected areas with a high propensity of landslides were studied in detail by field inspections, the findings that the majority of the landslides involved the shallow failure of loose bouldery colluvium were consistent with that reported by Franks (1996). Whilst detailed inspection had not been made of the other 782 landslides in this rainstorm, it is considered important that the assessment should take due account of the findings from the three study areas. The evidence suggests that a significant proportion of the 838 landslides may have involved failure of a thin colluvium, particularly for areas with a high propensity of landslides.

It may be inferred that the natural terrain landslides that occurred during the 4-5 November 1993 rainstorm have the following characteristics :

(a) the failures were likely to have been mostly induced by the extremely heavy rainfall, which was possibly the most severe experienced by the area, especially over the medium duration range of 6-hour to 12-hour,

(b) the majority of the landslides were shallow, with a depth of failure of less than 3 m,

(c) the scale of failure generally ranged from several tens of cubic metres to over one thousand cubic metres,

(d) the propensity of failure was relatively high, ranging from one landslide in every 0.07 km^2 to one landslide in every 11 km^2, with an average of one landslide in every 0.18 km^2, and

(e) a large proportion of the landslides may have involved the failure of a thin surface layer of loose bouldery colluvium (as deduced from field observations made at the 56 landslides in the three study areas) probably caused by the development of a perched water table in the layer due to infiltration during the extremely heavy rain.

It is noteworthy that the November 1993 Lantau natural terrain landslides, being medium-scale shallow failures triggered by extreme rainfall, contrast strongly with the 1990 Tsing Shan natural terrain landslide (King, 1996). The latter, which was comparatively a rare event, was of a much larger scale (about 20 000 m^3) and occurred at a time of much less intense rainfall (136 mm rainfall in five hours recorded at the nearest raingauge for the whole rainfall event and about 50 mm rainfall in 24 hours before the landslide was triggered).

The analyses and discussion described in the Sections 5.2 and 5.3 are based primarily on observations made at the three study areas on Lantau, but they are also considered likely to be applicable to the larger dataset of landslides as explained above.

The results of the analyses are likely to be applicable to natural terrain landslides elsewhere in Hong Kong that are of similar nature and on terrain with comparable characteristics subject to similar rainstorms, but may not necessarily be applicable to other types of natural terrain landslides, such as quasi-natural terrain landslides (King, 1996). Further work is needed to examine the effects of rainfall pattern on landslide propensity.

6. RECOMMENDED FURTHER R&D STUDIES

The following areas of further R&D work are recommended to advance the state of knowledge :

(a) Hazard Identification - the probable range of natural terrain hazards, including a consideration of different types of natural or quasi-natural terrain landslide that are potentially damaging and the different hazard scenarios, needs to be defined to facilitate risk assessment and formulation of risk management strategy.

(b) Field Studies of Landslides - further detailed field studies on natural terrain landslides, such as the present one and those by Franks (1996) and King (1996), are needed to gain a better insight into the factors affecting natural terrain landslide initiation and the mobility of landslide debris. More detailed studies, in different areas (especially after a heavy rainstorm hits the area), including similar studies involving a range of different types of natural terrain failure, should be carried out to enhance the fundamental understanding of the landslide processes and collect reliable data on factors affecting frequency, modes/mechanisms and triggers of failure and debris travel.

(c) Mechanism and Mobility of Debris Movement - consideration should be given to refining the simple classification of mechanisms of debris movement adopted in this Report (subject to availability of data of adequate quality), and there is a need for further development of empirical and analytical methods for assessing failure initiation and debris mobility to reduce the uncertainties in the current methods.

(d) Consequence Assessment and Risk Zoning - there is a need to develop a suitable methodology for assessment of the consequence of natural terrain landslides, and to formulate rational consequence criteria for application to regional-scale risk zoning or assessment.

(e) Site-specific Risk Assessment - Quantitative Risk Assessment (QRA) should be undertaken on pilot sites/areas to develop appropriate methods for assessing the frequency and consequence of different types of natural terrain landslides and to assess the feasibility of formulating site-specific QRA methodology.

(f) Mobility of Landslide Debris - further work is needed to extend the concept of travel angle of debris to natural terrain as discussed in Section 5.7.

(g) Rainfall - further work is needed to examine the influence of rainfall patterns on landslide propensity, taking into account possible interdependence of the various terrain attributes. It is recommended that this should be done by reference to a number of severe rainstorms with good quality data on natural terrain landslides.

7. SUMMARY

Correlations of over 800 landslides with the available GASP terrain attributes have shown that the propensity of landslides was comparatively higher for the following scenarios :

- a terrain gradient ranging from 30° to 40° (which is about seven times that for a gradient of 5° to 15°)

- solid geology of volcanics (about six times that for granite)

- areas with signs of past instability or erosion (about two to three times that where there are no signs of past instability and erosion)

In applying the findings of this study to the assessment of the likelihood of failure on natural terrain in other parts of Hong Kong, due account should be taken of the resolution of the GASP and geological data and the way the parameters were collected, as well as possible interdependency of the factors (e.g. the type of vegetation may be related to geology, gradient and elevation). In assessing any possible correlation between a certain parameter and the landslide propensity, it may be difficult to differentiate whether the apparent correlation is attributed to this parameter or to other dependent parameters. This is particularly problematic in the case where the landslide data are not complete and are of inadequate resolution. Given better data on the natural terrain characteristics, such as those which can be obtained from the Natural Terrain Landslide Inventory, more realistic correlations may be obtained.

It is noteworthy that apart from the effect of rainfall, landslide initiation in a natural terrain can also be affected by other factors, such as the nature of the slope-forming materials, presence of erosion pipes, subsurface groundwater conditions, type of vegetation, surface water flow pattern as governed by topography and slope surface conditions, and changes in local terrain gradient due to recent landslides or comparatively minor human activities together with other contributory factors, such as weathering of the soil and rock masses, deforestation due to hill fire, air pollution, etc. The correlation of landslide propensity on Lantau with the above factors could not be examined due to lack of reliable data, nor are they likely be able to be assessed in other situations.

The diagnosis of the natural terrain landslides in three study areas has shown the importance of having a rational classification of landslides (e.g. according to scale, mechanism of failure and types of material involved) to facilitate a proper examination of factors that can affect the frequency of the different types of landslide and to enhance the reliability of the empirical correlations for predictive purposes, particularly for site-specific risk assessments.

The above is important in the analysis of landslides given different rainstorms and terrain with different settings because a more diverse range of different types and mechanisms of failure could be involved. Without a sufficiently refined classification of failure types and mechanisms where supported by the available information, the reliability of any derived correlations may not be sufficiently accurate especially when the results are extrapolated for predicting the landslide frequencies elsewhere.

It should be noted that the 1993 Lantau natural terrain landslides, being generally of medium-scale shallow failures triggered by extreme rainfall, contrast strongly with the 1990 Tsing Shan natural terrain landslide. The latter was of a much larger scale (about 20 000 m^3) and occurred at a time of much less intense rainfall (136 mm rainfall in five hours recorded at the nearest raingauge for the whole rainfall event and about 50 mm rainfall in the 24 hours before the landslide was triggered).

The correlations obtained in the present study are considered applicable to natural terrain landslides elsewhere in Hong Kong that are of similar nature and terrain with comparable characteristics, but may not be necessarily be applicable to other types of natural terrain landslides (such as quasi-natural terrain landslides) subject to similar rainstorms. Provided that due consideration is given to the limits of applicability of the correlations, such broad trends may be useful for general zoning purposes or global risk assessment.

The need for further field studies is also highlighted in order to better understand the factors involved in natural terrain failure. For instance, according to the GASP data, most of the landslides occurred in terrain with a volcanics solid geology whereas the field studies conducted revealed that the vast majority of the landslides in the three study areas involved failure of a thin layer of colluvium and not the underlying partially weathered volcanic rock.

The natural terrain landslides on Lantau were induced by extreme rainfall. However, it has not been able to reliably assess the effects of rainfall intensity on landslide propensity from this rainstorm alone because the potential variability in local rainfall intensity and the actual timings of the landslides are not known with sufficient accuracy.

The mobility of the landslide debris varied greatly and was dependent on the mechanisms of debris movement.

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LIST OF TABLES

Table 1 - Maximum Rolling Rainfall and Estimated Return Periods for the November 1993 Rainstorm

Date	R11		R12		R33		N17		N18		68		126	
Duration	Maximum Rolling Rainfall (mm)	Estimated Return Period (Years)	Maximum Rolling Rainfall (mm)	Estimated Return Period (Years)	Maximum Rolling Rainfall (mm)	Estimated Return Period (Years)	Maximum Rolling Rainfall (mm)	Estimated Return Period (Years)	Maximum Rolling Rainfall (mm)	Estimated Return Period (Years)	Maximum Rolling Rainfall (mm)	Estimated Return Period (Years)	Maximum Rolling Rainfall (mm)	Estimated Return Period (Years)
5 minutes	11.5	1	12.5	2	10.0	1	17.0	8	11.0	1	-	-	-	-
15 minutes	31.5	3	31.0	3	18.5	1	37.5	9	29.5	2	-	-	-	-
1 hour	89.5	5	88.0	4	55.0	1	114.0	18	91.0	5	91.4	17	107.6	53
2 hours	168.5	22	151.5	12	98.0	2	190.5	49	148.0	10	175.8	57	196.8	133
6 hours	365.5	135	260.0	17	214.5	7	422.0	408	261.5	18	351.7	103	385.0	197
12 hours	490.5	235	299.0	12	302.5	12	575.5	904	293.0	11	466.5	161	442.1	109
24 hours	602.0	157	349.5	8	392.5	13	742.0	857	329.5	6	559.0	93	510.2	52
48 hours	631.0	73	365.0	5	416.5	8	775.0	321	339.0	4	575.4	41	527.9	25

Notes :

(1) Return periods were derived from the Gumbel equation based on historical rainfall records at the Hong Kong Observatory.

(2) Maximum rolling rainfall for raingauges R11, R12, R33, N17 and N18 was calculated based on rainfall records at :

(a) 5-minute intervals for duration of 1 hour,

(b) 15-minute intervals for duration of 2 hours,

(c) hourly intervals for duration 6 hours and more.

(3) Maximum rolling rainfall for raingauges 68 and 126 was calculated based on rainfall records at hourly intervals for duration of 1 hour and more.

Table 2 - Comparison of Rainfall Data Recorded at Selected Raingauges on Lantau with Other Raingauges for Major Landslide Events

DURATION	Duration (HOUR)	Sau Mau Ping (16/6/1972)	Sau Mau Ping (24/8/1976)	Pat Heung (20-21/5/89)	Baguio (8/5/1992)	Cheung Shan (16/6/1993)	Allway Gardens (27/9/1993)	Lantau (N17) (4/11/1993)	Lantau (N18) (4/11/1993)	Lantau (R11) (4/11/1993)	Tai Mo Shan (21-22/7/94)	Kwun Lung Lau (23/7/1994)	Pat Heung (5-6/8/94)	Castle Peak Road (7/8/1994)	Fei Tsui Road (13/8/1995)
		Intensity (mm)	Intensity (mm)	Intensity (mm)	Intensity (mm)	Intensity (mm)	Intensity (mm)	Intensity (mm)	Intensity (mm)	Intensity (mm)	Intensity (mm)	Intensity (mm)	Intensity (mm)	Intensity (mm)	Intensity (mm)
15 mins	0.3	-	-	20.5	30	25.5	19	37.5	29.5	31.5	103.5	33	32	23.5	35.5
30 mins	0.5	-	-	38	53.5	47	29	72.5	56.5	55	159	54.5	54	41	51
60 mins	1	96	67.5	50.5	102.5	82.5	42	114	91	88.5	185.5	94.5	76	73	94.5
120 mins	2	156	120	94	179	146.6	46.6	190.6	148	168.6	254.5	125.6	133	125	113.5
4 hrs	4	172	160	183.5	211.5	166	54	285	224.5	273.5	349	164	187	140.5	115
6 hrs	6	183	201	252	236.5	166.5	73	422	261.5	365.5	447.5	176	218.5	155.5	128.5
8 hrs	8	196	236.8	310	293.5	167	101.5	485	274.5	428.5	553.5	181.5	240.5	165	149
12 hrs	12	216	348	403	350	179.5	116.5	575.5	293	490.5	793	308	246.5	166.5	224.5
18 hrs	18	207	459	489.5	350	181	146	647.5	308	535.5	893.5	337	316	275	288.5
24 hrs	24	252	468	566	351	184	185.5	742	329.5	602	954	362	380	307	356
2 days	48	436.8	528	642	351	187.5	274	775	339	631	1012	544	434	375	390.5
3 days	72	-	-	647.5	351	187.5	318	777	340	633	1051.5	572	464	429	390.5
4 days	96	-	-	649.5	351	202	351.5	777.5	340.5	639.5	1052	586	464	452	390.5
5 days	120	-	-	662.5	351.5	205	382.5	777.5	340.5	639.5	1052	586	473.5	474	390.5
7 days	168	-	-	665.5	351.5	416.5	382.5	777.5	340.5	639.5	1061	586.5	505.5	477.5	402.5
15 days	360	-	-	683	351.5	564.5	508	777.5	340.5	639.5	1461	791	1658.5	661.5	942.5
31 days	744	-	-	952	562	747.5	508.5	777.5	367	708.5	1741	940.5	2536	1327	1303

Table 3 - List of Aerial Photographs Viewed

Date of Photography	Flying Height (Feet)	Photograph Number	Area Covered
11.11.92	10 000	A33106 - A33108 A33131 - A33133 A33174 - A33176 A33189 - A33191	Chi Ma Wan Mui Wo to Pui O Wan Discovery Bay Yam O to Discovery Bay
17.12.92	20 000	A33590 - A33591	Discovery Bay, Mui Wo and Chi Ma Wan Peninsula
4.2.93	5 500	A33886 - A33900 A33946 - A33955	North Lantau (Sha Lo Wan to Tai O) South Lantau (Shek Pik, Lantau Peak, Tung Chung Au, Wong Lung Hang, Discovery Bay and Silvermine Bay)
2.9.93	6000	A35719 - A35738	North Lantau (Ma Wan to Tung Chung)
16.9.93	20 000	CN4287 - 4290 CN4322 - 4323	West Lantau (Shek Pik to Fan Lau) North Lantau (Discovery Bay to Tung Chung)
4.10.93	20 000	CN4361 - CN4362 CN4513 - CN4515	Mui Wo, Chi Ma Wan, Cheung Sha and Sunset Peak North Lantau (Ma Wan, Tai Ho Wan, & Discovery Bay)
1.11.93	10 000	CN4933 - CN4937	North Lantau (Ma Wan to Tai Ho Wan)
5.12.93	6 000	CN5194 - CN5315	Lantau except Chi Ma Wan Peninsula
5.12.93	6 000	A37131 - A37160	Sha Lo Wan to Tai O
9.1.95	3 500	A40339 - A40344 A40365 - A40372	Chi Ma Wan Peninsula

Table 4 - Details of Natural Terrain Failures Reported to the GEO Following the November 1993 Rainstorm

Incident No.	Size (m^3)	Facility Affected	Type of Failure	Date Reported	Genuine Natural Terrain Failure?
MW 93/11/32	20	building lot	6 m x 6 m landslip on a 60° slope, 25 m above building platform	5.11.93	yes
MW 93/11/71	4	backyard of house	slump at toe of 50° slope	5.11.93	no
MW 93/11/81	40	building lot	failure originated from slope along drainage line	9.11.93	yes
MW 93/11/88 (MW SP/115)	19	1 lane of road	slump at toe of roadside slope	9.11.93	no
MW 93/11/98	10	building lot	slump at toe of 60° slope	12.11.93	no
MW 93/11/101	5	backyard of house	slump at toe of 60° slope	10.11.93	no
MW 93/11/108 (MW SP/24)	20	hiking track	failure scar 8 m high, hiking track destroyed	9.11.93	yes
MW 93/11/110 (MW SP/23)	21	local access road	slump at toe of 50° slope	10.11.93	no
MW 93/11/111	10	local access road	slump at toe of 60° slope	10.11.93	no
MW 93/11/116	20	footpath	slump at toe of 60° slope	16.11.93	no
MW 93/11/122	15	rear lane of building	slump at toe of 40° slope with 1.5 m toe wall	10.11.93	no
MW 93/11/124	10	rear lane of house	slump at toe of 50° slope	10.11.93	no
MW 93/11/127	5	road	slump at top of 33° slope between two roads	12.11.93	no
MW 93/11/130	8	open space	slump at toe of 60° slope	12.11.93	no
MW 93/11/137	45	footpath at crest of slope	slump at crest of 10 m high 60° slope	24.11.93	yes
MW 93/11/144	20	open space	gully erosion at toe of 30° slope	7.12.93	no
MW 93/11/146	5	building lot	slump near toe of 40° slope	26.1.94	no
MW 93/11/148	4	footpath	slump at toe of 50° slope adjoining footpath	1.2.94	yes
MW 93/11/149	30	footpath	landslide at 40°-50° slope above footpath	1.2.94	yes
MW 93/11/150	10	footpath	landslide at 50° slope above footpath	1.2.94	yes

Table 5 - Summary of Characteristics of Landslide Scarps (Area A) (Sheet 1 of 2)

Landslide No.	Gradient (Degree)	Length L (m)	Width W (m)	Depth D (m)	Height H (m)	Volume V (m_3)	L/W	D/L	Geology	Type of Failure	Special Feature	Terrain Code	Remarks
A1A	30	10	9	1	5	60	1.15	0.1	1	1a	1, 3	4Dr	
A1B	35	20	10	2	11	230	2.00	0.1	1	1a	1, 3	4Cn	soil pipes up to 200 mm x 20 mm
A2	34	12	9	1	8	65	1.38	0.08	1	1a	1, 3	4Cr	
A3	33	12	9	2	7	50	1.33	0.22	1	1a	3	4Cr	
A4	35	10	10	0.5	6	70	1	0.05	1	1a	3	4Br	
A5A	40	20	10	2	13	240	2	0.1	1	1a	1, 3	4Cn	30 mm dia soil pipes
A5B	40	12	15	1	8	140	0.8	0.08	1	1a	3	4Dn	
A6	35	20	17	2	23	400	2.35	0.05	1	1a	3	4Dn	
A7	49	40	8	2	25	190	5	0.05	2	1b	1, 3	5Cn	0.5 m colluvium on decomposed volcanic, 200 mm dia soil pipes in colluvium
A8	30	18	13	1.5	9	100	1.39	0.08	1	1a, 4	1, 2, 3	3Dr	
A9	45	18	8	1	13	60	2.25	0.06	1	1a	3	3Dr	
A10A	50	10	10	0.5	8	45	1	0.05	1	1a	1, 3	4Cn	
A10B	35	6	3	1.5	4	10	2	0.25	1	1a	3	4Cn	
A10C	45	14	9	1.5	10	75	1.56	0.11	1	1a	3	4Cn	
A10D	45	9	10	1	6	45	0.9	0.11	1	1a	3	4Cn	
A11	40	10	6	1	6	50	1.33	0.08	1	1a	3	3Dn	
A12	32	15	13	1.5	8	135	1.15	0.1	2	1c	3	5Mn	
A13A	37	16	9	2.5	9	45	1.18	0.16	1	1a	3	5Mn	
A13B	37	17	8	1.1	10	100	2.1	0.07	1	1a	1,3	4Dn	
A14	32	20	17	2	11	170	1.18	0.1	1	1a	1,3	4Dr	
A15	35	20	10	2	11	320	2	0.1	1	1a	3	4Dr	

Table 5 - Summary of Characteristics of Landslide Scarps (Area A) (Sheet 2 of 2)

Landslide No.	Gradient (Degree)	Length L (m)	Width W (m)	Depth D (m)	Height H (m)	Volume V (m_3)	L/W	D/L	Geology	Type of Failure	Special Feature	Terrain Code	Remarks
A16A	40	12	16	1.2	8	105	0.75	0.1	1	1a	1,3	5Cn	
A16B	32	28	11	0.6	15	100	2.5	0.02	1	1a	1,3	4D	
A16C	38	11	7.5	1	7	60	1.5	0.09	1	1a	3	4D	
A17A	38	35	14	0.6	21	150	2.5	0.02	1	1a	3	4Cn	
A18A	35	15	8	2.5	9	210	1.88	0.17	1	1a	3	4Cn	immediately below rock outcrop
A18B	35	20	12	0.6	11	40	1.67	0.03	1	1a	1,3	4D1	30 mm diameter soil pipes along colluvium/weathered rock interface
A18C	35	10	10	1	6	80	1.67	0.1	2	1c	1,3	4D1	200 mm x 200 mm soil pipes at side of scarp

Notes :
(1) Figures in ( ) are estimated from photographs.
(2) Refer to Appendix A for definitions of symbols.

Table 6 - Summary of Characteristics of Landslide Scarps (Areas B and C) (Sheet 1 of 2)

Landslide No.	Gradient (Degree)	Length L (m)	Width W (m)	Depth D (m)	Height H (m)	Volume V (m_3)	L/W	D/L	Geology	Type of Failure	Special Feature	Terrain Code	Remarks
B1A	30	10	9	1	5	60	1.15	0.1	1	1a	1, 3	4Cn	
B1B	40	17	8	1.7	11	140	2.18	0.1	1	1a	1, 2, 3	4Cn	
B2A	40	10	17	1.5	6.5	130	0.59	0.15	1	1a	1, 3	4Cn	immediate below rock cliff.
B3A	45	7	8	1	5	30	0.88	0.14	1	1a	1, 3	4Dr	soil pipes up to 100 mm dia.
B3B	40	12	5	1	9	30	2.4	0.08			1, 3	4Dr	soil pipes up to 30 mm dia.
B3C	40	14	5	1.5	11	30	2.8	0.11	1	1a	3	4Dr	
B3D	45	6	3	0.5	5	5	2	0.08	1	1a	1, 3	4Dr	
B4E	35	9	8.5	5	5	190	1.06	0.55	4	5a	-	5Mn	thin (0.5 m) colluvium on slope surface at crest of rock cliff, failure involves toppling failure of vertical jointed rock slab.
B5B	37	6	6	1	4	15	1.2	0.25	1	1a	1, 3	4Cr	
B5M B5A B5C	40 40	(6) (7)	(5) (5)	(1.5) (1.5)	(4) (4.5)	(15) (15)	(1.2) (1.2)	(0.25) (0.21)	1 1	1a 1a	3 3	4Cr	
B6	45	14	9	1.5	10	75	1.56	0.11	1	4+1a	1, 2, 3	3Cr	
B7A	38	10	10	1	6	70	1	0.1	1	1a	1, 3	4Cr	soil pipes up to 100 mm dia., failed prior to November 1993 rainstorm
B7B	42	12	8	0.5	8	35	1.5	0.04	1	1a	1, 2,3	4Cr	soil pipes up to 200 mm dia., failed prior to November 1993 rainstorm
B7M B7C B7D B7F	 40 40 40	 15 20 20	 9 8 10	 1.5 1.5 1	 10 13 13	 160 180 150	 1.67 2.5 2	 0.1 0.08 0.05	 1 1 1	 1a 1a 1a	 3 3 3	 4Cr	below rock cliff

Table 6 - Summary of Characteristics of Landslide Scarps (Areas B and C) (Sheet 2 of 2)

Landslide No.	Gradient (Degree)	Length L (m)	Width W (m)	Depth D (m)	Height H (m)	Volume V (m_3)	L/W	D/L	Geology	Type of Failure	Special Feature	Terrain Code	Remarks
B7E	40	20	10	1	13	150	2	0.05	1	1a	3	4Cr	
B8	40	8	9	1	5	35	0.89	0.12	1	4 + 1a	1,3	4Cr	soil pipes up to 200 mm dia
B9	31	27	15	1	14	250	1.8	0.04	1	1a	1,3	4Cr	below rock cliff
B10	36	15	18	1.5	9	210	0.8	0.06	1 + 2	1b	1,3	4Cr	small dia. soil pipes
B11A	35	11	3	1	6	20	3.7	0.09	1	1a	3	4Cn	
B11B	35	13	5.5	1	7	55	2.4	0.08	1	1a	3	4Cn	
B12	33	12	13	1.5	6	140	0.8	0.14	1 + 2	1b	1,3	2A	soil pipes 30 mm in dia. within colluvium
B13A	35	15	5	1.5	9	50	3	0.1	1 + 2	4 + 1b	1,2	4Cn	50 mm dia. pipes within colluvium
B13B	45	7	4	1.5	5	35	1.7	0.2	1 + 2	1b	-	4Cn	
B14	50	17	5	3	13	160	3.4	0.18	1 + 2	3b	-	2A	
C1	26	47	20	3	20	1000	2.35	0.06	1	1a	1,2,3	3D2	

Notes : (1) Figures in ( ) are estimated from photographs.
(2) Refer to Appendix A for definitions of symbols.

Table 7 - Summary of Characteristics of Flow Path of Debris (Area A) (Sheet 1 of 4)

Slip No.	Chainage (m)	Gradient (degree)	Inclined Length (m)	Width (m)	Aspect Angle (degree)	Geology	Terrain Code	Topography	Vegetation	Predominant Erosion Depth	Mode of Erosion	Deposition	Type of Debris Movement	Travel Angle	Channelised
A1A	0 - 10	30	10	7	150	1	4Dr	1	grass	scar	-	-	G		-
	10 - 65	32	55	7	150	1	4Dr	1	grass	n	-	1ax	G	G = 33°	N
	65 - 88	35	23	7	150	1	4Dr	1	grass	n	-	1ny	G		N
	88 - 120	32	32	5	150	1	4Dr	1	grass	n	-	1ny	M	M = 32°	N
	120 - 154	30	34	5	150	1	5Mn	1	grass	-	-	1ny	M		N
	154 - 170	50	16	3	150	4	5Mn	1	rock	-	-	2nz	H	-	N
A1B	0 - 20	35	20	10	175	1	4Cn	1	grass	scar	-	-	G		-
	20 - 74	31	54	10	175	1	4Cn	2a	grass	a	1	1bx	G	G = 32°	N
	74 - 84	34	10	5	175	1	4Cn	2a	grass	a	1	1bx	G		N
	84 - 96	28	12	4	175	1, 4	4Cn	2a	rock	-	-	2nz	H		N
	96 - 139	40	43	4	175	4	4Cn	2b	rock	-	-	2nz	H	H < 31°	Y
	139 - 176	20	37	4	110	1	4Cn	2b	rock	-	-	2nz	H		Y
A2	0 - 12	34	120	9	180	1	4Cr	2a	grass	scar	-	-	G	-	N
	12 - 40	30	28	6	180	1	4Cr	2a	grass	a	1	1ny	M	M = 30°	N
	40 - 142	30	102	4	205	1	4Cr	2a	grass	b	1	1ny	M		N
	142 -					1, 4	4Cr	2b	grass/rock	-	-		H	-	Y
A3	0 - 12	33	12	9	140	1	4Cr	2a	grass	scar	-	-	G	G = 31°	-
	12 - 35	30	23	5	140	1	4Cr	2a	grass	n	-	1ny	G		N
	35 -	-	-	-	-	-	4Cr	-	-	-	-	-	H	-	Y
A4	0 - 10	34	10	10	220	1	4Br	1	grass	scar	-	-	G	G = 29°	N
	10 - 55	27	45	4	200	1	4Br	2a	grass	n	-	1nx	G		N
	55 - 100	24	45	4	190	1	4Cn	2b	grass	a	1	2nz	M	M = 26°	N

Table 7 - Summary of Characteristics of Flow Path of Debris (Area A) (Sheet 2 of 4)

Slip No.	Chainage (m)	Gradient (degree)	Inclined Length (m)	Width (m)	Aspect Angle (degree)	Geology	Terrain Code	Topography	Vegetation	Predominant Erosion Depth	Mode of Erosion	Deposition	Type of Debris Movement	Travel Angle	Channelised
A5A	0 - 20	40	20	10	195	1	4Cn	1	grass	scar	-	1ex	G	G < 42°	N
	20 - 45	44	25	10	195	1	4Cn	1	grass	n	-	1ax	G		N
	45 - 120	25	85	4	170	4	4Cn, 3Hr	2b	shrubs, trees	n	-	1ny	M	M = 31°	Y
A5B	0 - 12	40	12	15	170	1	4Dn	1	grass	scar	-	-	G	G = 35°	N
	12 - 122	35	110	10	170	1	4Cn	1	grass	n	-	1ax	G		N
A6	0 - 20	31	20	17	140	1	4Dn	1	grass	scar	-	-	G	G = 31°	-
	20 - 130	31	110	9	140	1	4Dn	2a	grass	n	-	1ny	G		N
A7	0 - 80	40	80	8	195	2	5Cn	2a	grass	c	1	n	G	G < 40°	N
A8	0 - 20	39	20	13	125	1	3Dr	1	grass	scar	-	-	G	G = 39°	-
	20 - 100	39	80	13	125	1	3Dr	1	grass	n	-	1ax	G		N
A9	0 - 80	42	80	10	145	1	3Dr	1	grass	n	-	1ax	G	G < 42°	N
A10B	0 - 6	35	6	3	180	1	4Cn	1	grass	scar	-	-	G	G < 37°	-
	6 - 45	35	39	3	180	1	4Cn	1	grass	a	1	1nx	G		N
	45 - 85	40	39	2	165	1, 4	4Cn	1	grass	a	1	1nz	G		N
	85 - 255	24	170	2	155	4	4Cn	2b	rock	a	2	2nz	H	H < 28°	N
A10D	0 - 50	41	50	10	190	1	4Cn	1	grass	n	-	1ax	G	G < 41°	N

Table 7 - Summary of Characteristics of Flow Path of Debris (Area A) (Sheet 3 of 4)

Slip No.	Chainage (m)	Gradient (degree)	Inclined Length (m)	Width (m)	Aspect Angle (degree)	Geology	Terrain Code	Topography	Vegetation	Predominant Erosion Depth	Mode of Erosion	Deposition	Type of Debris Movement	Travel Angle	Channelised
A11	0 - 30	35	30	10	210	1	3Dn	1	shrubs	n	-	1bx	G	G = 35°	N
A12	0 - 15	32	15	13	190	2	5Mn	2a	grass	scar	-		G	G = 32°	-
	15 - 57	32	42	8	190	2?	3Dr	2a	grass	n	-	1ax	G		N
	57 - 71	30	14	11	190	2?	3Dr	2a	grass	n	-	1ax	G		N
	71 - 101	33	30	7	205	2?	3Dr	2a	grass	n	-	1ax	G		N
A13A	0 - 16	37	16	9	130	1	5Mn	1	grass	scar			G	G < 38°	-
	16 - 40	35	24	12	130	1	5Mn	1	grass	n	-	1ax	G		N
	40 - 90	40	50	9	130	1	5Dn	1	grass	n	-	1ax	G		N
	90 -	32	-	-		4	4Dr	1	rock	n	-	2ny	M	-	N
A13B	0 - 17	37	17	9	120	1	4Dn	1	shrubs	scar	-	-	G	G = 31°	-
	17 - 37	31	20	9	120	1	4Dn	1	shrubs	n	-	1ax	G		N
	37 - 57	26	20	5	120	1	4Dn	1	grass	n	-	1ax	G		N
A14	0 - 20	32	20	17	140	1	4Dn	1	grass	scar	-				
	20 - 110	30	90	8	140	1	4Dn	1	grass	n	-	1bx	G	G = 32°	N
	110 -	32	-			1	4Dn	1	grass	n	-	1bx	G		N
A15	0 - 95	33	95	8	110	1	4Dr	1	grass	scar + path	-	1bx	G	G = 33°	N
A16A	0 - 60	37	60	16	160	1	5Cn	1	grass	scar + path	-	1ax	G	G = 37°	N
	60 -	-	-	-	-	4	5Cn	2b	grass	n	-	2nz	H	-	Y

Table 7 - Summary of Characteristics of Flow Path of Debris (Area A) (Sheet 4 of 4)

Slip No.	Chainage (m)	Gradient (degree)	Inclined Length (m)	Width (m)	Aspect Angle (degree)	Geology	Terrain Code	Topography	Vegetation	Predominant Erosion Depth	Mode of Erosion	Deposition	Type of Debris Movement	Travel Angle	Channelised
A17	0 - 32	39	32	14	175	1	4Cn	2a	grass	scar	-	-	G	G = 35°	-
	32 - 104	34	72	8	175	1	4Cn	2a	grass	a	1	1ax	G		N
	104 - 270	25	166	5	150	1	4Cn	2a	grass, shrubs	b	1	2nz	M & H	H < 27°	N
A18A	0 - 15	35	15	8	120	1	4Cn	2a	grass	scar	-	1bx	G	G = 32°	-
	15 - 98	32	83	11	120	1	4Cn	2a	grass	a	-	1ax	G		N
	98 - 320	23	222	4	125	1, 4	4Cn	2a	grass, rock	a	-	2az	H	H < 26°	N
A18B	0 - 20	35	20	12	130	1	4D1	2a	grass	scar	-	1cx	G	G = 31°	-
	20 - 117	30	97	6	130	1	4Cn	2a	grass	a	-	1ax	G		N
	117 - 375	27	258	4	115	1, 4	4Cn	2a	grass	a	-	2az	H	H < 28°	N

Table 8 - Summary of Characteristics of Flow Path of Debris (Area B) (Sheet 1 of 4)

Slip No.	Chainage (m)	Gradient (degree)	Inclined Length (m)	Width (m)	Aspect Angle (degree)	Geology	Terrain Code	Topography	Vegetation	Predominant Erosion Depth	Mode of Erosion	Deposition	Type of Debris Movement	Travel Angle	Channelised
BIB	0 - 17	40	17	8	180	1	4Cn	2b	shrubs	scar	-	-	G	-	Y
	17 - 94	35	77	8	155	1	4Cn	2b	shrubs	a	1	-	M	M = 25°	Y
(BIA)	94 - 156	30	62	11	180	1	4Cn	2b	shrubs	b	1		M		Y
	156 - 227	25	61	12	180	4	4Cn	2b	rock/trees	b	1	-	M		Y
	227 - 277	15	50	10	200	4	4Cn	2b	rock/trees	n	-	c 1 y	M		Y
	277 - 307	20	30	6	200	4	4Cn	2b	rock/trees	n	-	a 2 z	H	H < 22°	Y
B2MA-A (B2A, B2B)	0 - 30	40	30	17	160	1	4Cn	3	shrubs	scar	-	-	G	-	-
	30 - 95	40	65	40	160	1	4Cn	3	shrubs	a	1	-	G		N
	95 - 218	26.5	123	8	190	1	4Cn	2b	shrubs	b	1		M	-	Y
B2MB-B (B2A, B2C)	0 - 30	36	30	17	200	1	4Cn	3	shrubs	scar	-	-	G	G = 32.5°	N
	30 - 86	36	56	40	200	1	4Cn	3	shrubs	a	1	-	G		N
	86 - 130	26.5	44	8	165	1	4Cn	2a	shrubs	a	1	a 1 y	G		N
	130 - 230	26.5	100	7	165	1	4Cn	2b	shrubs	b	1 + 2	-	M	M < 28°	Y
B2M A-A+B-B	230 - 263	26.5	33	7	205	1	4Cn	2b	shrubs	b	1	a 1 y	M		Y
	263 - 295	18	32	6	205	4	4Cn	2b	rock/trees	a	2	v 1 y	M/H	-	Y
	295 - 550	18	255	5	165	4	4Cn	2b	rock/trees	n	-	n ? z	H	H < 24°	Y
	550	18				4	2Hr	2b	rock/trees	n	-	n ? z	H		Y
B3B	0 - 12	40	12	5	235	1	4Dr	2a	shrubs	scar	-	-	G	G < 40°	N
	12 - 47	40	35	5	235	1	4Dr	2a	shrubs	n	-	a 1 x	G		N
B3A	0 - 7	45	7	8	260	1 + 2	4Dr	2a	shrubs	scar	n	-	G	G < 45°	N
	7 - 19	45	12	8	260	1	4Dr	2a	shrubs	n	-	a 1 x	G		N

Table 8 - Summary of Characteristics of Flow Path of Debris (Area B) (Sheet 2 of 4)

Slip No.	Chainage (m)	Gradient (degree)	Inclined Length (m)	Width (m)	Aspect Angle (degree)	Geology	Terrain Code	Topography	Vegetation	Predominant Erosion Depth	Mode of Erosion	Deposition	Type of Debris Movement	Travel Angle	Channelised
B4E	0 - 9	40	9	9	115	1 & 4	5Mn	1	rock/grass	scar	-	-	G	G < 40°	N
	9 - 69	40	69	9	115	4	4Cr	1	rock/grass	-	-	a 1 x	G		N
	69 - 139	35	70	8	180	1	4Cr	2a	shrubs	a	1	a 1 y	M	M < 39°	Y
	139 - 189	35	50	5	180	1	4Cr	2b	shrubs	a	1	b 1 y	M		Y
	189 - 244	26	55	4	140	1 & 4	3F	2b	rock/shrubs	-	-	n ? z	H	H < 36°	Y
B5A	0 - 16	40	16	5	170	1	4Cr	1	grass	scar	-	-	G	G < 39°	N
	16 - 66	39	50	5	170	1 & 4	4Cr	1	rock/grass	a	1	n 1 y	G		N
	66 - 71	45	5	6	190	1 & 4	4Cr	2a	shrubs	a	1	n 1 y	M	M < 37°	N
	71 - 108	35	37	6	190	1 & 4	4Cr	2a	shrubs	a	1	n 1 y	M		N
	108 - 171	36	63	4	160	1 & 4	4Cr	2a	shrubs	a	1	n 1 y	M		Y
B5B	0 - 8	37	8	8	150	1	4Cr	1	grass	scar	-	-	G	G = 37°	-
	8 - 25	37	17	8	150	1	4Cr	1	grass	-	-	b 1 x	G		N
B6	0 - 30	30	30	9	170	1	3Cr	1	shrubs/trees	-	-	b 1 x	G	G = 30°	N
B7A	0 - 10	38	10	10	140	1	4Cr	1	shrubs	-	-	-	G	G = 33°	N
	10 - 63	32	53	10	140	1	4Cr	1	shrubs	-	-	a 1 x	G		N
	63 - 110	22	47	3	210	1	4Cr	1	shrubs	-	-	a 2 y	H	H < 28°	N
B7M	0 - 39	40	39	25	150	1	4Cr	1	shrubs	scar	-	-	G	G = 37°	N
	39 - 100	35	61	25	150	1	4Cr	1	shrubs	-	-	a 1 x	G		N
	100 - 310	18.5	210	5	210	1	4Cr	2b	trees	a	1	b 2 z	H	H < 24°	Y
	310 - 417	21	97	5	210	4	4Cn	2b	trees	n	2	n 2 z	H		Y

Table 8 - Summary of Characteristics of Flow Path of Debris (Area B) (Sheet 3 of 4)

Slip No.	Chainage (m)	Gradient (degree)	Inclined Length (m)	Width (m)	Aspect Angle (degree)	Geology	Terrain Code	Topography	Vegetation	Predominant Erosion Depth	Mode of Erosion	Deposition	Type of Debris Movement	Travel Angle	Channelised
B8	0 - 30	33	30	9	145	1	4Cr	1	shrubs	-	-	b 1 x	G	G = 33°	N
B9	0 - 26	33	26	15	170	1	4Cr	2a	grass	scar + path	-	a 1 x	G	G = 33°	N
	26 - 95	40	69	8	170	4	4Cr	2a	grass	n	-	a 1 y	M	M < 36°	N
	95 - 117	35	22	10	170	1 & 4	4Cr	2a	grass	n	-	a 1 y	M		N
	117 - 150	35	33	10	170	1 & 4	4Cr	2a	trees	n	-	a 1 y	M		N
	150 - 158	28	8	5	170	1	4Cr	2a	shrubs/trees	n	-	a 1 y	H	H < 33°	N
	158 - 168	33	10	4	170	1	4Cr	2a	shrubs/tree	n	-	a 1 y	H		N
	169 - 201	30	33	4	170	1	4Cr	2a	shrubs/trees	n	-	a 1 y	H		N
	201 - 223	25	22	4	185	1	4Cr	2a	shrubs/trees	n	-	a 1 z	H		N
	223 - 245	22	22	2	185	1	4Cr	2a	shrubs/trees	n	-	a 1 z	H		N
B10	0 - 74	35	74	18	160	1	4Cn	1	shrubs/trees	n	-	b 1 x	G	G = 35°	N
B11M	0 - 11	35	11	10	165	1	4Cn	1	shrubs	scar	-	-	G	G = 34°	N
	11 - 29	37	18	10	165	1	4Cn	1	shrubs	n	-	b 1 x	G		N
	29 - 50	30	21	5	165	1	4Cn	1	shrubs	n	-	b 1 x	G		N
	50 - 100	28	50	5	140	1	4Cn	1	shrubs/trees	n	-	n 2 y	M	M < 31°	N
B12	0 - 11	33	11	13	125	1 + 2	2A	1	shrubs	scar	-	-	G	G = 31°	N
	11 - 24	30	13	10	125	1	2A	1	shrubs/trees	n	-	d 1 x	G		N
	24 - 40	25	16	8	125	1	2A	1	trees	-	-	a 2 y	M	M < 29°	N

Table 8 - Summary of Characteristics of Flow Path of Debris (Area B) (Sheet 4 of 4)

Slip No.	Chainage (m)	Gradient (degree)	Inclined Length (m)	Width (m)	Aspect Angle (degree)	Geology	Terrain Code	Topography	Vegetation	Predominant Erosion Depth	Mode of Erosion	Deposition	Type of Debris Movement	Travel Angle	Channelised
B13	0 - 15	35	15	6	115	2	4Cn	1	shrubs	n	-	b 1 x	G	G = 33°	N
	15 - 27	30	12	6	115	2	4Cn	1	shrubs	n	-	b 1 x	G		N
	27 - 48	30	21	5	115	2	4Cn	1	trees	n	-	a 2 y	H	H < 32°	N
B14	0 -16	34	16	5	125	1 + 2	2A	1	shrubs	scar + path	-	e 1 x	G	G = 34°	N

Table 9 - Summary of Characteristics of Flow Path of Debris (Area C)

Slip No.	Chainage (m)	Gradient (degree)	Inclined Length (m)	Width (m)	Aspect Angle (degree)	Geology	Terrain Code	Topography	Vegetation	Predominant Erosion Depth	Mode of Erosion	Deposition	Type of Debris Movement	Trail Angle	Channelised
C1	0 - 47	28	47	15	90	1	3D2	2a	grass	scar	-	-	G	G=20°	-
	47 - 118	15	71	12	90	1	3D2	2a	grass	b	1	d1x	G		N
	118 - 139	15	21	11	50	1	3D2	2a	grass	a	1	1ax	M	-	N
	139 - 183	24	44	15	50	1 + 4	3D2	2b	grass+rock	n	-	a2z	H	H<20°	N

Note : Refer to Appendix A for definition of symbols.

Table 10 - Volume of Landslides and Size of Catchment Areas (Sheet 1 of 4)

Slip No.	Source Landslide Volume (m^3)	Mode of Debris Movement	Total Volume of Landslide (m^3) (source + entrained volume)	Catchment Area (m^2)
A1A	60	gravitational hydraulic	60 60	800 5,500
A1B	230	gravitational hydraulic	230 295	1,200 62,000
A2	65	mixed	195	12,500
A3	50	gravitational	50	4,000
A4	70	gravitational mixed	70 95	4,500 12,500
A5A	240	gravitational mixed	240 460	2,000 25,000
A5B	140	gravitational	140	3,500
A6	400	gravitational	400	3,000
A7	190	gravitational	190	1,000
A8	100	gravitational	100	2,000
A9	60	gravitational	60	1,000
A10B	10	gravitational hydraulic	10 265	1,500 13,000
A10D	45	gravitational	45	500
A11	50	gravitational	50	200
A12	135	gravitational	135	1,500

Table 10 - Volume of Landslides and Size of Catchment Areas (Sheet 2 of 4)

Slip No.	Source Landslide Volume (m^3)	Mode of Debris Movement	Total Volume of Landslide (m^3) (source + entrained volume)	Catchment Area (m^2)
A13A	45	gravitational	45	2,000
A13B	100	gravitational	100	800
A14	170	gravitational	170	2,500
A15	320	gravitational	320	1,500
A16A	105	gravitational	105	1,600
A17	225	gravitational hydraulic	225 465	2,100 22,500
A18A	210	gravitational hydraulic	210 290	1,600 22,000
A18B	80	gravitational hydraulic	80 370	1,800 22,000
B1	200	mixed hydraulic	200 690	39,000 40,000
B2 (A-A + B-B)	590	gravitational mixed hydraulic	590 1,000 1,420	9,300 27,000 45,000
B3B	30	gravitational	30	500
B3A	30	gravitational	30	200
B4E	190	gravitational mixed hydraulic	400 740 905	1,000 20,000 23,000

Table 10 - Volume of Landslides and Size of Catchment Areas (Sheet 3 of 4)

Slip No.	Source Landslide Volume (m^3)	Mode of Debris Movement	Total Volume of Landslide (m^3) (source + entrained volume)	Catchment Area (m^2)
B5A	30	gravitational mixed	30 340	3,000 9,000
B5B	15	gravitational	15	200
B6	75	gravitational	75	6,000
B7A	70	gravitational hydraulic	70 70	1,000 28,000
B7M	640	gravitational hydraulic	640 1260	1,500 67,000
B8	35	gravitational	35	4,000
B9	250	gravitational mixed hydraulic	250 310 360	750 8,000 24,000
B10	210	gravitational	210	1,800
B11M	75	gravitational mixed	75 125	500 7,000
B12	140	gravitational mixed	140 140	3,000 3,500
B13	85	gravitational hydraulic	85 85	300 3,500
B14	160	gravitational	160	100

Table 10 - Volume of Landslides and Size of Catchment Areas (Sheet 4 of 4)

Slip No.	Source Landslide Volume (m^3)	Mode of Debris Movement	Total Volume of Landslide (m^3) (source + entrained volume)	Catchment Area (m^2)
C1	1000	gravitational	1,000	6,000
		hydraulic	1,500	9,000

Notes :
(1) The source volume has been determined by reference to the measurements and shape of the landslide scarp while the volume of entrained material has been evaluated taking into account the erosion depth.
(2) The travel angles of the debris have been determined based on the runout of debris of a specific movement mechanism with respect to the landslide crown and these have been plotted against the total volume of debris for different movement mechanisms in Figure 18. As the debris associated with a given landslide may involve different movement mechanisms along different portions of the trail, the travel angle corresponding to each movement mechanism has been treated as individual data points. Thus, a given landslide may have a number of data points if there are more than one mechanism of debris movement.

LIST OF FIGURES

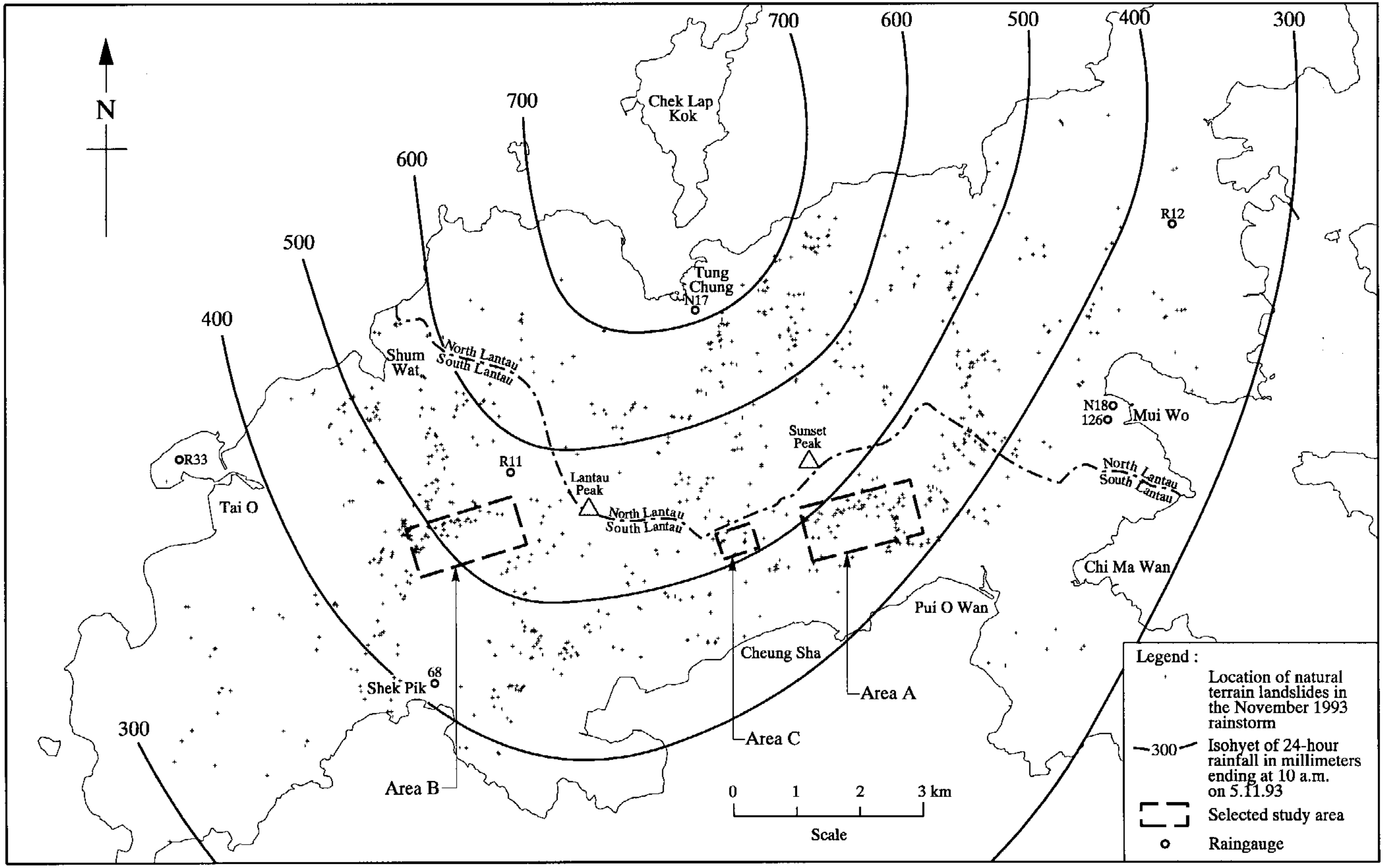


Figure 1 - Location of the November 1993 Natural Terrain Landslides on Lantau

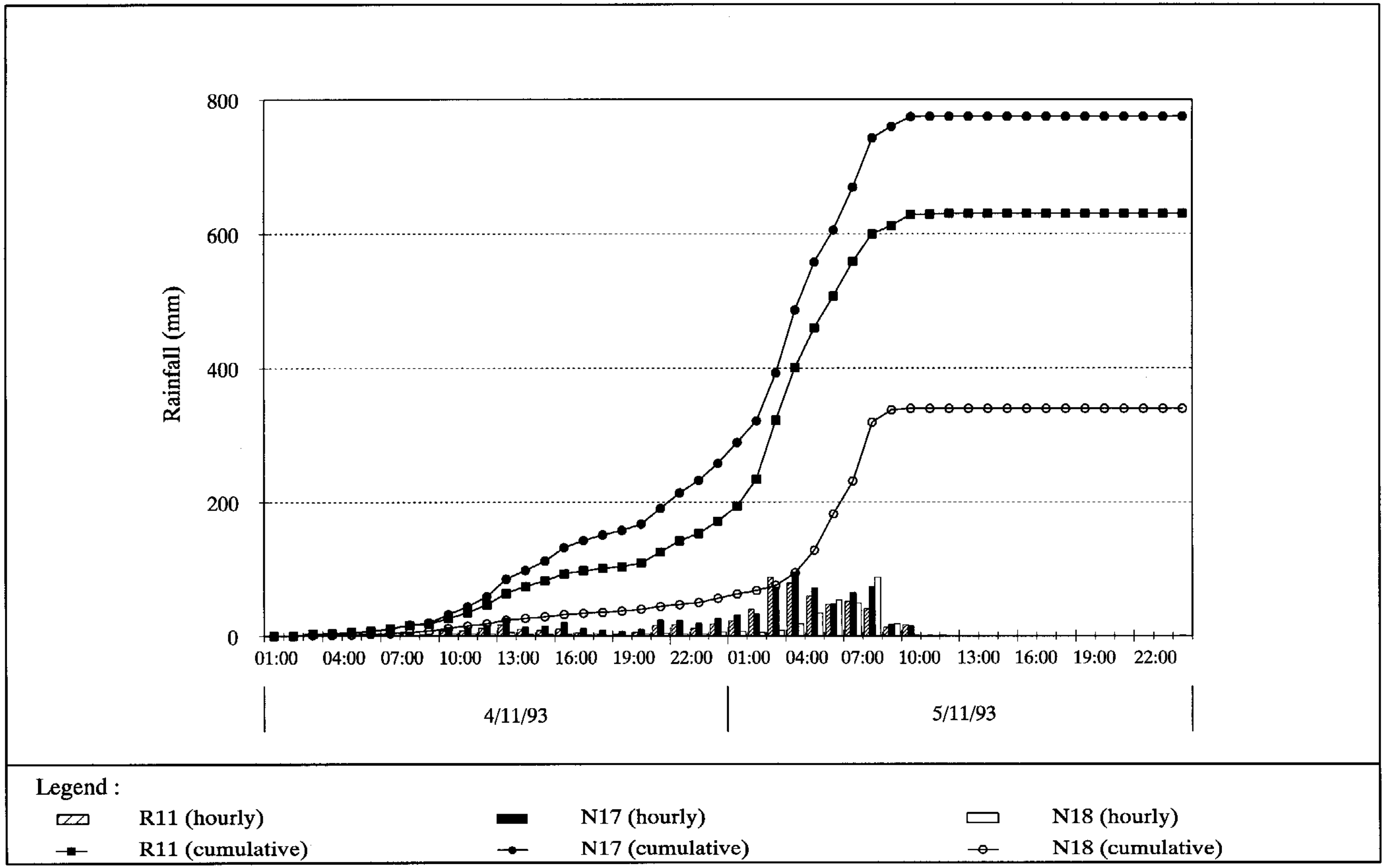


Figure 2 - Hourly Rainfall Recorded by Raingauges N17, R11 and N18

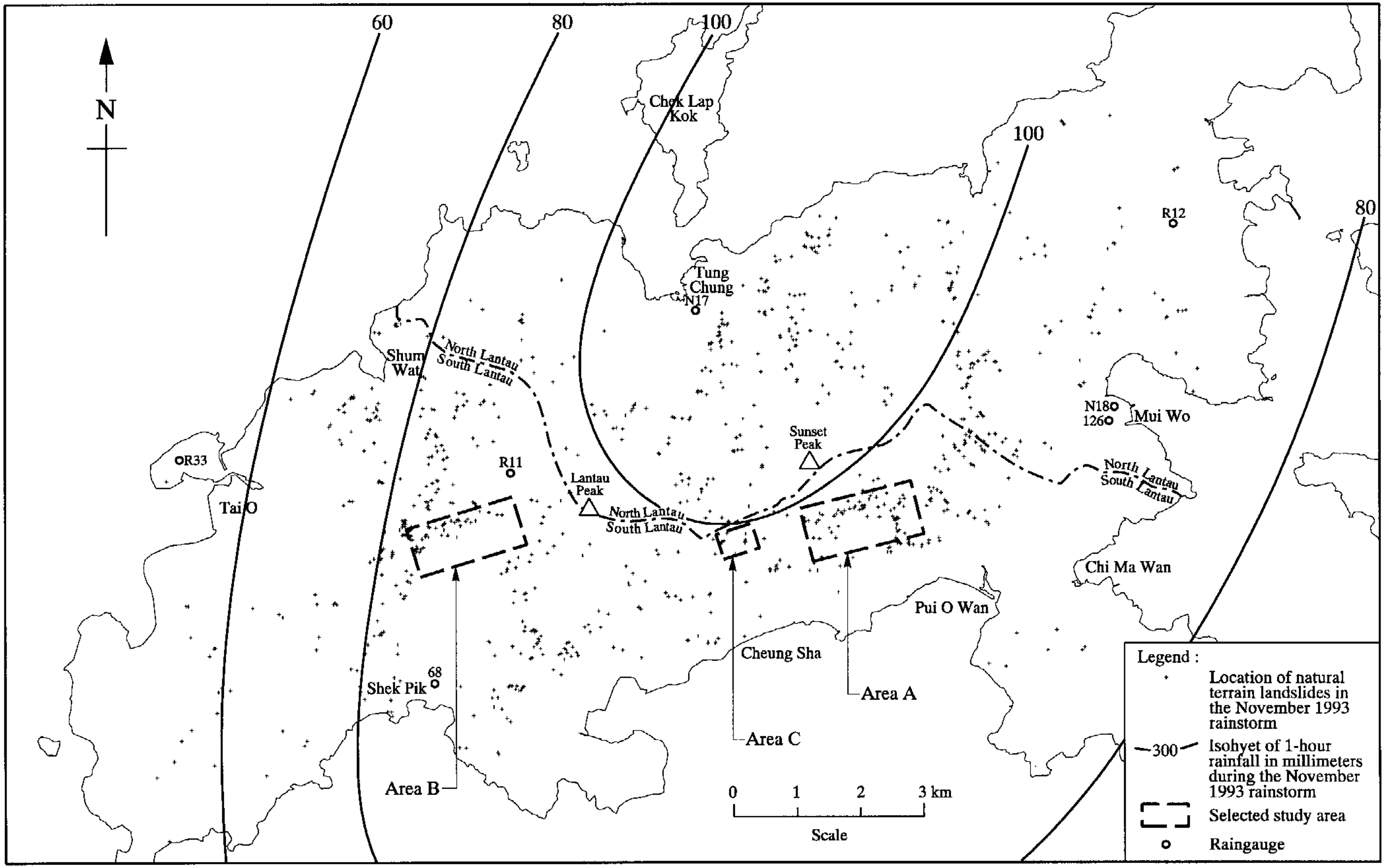


Figure 3 - Maximum 1-hour Rolling Rainfall Distribution

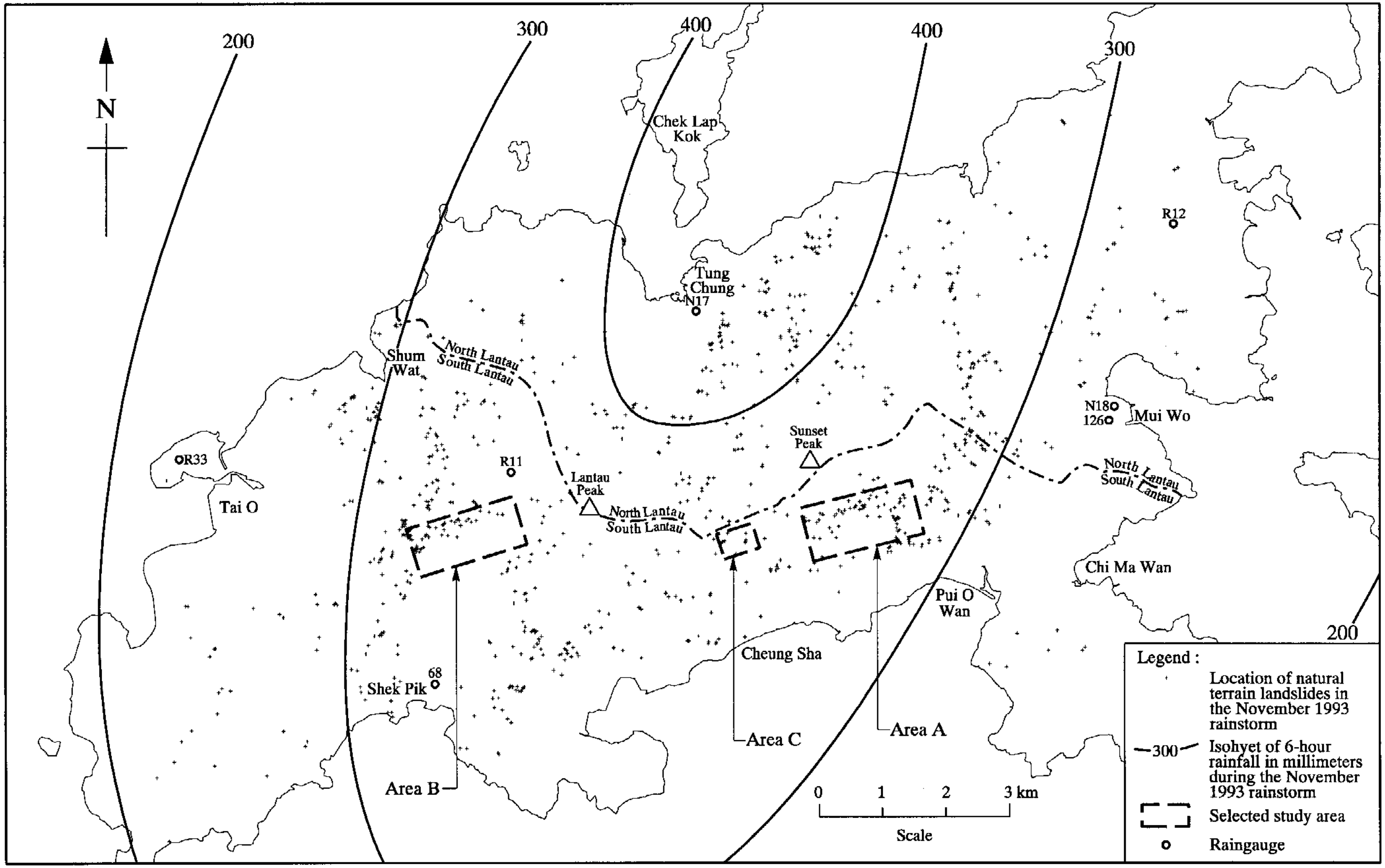


Figure 4 - Maximum 6-hour Rolling Rainfall Distribution

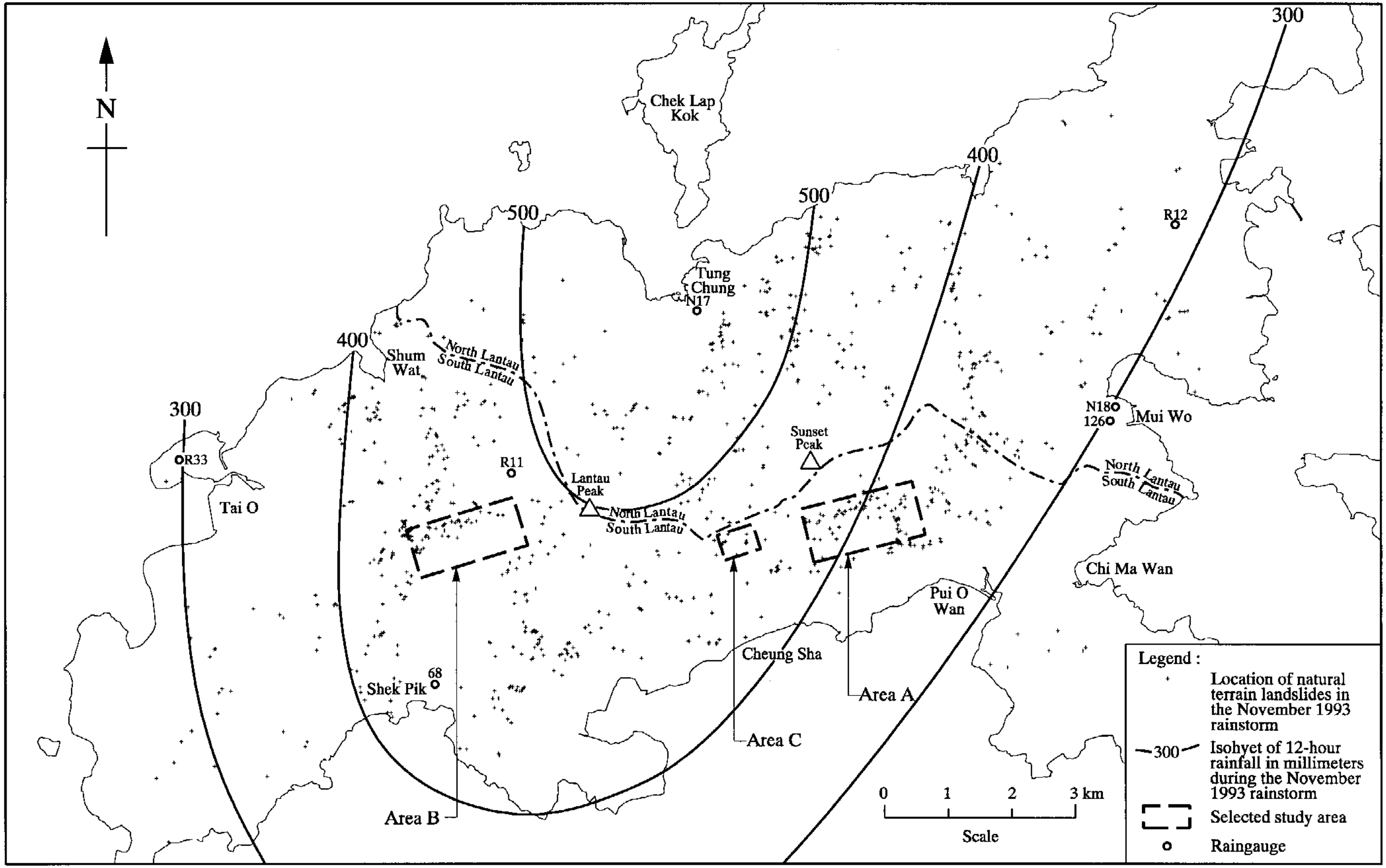


Figure 5 - Maximum 12-hour Rolling Rainfall Distribution

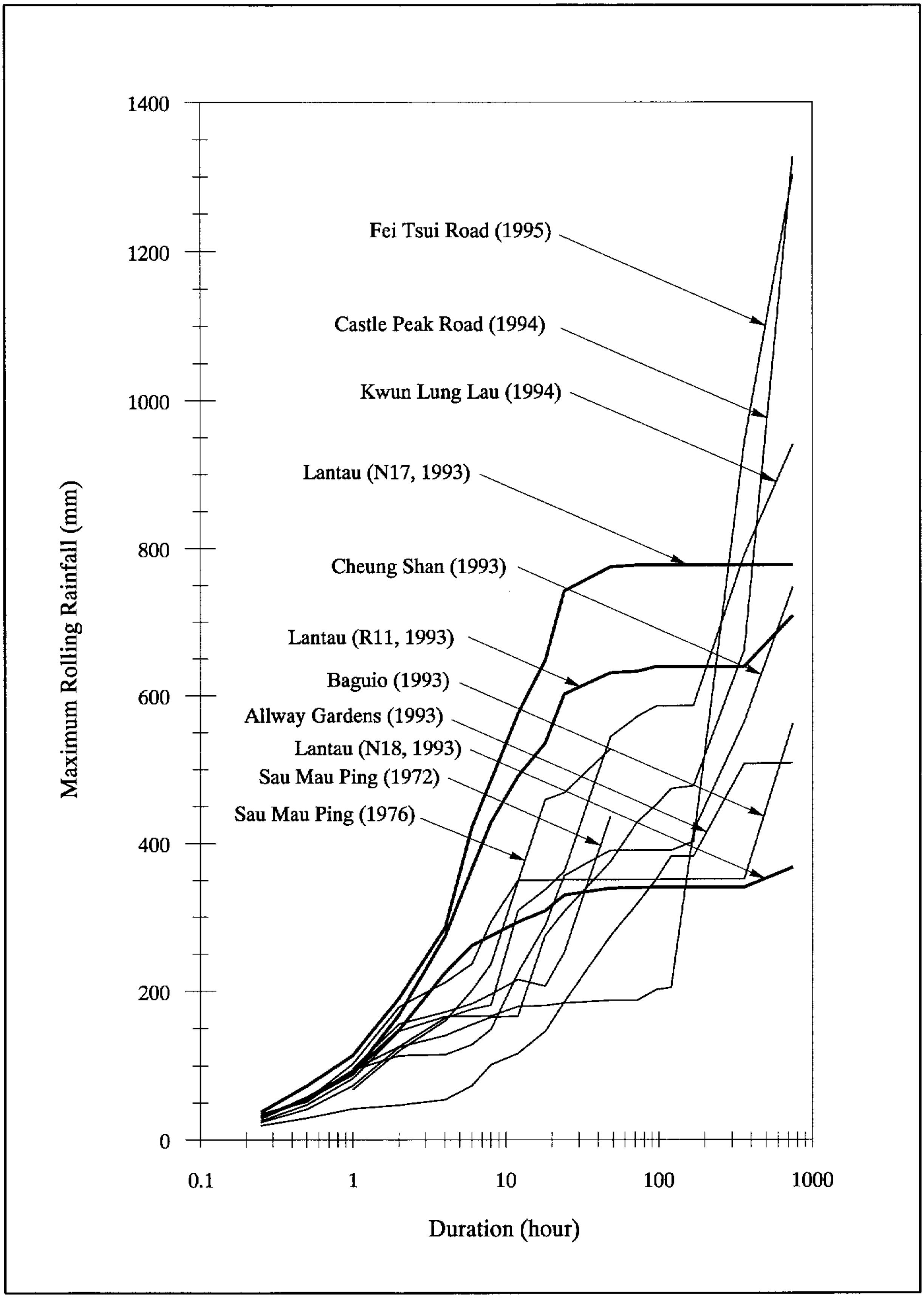


Figure 6 - Comparison of Rainfall Data Recorded at Selected Raingauges on Lantau with Other Raingauges for Major Landslide Events

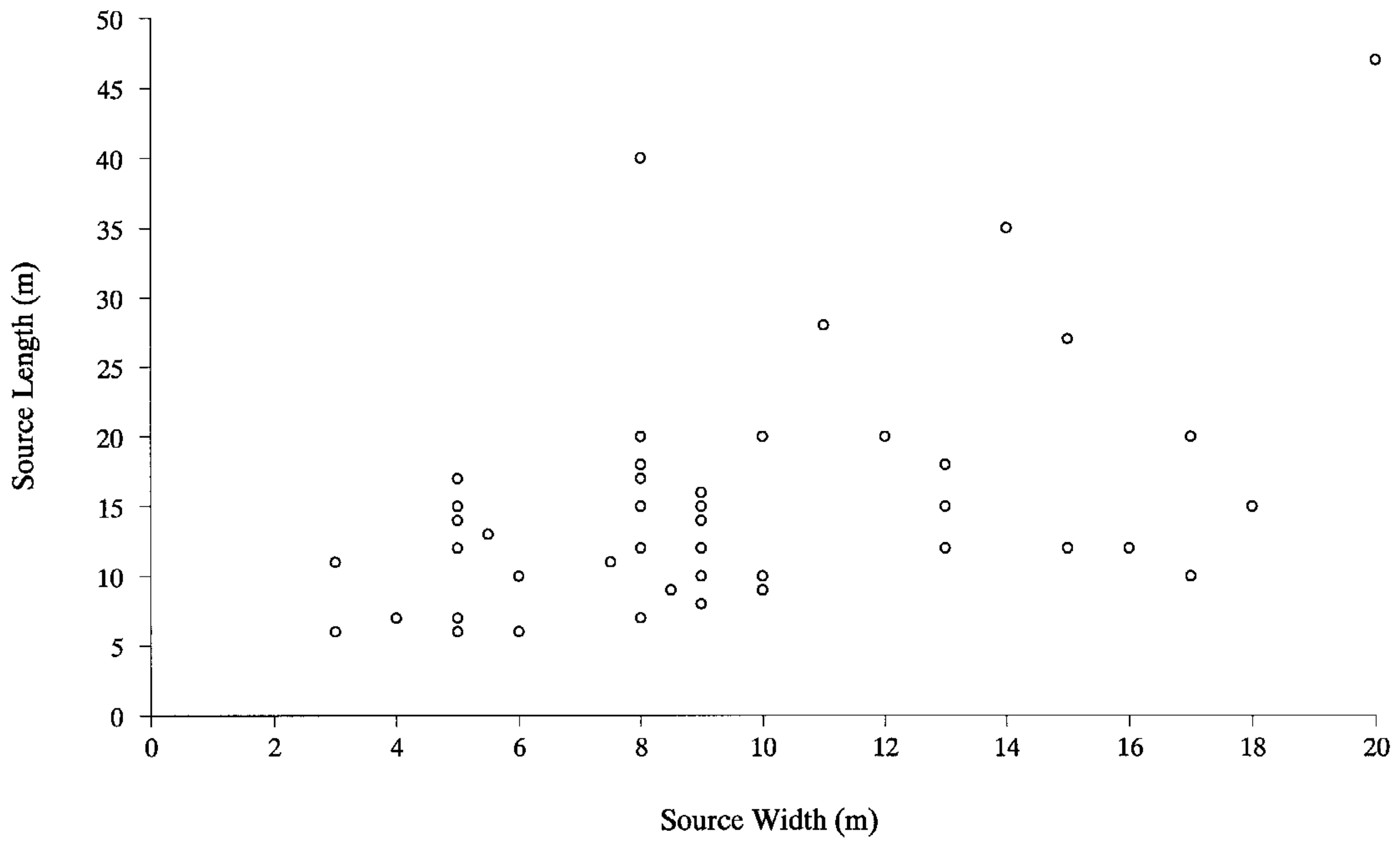


Figure 7 - Relationship between Source Length and Width of Landslides

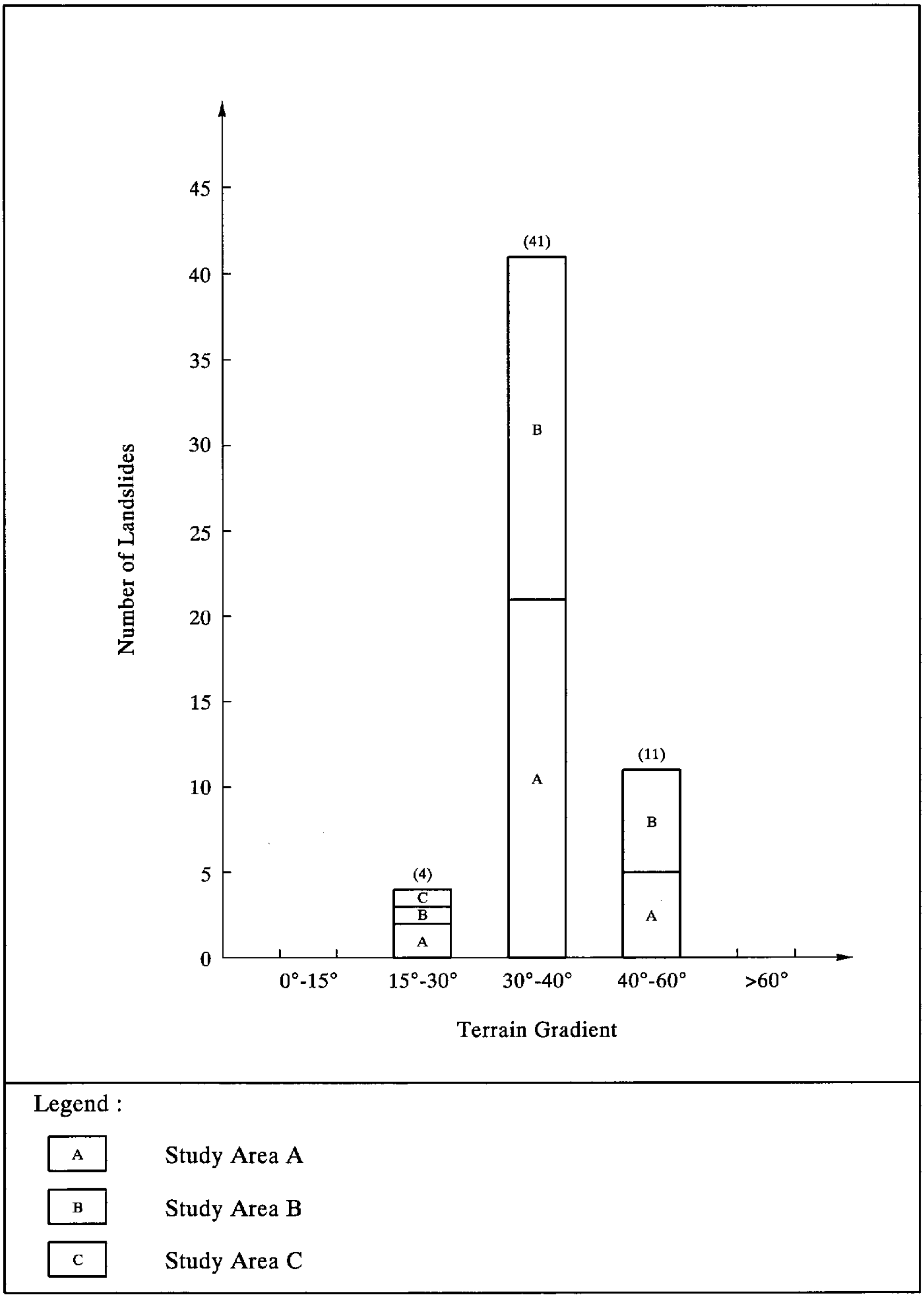


Figure 8 - Distribution of Landslides with Respect to Terrain Gradients for the Three Study Areas

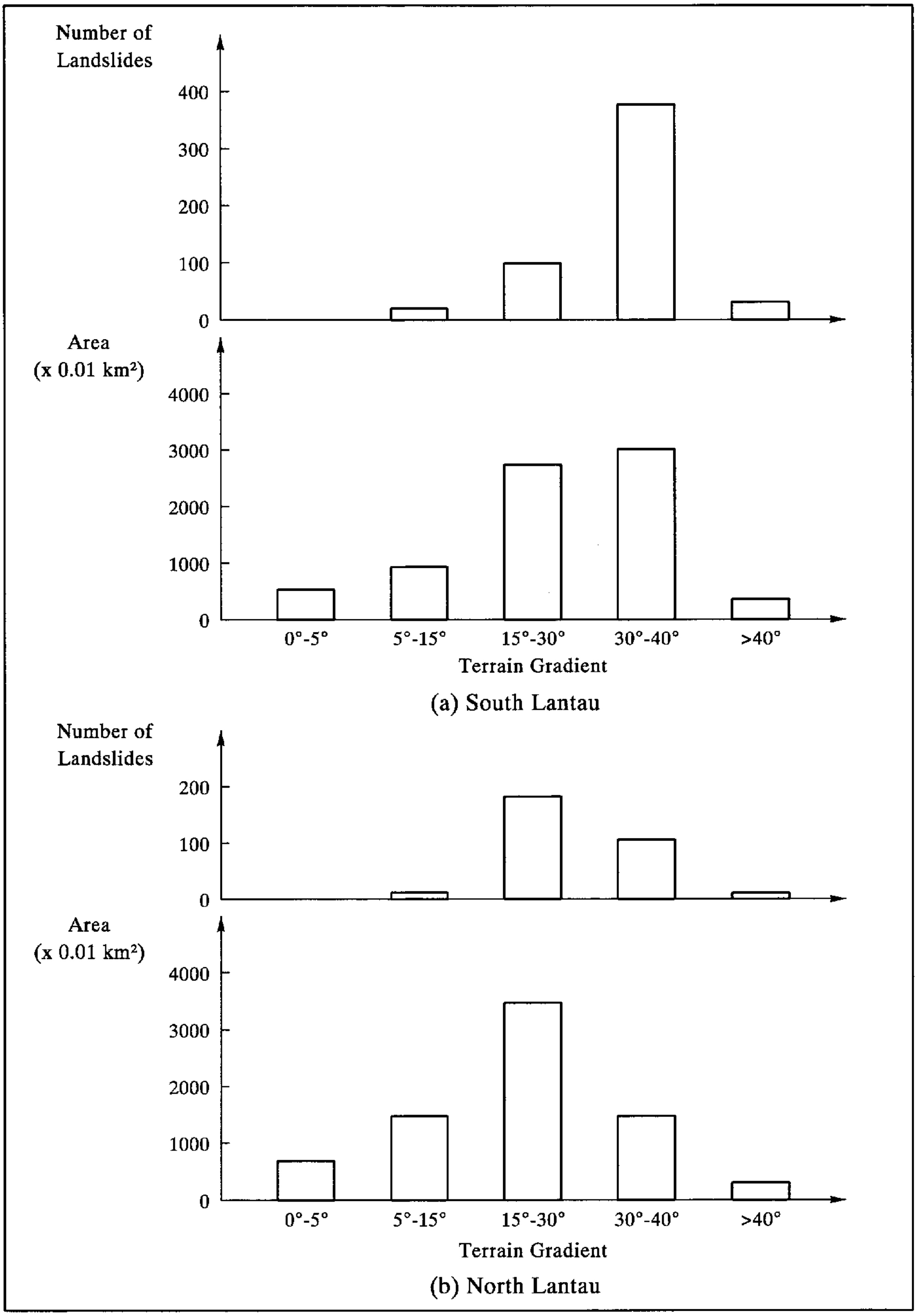


Figure 9 - Distribution of Landslides with Respect to Terrain Gradient

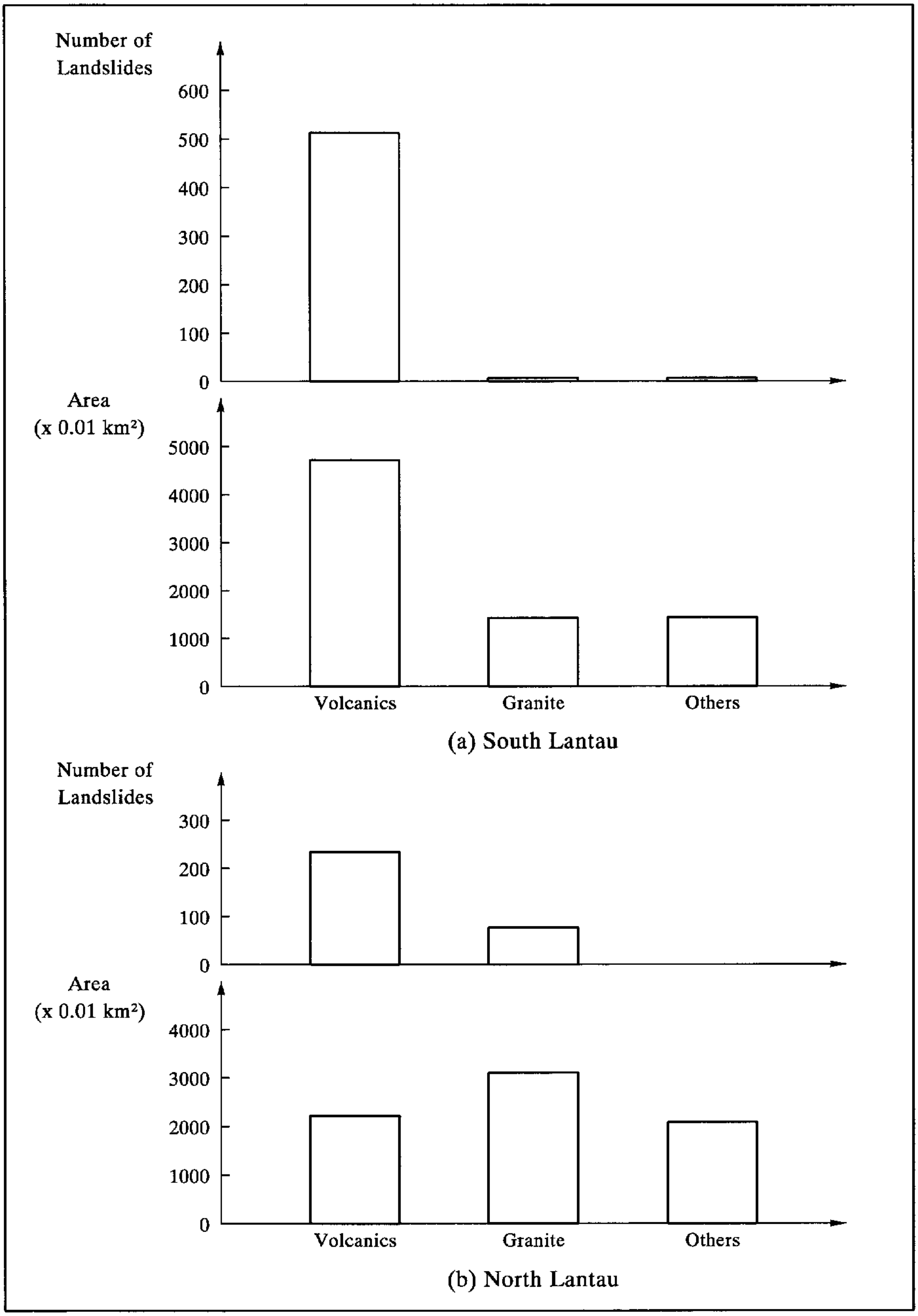


Figure 10 - Distribution of Landslides with Respect to Solid Geology

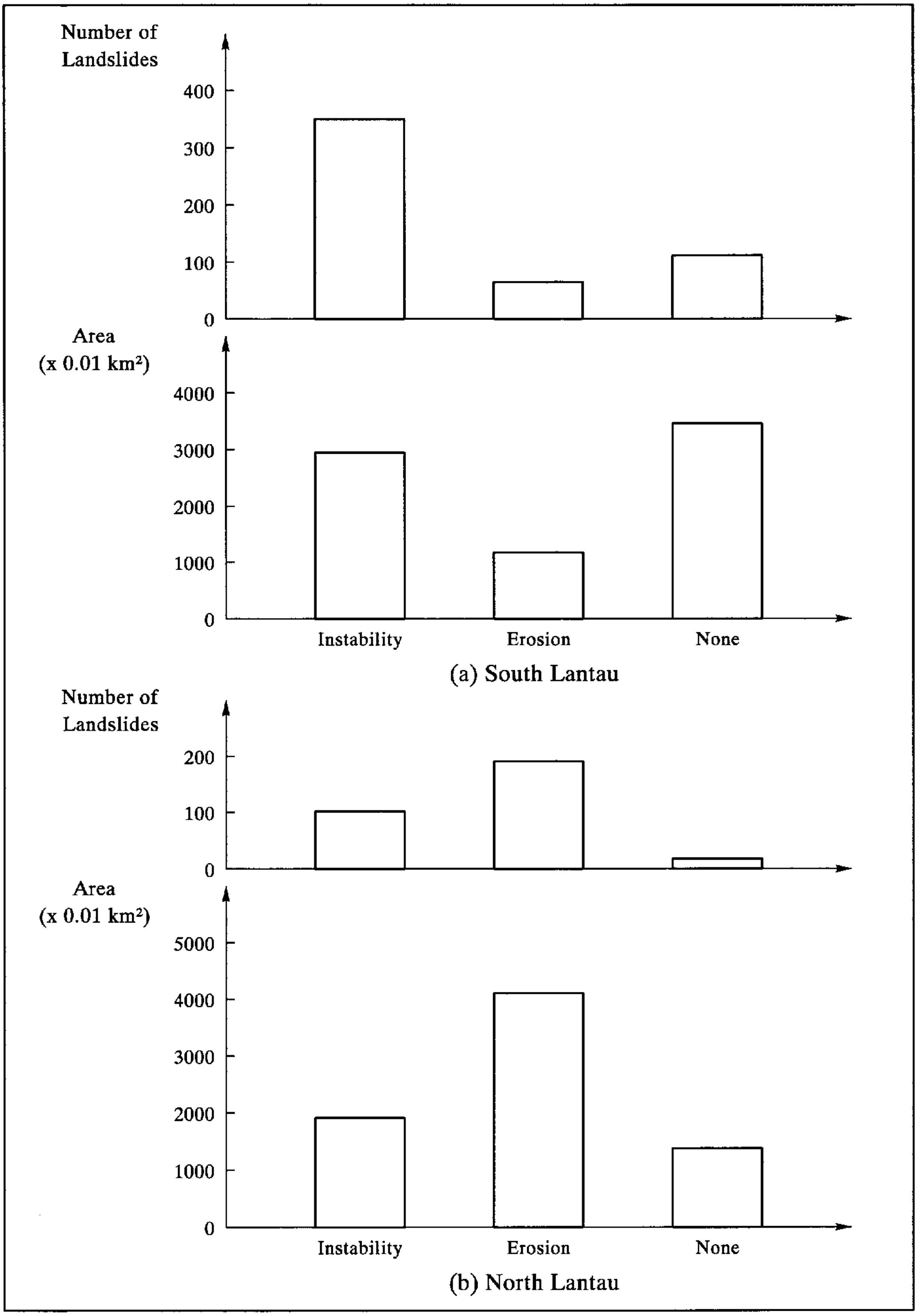


Figure 11 - Distribution of Landslides with Respect to Areas with Instability or Erosion

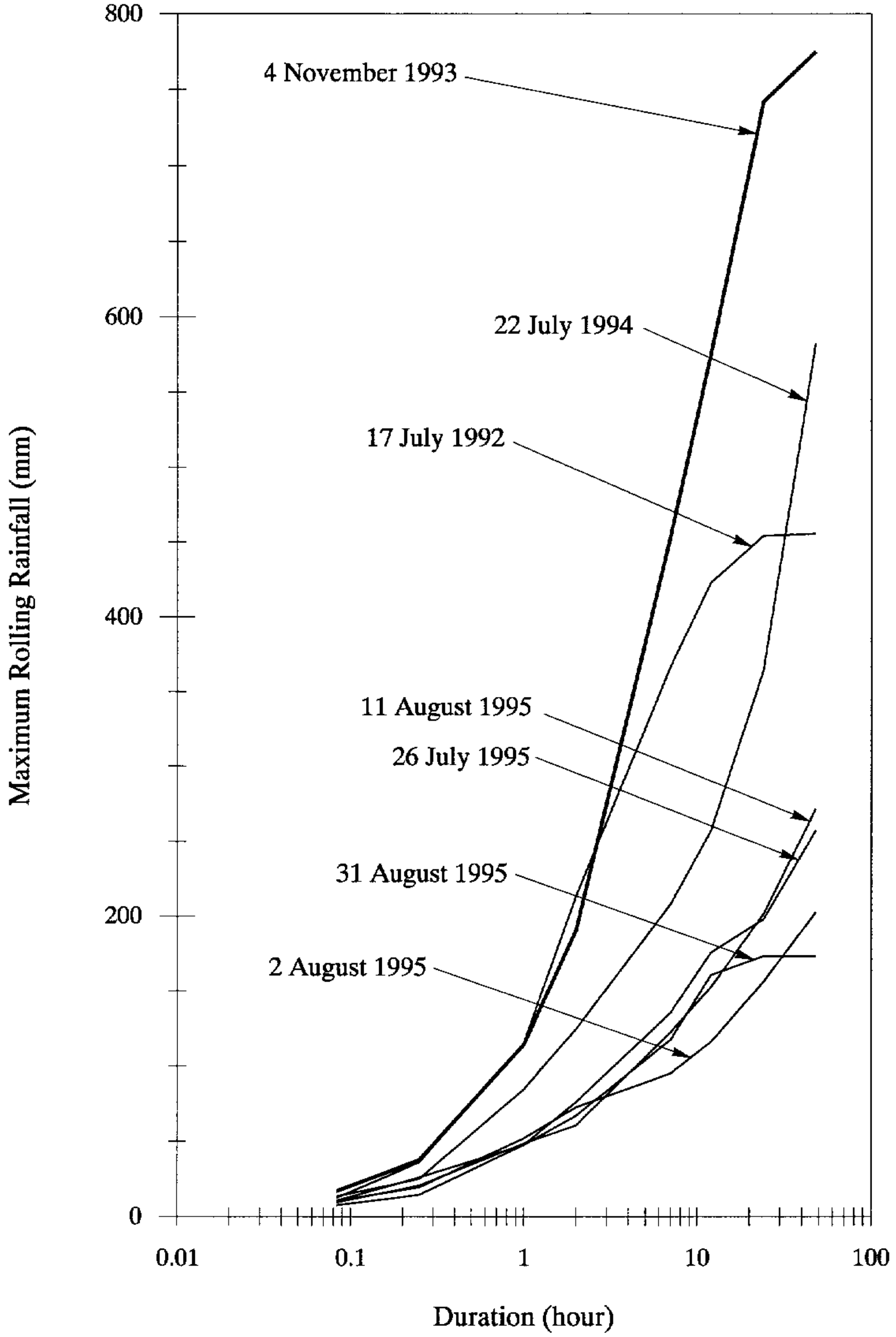
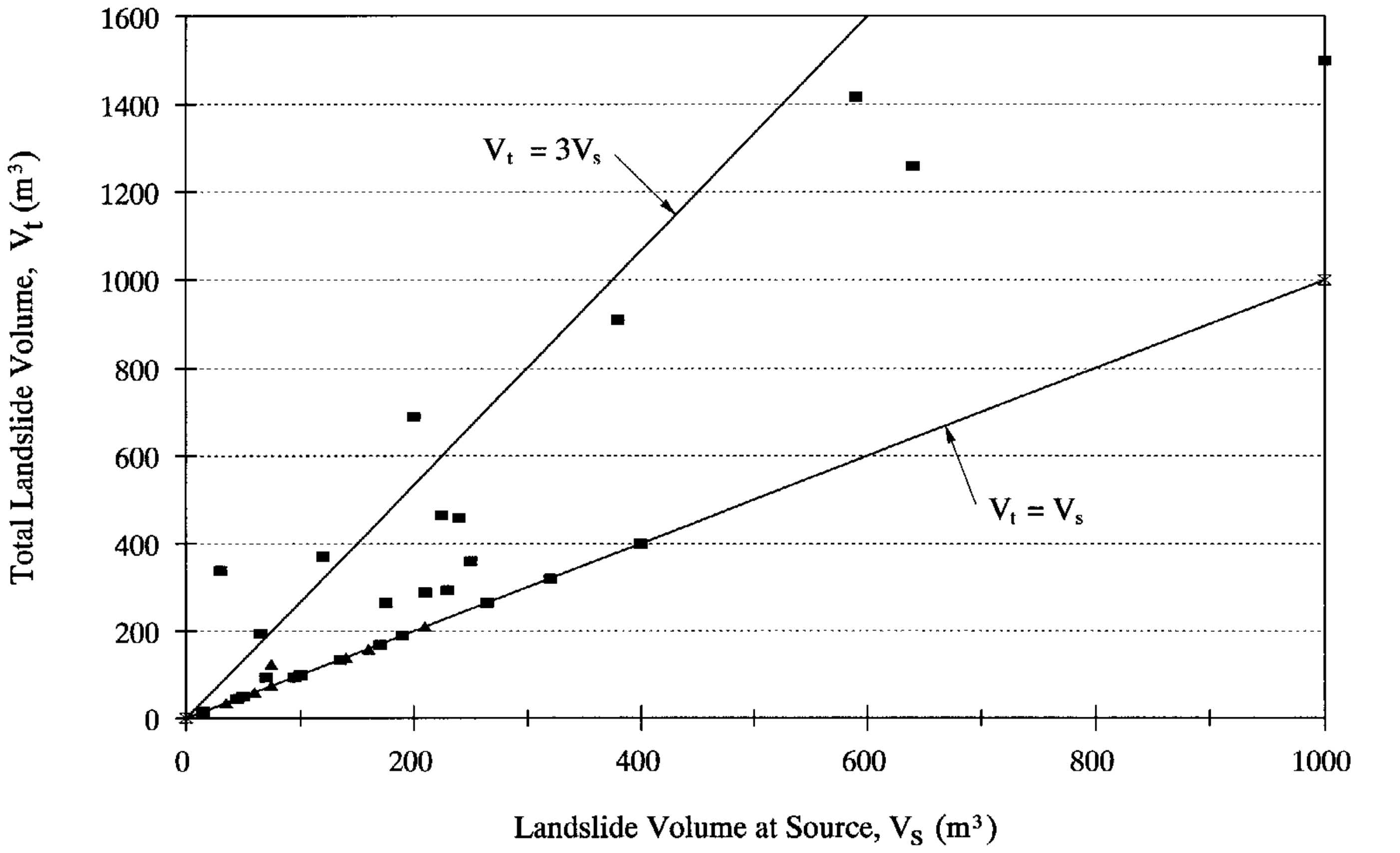


Figure 12 - Maximum Rolling Rainfalls at Raingauge N17 for Major Rainstorms



Legend :

■ Along streamcourse ▲ Along planar slope

Figure 13 - Comparison of Landslide Volume at Source with Total Landslide Volume

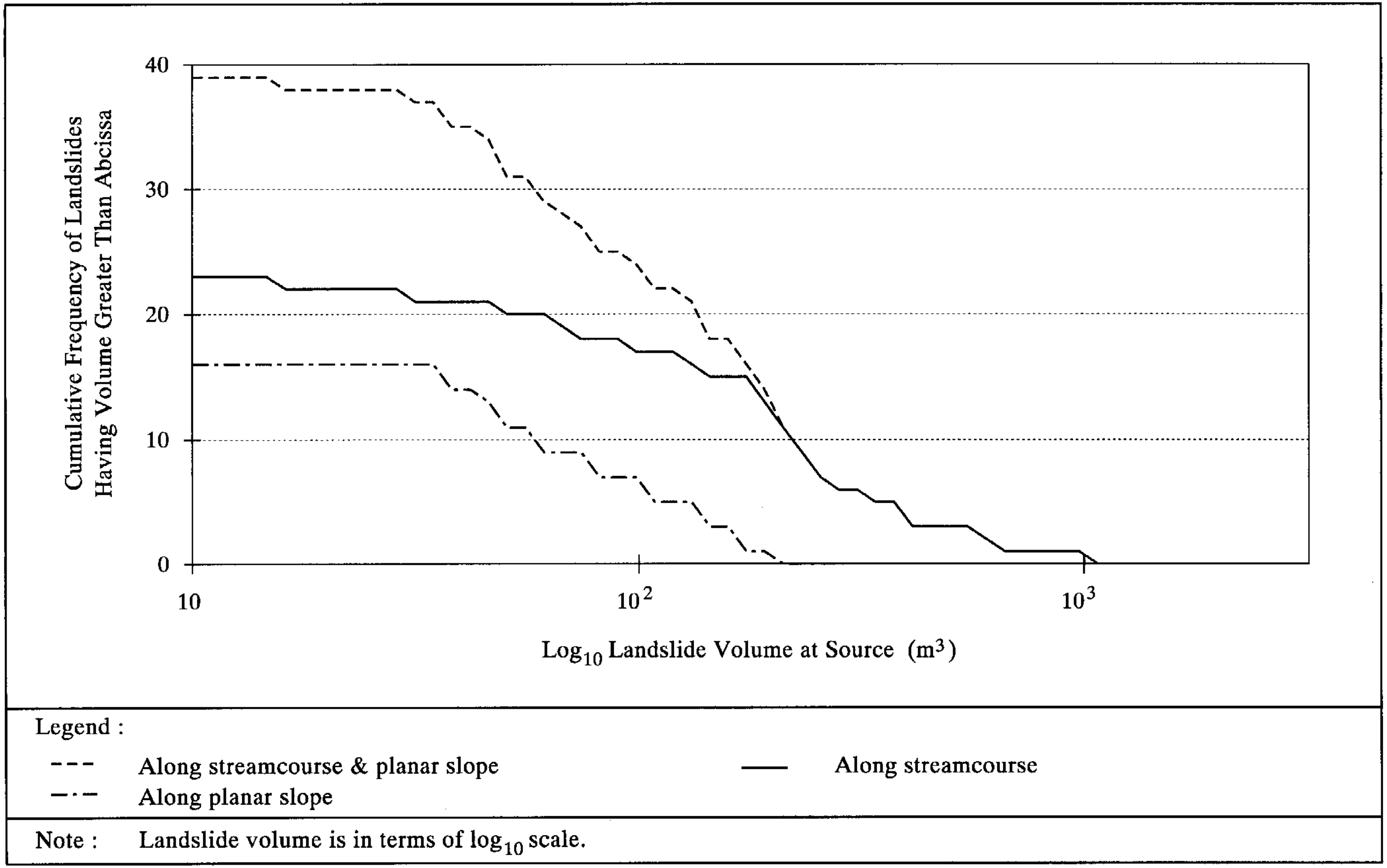
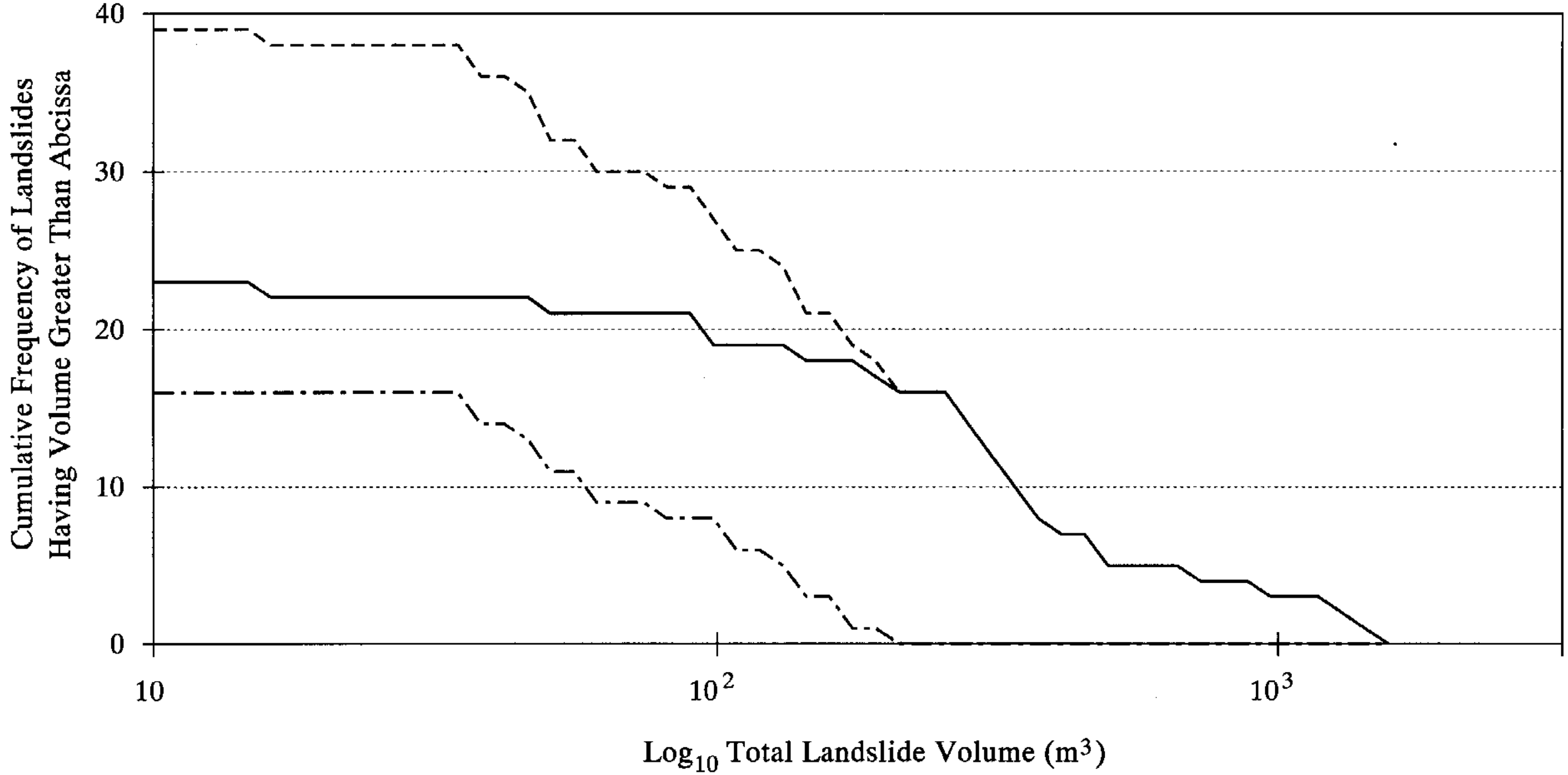


Figure 14 - Landslide Frequency against Source Landslide Volume



Legend :

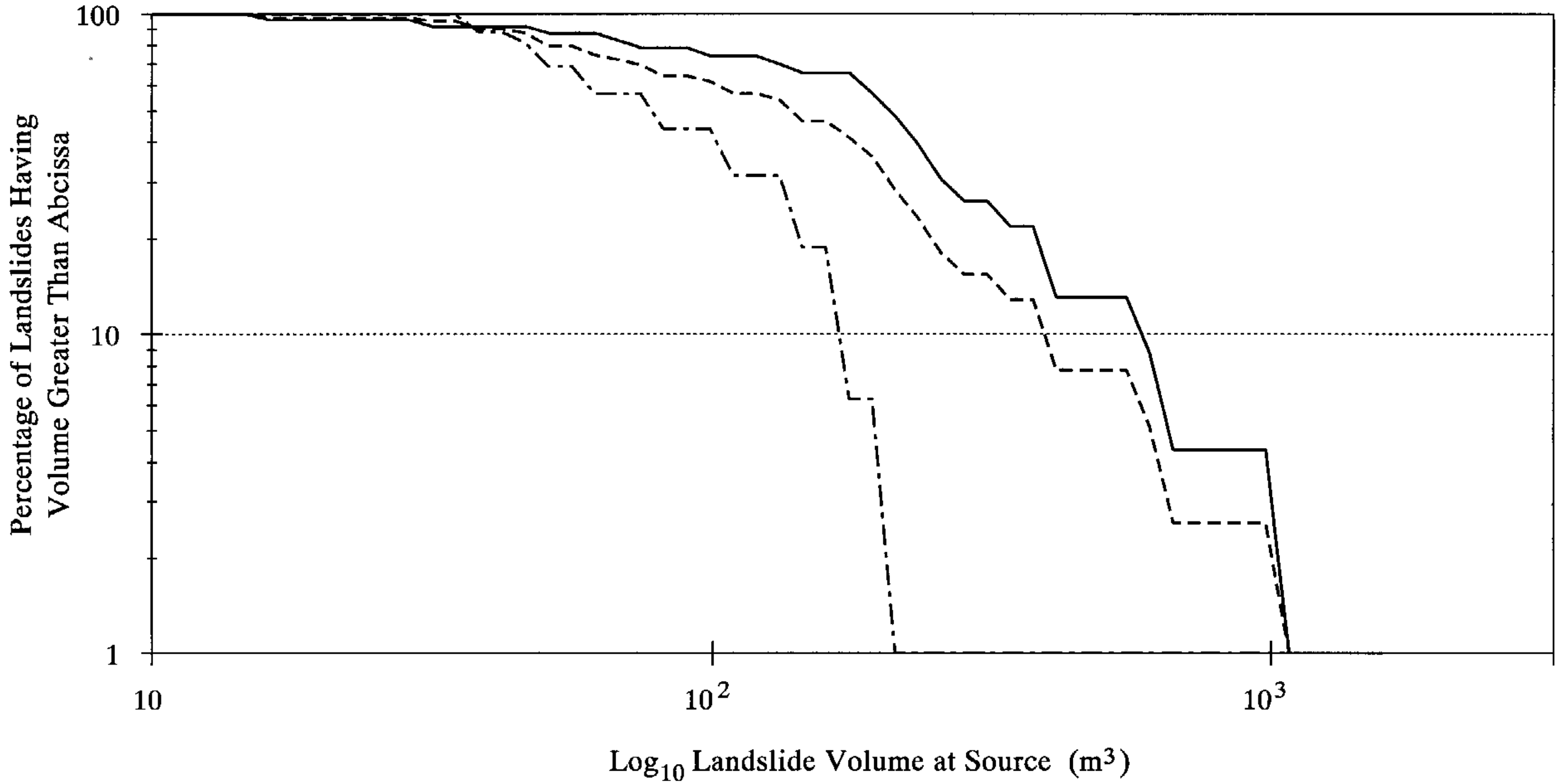
- - - Along streamcourse & planar slope

—— Along streamcourse

—·— Along planar slope

Note : Landslide volume is in terms of log_{10} scale.

Figure 15 - Landslide Frequency against Total Landslide Volume

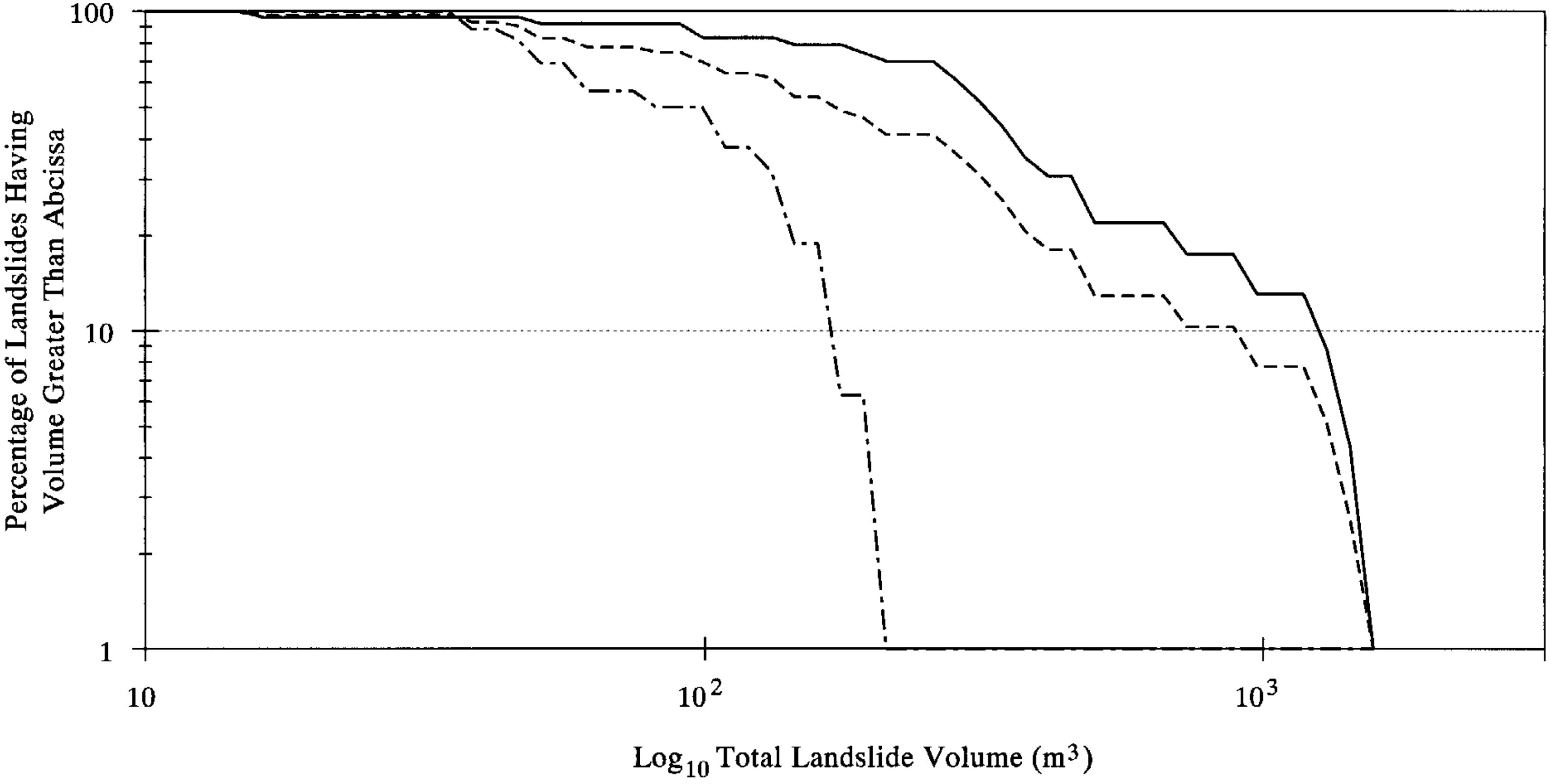


Legend :

- - - Along streamcourse & planar slope	—— Along streamcourse
—·— Along planar slope	

Note : Landslide volume is in terms of log_{10} scale.

Figure 16 - Cumulative Landslide Frequency against Source Landslide Volume



Legend :

- - - Along streamcourse & planar slope
—— Along streamcourse
—·— Along planar slope

Note : Landslide volume is in terms of log_{10} scale.

Figure 17 - Cumulative Landslide Frequency against Total Landslide Volume

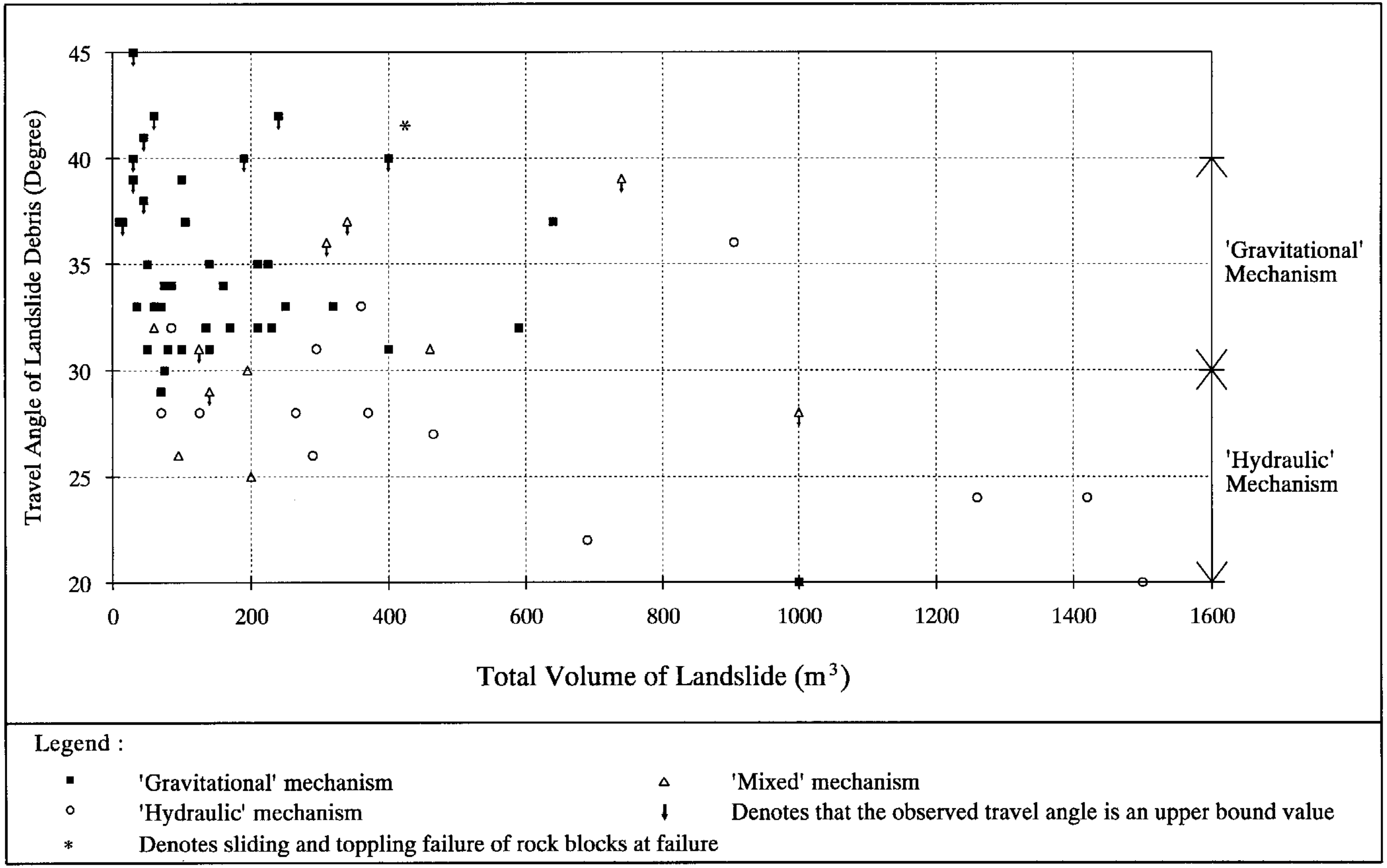
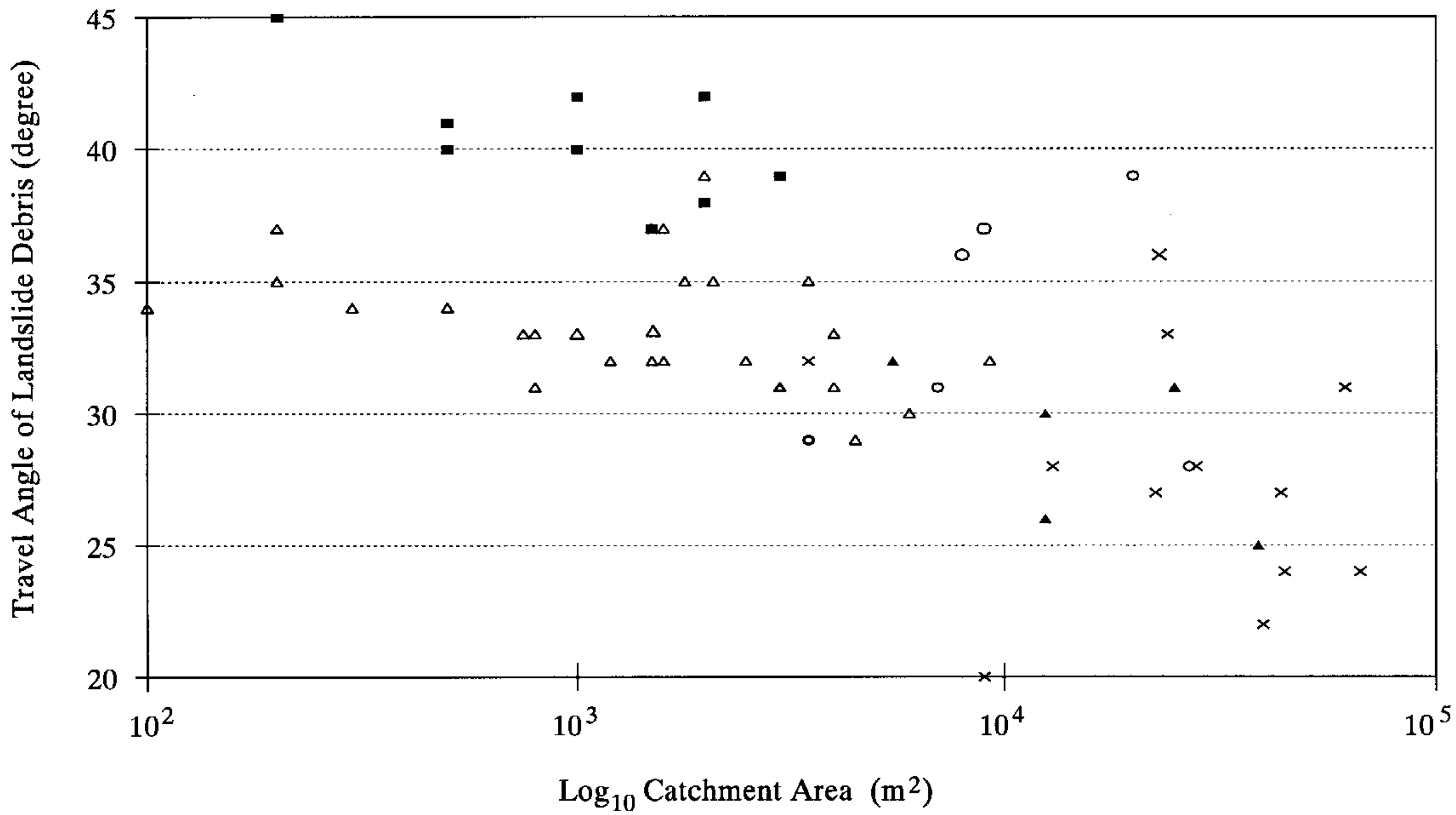


Figure 18 - Mobility of Landslide Debris

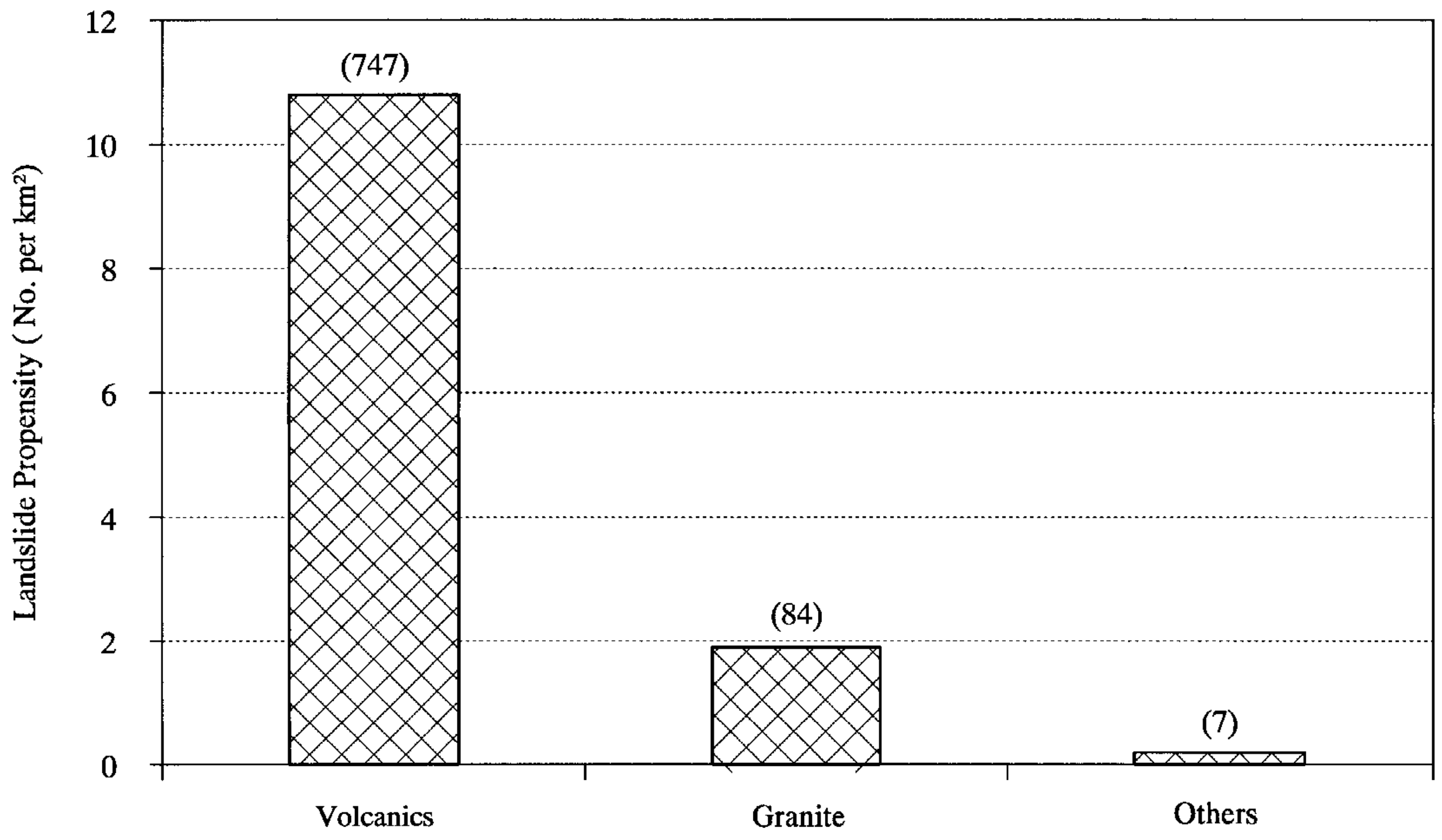


Legend :

△	Gravity type deposit	■	Gravity type deposit (upper bound)
▲	Mixed type deposit	○	Mixed type deposit (upper bound)
×	Hydraulic type deposit (upper bound)		

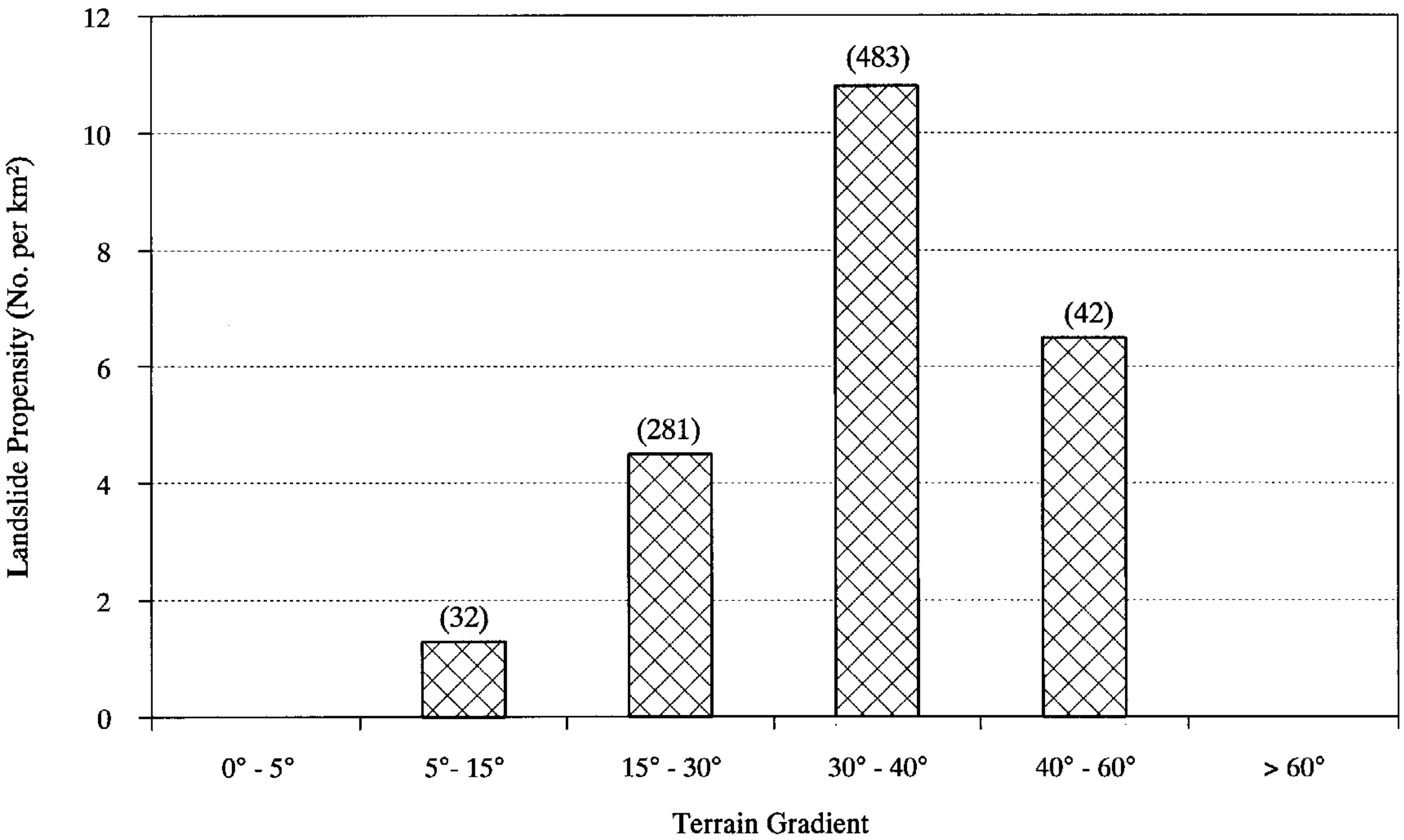
Note : Catchment area is in terms of log_{10} scale.

Figure 19 - Relationship between Mobility of Landslide Debris and Catchment Area



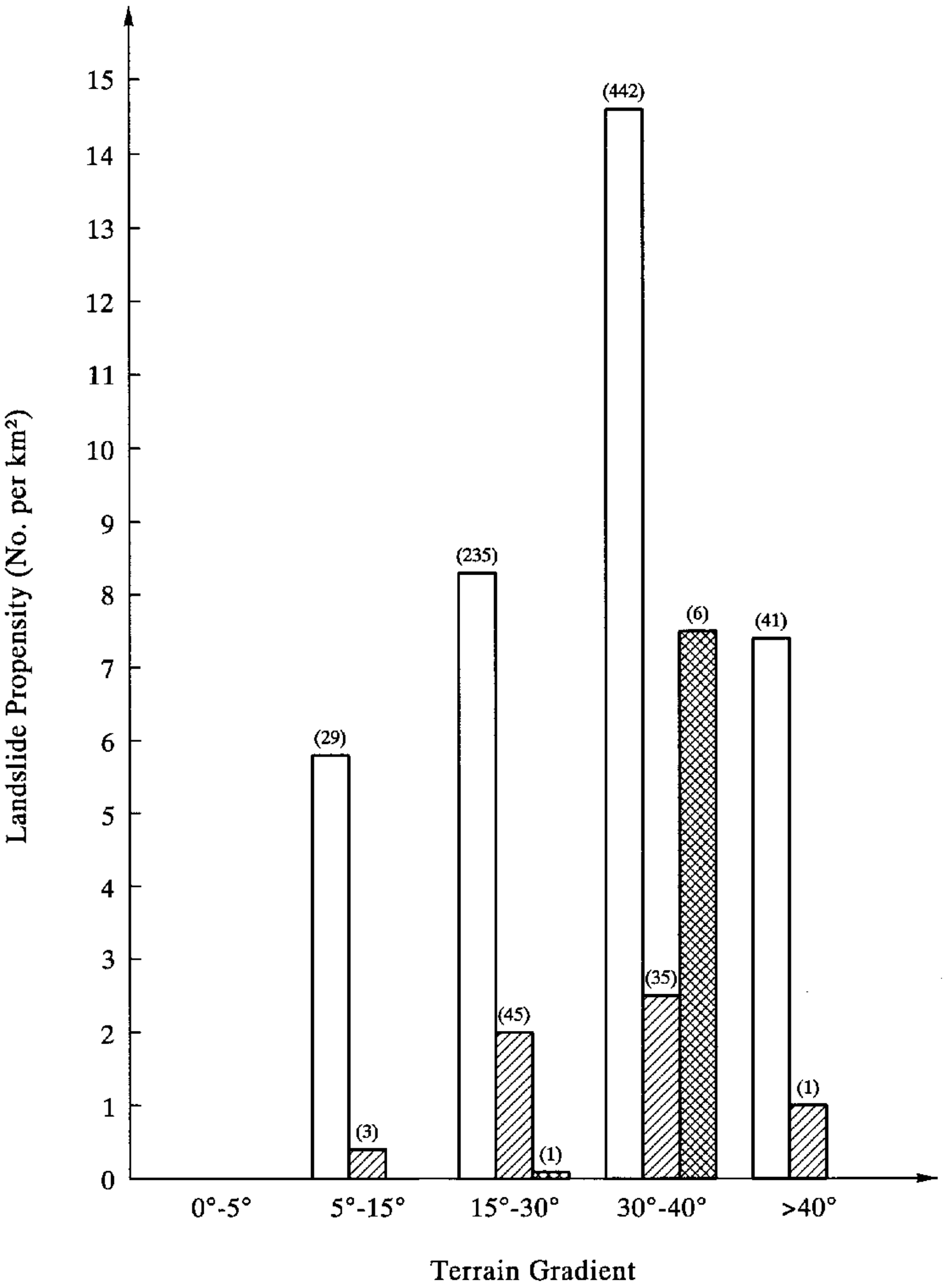
Note : Number of landslides given in blankets.

Figure 20 - Correlation of Landslide Propensity with Geological Units Based on GASP Data



Note : Number of landslides given in blankets.

Figure 21 - Correlation of Landslide Propensity with Terrain Gradient



Legend :

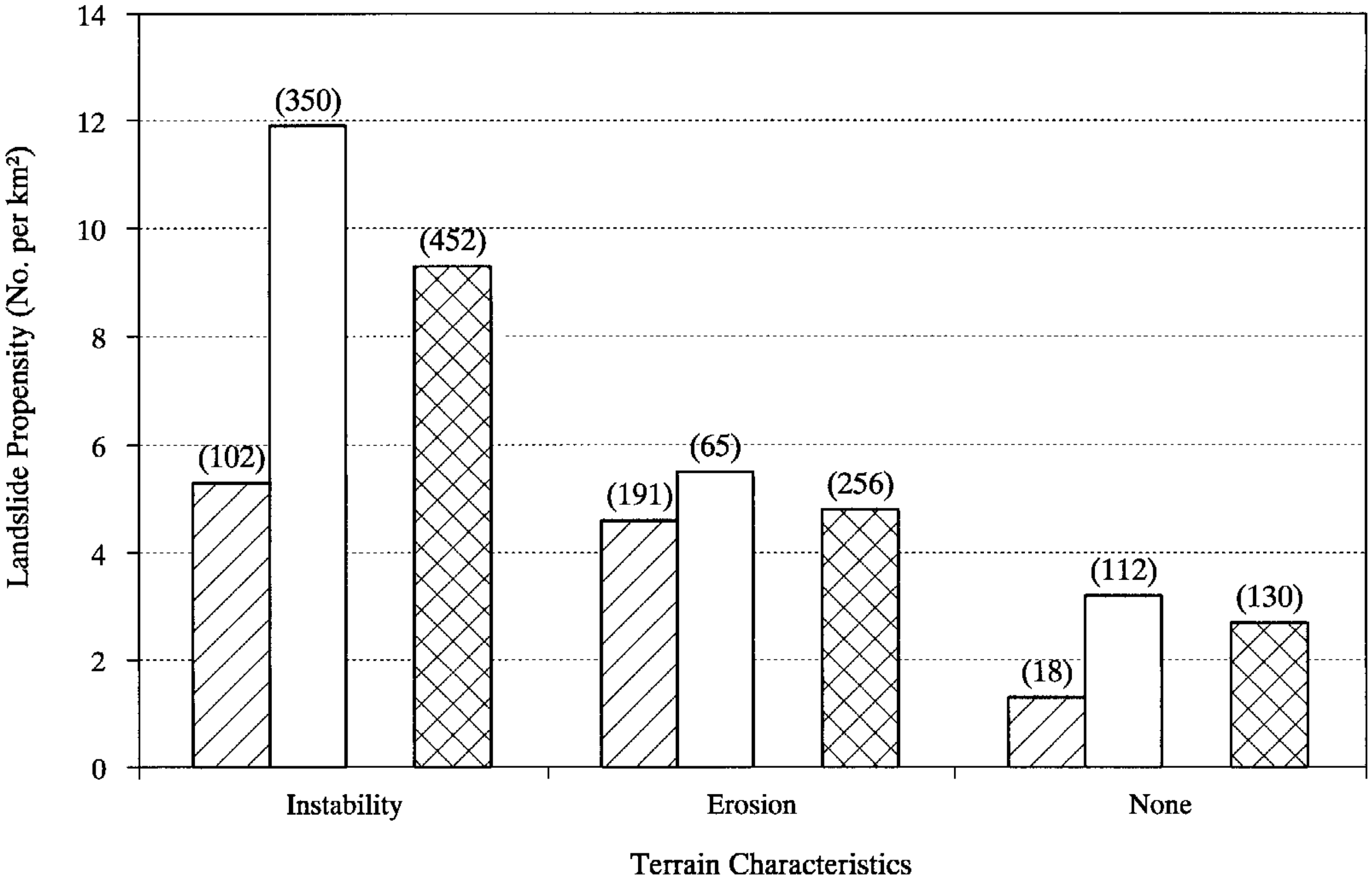
Volcanics

Granite

Others (including sedimentary and other rocks)

Note : Number of landslides given in brackets.

Figure 22 - Correlation of Landslide Propensity with Geological Unit and Terrain Gradient

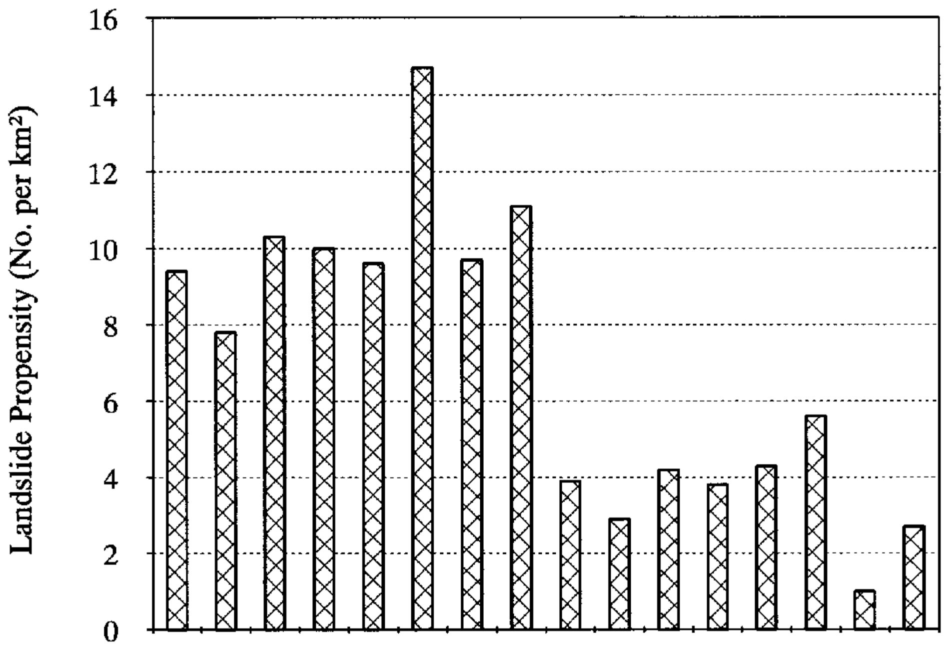


Legend :

▨ North Lantau □ South Lantau ⊠ All

Note : Number of landslides given in blankets.

Figure 23 - Correlation of Landslide Propensity with Terrain Units Identified in GASP as Having Been Subjected to Instability or Erosion



Terrain Component	C	D	M	A	B	C	D	M	A	C	D	F	A	D	G	H
Gradient	40° to 60°			30° to 40°					15° to 30°				5° to 15°			

Types of Landform

Legend :

A	Crest or ridge	F	Footslope - concave
B	Sideslope - straight	G	Footslope - convex
C	Sideslope - concave	H	Drainage plain
D	Sideslope - convex	M	Cliff / Rock outcrop

Notes :
(1) Data for South Lantau are shown. Detailed information on the types of landform in North Lantau is not available.
(2) See GCO (1988b) for a full list of terrain components. No landslide was found to have occurred on other types of landform.

Figure 24 - Correlation of Landslide Propensity with Landform

LIST OF PLATES

Negative No. SP94269C4

Plate 1 - Erosion Pipes Exposed at Back Scarp

APPENDIX A

NOMENCLATURE SYSTEM USED FOR RECORDING NATURAL TERRAIN LANDSLIDES ON LANTAU ISLAND

CONTENTS

A.1 NOMENCLATURE SYSTEM USED FOR RECORDING LANDSLIDES

A.1.1 Terminology

In this Report, "natural terrain" refers to land that is principally in a natural state, with negligible influence from human activities on its stability.

In the study, soil and rock were described in accordance with Geoguide 3 (GCO, 1988). The nomenclature recommended by the International Association of Engineering Geology (IAEG) Commission on Landslides and other Mass Movements on Slopes (IAEG, 1990) was adopted to describe features of the landslides.

The concept of rheological classification suggested by Pierson & Costa (1987) was followed in describing the nature of debris movement. To apply this rheological classification system, detailed information on the velocity of debris movement and the sediment-water state of the debris is required. Such information was not available for many of the landslides due to the limited data.

For the purposes of a factual documentation of the landslides, the following simplified classification of the nature of debris movement (as opposed to mechanism of failure initiation), based on the likely extent of influence by surface water (e.g. significant gully or sheet erosion of in-situ material or signs of any hydraulic sorting of the debris), was adopted in this report :

(a) 'Gravitational' (or 'Sliding') movement - this refers to debris movement which has arisen principally by virtue of its self weight without any significant influence from or action of surface water. The debris downslope movement may involve sliding, disintegration of the soil/rock mass, collision, bouncing and rolling, but the majority of the cases are believed to have involved principally sliding. Minor erosion and wash-out action may also occur, particularly subsequent to the deposition of the bulk of the debris. This typically occurs where the amount of surface water which could reach or mix with the debris is insignificant, e.g. landslides on essentially planar sloping terrain associated with a small catchment.

(b) 'Hydraulic' movement - this refers to debris movement which has arisen principally as a result of action of surface running water. This typically occurs where the debris is fed by a large amount of water which drives the debris downslope under a state of low solid content, e.g. debris movement along a major stream course with a large amount of running water.

(c) 'Mixed' movement - this refers to debris movement which is intermediate between 'Gravitational' and 'Hydraulic', i.e. both the self weight of the material and the effects of surface water might have considerable contribution to debris movement. This typically occurs where the landslide debris is mixed by a fair amount of surface water but the solid content still has an appreciable influence on debris movement, e.g. debris movement along a local stream course with a fair amount of surface running water. In practice, where debris movement cannot be clearly identified as 'Gravitational' or 'Hydraulic', it would be grouped under the 'Mixed' category.

The type of debris movement may be further classified as 'channelised' or 'non-channelised'. The term 'channelised' refers to the channelised transport of a significant load of debris.

A.1.2 Numbering System Used for Identifying Landslides

The following numbering system was used to identify the landslides :

(a) Where there is more than one landslide in the study area, the landslides in the area are numbered from east to west.

(b) Each landslide number is prefixed by a letter which denotes the study area, e.g. landslide A2 is the second landslide from the eastern boundary of Area A.

(c) Occasionally the debris trails of several landslides that are close to each other merge, and it is not practical to separate the debris trails further downhill. In such cases, the landslides are assigned a group number, e.g. A5, and the individual scarps are numbered according to this group number with a suffix added to distinguish between different scarps, e.g. A5A and A5B.

A.2 DEFINITIONS OF SYMBOLS

A.2.1 Landslide Source

The attributes are defined as follows :

(a) Geology :

1 colluvium
2 weathered volcanic
3 weathered granite
4 rock cliff/face

(b) Type of Failure :

1a thin colluvium above weathered rock
1b thin colluvium + weathered volcanic/granite above bedrock
1c weathered volcanic/granite above bedrock
2 rockfall generating subsequent failure
3a slip in thick colluvium
3b slip in thick weathered rock
4 slip associated with small cutting
5 multi-failure

(c) Special Features :

1 soil pipes
2 convergent flow of surface water
3 mechanism for development of perched water table

(d) Terrain Code :

As extracted from the relevant terrain classification map (Table A1)

A.2.2 Flow Path of Debris

The attributes are defined as follows :

(a) Geology :

1 colluvium
2 weathered volcanic
3 weathered granite
4 rock cliff/face

(b) Topography :

1 along relatively planar slope
2a along local depression
2b along well defined drainage channel
3 along convex surface

(c) Predominant Erosion Depth :

negligible	0.5	0.5 -1.0	1.0 -1.5	1.5 -2.0	2.0 - 3.0	3
n	a	b	c	d	e	f

(d) Mode of Erosion :

1 erosion within colluvium or weathered volcanic/granite mantle
2 bedrock exposed by erosion

(e) Deposition :

Mode -

1 primary - associated with landslip
2 secondary - deposition associated with erosion of primary deposit by surface water

Depth -

negligible	0.5	0.5 -1.0	1.0 -1.5	1.5 -2.0	2.0 - 3.0	3
n	a	b	c	d	e	f

Sorting -

x no sorting
y some sorting
z significant sorting

(f) Type of Debris Movement

G gravity/sliding
H hydraulic
M mixed (gravity/sliding + hydraulic)
N not classified

A.3 REFERENCES

Pierson, T.C. & Costa, J.E. (1987). A rheological classification of subaerial sediment-water flows. Debris Flows/Avalanche : Process, Recognition and Mitigation, Geological Society of America, Boulder, Colorado, pp 1-12.

LIST OF TABLES

Table A1 - Legend for Terrain Classification Map

(a) North Lantau

Slope Gradient	Code	Terrain Component	Code	Erosion	Code
0 - 5°	1	Crest or ridge	A	No appreciable erosion	
5 - 15°	2	Sideslope - Straight	B	Sheet erosion - minor	1
15 - 30°	3	- concave	C	- moderate	2
30 - 40°	4	- convex	D	- severe	3
40 - 60°	5	Footslope - straight	E	Rill erosion - minor	4
>60°	6	- concave	F	- moderate	5
		- convex	G	- severe	6
		Drainage plain	H	Gully erosion - minor	7
		Floodplain	I	- moderate	8
		Coastal plain	K	- severe	9
		Littoral zone	L		
		Cliff/Rock outcrop	M	Well defined - integral - recent	a
		Cut - straight	N	landslip - relict	b
		- concave	O	> 1 ha - scar - recent	c
		- convex	P	in size - relict	d
		Fill - straight	R	- debris - recent	g
		- concave	S	- relict	k
		- convex	T		
		General disturbed terrain	V	Development - integral - recent	n
		Reclamation	Z	of general - relict	o
		Alluvial plain	X	instability - scar - recent	p
		Waterbodies - Natural stream	1	- relict	r
		- Manmade stream	2	- debris - recent	s
		- Water storage dam	3	- relict	t
		- Fish pond	4		
				Coastal - integral	w
				- scar	y
				- debris	z

(b) South Lantau

Slope Gradient	Code	Terrain Component	Code	Erosion	Code
0 - 5°	1	Crest or ridge	A	No appreciable erosion	
5 - 15°	2	Sideslope - straight	B	Sheet erosion - minor	1
15 - 30°	3	- concave	C	- moderate	2
30 - 40°	4	- convex	D	- severe	3
40 - 60°	5	Footslope - straight	E	Rill erosion - minor	4
>60°	6	- concave	F	- moderate	5
		- convex	G	- severe	6
		Drainage plain	H	Gully erosion - minor	7
		Floodplain	I	- moderate	8
		Coastal plain	K	- severe	9
		Littoral zone	L		
		Cliff/Rock outcrop	M	Well defined landslip	a
		Cut - straight	N	> 1 ha in size	
		- concave	O		
		- convex	P	General instability - recent	n
		Fill - straight	R	- relict	r
		- concave	S		
		- convex	T	Coastal instability	w
		General disturbed terrain	V		
		Reclamation	Z		
		Alluvial plain	X		
		Waterbodies - Natural stream	1		
		- Manmade stream	2		
		- Water storage dam	3		
		- Fish pond	4		

APPENDIX B

DESCRIPTION OF CHARACTERISTICS OF TERRAIN COMPONENTS ON LANTAU ISLAND

CONTENTS

B.1 GEOTECHNICAL AREA STUDIES PROGRAMME

B.1.1 General

A Geotechnical Area Studies Programme (GASP), which aims to provide systematic geotechnical input for land management and development planning, was carried out by the Geotechnical Engineering Office between 1979 and 1985. GASP covers the whole territory of Hong Kong.

In GASP, Lantau Island has been divided into two regions, namely North Lantau and South Lantau (Figure 1), separated by the main east-west watershed associated with Lantau Peak and Sunset Peak. The results of the area geotechnical study of North Lantau at a scale of 1:20 000 are given in GASP Report VI (GCO, 1988a), and those of the corresponding study for South Lantau given in GASP Report XI (GCO, 1988b). The relevant data are described in the following sections.

B.1.2 North Lantau

North Lantau has an area of 7 403 hectares. The topography of the area is characterised by a narrow coastal plain, which rises rapidly over undulating footslope terrain, to an almost northeast trending range of ridges.

The area is mainly underlain by volcanic rocks of the Repulse Bay formation, and the younger granitic suite of rocks. Terrain in decomposed granite is typically of low, undulating relief. Steep terrain is generally associated with the volcanic rocks. Colluvial deposits exist over much of the footslope terrain as extensive blankets, or occur adjacent to drainage lines associated with volcanic terrain.

The North Lantau terrain is generally steep with 70% of the area steeper than 15°.

A large portion (63%) of North Lantau is classified as being of sideslope, of which about 24% is steep (>30°) sideslope.

The condition of the terrain has been classified in terms of erosion and instability. About 25% of the area is assessed as having been affected by past instability.

B.1.3 South Lantau

South Lantau has an area of 7 589 hectares. The area is mainly underlain by volcanic and volcaniclastic rocks. Less than 20% of the area is covered by intrusive granitic rock, which can be found mainly in the Chi Ma Wan Peninsular. Major areas of steep terrain exist around the ridges which trend southwest from Lantau Peak, and on the upper sideslopes to the southeast of Sunset Peak.

More than 80% of the area has a gradient steeper than 15°. About 45% of the terrain in South Lantau is steeper than 30°, while that of North Lantau is about 24%.

A large portion (73%) of South Lantau is classified as sideslope landform, among which more than 40% is steeper than 30°.

About 54% of the area is affected by instability or erosion.

B.2 PILOT STUDY AREAS

B.2.1 Study Area A

Study Area A is located in the southeast sideslope of Sunset Peak (Figure 1). It covers an area of about 130 hectares, within which 62 natural slope landslides occurred in the November 1993 rainstorm. The area is traversed by a narrow unpaved footpath at about 350 mPD. The slopes above the footpath are generally steeper than 30°. The slopes below the footpath are less steep, and are in general less than 30°. The footpath is about 1m wide, with small cuttings (within 2 m high) and fills on each side.

Geological maps of scale 1:20 000 are available for the area (Sheets 9 and 13, Series HGM20, prepared by the Hong Kong Geological Survey in 1994). The bedrock in the study area is volcanic rock of Repulse Bay Formation. The volcanic rock can be further divided into Rhyolite lava and tuff, and Rhyolite lava.

B.2.2 Study Area B

Study Area B is located in the south-facing sideslope below Ngong Ping Plateau (Figure 1) and is within the catchment area of Shek Pik Reservoir. It covers an area of about 100 hectares, with 52 natural slope landslides in the November 1993 rainstorm. The study area is traversed by the east-west aligned Lantau Trail at about 240 mPD. This hiking trail is an unpaved footpath with a width of about 1m. It connects Keung Shan Road to the Ngong Ping Plateau. Starting from Keung Shan Road, the gradient of the natural slope above the trail varies from about 33° for the first 350m section, to about 37° for the central 500m section, and about 30° for the last 450m section. Below the trail, the gradient of the natural terrain is generally less than 30°. Small (less than 2 m in height) cuttings and fills are present on each side of the trail.

According to the available 1:20 000 geological map (Sheet 9, Series HGM20, prepared by the Hong Kong Geological Survey in 1994), the area is underlain by volcanic rock of the Repulse Bay Formation. The volcanic rock can be subdivided into Rhyolite lava and tuff, and tuff and tuffite.

B.2.3 Study Area C

Study Area C is located near Pak Kung Au at about 1 km to the west of Area A (Figure 1). One landslide in this area, which resulted in a mobile debris, was studied. The landslide occurred at a small valley at about 410 mPD. The debris travelled about 180m downslope until it met a stream course at about 340 mPD. The average slope gradient is about 21°.

The bedrock geology in the landslide location is Rhyolite lava and tuff.

APPENDIX C

SLOPE STABILITY ANALYSES

CONTENTS

C.1 INTRODUCTION

The depth to length ratio of the landslide scarps inspected in study areas A, B & C are in general low and hence the landslides can be analyzed using infinite slope assumptions.

The Factor of Safety, F, is given by :

$$F = \frac{c' + (\gamma D - \gamma_w h_w) \cos^2\alpha \tan\phi'}{\gamma D \sin\alpha \cos\alpha}$$

where c' = cohesion intercept
ϕ' = angle of shearing resistance
D = depth of weaker soil
h_w = height of water table above the base of weaker soil
γ = bulk unit weight of soil
γ_w = unit weight of water
α = slope gradient

C.2 SLOPE STABILITY ANALYSES

The calculations were performed using a spreadsheet program. Slope gradients ranging from 25° to 45° were considered. The shear strength parameters were taken as $c' = 2$ to 5 kPa and $\phi' = 37°$ (the possible increase ϕ' due to presence of coarse fragments has been allowed for following the recommendations by Irfan & Tang, 1993), and the soil bulk unit weight was taken as 18 kN/m^3. The heights of the water table for a factor of safety of unity for different combinations of conditions were calculated. The results are shown in Figure C1.

The scenario considered in the analyses relates to a thin surface colluvium, or a relatively weak and permeable saprolitic soil of limited thickness overlying stronger less permeable partially weathered rock where there is sufficient permeability contrast for the development of a perched water table.

LIST OF FIGURES

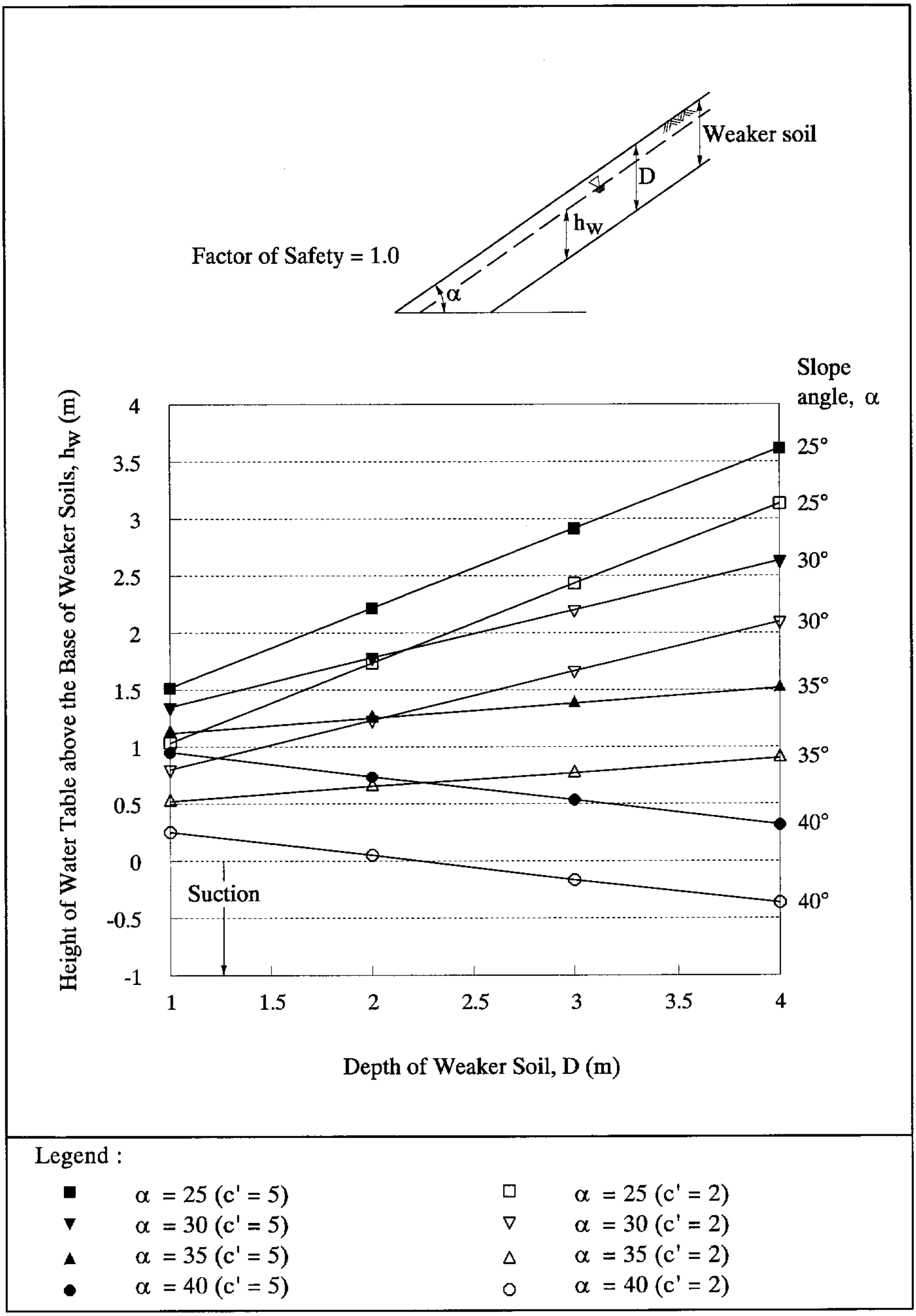


Figure C1 - Results of Infinite Slope Analyses

LIST OF DRAWINGS