STUDY OF RAINFALL INDUCED LANDSLIDES ON NATURAL SLOPES IN THE VICINITY OF TUNG CHUNG NEW TOWN, LANTAU ISLAND

GEO REPORT No. 57

C.A.M. Franks

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

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

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PREFACE

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Andrew Malone
Principal Government Geotechnical Engineer
January 1998

FOREWORD

This report documents the methodology, results and conclusions of a study of some recent and relict rainfall induced landslides on natural slopes overlooking the Tung Chung New Town Development Area.

The study was focused on landslides that occurred during heavy rainfalls in 17 July 1992 and 5 November 1993. The study also examined the evidence for previous landslides primarily from examination of aerial photography. The geomorphological, geological and other factors that may influence the generation of rainfall induced landslides were examined. The study also proposes a number of rainfall induced landslide models to describe the characteristic landslides observed.

The study was carried out by Dr C.A.M. Franks. The comments made by Dr R.P. Martin, Dr T.Y. Irfan, Mr W.C. Au, Mr H.H. Choy, Dr R.J. Sewell, Mr P. Kirk and Mr J.P. King on the draft report were considered when finalising the report. The report drawings and maps were produced by technical officers Mr P.C Cheng and Ms W.L. Chan under the supervision of Mr K.W. Cheung and Mr P.C. Kam respectively. Their contributions are gratefully acknowledged.

H.H. Choy
Atg. Chief Geotechnical Engineer/Planning

ABSTRACT

This report describes the methodology, results and conclusions of a study of some recent and relict rainfall induced landslides on natural slopes overlooking the Tung Chung New Town Development Area.

The study was carried out to document the characteristics of these landslides and to define the criteria that may be appropriate to develop a hazard assessment and zoning method. The study was focused on landslides that occurred during heavy rainfalls in 17 July 1992 and 5 November 1993, when over 80 landslides occurred in the study area. The study also examined the evidence for previous landslides primarily from examination of aerial photography. The study examined the geomorphological, geological and other factors that may influence the generation of rainfall induced landslides. The study also proposes a number of landslide models to describe the characteristic landslides observed.

The results of the study indicate that channelised debris flow landslides are potentially the most hazardous as they result in larger volumes of mobilised debris with long debris trails. The debris from these long trails may impact on developable land. The maximum magnitude landslide, estimated from field observation, comprised of approximately 2000 m^3 of debris and was a channelised debris flow that occurred during the November 1993 rainstorm. This landslide had a total trail length of 450 m from the scarp at 180 mPD (35° slope) and deposited debris on a development platform at 24 mPD.

The limited data set indicates that for channelised debris flows the lower limit of slope angles on which deposition takes place (deposition point) is 8° whilst for non-channelised landslides the lower limit of slope angles on which deposition of debris takes place is 10°. The average runout distance from the deposition point is 28 m and 47 m for non-channelised and channelised debris flows respectively. However, the range of runout distance is quite large for both types of landslide.

CONTENTS

1. INTRODUCTION

1.1 General

In October 1989 the Hong Kong Government announced its intention to proceed with the construction of a new international airport at Chek Lap Kok. As part of the associated infrastructure development a new town is planned at Tung Chung (Figure 1). The Recommended Outline Development Plan for Tung Chung was issued in March 1992 (TDD, 1992). Parts of Packages 1, 3 and 5 are adjacent to steep natural slopes (Figure 2). Construction of the Phase I area of the new town (which includes parts of packages 1 and 3) started in 1992. The Phase II construction of Package 3 commenced in 1994. Phase II, Package 5 construction will commence in 2000 and continues through to 2006.

Previous studies (GCO, 1988a ; Franks, 1991, 1992 and Woods, 1993) indicated that much of the area covered by North Lantau was subject to high to extreme geotechnical constraints to development. The Tung Chung area is no exception as most of the hillsides are steep (> 30°), the peaks are amongst the highest in the Territory and the slopes are covered with colluvium, or soils derived from weathered bedrock. These soils are often prone to instability during or following periods of heavy rainfall. Woods (1993) highlighted several areas where landslide hazard was deemed to pose a significant constraint to downslope development (Section 6.1).

A major landslide from a natural slope on Tsing Shan (Castle Peak) occurred in 1990 and had a debris runout of 390 m (Langford & Hadley, 1991). Although this landslide is not in the Study Area it heightened the awareness of this potential geological hazard and the risk to developments located at some distance from a landslide site. Subsequent heavy rainfalls in July 1992 and November 1993 resulted in widespread landslides in North Lantau. This prompted a more detailed investigation of the potential landslide hazard in the Tung Chung area which is geographically similar to the Tsing Shan landslide area.

This report documents the study of rainfall induced landslides from natural slopes in part of the Tung Chung Development Area.

1.2 Objectives

The intention of this study is to characterise and define the extent of landslide main scarps and associated deposits, predominantly resulting from the 1992 and 1993 rainstorms, that exist on natural slopes overlooking the proposed development area of the Tung Chung New Town. The study also documents and examines the geomorphic and other factors (such as rainfall and vegetation) present at a number of the landslide sites and attempts to define relationships between these factors and the sites.

The study is intended to be carried out in two phases with the phase one being a documentation of landslides on natural slopes in part of the Tung Chung Development Area. The results of the study will be used to develop a landslip hazard zoning for the area in phase two.

The initial intention was to locate areas of significant hazard potential and then to carry out more detailed ground investigation of the materials. However a review of the initial results from a pilot ground investigation study of the Tsing Shan landslide (King, in prep.) indicated that significant cost would be involved with an uncertain return in terms of the direct applicability of the results to an area hazard study. Although detailed ground investigation of the potential landslide source materials was deleted from the study a few water replacement in situ density tests were carried out in colluvium materials exposed in the Tung Chung New Town area (Section 5.4.2).

This phase of the study is focused on defining and documenting the landslide mechanisms that are prevalent within the study area to determine the trail length and runout distances and factors controlling these.

1.3 Location of the Study Area

The Study Area is centred on Tung Chung, midway along the northern coast of Lantau Island (Figure 1). Following preliminary field work and aerial photograph interpretation (API) of the area, the incidence of recent significant landsliding was confirmed to be confined to the eastern part of this region primarily within sheet 9-SE-B. The study was therefore focussed on this area (Section 3.1) and covers a land area of about 800 ha.

The western boundary of the area extends from the eastern side of the old Tung Chung town (Ma Wan Chung) and southwards to the hills overlooking the old Tung Chung Fort. The southern boundary of the Study Area continues eastward from these hills along the main catchment boundary to Pok To Yan. The eastern boundary of the area coincides with the coastline at the headland midway between Tai Po and Pak Mong.

2. STUDY METHODOLOGY

2.1 General

Site inspection of previous landslide scarps and colluvium deposits in the Tung Chung area was carried out in combination with API and assessment of previous terrain classification mapping (Emery and Houghton, 1991). This involved walk-over surveys to verify the API and limited mapping of colluvium exposed by the current construction activities (Tables 1 and 2).

2.2 Desk Study

A desk study was carried out to examine all available documented geological and geotechnical information directly relevant to the Study Area as well as a technical review of methodologies relevant to the study. The documents examined included : -

(a) Ground investigation and laboratory testing reports from the Geotechnical Information Unit of the Civil Engineering Library. These include the insitu density test reports on colluvium in Tung Chung : i) CED Contract No. GE/93/08 - Ground Investigation, NT West Term Contract, Lam Geotechnics Ltd., and ii) Lab. Testing Report GEO/97/113, Hong Kong Testing Co. Ltd.

(b) GASP Report VI, North Lantau (GCO, 1988a). The Geotechnical Land Use Map accompanying this report indicates that a large proportion of the Study Area has high to extreme geotechnical limitations to development.

(c) Unpublished terrain classification maps for the four 1 : 5000 map sheets covering the Study Area. These maps were prepared by Mr Keith Emery of the Department of Land & Water Conservation formerly the Department of Conservation and Land Management (CaLM) of New South Wales, Australia, under a previous consultancy agreement with the GCO.

(d) Aerial photographs of the area dating back to 1945. A list of the aerial photographs examined is given in Table 5.

(e) 1 : 5000 geology maps for map sheets 9-SE-A,-B,-C and -D, prepared by the Hong Kong Geological Survey. 1 : 20000 geology map for sheet 9 and geological memoir No. 6.

(f) The results of previous and existing studies of colluvium undertaken by GEO including the Mid-Levels studies (GCO, 1982), the more recent studies of Tsing Shan debris flow and flood carried out by King (in prep.) and some papers on landslide hazard and risk assessment methodology, e.g. (Fell, 1994).

2.3 Field Study

The majority of the fieldwork was carried out between mid-January and April 1994. Because of the steepness of the terrain and the size and remoteness of the area, considerable use was made of Government Flying Service helicopters to maximise the time spent on site. Access to much of the coastline was made by boat. Many of the landslide sites identified from API were located in densely vegetated and steep terrain which was often difficult or impossible to access.

From the more than 80 recent scarps identified from API some 52 were inspected in the field. During the fieldwork, observations were made of the landslide type, scarp and debris trail morphology including the nature of the materials involved, hydrogeology and vegetation at a number of the landslide sites. The steepness of the terrain, evidence of past instability, erosion and hydrological features were also noted. The completed field sheets are summarised in a landslide database for Tung Chung in dBase format (Section 6.2 and Appendix B).

3. SITE DESCRIPTION

The Study Area comprises mostly rugged, mountainous terrain which rises rapidly in elevation away from the coastline. Major peaks within the study area include Pok To Yan and Por Kai Shan with elevations of 529 mPD and 482 mPD respectively in the southern and eastern part of the area.

The steepness of the terrain in the area is well illustrated by Figure 3, which shows land with a slope gradient greater than 30 degrees. Also, in many places there are precipitous cliffs, as for example on the southern slopes of Pok To Yan.

The only significant areas of flat-lying land are the low-lying, alluvial plains in the vicinity of Tung Chung (Plate 1) and the alluvial fans which project into the sea in the vicinity of Tai Po (Figure 1).

The sideslopes of the major valleys are generally steep. However, lower down, slope gradients diminish as they approach the valley floor, especially where the slopes are blanketed by colluvium. The ground profile over ridge crests varies from very sharp, as for example Pok To Yan (Plate 2), to well rounded, as for example over the north-south trending ridgeline of the hills to the south of Tung Chung Fort (Plate 3).

4. EXISTING AND PROPOSED DEVELOPMENTS

4.1 General

Prior to the start of construction work for the airport at Chek Lap Kok, the population in the area numbered less than 3000. The majority lived in the villages in and around the flat, low-lying area in the vicinity of Tung Chung, especially the main village of Ma Wan Chung.

The broad, flat, low-lying plains in Tung Chung were previously devoted primarily to the cultivation of rice but have long since been abandoned. The land was previously largely undeveloped, although this is rapidly changing as a result of the Tung Chung Development.

Scars associated with old mine workings are found on the hills around Wo Liu Tun, in the area between the Wong Lung Hang and Tung Chung valleys.

4.2 Future Developments

The major new developments will be the Tung Chung New Town and associated access roads and support facilities, North Lantau Expressway, and Airport Railway.

The alignment of the North Lantau Expressway is mostly on reclamation (Figure 2), however, as the route curves inland to approach the site of the new airport at Chek Lap Kok some high cuts have been formed in the steep hillsides. The Airport Railway follows a similar alignment. Much of the Tung Chung New Town will be accommodated on the flat-lying land in the vicinity of Tung Chung. The only significant excavation into hillslopes are around the peninsula directly to the east of Tung Chung, along the southern, uphill side of the North Lantau Expressway and along the southern side of the eastern portion of Road P2. The service reservoir site, situated on the hill at Ling Pei above Tung Chung Fort, required considerable earthworks and in the process removed several landslide scarps (Figure 2).

Prior to 1997 the majority of the development will be on reclamation between Lau Fau Sha and Tai Po. Further development, to the east of Tai Po and in the Tung Chung valley, is planned up to the year 2011, with only relatively minor development beyond that date (TDD, 1992).

5. ENGINEERING GEOLOGY

5.1 General

The engineering geology of the study area is based primarily on a review of the previous engineering geology study of Tung Chung (Woods, 1993), and observations from limited field work. The North Lantau database, which contains recent ground investigation data for the North Lantau development area has also been interrogated to provide additional data not available at the time of the previous study by Woods (1993).

5.2 Solid Geology

Bedrock in the area is dominated by Mesozoic volcanic rocks (Langford et al, 1995 ; Langford et al, 1996). Along the coastline however, and extending a short distance inland, the bedrock is formed of intrusive granitoid rocks. These include feldsparphyric rhyolite, which extends from Tung Chung eastward to Pak Mong. Narrow dykes of lamprophyre and basalt are found within the feldsparphyric rhyolite and are rare within the volcanics. Quartz veins are common within all rock types.

The volcanic rocks consist mainly of tuff and lava which are commonly banded. The former include both fine and coarse ash types. Thick horizons of sedimentary rocks including siltstones, mudstones and sandstones as well as tuffites (redeposited pyroclastics), are known to occur within the volcanic sequence to the south of the study area but their extent within the immediate study area is not well defined.

The feldsparphyric rhyolite forms the predominant bedrock along the coastline from Tung Chung to Pak Mong and occurs as a dense swarm of dykes which generally trend in an ENE or NE direction. At the eastern extreme of the study area below the peak of Pok To Yan it extends less than 400 m inland where it has a faulted, NE-trending contact with the older volcanic rocks of the Lantau Formation. This contact is obscured by colluvial deposits overlying the bedrock.

5.3 Geological Structure

The fault pattern of Hong Kong has a well defined northeast, northwest and north-northwest pattern. A number of faults exist within the Study Area and coincide with major photogeological lineaments identified during this study (Figure 4). Woods (1993) has confirmed that the principal joint sets conform well with the orientations of the major faults.

5.4 Superficial Geology

5.4.1 General

For the purpose of this report, superficial deposits are defined as materials which have been transported by water action or gravity and which mask both the underlying bedrock and its associated mantle of weathering products. The superficial deposits include colluvium and alluvium. However, as significant amounts of alluvium are not found on the hillslopes it is not considered further in this report. No detailed mapping of the distribution of different classes of colluvium or other superficials has been carried out as this was outside the scope of work for the study.

5.4.2 Colluvium

Fairbridge (1968) defined colluvium as heterogeneous materials which have accumulated on the lower parts or at the base of slopes through the action of gravity, soil creep, sheet erosion, slope-wash or debris flow. Criteria for recognising colluvium and distinguishing it from residual soils, are outlined by Huntley and Randall (1981), GCO (1982), Ruxton (1988) and more recently by Irfan and Tang (1992). Different ages of colluvium have been recognised in Hong Kong and it is likely that much of the colluvium was deposited from the mid-Pleistocene through to the Holocene. Three classes of colluvium were identified in the Mid-Levels study (GCO, 1981) and are assumed to be widespread throughout the Territory. These classes have been further subdivided into sub-classes at other sites based on engineering considerations by Irfan & Tang (1992). For the purposes of this study the criteria given in GCO (1982) have been used for describing the colluvium (Table 1).

Deposits of colluvium are widespread in the study area, as can be seen in Drawing No. EG369. The extent of colluvium shown on this drawings is based on API by CaLM Consultants to the GCO, with minor modifications by Woods (1993) from subsequent API and field checking. Deposits of colluvium occur most commonly as ribbon-like deposits infilling drainage courses (Plate 4). Such deposits are likely to be not much thicker than 2 or 3 metres. There are however deposits which are considerably thicker and of greater areal extent, particularly within the alluvial plain of Tung Chung and, on some hillslopes in the Study Area. Of particular note are the large deposits which occur on the north-facing hillslopes to the south and southwest of Tai Po (Plate 5). A number of drillholes in these deposits indicate the thickness is generally up to about 10 m thick, although a maximum thickness of 17.5 m was recorded in Borehole No. TRL103, near the youth camp at Tai Po.

The character of colluvium is best seen in exposures, rather than from samples obtained from boreholes. Exposures of colluvium in road cuttings for the Tung Chung New

Town access road Phase 1 area below Pok To Yan (Plate 6) demonstrate the wide grading of the material comprising these deposits. The colluvium observed in exposures typically consists of cobbles and boulders, of primarily feldsparphyric rhyolite with some tuff, in a matrix of mottled reddish brown and yellowish brown gravelly, sandy, slightly clayey silt. The cobbles and boulders are typically subangular and moderately to highly decomposed with a patina up to 50 mm thick. Test pits excavated into this material (Plate 7 and Table 2) indicate bulk insitu density of 2.2-2.3 Mg/m^3 for the overall deposit using the water replacement method and 1.7 Mg/m^3 for the matrix using the sand replacement method (with in situ moisture content in the range 10.7-16.6%). The mottled nature, relative high density of the deposit and presence of a patina on the coarse materials indicates that the colluvium is of intermediate age, which is equivalent to Class 2 using the definitions from the Mid Levels Area study (GCO 1982). Isolated lobes of younger (Class 3) colluvium were also noted across this site and are characterised by a less compact structure of the matrix and the colour being light yellowish brown (Plate 8).

In areas of colluvium, the ground surface is commonly very bouldery with individual boulders often measuring several metres across (Plate 9). Also, stream courses which pass through areas of colluvium are generally choked with large boulders.

5.5 Residual Soils and Saprolite

The bedrock in this area, as elsewhere in Hong Kong, has been subject to weathering over a very long period of time, and this process continues today. Bennett (1984) considers that the development of thick weathering profiles in the region commenced in the Late Pliocene.

The typical thickness of saprolite across the study area is around 5 to 10 m, however there are a number of localities where the weathering depth is much greater. Boreholes drilled into the slopes to the south of Tung Chung fort indicated depths of weathering in the range 20 to 30 m and it is likely that this is the result of pre-existing hydrothermal alteration. Mining activity in these hills has previously been noted by Woods (1993) and this tends to support the view that mineralisation associated with hydrothermal processes have been prevalent. The north west facing slopes to the south of Tai Po also appear to be deeply weathered at a number of locations and this may be associated with the major north-east trending fault (Figure 4) that truncates the predominantly volcanic sequences to the south from the feldsparphyric rhyolite which forms the lower angle footslopes along the coastline.

5.6 Hydrology

The major valleys, including the main Tung Chung valley, and the Wong Lung Hang valley, are all remarkably straight in plan and are evidently structurally controlled (Woods, 1993). Their orientations conform well with the regional structural pattern. Other smaller stream courses, many of which are ephemeral, simply drain from high points near ridge crests directly down to the stream courses in the major valleys.

The streams draining the slopes in the study area generally flow in a northeasterly or northwesterly direction. A perennial stream to the south of Pok To Yan follows a major photolineament and flows in a northeasterly direction to join the prominent northwesterly flowing stream that flows towards Ma Wan Chung along the valley extending from the catchwater below Lin Fa Shan (Figure 4). The northern slopes of Pok To Yan are drained by numerous small streams most of which only flow after or during heavy or prolonged rainfall. The hillsides are often deeply gullied as a result of erosion caused by ephemeral streams. The catchment boundaries interpreted from the topographic base maps reveal a complex system of narrow long catchments associated with these gullies within a much larger main catchment formed by the ridgeline divide.

Along the coast numerous springs and seepages are evident, during the dry season, at the contact between partially weathered bedrock zones PW 0/30 and PW 50/90 (GCO, 1988b). Further upslope the location of springs or near surface groundwater is difficult to determine due to the dense vegetation cover. However, using API, it is sometimes possible to infer the presence of springs from changes in vegetation growth.

5.7 Groundwater

Examination of records from piezometers installed in boreholes across the study area for previous site investigations indicates that in general the regional groundwater table lies within partially weathered bedrock zone PW 50/90 or within the immediate overlying saprolite. The relative permeability of colluvium deposits when compared with underlying saprolite allows for the development of transient perched water tables at the interface during or following periods of intense rainfall.

6. LANDSLIDE CLASSIFICATION AND CHARACTERISATION

6.1 General

Fell (1994) has suggested that the probability of a particular landslide occurring can be determined in a number of ways ; i) probabilistic methods, ii) historical data, iii) rainfall relationships, and iv) using geomorphological and geotechnical data.

Of these methods perhaps the latter three offer the best scope for further development and form the basis of this study as it is considered that the existing stability of natural slopes in an area serves as a guide to the likely future stability of the slopes. In this regard slopes which show signs of repeated instability, either in terms of active regression of individual scarps or in a broader sense where repeated failures are observed over time within the same catchment, are considered to be indicative of future likely instability.

The relationship of rainfall to landslides has been studied previously and is well documented for Hong Kong conditions in relation to man-made slopes (Brand et al, 1984 ; Premchitt, 1991), but less so for natural slopes. This aspect is covered in more detail in Section 7.

A number of terms are used to describe the landslide features in this study and these are fully defined in Appendix A. Using this scheme the *source* area of the landslide is defined by a *surface of rupture* which comprises the *main scarp* and scarp *floor*. Downslope of the *source* is the landslide *trail* which together with the *source* forms a landslide *scar*.

The term *relict* as used in this report refers to landslides that have scars that are still well defined. In terms of this study *recent* landslides are those that occurred as a result of the 1992 and 1993 rainstorms. Assessment of available aerial photography from 1945 until 1994 at a variety of flying heights has proved to be useful in identification of both *relict* and *recent* landslides as well as those areas which have continued to show signs of general instability.

Previous studies in the area have included ; the GASP study (GCO, 1988a) at a scale of 1 : 20 000 for which terrain classification mapping (TCM) using API was carried out, and a regional engineering geology study at a scale of 1 5 000 (Woods, 1993). The latter study also included detailed TCM at a scale of 1 : 5,000. The engineering geology study and in particular the TCM for that formed a useful thematic data set for the current study.

The study by Woods (1993) highlighted locations in the Tung Chung area where landslides on natural slopes appear to have been generally more prolific than at other sites. Additional detailed API for the present study has further defined these locations. Within the confines of the study area, these are (see Drawing Nos. EG 369, EG 490 & EG 491) :

(a) hillslopes on the northern side of Pok To Yan,

(b) hills directly above and south of Tung Chung Fort.

In general, the relative incidence of both *relict* and *recent* landsliding on natural slopes elsewhere within the study area is considered to be low.

Almost all of the planned development in Tung Chung is either on flat lying or very gently sloping land or on reclamation. However, some of these developements are at the toe of steep natural slopes. Hence, natural slope failures will only be of consequence in terms of the encroachment of landslide debris into areas of development. The types of natural slope landsliding that commonly occur on slopes in the study area include *debris flows,* and *channelised debris flows* (viz. debris torrents, Hungr, 1984). The term channelised here refers to the channelised transport of a significant load of sediment that may include landslide debris.

Debris flows, which invariably occur during periods of prolonged or heavy rainfall, and which involve highly mobile, saturated material, can travel long distances when the debris is *channelised.* This type of landslide is potentially the most hazardous because of the rapid flow mechanism, long trail length and consequent run out.

An example of this type of failure is the debris flow in 1991, on the eastern flanks of Tsing Shan near Tuen Mun New Town, which involved many thousands of cubic metres of debris. It occurred during a typhoon with 140 mm of rainfall recorded in the 6 hours directly preceding the incident. From the top of the failure scar to the toe of the debris trail was a distance of approximately 1025 m, with a drop in elevation of about 390 m (Chan et al, 1991).

The debris flow was apparently initiated by a relatively small joint controlled failure on the steep rock slopes which flank the summit of Castle Peak.

The Tsing Shan debris flow study (King, in prep.) documented in some detail the characteristics of a *channelised debris flow* and outlined a proposed method of hazard assessment for the siting of developments within the probable flow path of a design debris flow from within the catchment.

6.2 Landslide Database

Some 52 of the more than 80 landslides which were activated during the 1992 and 1993 rainstorms, were accessible and field surveyed to gather detailed data. A landslide database was developed to assist in the study of the landslide characteristics in the study area. The format of the database is given in Appendix B. The complete data set is held in GEO file GCP 2/A3/5. The information recorded includes data relating to the landslide source (main scarp and surface of rupture) and data relating to the associated landslide trail as shown below. The ranges of the data relating to some of the attributes shown below are given in Tables 3 and 9.

Source	Trail	
natural slope angle	slope angle of trail	erosion
depth of scarp	depth	morphology
width of scarp	width	terrain classification
length of surface of rupture	length	previous instability
displaced material	displaced material	drainage order
previous activity	substrate	vegetation
		predominant characteristic

The data were measured either from field survey or estimated by API. API was used to determine spatial and temporal distribution of the landslides as well as some limited geometric data for those sites which could not be accessed in the field. Terrain Classification Mapping (TCM) data were also added to the database. The TCM data were obtained from mapping previously undertaken for the GEO by consultants from CaLM at scale of 1 : 5,000. The available rainfall data from rain gauges close to the study area were also input to the database.

The data were analysed to determine the range of typical geometric and volume characteristics of the landslides in relation to a number of factors such as slope angle, previous activity, superficial geology, vegetation and geomorphology. Typical landslide models were then defined based on the dominant characteristics of the landslide trail. Tables 3 to 11 summarise some of these relationships (Section 6.4).

Each of these landslide models had common features which included the following :

(a) a landslide main scarp (in the source area of the landslide),

(b) a landslide debris trail (Section 6.4.3) where the transport of debris predominates, although erosion and deposition also occur, and,

(c) a deposition fan (or run out zone), where the width of the landslide debris trail increases significantly by spreading out and the majority of the landslide debris is deposited.

6.3 Development and Distribution of Landslides from 1945 to 1995

The distribution of both *relict* and *recent* landslides within the study area showing the location of the source and the length and direction of the trail is given in Drawing Nos. EG490 and EG491 and is primarily based on examination of the aerial photographic record from 1945 to 1994. The aerial photographic record since 1945 is not complete for every year within the study area (the photographs examined are listed in Table 5). A baseline of 1945 was chosen as this is the earliest available air photograph coverage.

6.3.1 Temporal Distribution

The API examination shows a number of periods during which significant numbers of landslides have occurred. These periods are 1956 to 1964, 1964 to 1973, 1974 to 1979, 1979 to 1982, 1991 to 1992 and 1993 to 1994. The most likely heavy rainstorms triggering these events are considered to be those that occurred in 1949, 1952, 1959, 1960, 1972, 1976, 1982, 1992 and 1993 as they correspond to periods of generally extreme levels of prolonged rainfall over the Territory of Hong Kong (Section 7.1 and Table 13).

The 1945, 1956 and 1963 aerial photographs show mainly degraded main scarps and debris trails and hence these events are considered to be the result of storms that occurred some years previously. The 1963 aerial photography shows that most of the landslide activity is confined to the slopes below Por Kai Shan to the south east of Tai Po (Drawing No. EG490), many of these landslides had long trail lengths. The 1973 and 1982 aerial photographs show only minor landslide activity, even though these years are known to have had intense rainstorms recorded at the Royal Observatory rain gauge in Tsim Sha Tsui. The 1973 aerial photographs show most of the main scarps on the hills to the south east of Tai Po whilst the 1982 aerial photographs show most of the main scarps on the hills to the south of Tung Chung Fort. The 1979 aerial photographs show quite widespread landslide activity and this is considered likely to be the result of the 24/25 August 1976 rainstorms. The landslide activity observed on the 1993 aerial photographs show most of the main scarps on the hills to the south of Tai Po whilst the 1994 aerial photographs show landslide activity to be widespread in the study area, this is consistent with the intensity of rainfall and duration experienced which was much heavier and longer during the storms of 5 November 1993 than 18 July 1992 (Section 7.3).

6.3.2 Spatial Distribution

The spatial variation of landslides across the study area has been compared, in general terms, with the underlying bedrock, topography and vegetation. In general the slopes where the underlying bedrock is volcanic appear more susceptible to landsliding than the slopes underlain by feldsparphyric rhyolite, but this may be because the topographic relief and slope gradient is generally higher when the bedrock is volcanic. In fact previous researchers (Vandine, 1985) have discounted the underlying bedrock geology as a predisposing factor to debris flow landslides. This aspect is unclear and will need to be studied further. Another factor appears to be the presence or absence of thick vegetation. The slopes to the south of Tai Po village, have experienced relatively few landslides over the period 1945 to 1995 (vegetation on these slopes was sparse in period 1945 to 1956 but rapidly gained in growth over the remaining period) because the slopes there are currently very thickly vegetated compared to the slopes to the south east and south west of Tai Po village. However, Johnson & Rodine (1984) have suggested that lack of vegetation is not a necessary precondition for debris flow landslides, because such events are known to have developed both in forested and in grass-covered areas and there are instances in the study area which corroborate this. However, the vast majority of landslide sources within the study area occurred in areas with low scrub and grass. Geomorphology and drainage are considered to be important factors controlling susceptibility to debris flow landslides (Vandine, 1985 and Reneau & Dietrich, 1987) and this is confirmed within the present study where most landslides occur within or adjacent to significant drainage lines. It is recommended that these aspects should be studied in more detail in the next phase of the study.

6.4 Landslide Types and Processes

6.4.1 General

The characteristics of the landslides within the study area have generally been assessed by reference to the data obtained from those events that occurred during the 1992 and 1993 rainstorms, i.e. the *recent* landslides. Most of the landslides identified during this study are small magnitude (< 250 m^3) and can be characterised primarily as *debris flows* using the terminology of Varnes (1978) although a few debris slides were also observed. Within this report the landslides are further described in terms of the characteristics of landslide trail associated with the landslide scarp. The landslides are initiated typically from sources with shallow scarps (< 1.5 m) within predominantly residual or saprolite soils, or young (Class 3) colluvium (Section 5.4.2 and Table 1). They typically have a main scarp width of 10 m to 20 m.

The sources are generally high up within the catchment close to the catchment divide (Plate 10) on steep slopes (30° - 40°). Following the parent landslide, the displaced material will generally become significantly disaggregated forming an elongated trail of *debris* below the source (*debris flow*). However a few landslides were observed where the displaced material has remained relatively intact within the elongated trail (*debris slide*).

Examination of the terrain classification mapping (TCM) data indicates that most (96%) of the landslide trails are found within slope classes that correspond to 15° to 40 ° and 71% are found on slopes within the range of 15° to 30°.

6.4.2 Characteristics of Landslide Sources

The main scarp widths are typically small, in the range of 5 to 30 m and with source width to length ratios of 1 to 2 (Table 2). The average volume of material mobilised from the source is typically between 100 and 400 m^3 with extremes up to 1500 m^3. The majority of these sources involved colluvium and residual soil only and some 64% have been active only once during the previous 50 years as inferred from API (Table 4). Many of the main scarps (65%) show evidence of soil piping (Plates 11 and 12) and this appears to be most prevalent within those main scarps formed in residual soil (84%) or colluvium (55%). There is a strong correlation between main scarps formed in residual soils that have previously been active and the presence of soil pipes. Examination of TCM data indicates that 68% of the sources are formed in terrain that has experienced previous instability in terms of the existence of *relict* scarps (44%) or colluvium. Most of the surfaces of rupture are relatively free of debris (Plate 13) indicating that the debris is typically highly mobile and freely flows downslope. However, at a small number of the sources the displaced material remains relatively intact overlying the surface of rupture forming a landslide trail of more limited length (Plate 14).

Table 6 summarises the numbers of landslides and estimated source volumes of landslides resulting from the rainstorms of 18 July 1992 and 5 November 1993. It was not possible to inspect all the landslides as access was often restricted by thick vegetation and some of the volumes have been assessed from the API. The table indicates that similar numbers of landslides occurred in 1992 and 1993, but in 1992 no landslides with sources of volume > 400 m^3 were observed.

6.4.3 Characteristics of Landslide Trails

In general the trails resulting from the downslope displacement of disaggregated displaced material are complex. Within any particular section of the trail the dominant transport mechanism in combination with other site and event specific factors may result in either *deposition* of debris or *erosion* of the underlying materials (substrate) as the predominant characteristic.

Geomorphological effects may result in additional complexities such as *channelised debris flow* or the abrupt termination of the trail (referred to as *terminated deposition*). Intense rainfall following the initial failure can result in secondary flooding of the previously deposited landslide debris leading to an *outwash* of the debris and secondary deposition as an alluvial deposit. In addition, the trails associated with small failures on the sides of steep drainage gullies have been classified as a separate group referred to in this report as *gully side slide*. Table 7 describes the terms used to characterise the sections within the trail.

The trails from each of 52 landslides assessed in the field have been examined in detail. During the field inspection each trail was divided into sections along which the slope angle is approximately even and the trail width is generally uniform. The predominant characteristic of the debris trail along any section of the trail was determined and described in terms of the geometrical and other site specific factors associated with the trail (Table 9). As the whole trail comprises a number of trail sections each with different characteristics the full trail description for each landslide model may need a number of these section descriptors. As an example (Table 10) a landslide trail may comprise two trail sections ; erosion (ERO) and deposition (DEP). Many of the trails are simple with deposition of debris as the predominant characteristic along the complete length of the trail. Others trails are more complex and comprise a number of sections that may include some or all of the following ; erosion, deposition, outwash, terminated deposition or channelised debris flow.

Statistical assessment of the trails has been made in terms of the total length of all the trails within the study area which have a particular predominant characteristic. Examination of slope morphology (Table 8) indicates that for a concave down-slope section, erosion and terminated deposition trails predominate, whilst for a planar down-slope section, deposition, outwash, channel and gully side slip trails predominate. For most trails a concave cross-section is indicated the exception is for gully side slide where a planar cross-section is indicated.

The majority (i.e. 55%, Table 9) of the landslides had a trail that contained some sections where deposition predominates, whilst erosion of the substrate accounts for 20% and outwash 13% of the other landslide trails. Channelised debris flows account for 9% of the total length of the trails inspected.

6.4.4 Landslide Models

Two landslide models comprising eight types have been defined in terms of the character (i.e. deposition, erosion etc) and complexity (i.e. number of trail sections within the trail) of the landslide trails (Table 10).

The two landslide models are :

(a) *unconstrained landslides* which include debris flows with predominant deposition, debris flows with erosion and outwash, and debris slides.

(b) *constrained landslides* which include terminated deposition, gully side slip, gully erosion and channelised debris flows.

Tables 10 and 11 summarise the landslide model and types that were observed during the study. The majority (69%) of the landslides inspected are unconstrained. Some 41% are debris flows and comprised a single characteristic within the trail, the predominant characteristic being deposition, whilst 28% of the landslides exhibited other characteristics including erosion of the substrate and outwash of the debris. The remaining 31% of landslides were influenced by geomorphological factors such as ; i) constraints to the downslope run out, and ii) constraints to deposition due to channelisation of the trial.

These latter landslides exhibit quite complex trails combining elements of deposition, gully erosion, channel, terminated deposition and debris outwash characteristics (Tables 7 and 10).

6.5 Event Magnitudes and Trail Lengths

6.5.1 General

Some 76% of the landslides had a source volume of < 400 m^3. The remaining 24% had much larger source volumes up to 1500 m^3. All of the larger (> 400 m^3) landslides occurred during the 5 November 1993 rainstorm when 742 mm of rain fell in 24 hr (Section 7.3).

Those landslides with trails that are less complex generally have a small source volume < 400 m^3 and have relatively short trails whilst those landslides that give rise to long complex trails generally have a larger source volume > 400 m^3 and generally exhibit a unique character. Table 10 details the range of trail lengths together with the range of volume of *entrained debris* resulting from erosion for each landslide model type from i) to viii).

The range of trail length is different for each of the landslide model types. For each type the trail length is generally in proportion to the *total magnitude of the event* and the slope angle. The *total magnitude of the event* is the volume of the displaced source material plus the volume of any additional entrained material due to erosion along the trail (Section 6.5.1). The amount of erosion will also depend upon a number of other site specific factors and these will in turn influence which landslide model type is appropriate to describe the event and the ultimate trail length.

Analysis of these other site factors has not been considered during this preliminary phase of the study. In the absence of any abrupt termination of the debris trail, say for example due to the influence of a sudden geomorphological change (but other site specific factors may also influence this), the landslide trail will continue to develop until the slope angle reduces to some critical value. At this critical value of slope angle, deposition of the debris will predominate and a deposition fan of material will be formed at the end of the trail (Section 6.5.2) as *run out of debris*. In terms of this study the total trail length includes this deposition fan section.

6.5.2 Landslide Magnitude

For a channelised debris flow the landslide (or event) magnitude is the total volume of coarse and fine debris material transported to the deposition fan in the course of a single event. This depends on the size of the source area and the vulnerability of the source materials to be mobilised under flood flow conditions (Hungr et al, 1984). Hungr et al (1984) consider that the magnitude is proportional to the length of the channel upstream of the deposition area (including major tributaries) to the points of origin.

The maximum *recent* landslide magnitude on the slopes above the Tung Chung New Town Phase 1 area resulted from a channelised debris flow (Plate 23). The initial scarp volume was estimated to be 1500 m^3 and the debris incorporated colluvium and weathered bedrock (Plate 24). Subsequent erosion along the channel (Plates 25) is estimated to have increased the magnitude to a total of about 2300 m^3. The debris trail had a total length of about 450 m from a scarp elevation of about 180 mPD to the site formation level of 24 mPD with the formation of a debris deposition fan starting on a 18° slope (Plate 26) which had no channel confinement. However subsequent re-mobilisation of the debris, possibly caused by a surge in the rainfall runoff, and further channel confinement downslope (Plate 27) resulted in an additional deposition fan on an 8° slope.

The available recent historical data does not allow for a direct prediction of a maximum magnitude event in the study area. However, using the available data from the 1992 and 1993 rainstorms the maximum debris flow event for the slopes above Tung Chung development is about 2300 m^3 and occurred on 5 November 1993 during a rainstorm with an estimated return period in the range of 40 to about 800 years (Section 7.3).

6.5.3 Runout Length and Width

Hungr et al (1984) considered run out length for channelised debris flow landslides to be the distance that the landslide debris will flow downslope from the point at which initial deposition commences (*deposition point*) to the point at which the landslide trail terminates.

Hungr et al (1984) reported a limiting angle of 8° to 12° with channel confinement and 10° to 14° in its absence, for the deposition point. Furthermore Hungr et al (1987) concluded that the presence of channel confinement is crucial to the maintenance of flow for slopes less than 18° and that a width to depth ratio of less than 5 is required for confined flow. The runout formula presented by Hungr et al (1984) calculates runout distance for confined flows downstream of a point where the channel slope angle reduces to 10°. However, these figures are for very large magnitude debris flows (in the range of 10,000 to 55,000 m^3) and such large magnitude landslides may involve different transport mechanisms than those examined in this study.

The landslide data collected in this study indicates that for *unconstrained* landslides the point at which deposition of a debris fan occurs (*deposition point*) is on average when the slope angle reduces to less than 21° (average of 27° - the standard deviation of 6°). If the landslide is *constrained* and part of the debris trail involves channelised debris flow then the point at which deposition of a debris fan occurs is either when channelisation ceases or on average when the slope angle of the stream bed within the channel falls below 20° (average 25° - std. dev. 5°).

Examination of the field data indicates that most debris deposition occurs on slope angles in a wide range of 8° to 40° (Table 9, and Figure 5). The wide variation is considered due to the wide range in magnitude of the events studied and the variation in landslide debris transport mechanisms and landslide types observed. Some are *unconstrained* involving only deposition from simple debris flows whilst others are *constrained* and are associated with channelised debris flows. The limited data from the study area indicates that a lower bound angle for deposition is 8° with channel confinement or 10° without channel confinement. In general however, *unconstrained* landslides are more likely to deposit on steeper slope angles. Figure 5 shows that for most *unconstrained* landslides the maximum (i.e. 90%) deposition of debris, as a percentage of the source (main scarp) volume, occurs in slope angles from 26° to 30°. A typical range of slope angles for deposition of at least 30% or more of the debris from the main scarp volume is from 20° to 36°.

Table 9 indicates that the average length of trail section where deposition predominates is 28 m with a standard deviation of 22 m and a range from 2 to 100 m. It is suggested that the length of a typical trail section (or trail unit length) be considered to be the average plus one standard deviation giving a *trail unit length* of 50 m for a deposition section. This trail unit length for deposition can then be applied to the deposition fan for a preliminary hazard zoning (Section 8.2).

The width of deposition within the trail is generally controlled by the topographic setting. Most of the debris flows are controlled by drainage lines or hollows, in some cases these are quite subtle in others the drainage line has quite steep sides. In general the width of the trail ranges up to 30 m for *unconstrained* debris flow, where the topographic controls are relatively subtle, but is unlikely to exceed 8 m for *channelised debris flow*.

For most of the landslides examined, if the slope is greater than 20°, the deposit is unlikely to fan out greatly from the debris trail to form a prominent debris fan downslope of the *deposition point*. If the slope is much more shallow then some fanning out of the deposit is likely, however this was not measured directly during the field survey as quite often even minor topographic relief restrains the lateral spread of debris. The maximum width of debris within a zone of deposition was 30 m and this is considered to be a suitable upper bound for lateral spread. This is equivalent to a spread angle of 23° (for a debris trail width of 10 m and trail unit length of 50 m).

It is considered that run out length can be estimated either by ; i) applying the design landslide across the deposition fan, assuming an appropriate deposition thickness (Table 9), or, ii) by making use of the appropriate trail unit length.

A theoretical design landslide may be estimated, using the method proposed by Hungr et al (1984) for channelised debris flows, based on the length of the drainage line (in metres) multiplied by the rate of erosion (in m^3/metre) along the drainage line length. From Table 9 the average erosion rate is 3.66 m^3/m for a channelised debris flow. Therefore the theoretical design landslide for each drainage line that has a slope greater than 8° and less than 35° can be calculated. A number of drainage lines meet these criteria within the study area and they have lengths ranging from about 50 m to 550 m. Therefore for the maximum drainage line length of 550 m determined for the study area, the calculated additional volume of entrained debris is 2013 m^3. The estimated maximum landslide source volume should also be added to this, for the 1993 rainstorm this is 1500 m^3. On this basis a theoretical maximum design landslide for the hillslopes above the Tung Chung New Town development is estimated to be 3500 m^3. This is about 1.5 times the field estimated maximum total event magnitude for the 5 November 1993 rainstorm (Section 6.5.1).

In terms of runout length if the deposition thickness is 0.69 m, trail width of 8 m, lateral spread angle of 23° and assuming an average of 40% of the debris is deposited at the deposition fan (Table 9) then a run out length of 82 m is determined for the maximum design landslide and 49 m for the field estimated maximum total event magnitude for the 5 November 1993 rainstorm. This compares with the trail unit length of 50 m for deposition (Table 9).

6.6 Landslide Hazard Assessment

Landslide hazard assessment is a preliminary exercise to landslide hazard zoning (Section 8.2) and involves a determination of the *probability* of a particular landslide type on a natural slope occurring at a site (main scarp) as well as an estimate of the *consequences* of that landslide. A number of factors are considered to be significant in pre-disposing a natural hillside to landslides during intense rainfall. These are ; slope angle and elevation, ground surface cover (vegetation), slope morphology, hydrology (catchment characteristics), signs of previous instability, and geology (Table 12). Some of these factors are likely to be mutually exclusive whilst others are likely to be inter-related. This aspect has not been addressed in this report in detail. Further studies should consider an assessment of this inter-relationship as well as the relative weighting of such factors to define absolute probabilities with some degree of confidence. A preliminary hazard assessment of an area can be made assuming equal weighting of the factors to derive a relative probability of hazard map.

In terms of risk to developments and population downslope (elements at risk) of a source the consequences can be thought of as the impact of the trail and associated debris on the elements downslope of the main scarp. The risk is a function of the elements at risk and the potential hazard resulting from runout of displaced material downslope of the main scarp (i.e. trail length). The potential hazard is a function of the magnitude of a design landslide together with an estimate of its probability of occurring (or recurrence interval). A detailed assessment of recurrence interval is outside the scope of this phase of the study but is recommended for further study during the next phase.

7. RAINFALL AND LANDSLIDES

7.1 General

In the rugged terrain of Hong Kong, the distribution and intensity of rainfall during a storm can vary dramatically with respect to both geography and time. The Royal Observatory and GEO have installed a network of rain gauges across the Territory which comprises 69 automatic and 116 manual gauges at a total of 145 locations. These rain gauges range from automatic instantaneous rate of rainfall recorders to those which are read manually once every month. The principal gauge (R01) is located at the Royal Observatory's headquarters in Tsim Sha Tsui where a continuous rainfall record has been kept at this location since 1884 excluding the years 1939 to 1946.

The locations of rainfall gauges that cover the Territory of Hong Kong are shown on Figure 6. It can be seen from this that not many gauges are located within or close to the study area on Lantau Island. Rainfall data in the study area is only available from 1988 (N179, daily 24 hour intervals), 1993 (A08) and 1991 (N17, 15-minute intervals). The method of recording rainfall 24-hour rainfall data is significant as the rolling 24-hour rainfall is not equal to the daily 24-hour data. The reasons are clear when it is recognized that the most of the daily rainfall data is measured from 3 pm to 3 pm.

Assessment of relatively short duration rainstorms (i.e. > 100 mm in 24 hours) recorded at the RO principle gauge does not show significant correlation with rainstorms over Lantau. However it is considered that if the storm persists over several days then heavy rainfall over Lantau during the same storm is likely. The paucity of relevant rainfall data for this study makes analysis of the likely rainfall trigger threshold and landslide magnitude return period relationships difficult to determine with any confidence.

For the purpose of this study it is assumed the following severe storms will have produced similar very high rainfall on the high slopes of the central Lantau Island : 14/15 June 1959, 18/19 August 1972, 24/25 August 1976, 16 August 1982, 18 July 1992, 5 November 1993. Table 13 shows the historical record of severe storms over Hong Kong during that last 35 years. It should be noted that the 24-hour rainfall at RO1 during the 7/8 May 1992 rainstorm did not result in unusually heavy rainfall over Lantau. However API over the same period tends to confirm the assumption that some of these storms are likely triggers for the landslide events identified.

7.2 Relationship between Rainfall and Landslides

7.2.1 General

Previous studies in other parts of the world (eg. Costa, 1984 ; Campbell 1975 ; Eyles, 1979) of the relationship between rainfall and landslides from natural slopes have concluded that both antecedent rainfall and a critical intensity of rainfall are equally important factors triggering landslides on natural slopes. The significant period of antecedent rainfall, however, may vary from hours to weeks depending on local site conditions, particularly soil permeability and thickness (Wieczorek, 1987). In the case of high permeability soils such as those of Hong Kong the period of necessary antecedent rainfall is considered to be extremely short. In most mountain areas rainfall data is sparse and the intensity of rainfall required to trigger landslides is poorly known. Caine (1980) defined a limiting threshold for slope failures based on observations of 73 landslides worldwide. More recently Wieczorek (1987) studied the intensity-duration characteristics of storms that initiate landslides. He concluded that antecedent rainfall is important to determine **whether** landslides will initiate, whilst rainfall intensity and duration are important to determine **where** landslides will occur. Other factors are also important such as geomorphology, soil thickness and slope angle. Wieczorek (1987) also concluded that storms of long duration and moderate intensity can cause landslides in thick soils on moderate slopes beneath concave slopes where groundwater flow converges. It is considered possible that storms of short duration and high intensity can trigger landslides on steep planar hillsides where shallow bedrock beneath a thin soil mantle allows the rapid development of pore pressures and the reduction of soil suction.

The recurrence intervals of debris flows on natural slopes are not considered to be controlled solely by rainfall frequency (Costa, 1984), since it is known that a small rainstorm may produce a debris flow in a drainage basin at one time, but a large rainstorm another time may only produce flash flooding. It is considered that the availability of debris source materials (i.e. loose sediments, colluvium, etc) is also important. This is supported in part by the circumstances surrounding the Tsing Shan debris flow.

7.2.2 Intense Rainstorms

Rainfall at a single location does not occur evenly during a storm but tends to build up in surges to a peak intensity before reducing again. The intensity and duration of a storm can only be assessed in detail by analysing the instantaneous rainfall rate data. However rainfall data obtained from longer periods of monitoring can be used to give some indication of longer period duration rainfall. For example, 15-minute duration rainfall data can be usefully used to give rolling 1-hour up to 24-hour totals. The only data of relevance to this study is that from the GEO gauge N17 which has 15-minute data from 1992 to date. Figures 9 and 10 show graphically the surges in 1-hour duration rainfall that occurred during the 18 July 1992 and 5 November 1993 rainstorms. However, in most studies of the relationship between rainfall and landslides the magnitude of the rainfall and duration for that magnitude are quoted. Commonly maximum rainfall levels for rolling duration times of 1-hour, 4-hour, 6-hour and 24-hour are analysed.

The relationship between rainfall and landslides primarily from man made slopes, in Hong Kong has previously been studied by Brand et al (1984) and the salient aspects have recently been summarised by Premchitt (1991). The vast majority of landslides in Hong Kong are generally shallow and caused by heavy rainfall over a relatively short time period ("intense rainfall") and antecedent rainfall is not considered to be a significant contributory factor. It is considered that intense rainfall will produce erosion of susceptible materials that are exposed or have little surface protection, e.g. recent main scarps and a number of examples of this erosive power have been observed in the study area (Plate 28).

Threshold figures of intense rainfall have been established in Hong Kong primarily for landslides involving man made slopes, the numbers of documented natural slope failures being much smaller. Brand et al (1984) determined that it is unlikely that landslides will occur if less than 100 mm of rain falls in 24-hours but that it is almost certain that landslides will occur whenever the 24-hour rainfall exceeds 200 mm. Other patterns have been established for short term intensities and the critical 1-hour rainfall has been estimated to be 70 mm. More recent assessment of the relationship of rainfall and landslides in Hong Kong has established a relationship linking 24-hour rainfall and 1-hour rainfall with the likelihood of widespread landslides (Kay & Chen, 1995). This latter relationship shows that the time period for antecedent rainfall to build to critical levels in Hong Kong soils is quite short. This is quite likely a reflection of the relatively permeable nature of Hong Kong soils.

Table 14 shows the maximum rainfall for various durations, recorded at the GEO rain gauge N17, in Tung Chung for three major rainstorms in 1992, 1993 and 1994. The data give some indication of a likely trigger level for landslides on natural slopes in Tung Chung. During the July 1994 rainstorm no landslides were noted with a 1-hour rainfall level of 77 mm whereas the 1-hour figures for the 1992 and 1993 rainstorms were 111 mm and 94 mm respectively. It is of interest to note that the maximum rolling 24-hour records which resulted in widespread landslides in Tung Chung are 454 mm and 746 mm for the 1992 and 1993 rainstorms respectively. By way of comparison the 22 July 1994 rainstorm maximum rolling 24-hour record of 364 mm did not cause widespread landslides on natural slopes in the study area. The inference is that a sustained level of heavy rainfall over a period in excess of 1 hour is required to cause widespread landsliding on natural slopes in an area. It is suggested that threshold levels for widespread landsliding caused by intense rainstorms in the area could be in the region of 90 mm, 200 mm and 400 mm for the rolling 1-hour, 4-hour and 24-hour duration periods respectively. Figures 7 and 8 give an indication of the rolling 24-hour rainfall spatial distribution across the study area for the 17/18 July 1992 and 4/5 November 1993 rainstorms.

It follows then that an estimate of the likely return period for a given intensity of rainstorm may give an indication of the likely return period that will result in widespread landsliding in an area.

7.3 Return Period for Intense Rainstorms

The maximum rainfall for various durations for some major rainstorms in the Territory recorded at the Royal Observatory since 1959 are shown in Table 13. The estimates of return period are based on Gumbel's method proposed in Peterson & Kwong (1981). From Table 13 the highest rolling 24-hour rainfall during this period was 416.2 mm for the storm in August 1972. This is significantly lower in magnitude than that recorded in Tung Chung for the storms in July 1992 and November 1993.

The return period of 182 years for the 4-hour rainfall in 1992 is exceptionally high, whilst the return periods for the 6-hour rainfall and rolling 24-hour rainfall in 1993 are even higher still at 378 and 796 years respectively. The return period for the (July 1994) 1-hour rainfall is 7 years which is not exceptional. The large numbers and larger magnitude landslides that resulted from the heavy rainstorm in 1993 are reflected in the very long return periods for the longer duration high intensity storms.

The heavy rainstorms in Tung Chung during in 1992 and 1993 can be compared with previous heavy rainstorms recorded by the Royal Observatory at Tsim Sha Tsui as follows :

1 - day total (daily record 3 pm to 3 pm) gauge RO1

Rank	Period	Amount
1	19 Jul 1926	534.0 mm
2	30 May 1889	520.6 mm
3	12 Jun 1966	382.6 mm
4	15 Jul 1886	342.3 mm
5	16 Aug 1982	334.2 mm
6	8 May 1992	324.1 mm
7	21 May 1989	322.8 mm
8	29 May 1889	320.6 mm

By way of comparison the 1-day rainfall recorded at GEO rain gauge N17 in Tung Chung during 5 November 1993 was 520 mm, however the rolling 24-hour rainfall total from 10 am, 4 November 1993 to 10 am, 5 November 1993 was 742 mm with a corresponding return period of 796 years.

2 - day total (daily record 3 pm to 3 pm), gauge RO1

Rank	Period	Amount
1	29-30 May 1889	841.2 mm
2	19-20 Jul 1926	561.2 mm
3	24-25 Aug 1976	512.6 mm
4	22-23 Jul 1994	492.1 mm
5	11-12 Jun 1966	460.4 mm
6	14-15 Jun 1959	452.0 mm

By way of comparison the 2-day rainfall recorded at GEO rain gauge N17 in Tung Chung during 22/23 July 1994 was 550 mm and during 4-6 November 1993 was 743.5 mm.

The estimates of return period quoted here are based on Gumbels method and cognisance should be taken that the method is based on data from the principal datum (R01) and presently little is known about areal variability of extreme rainfall over the Territory. Recent studies by the RO (Lam & Leung, 1994) have attempted to address this problem, however the data set is limited. They conclude that the short term data is insufficient to establish significant conclusions. More recently, attention (Wong & Ho, 1996) has been focused on the need to examine in some detail the effects of spatial, topographical and meteorological factors on the interpretation of rainfall data at a point (i.e. rain gauge) and extrapolation to an area.

Some other factors highlighted by Wong & Ho (1996) include ; the aerial extent of the rainstorm and its duration and size of the area affected by a specific rainstorm relative to the area of Hong Kong. Malone (1996) has suggested consideration be given to the aerial extent that exceeds a pre-defined intensity for a given duration. In the context of the natural slope landslides at Tung Chung, 400 mm for a maximum rolling 24-hour rainstorm is indicated. On this basis and with reference to Figure 8 the area affected by the 400 mm contour during the 5 November 1993 rainstorm is about one sixth of the land area of Hong Kong. As the overall return period for Hong Kong for this storm is determined to be 796 years then the actual return period for this land area will be only 132 years.

Wong & Ho (1996) have carried out an assessment of the statistical uncertainties in the determination of a return period for the 5 November 1993 rainstorm at Tung Chung. Allowing for these uncertainties they have determined a return period of 40 years for this rainstorm compared with the almost 800 years calculated using Gumbels method.

8. DISCUSSION

8.1 General

This study has examined 52 of the most recently activated landslides on the natural hillsides that overlook the Tung Chung New Town Development Area. A computerised landslide database was prepared to store the data that was collected and this was analyzed to determine what factors may predispose a natural slope to landslides during heavy rainstorms. In particular some of the factors that result in extended runout of landslide debris were determined. This information will be of use in developing a strategy for hazard zoning of the area below the slopes.

The rainstorms in July 1992 and November 1993 resulted in over 80 landslides on the natural slopes within the study area. The range of event magnitudes, accumulation and depletion zones, trail length and runout distance of these landslides has been examined with respect to a number of factors including slope angle, vegetation, substrate materials, drainage characteristics and geomorphology. The data have highlighted some factors that will be useful for defining potential hazards to downslope developments resulting from natural slope landslides caused by intense rainstorms. In addition some criteria are indicated that could be used to develop hazard zoning methodologies for such events. However further work and data collection is required to define some of these relationships with a higher degree of confidence, i.e. any pre-disposition of landslide source with particular bedrock and superficial geology.

8.2 Suggested Criteria for Hazard Zoning

Once it is determined that an area is likely to be pre-disposed as a source of landslides then a more detailed hazard zoning can be usefully undertaken to determine the areal extent of the potential hazard in terms of the landslide that will result. In terms of this study the most significant potential hazard is that resulting from a constrained landslide such as a channelised debris flow as this will produce a trail of debris with much greater runout than that resulting from an unconstrained landslide.

Assessment of the data for Tung Chung indicates that for channelised debris flows a lower bound natural slope angle of 8° for the deposition point is appropriate for hazard zoning. However, should channelisation cease then deposition is likely to begin at slope angles of 20° with a lower bound of 10°. For unconstrained landslides, deposition of debris on a natural slope angle of 21° is appropriate for hazard zoning, although lower bound slope angles of 10° are indicated in some situations.

The geomorphological characteristics of each drainage line within the catchments in the study area are difficult to fully categorise due to their inherent variability. To cater for this variability it is considered prudent to apply a confidence factor to the results if these are to be used for hazard zoning purposes. The Slope Manual (GCO, 1984) recommends safety factors for analysis of slopes against failure of between 1.0 and 1.4 for negligible to high consequence to life and economic loss respectively for a 10-year return period of rainfall. In terms of impact on the Tung Chung development then the resulting landslides will be high consequence if they impact on the developed area. Adopting a factor of 1.4 gives a maximum runout of 70 m from the point of deposition (based on trail unit length for deposition). It is considered that this should be adopted for use in a preliminary hazard zoning.

8.3 Landslide Recurrence Interval and Rainfall

It is recognised that the measured level of rainfall by itself is not a precise predictor of landslide initiation as precipitation varies across an area. However it is considered that some initial estimate of recurrence intervals for large landslides can be made by assuming a broad relationship between widespread landslide initiation and major rainstorm events. The return period in the study area for the 5 November 1993 rainstorm is estimated to be in the range of 40 to almost 800 years. However, this is based on an extrapolation of the data far beyond the range of the available historical rainfall record applied to areas quite far apart as well as a number of other statistical uncertainties (Section 7.3). Indeed within the historical API record two rainstorms that have affected the Study Area have produced constrained landslides with long run outs within the same drainage line on the slopes above Tung Chung development viz 1972 and 1993 (Drawing No. EG490 ; trail 5A2). On this basis it may be considered more prudent to adopt a return period of 1 in 40 years for the design landslide, however this aspect should be reviewed in more detail in any follow up studies.

Comparisons with the Tsing Shan landslide with a trail length of 1025 m should be cognisant of the differences in geomorphology (scarp elevation about 400 mPD, slope angle of channelised portion of drainage line 30°) and event magnitude (18,000 m^3). The return period for the rainstorm that resulted in the Tsing Shan landslide is not long (about 2 years) and this suggests that other factors are more significant such as the particular geomorphic setting and availability of source materials ; i.e. the steep cliffs above the scarp that produced an accumulation zone of loose boulders that subsequently failed into a debris filled steeply sloping channel.

9. CONCLUSIONS

Based on an analysis of *recent* and *relict* landslides within the study area that occurred during the past 50 years, the following conclusions have been reached ;

(i) The largest magnitude rainfall induced landslides are those that result in channelised debris flow and these are the events that produce the longest trails and debris runouts and hence are potentially the most hazardous.

(ii) Most of the rainfall induced landslides that have occurred on the natural slopes above the Tung Chung New Town Development are unconstrained with debris volumes generally less than 400 m^3. These landslides generate relatively short trails, generally less than 50 m in length.

(iii) Some rainfall induced channelised debris flow landslides have occurred in the Study Area with debris volumes > 2000 m^3. These landslides generate long trail lengths and run outs which have impacted on the boundary areas of the Tung Chung New Town Development.

(iv) The available data indicates that a significant risk exists of landslide debris runout impacting on parts of the Tung Chung New Town Development if no mitigating measures are implemented.

(v) During intense rainfall, larger magnitude events have resulting in channelised debris flows on at least two previous occasions in 1972 and 1993. For the longest drainage lines examined in the study area, a theoretical design landslide of 3,500 m^3 is considered to be an upper bound for this type of landslide.

(vi) For unconstrained landslides the runout length based on trail unit length for deposition is 50 m from the deposition point (or 70 m if a safety factor of 1.4 is adopted). The average of the range for the deposition point is where the slope angle reduces to 21° with a lower bound of 10°. The average trail width is 9 m with an upper bound of 30 m. The whole trail lengths typically range from 5 to 100 m.

(vii) For constrained landslides resulting in channelised debris flows, the runout length based on unit trail length for deposition is 50 m from the deposition point, or 70 m if a safety factor of 1.4 is adopted. The runout length based on the theoretical design landslide is 82 m from the deposition point assuming a deposition thickness of 0.69 m. The average of the range for the deposition point is where the slope angle reduces to 20° with a lower bound of 8°. The average trail width is 6 m with an upper bound of 8 m. The whole trail lengths typically range from 70 to 450 m.

10. RECOMMENDATIONS

The results of this preliminary study have indicated some of the factors which influence the potential for rainfall induced landslides on natural slopes above the Tung Chung New Development. Some of these factors can be used to estimate a theoretical design landslide for hazard zoning purposes.

However, the recurrence intervals of the theoretical design landslide are not known with confidence and it is recommended that further studies be carried out to refine the magnitude/recurrence interval relationships. It particular the spatial variation of rainfall across a mountainous area such as Lantau during a storm is poorly understood and it is recommended that further rainfall gauges are installed and monitored to gather the appropriate data for the study area.

A preliminary hazard zoning should be developed based on the criteria suggested. Making use of a GIS would allow considerable flexibility in developing such a zoning and is recommended.

It is further recommended that additional work be carried out to define in more detail the relationships between the development of rainfall induced landslides on natural slopes and various site and event specific factors not covered in this study.

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Table 1 - Definitions of Colluvium Classes in the Mid-Levels Area (GCO, 1982)

CLASS 1 (oldest)	DESCRIPTION
Matrix -	stiff to very stiff, mottled dark red and yellowish brown slightly clayey sandy SILT, with some gravel in the east.
Cobbles - and Boulders	commonly comprising 75 to 100% but may be as low as 25% subrounded minor angular, mainly highly to completely decomposed, some moderately decomposed, no patinas. (type location refer to Irfan & Tang, 1992)
CLASS 2 (intermediate age)	
Matrix -	Firm to stiff, mottled dark red and yellowish brown clayey sandy SILT, with some gravel in the east.
Cobbles - and Boulders	commonly comprising 0 to 50% and up to 80% subangular to subrounded, mainly moderately to highly decomposed, occasionally slightly decomposed. Patinas. commonly 30 to 60 mm thick and may be up to 100 mm thick. (type location refer to Irfan & Tang, 1992)
CLASS 3 (youngest)	
Matrix -	soft to firm, uniform pale brown to yellowish brown, slightly clayey sandy SILT, with some gravel in the east.
Cobbles - and Boulders	commonly comprising 25 to 50% in the west, 50 to 75% and up to 100% in the east, angular to subrounded, mainly slightly to moderately decomposed with patinas generally a few mm and up to 10 mm. (type location refer to Irfan & Tang, 1992)

Table 2 - Description of Colluvium Exposed in Road P2, Phase 1 (Package 1), Tung Chung New Town Development

Parameter		COLLUVIUM LAYER			
		1	2	3	4
Thickness (m)		1.0	2.0	1.5 - 2.0	1.5
Underlain by:		layer 2	layer 3	layer 4	Completely decomposed feldsparphyric rhyolite
MATRIX	Colour	Light yellowish, brown, uniform	Light yellowish brown and reddish brown, mottled	Reddish brown and light yellowish grey, mottled	Reddish brown and light grey, mottled
	Grain Size	gravelly, sandy, silt with some clay	gravel and clay with some silt and sand	gravel and clay with silt	clay and silt with gravel
	Strength/ Cementation	Medium dense/none	Medium dense/slight	Dense/moderate	very dense/moderate
COBBLES AND BOULDERS	Cobbles (%)	30	30	50	40
	Weathering Grade	III & IV	III & IV	IV & V	IV & V
	Angularity	Sub angular and angular	sub angular and sub rounded	sub rounded	sub rounded
	Boulders (%)	20	40	30	35
	Weathering Grade	II & III	II & III	III & IV	III & IV
	Angularity	Sub angular and angular	Angular	Sub angular	Sub angular
Insitu Weathering		Slight	Moderate	Moderate	High

Table 3 - Geometry of Landslide Sources (Average of Range in Bold)

Surface of Rupture Length (m) (Range)	Main Scarp Width (m) Range	Source Volume (m^3) (Range)	Natural Slope Angle (°) (Range)	No. of Slides (as % of all scarps)	Material Composition of Source (as % of No. of slides)
9 (5 - 25)	5 - 9	**76** (13 - 400)	**37** (28 - 80 +)	39 (45%)	Colluvium 70% Residual Soil 30%
15 (8 - 25)	10 - 14	**286** (50 - 650)	**34** (28 - 50 +)	29 (34%)	Colluvium 50% Residual Soil 50%
15 (10 - 30)	15 - 19	**520** (150 - 1250)	**36** (29 - 45 +)	13 (15%)	Colluvium 40% Residual Soil 60%
20 (20)	20 - 24	**400** (400)	**40** (40)	1 (1%)	Colluvium
18 (12 - 30)	25 - 30	**450** (450 - 1500)	**37** (38 - 40)	4 (5%)	Colluvium (50%) Weathered Rock (50%)

Note: + The very steep slope angles are from scarps on the sides of steep drainage channels

Table 4 - Summary of Main Scarp Activity as Inferred from API

Activity*	No. of Main Scarps Examined by API	% of all Main Scarps Examined with Activity
1 2 3 4 5	55 19 8 3 1	64 22 10 3 1
* Number of times main scarp location has been active in the period 1945 to 1995	86	100

Table 5 - Aerial Photographs Examined During the Study

Date of Photography	Flying Height (Feet)	Flight Line and Photograph Numbers
11/11/1945	20,000	4092 - 4093
27/12/1956	16,700	F21.81A/RAF/0037-0040
22/1/1962	12,500	F42/81A/RAF/642 31-36 F41/81A/RAF/642 29-33
25/1/1963 24.2.1963	3,900 7,000	4641 - 4643 0955 - 0960
9/1964 1964	7,000 12,500	2937 - 2938 2923 - 2920 2556 - 2554
4/4/1973 20/12/1973	6,000 12,500	3916 - 3919 8022 - 8023
20/11/1974	12,500	9558 - 9559
31/8/1977	12,500	19138 - 19143
10/1/1978	12,500	20780 - 20781 20788 - 20790
28/11/1979	10,000	27992 - 27993
11/2/1981	25,000	36752 - 36753
10/10/1982	10,000	43525 - 43527 44484 - 44486
30/11/1983	10,000	51355 - 51350
22/11/1984	6,000	57264 - 57266
4/10/1985	15,000	A02631 - A02632
19/12/1986	3,500 10,000	A07858 - A07864 A08236 - A08238
4/6/1988 25/10/1988	10,000 4,000	A13632 - A13635 A14900 - A14903
1/12/1989	20,000	A19967 - A19968
6/12/1990 8/3/1990 4/12/1990	4,000 4,000 10,000	A24931 - A24933 A20394 - A20397 A20431 - A20432 A24783 - A24784
8/3/1991 21/10/1991	10,000 10,000	A28991 - A28995 A28549 - A28550
11/11/1992	10,000	A33179 - A33180
4/10/1993	20,000	CN4320 - CN4321 CN4313 - CN4314
5/12/1993 **5/12/1993** 4/2/1993	6,000 10,000 5,500	CN5204 - CN5208 CN5231 - CN5233 CN5319 - CN5323 CN5195 - CN5198 A33911 - A33912
24/10/1994	10,000	A39693 - A39696

Note: 1. Dates in bold indicate when new or reactivated landslide scarps and debris trails are **first** noted

Table 6 - Landslide Source Volumes Resulting from Rainstorms on 18 July 1992 and 5 November 1993

Source Volume(m^3)	18 July 1992		5 November 1993	
	Total No. of Slides	Field Inspected Slides	Total No. of Slides	Field Inspected Slides
< 50	12	3	9	2
50 - < 100	10	7	5	4
100 - < 200	12	5	11	11
200 - 400	9	7	11	5
> 400	0	0	12	10
Total	43	22	45	32

Table 7 - Terms used to Characterise Trail Unit Sections

Trail Unit Section Characteristic	Description
DEPOSITION (DEP)	This is the most common characteristic observed for trial sections. In terms of the total length of the 52 landslide trails field inspected during the study, 55% exhibit this characteristic. Deposition in varying degrees often occurs immediately following the parent landslide and can start within the surface of rupture extending downslope along the trail for some distance. Plate 15 shows an example from the hillslopes to the southwest of Tai Po. The thickness of deposition is typically in the range 0.1 to 1.5 m with slope angle in the range 20° to 40° (see Table 9). Secondary characteristics associated with deposition include the likelihood of erosion channels cutting through the deposited materials to the substrate as a result of hyper-concentrated water flows.
EROSION (ERO)	Erosion is the second most common (20%) characteristic recognised within the trails in the study area (Plate 16). The depths of erosion vary usually within the range of 0.1 to 1.0 m. Secondary debris trail characteristics include washouts and some lateral deposition along the edges of the trail. Erosion most often takes place immediately downslope from the main scarp but can also occur within the trail, following an initial deposition phase, as a result of hyper-concentrated water flows.
OUTWASH (WO)	This characteristic is the result of hyper-concentrated water flow probably as a result of blockage within the drainage line up slope and the subsequent build up of surface water behind. As the blockage fails a sudden surge of flow downslope results leading to a washout of material from the previously deposited debris (Plate 17). The remaining deposit is characterised by materials in the sand and silt size with few larger sized fragments. The thickness of the deposit is usually thin (< 0.1m) and the length of runout is moderate (average of 36 m). Other characteristics include evidence of vegetation flattening and minimal erosion.
TERMINATED DEPOSITION (TERM)	This characteristic is essentially the same as that described under deposition above but occurs as the result of obstructions to the flow path such as terminating in a gully or hollow (Plate 18). The occurrence of this is minor accounting for less than 1% in terms of total length of trail sections examined. Secondary components include the possibility of some limited erosion of the underlying substrate.
CHANNELISED (CH)	This characteristic is found for 9% of the trail sections but needs a number of predisposing factors for it to occur. These include; a) the catchment should be concentrated into a deeply incised and steeply sloping drainage line or channel (Plate 19), and b) the debris should be sufficiently mobilised to reach the drainage line. If these factors exist then it is likely that the landslide debris will flow along the channel if the slope angle is greater than 20° and the width to depth ratio of the channel is greater than some critical value. As the ratio drops below this critical value or the slope angle reduces then deposition starts to occur. Additional characteristics include the likelihood of blockage of the drainage line prior or subsequent to the final deposition phase with subsequent rapid remobilisation of the materials and downslope washouts (flooding) as impounded runoff collects upslope. The outwash phase is also a likely mechanism for remobilisation of the deposited debris should surges of runoff occur due to short duration intense rainstorms after the initial event. As a result of subsequent washouts there is a high likelihood of erosion of the initially deposited debris with the creation of downcut channels extending into the substrate materials (Plate 20). Also the buildup of surface runnoff behind areas of slope blockage leads to the formation of large volumes of water mixed with debris flowing downslope over and around the displaced landslide materials leading to the lateral deposition of materials at the periphery of the trail combined with flattening of grass and vegetation in the direction of flow (Plate 21). The high levels of waterborne materials are evident by examination of the height of vegetation damage (e.g. tree and shrub bark scraped and debris lodged within branches) adjacent to the trail.
GULLY SIDE SLIDE (GSS)	This characteristic trail section occurs on the steep slopes that are formed adjacent to incised gullies usually downcut through old colluvium (Class 2 or 3, Plate 22). The main scarp of the associated landslide is generally formed close to the slope break point or higher on a convex slope profile on steep slopes usually > 35°. The substrate material is predominantly colluvium and weathered rock. The associated landslide typically results from a compact shallow main scarp with a limited runout length (< 10 m) and are generally terminated in the gully bottom. The material composition of the debris is predominantly sub-rounded gravel and cobble size rock fragments in a matrix of silt and sand. Minor erosion of the substrate is common as a result of hyper-concentrated flows subsequent to the initial failure.

Table 8 - Dominant Trail Unit Section Characteristics and Associated Slope Morphology

MORPHOLOGICAL CHARACTERISTIC	Predominance of Trails within the Tung Chung Study Area with these Morphological Characteristics											
	DEPOSITION		EROSION		OUTWASH		TERMINATED DEPOSITION		CHANNEL		GULLY SIDE SLIDE	
	down slope	cross section	down slope	cross section	down slope	cross section	down slope	cross section	down slope	cross section	down slope	cross section
CONCAVE	37%	**62%**	**46%**	**91%**	0%	**63%**	**50%**	**100%**	20%	**80%**	0%	45%
CONVEX	10%	5%	14%	0%	13%	0%	**50%**	0%	0%	0%	0%	0
PLANAR	**53%**	33%	41%	9%	**87%**	37%	0%	0%	**80%**	20%	**100%**	**55%**

Table 9 - Characteristics of Trail Unit Sections and Related Aspects (Range of Values Is Given in Parentheses, Average of Range in **Bold**)

CHARACTERISTIC	DEPOSITION	EROSION	OUTWASH	TERMINATED DEPOSITION	CHANNEL	GULLY SIDE SLIDE
	avg. std. dev.	avg. std. dev.	avg. std. dev.	avg. std. dev.	avg. std. dev.	avg. std. dev.
Trail Width (m)	**9** (1-30) 7	**8** (1-18) 4	**5** (3-10) 3	**6** (1-10) 4	**6** (3-8) 3	**10** (3-20) 5
Length (m)	**28** (2-100) 22	**25** (5-52) 15	**36** (4-100) 29	**10** (10) 0	**47** (15-100) 30	**7** (4-10) 3
Slope Angle (°)	**27** (10-40) 6	**27** (16-45) 7	**32** (10-42) 8	**24** (20-28) 4	**25** (8-30) 5	**36** (20-47) 9
Thickness of Deposition (m)	**0.32** (0.1-1.50) 0.37	**0.20** (0-1.0) 0.25	**0.09** (0.02-.1) 0.03	**0.60** (0.2-1.0) 0.40	**0.45** (0-1.5) 0.56	**0.58** (0.1-1.0) 0.42
Composition of Substrate Material	Predominantly colluvium and residual soil	No predominant material type, includes colluvium, residual soil and weathered rock	Predominantly colluvium with some residual soil	Predominantly colluvium with some residual soil	Predominantly colluvium with some residual soil	Weathered rock and colluvium
Composition of Displaced Materials	Predominantly silt and sand with traces of clay and with some sub-rounded and sub-angular gravel, cobble and boulder size decomposed rock fragments	Predominantly silt and sand with trace of clay and gravel size decomposed rock fragments	Silt and sand with few sub-angular gravel cobble and boulder size decomposed rock fragments	Predominantly silt and sand with traces of clay and with some sub-rounded and sub-angular gravel, cobble and boulder size decomposed rock fragments	Predominantly silt and sand with trace of clay and gravel size decomposed rock fragments	Predominantly sub-rounded and sub-angular gravel, cobble and few boulder size decomposed rock fragments with some silt and sand with traces of clay
Erosion Volume per metre length of trail (m^3/m)	0.24	2.28	-	-	3.66	0.14
Percentage Deposition of Initial volume from Main scarp (%)	**40** (0-90)	**8** (0-50)	**18** (0-50)	**70** (60-80)	**9** (0-15)	**56** (5-90)
Secondary characteristics	Erosion with channels downcut within debris sometimes through to substrate materials. This results from the hyper-concentrated stream flows during runoff subsequent to initial failure	Wash out and lateral deposition	Deposition	Wash out and lateral deposition	Wash out and lateral deposition	Terminal deposition
Percentage Length of Trails with this Characteristic (%)	55%	20%	13%	1%	9%	2%

Table 10 - Landslide Model Types and Associated Characteristic Trail Unit Sections

Landslide Event	Landslide Model Type	Characteristic Trail Unit Sections	Total number of slides with this trail model	Predominance of this model as a Percentage of all slides examined during the study (out of 52)	Number of Landslides of this Type in Year of Activity	
					1992	1993
Debris Flow	i)	Deposition (DEP)	16	30%	6	10
Debris Flow	i)	DEP & DEP	3	5%	0	3
Debris Flow	i)	DEP & DEP & DEP	1	2%	0	1
Debris Flow	ii)	ERO & DEP	1	2%	0	1
Debris Flow	ii)	DEP & ERO	1	2%	0	1
Debris Flow	ii)	DEP & ERO & ERO & DEP	1	2%	0	1
Debris Flow	ii)	DEP & ERO & DEP & DEP	1	2%	0	1
Debris Flow	ii)	DEP & DEP & ERO & DEP	1	2%	1	1
Debris Flow	ii)	ERO & DEP & ERO	1	2%	0	1
Debris Flow	iii)	outwash (WO)	4	8%	3	1
Debris Flow	iii)	DEP & WO	3	6%	3	0
Debris Flow	iii)	DEP & WO & DEP	1	2%	0	1
Debris Flow	iii)	WO & WO	1	2%	1	0
Debris Slide	iv)	DEP	2	3%	2	0
Debris Flow	v)	Terminated Deposition (TER)	2	3%	0	2
Debris Flow	v)	DEP & TER	2	3%	0	2
Gully Side Slide	vi)	Gully Side Slide (GSS)	6	12%	5	1
Gully Erosion	vii)	Erosion (ERO)	2	3%	1	0
Gully Erosion	vii)	ERO & ERO & ERO	1	2%	0	1
Channelised Debris Flow	viii)	ERO & ERO & ERO & DEP & Channel	1	2%	0	1
Channelised Debris Flow	viii)	ERO & DEP & Channel & DEP & DEP	1	2%	0	1
Channelised Debris Flow	viii)	DEP & Channel & Channel & DEP & ERO & ERO & ERO & DEP	1	2%	0	1
Channelised Debris Flow	viii)	ERO & Channel & DEP & GSS	1	2%	0	1

Table 11 - Range of Values for Whole Trail Lengths and Erosion Volumes for Landslide Model Types

LANDSLIDE MODEL		Typical main source volume< 400 m^3		Typical main source volume> 400 m^3	
Unconstrained Trail	Type	Trail length m (% occurrence)	Erosion range (average) m^3	Trail length m (% occurrence)	Erosion range (average) m^3
Debris Flow - predominantly depositional	i)	15 - 100 (31%)	0 - 30 (15)	35 - 70 (7%)	0 - 20 (10)
Debris Flow - deposition and erosion	ii)	20 - 85 (11%)	12 - 80 (46)	no data	no data
Debris Flow - deposition and outwash	iii)	5 - 100 (17%)	0 - 20 (10)	no data	no data
Debris Slide	iv)	2 - 10 (3%)	0	no data	no data
Constrained Trail					
Debris Flow -Terminated deposition	v)	10 (3%)	0	10 - 16 (3%)	0 - 25 (12)
Gully side slide	vi)	4 - 10 (10%)	0	10 (2%)	10
Gully erosion	vii)	25 - 95 (5%)	50 - 330 (190)	no data	no data
Channelised Debris Flow - includes deposition, erosion and channelised flow	viii)	no data	no data	70 - 450 m (8%)	90 - 860 (470)

Table 12 - Suggested Factors Predisposing Natural Slopes to Landslides

FACTOR NO.	DESCRIPTION OF FACTOR
1. SIGNS OF PREVIOUS INSTABILITY	a) Relict main scarps b) Evidence of activity at same scarp within API history
2. GEOLOGY	a) Class 3 colluvial deposits within catchment b) Class 1 and 2 colluvial deposits within drainage line c) Surficial deposits within catchment d) Presence of decomposed volcanics
3. HYDROLOGY	a) Catchment at elevation > 130 m b) Narrow drainage channel (i.e. channel side slopes > 25°) c) Rock cliff within drainage line or above catchment
4. SLOPE ANGLE	a) Steep slopes > 30° within catchment b) Steep slopes within or above catchment > 35°
5. SLOPE MORPHOLOGY	a) Concave profile along slope contour b) Concave or planar profile down slope
6. VEGETATION	a) Grass/low scrub or bare slope b) Lack of dense vegetation with trees

Table 13 - Maximum Rainfall Intensities at Royal Observatory, Tsim Sha Tsui and Estimated Return Periods for Some Significant Rainstorms

Storm Date Ending date and **(time)** of rolling 24-hour data		Duration of Measurement Period for Rainfall 24 hours [1]	1 day	2 days
14/15 June 1959 **15 (17:00)**	Rainfall (mm)	308.9	270.3	452
	Return Period (Years)	5	3	11
12/13 Oct 1964 (Typhoon Dot) 12 **(12:00)**	Rainfall (mm)	303.8	246.5	333.1
	Return Period (years)	5	2	3
11/12 June 1966 12 **(12:00)**	Rainfall (mm)	401.2	382.6	460.4
	Return Period (Years)	14	11	12
18/19 August 1972 (Typhoon Betty) 21 **(01:00)**	Rainfall (mm)	186.8	186.8	446.4
	Return Period (Years)	1	1	10
24/25 August 1976 (Severe Tropical Storm 25 **(11:00)**	Rainfall (mm)	416.2	261.3	512.6
	Return Period (Years)	17	3	20
28/29 May 1982 (SW Monsoon) 29 **(11:00)**	Rainfall (mm)	394.3	258.4	437.4
	Return Period (Years)	13	3	10
16 August 1982 (S.T.S Dot) 16 **(03:00)**	Rainfall (mm)	360.8	334.2	414.6
	Return Period (Years)	9	6.5	8
17 June 1983 (heavy rain and thunderstorms) 18 **(01:00)**	Rainfall (mm)	346.7	346.7	350.5
	Return Period (Years)	7.5	7.5	3
20/21 May 1989 (rainstorm) 21 **(06:00)**	Rainfall (mm)	387.8	322.8	425.7
	Return Period (Years)	12	5.5	8
7/8 May 1992 8 **(19:00)**	Rainfall (mm)	324.7	324.1	386.2
	Return Period (Years)	6	6	6
17/18 July 1992 18 **(20:00)**	Rainfall (mm)	178.4	177.7	184.4
	Return Period (Years)	1	1	1
4/5 November 1993 5 **(09:00)**	Rainfall (mm)	106.6	86.1	122.3
	Return Period (Years)	1	1	1
22/23 July 1994 22 (20:00)	Rainfall (mm)	310.2	297	492.1
	Return Period (Years)	5	4.5	17

Note: 1. Rolling 24-hour rainfall used.

Table 14 - Maximum Rainfall Intensities at N17, Tung Chung for Some Heavy Rainstorms and Estimated Return Periods

Duration	Rainstorm on 18 July 1992			Rainstorm on 5 November 1993			Rainstorms on 22/23 July 1994		
	Rainfall	Ending Time	Estimated Return Period (Years)	Rainfall (mm)	Ending Time	Estimated Return Period (Years)	Rainfall 1 mm)	Ending Time	Estimated Return Period (Years)
15-minutes	37	10:15	6	37	04:15	6	25	19:15 (23.7.94)	1
1-hour	111	10:00	70	94	04:00	21.5	77	05:00 (23.7.94)	7
4-hours	311	12:00	182	285	06:00	96	176	06:00	7
5-hours	336	13:00	144	349	08:00	190	195	07:00	5.5
6-hours	354	13:00	104	421	08:00	378	198	08:00	3.5
Rolling 24-hours	454	18:00	28	742	11:00	796	280	24:00	3.7

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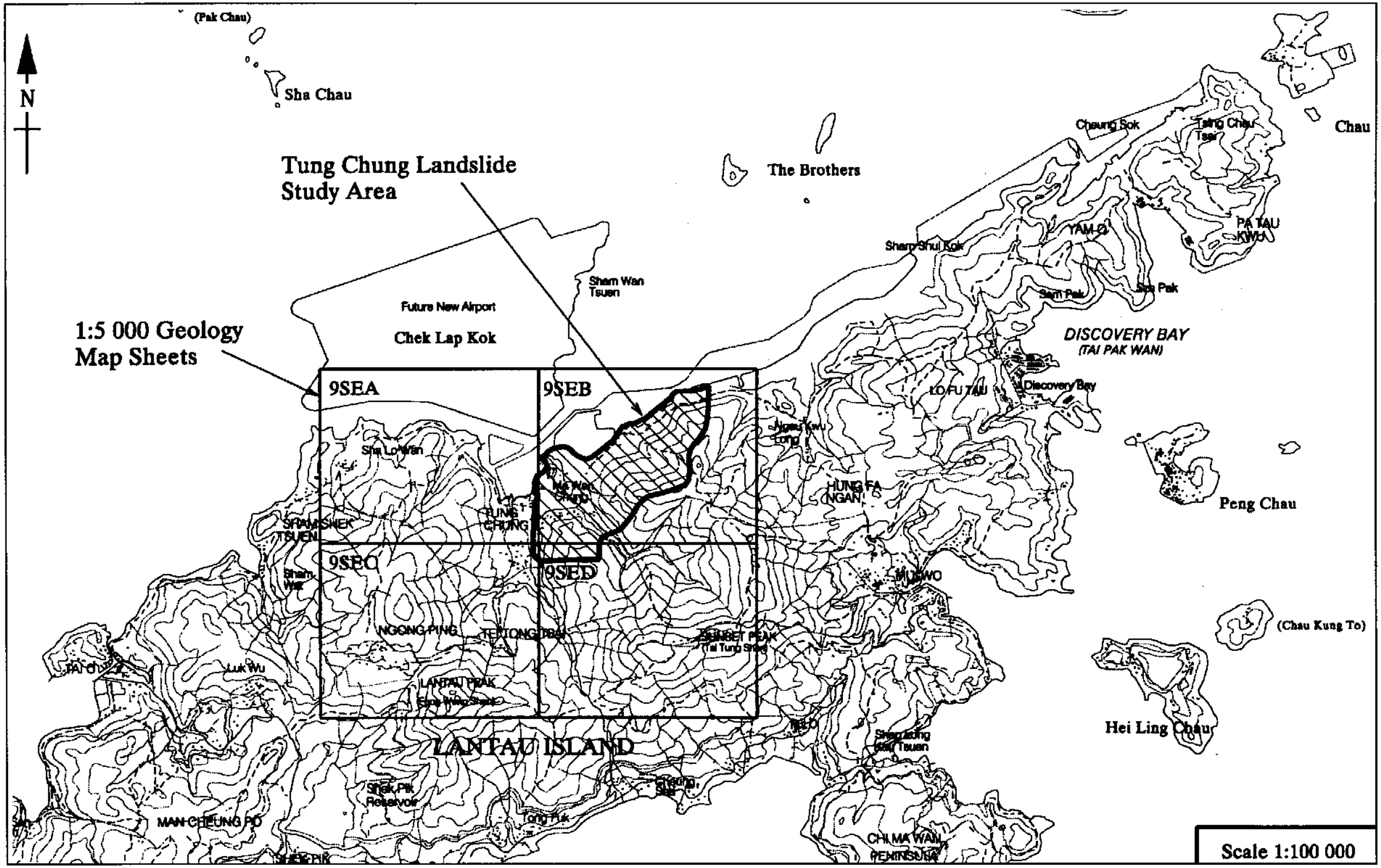

Figure 1 - Location of the Tung Chung Landslide Study Area

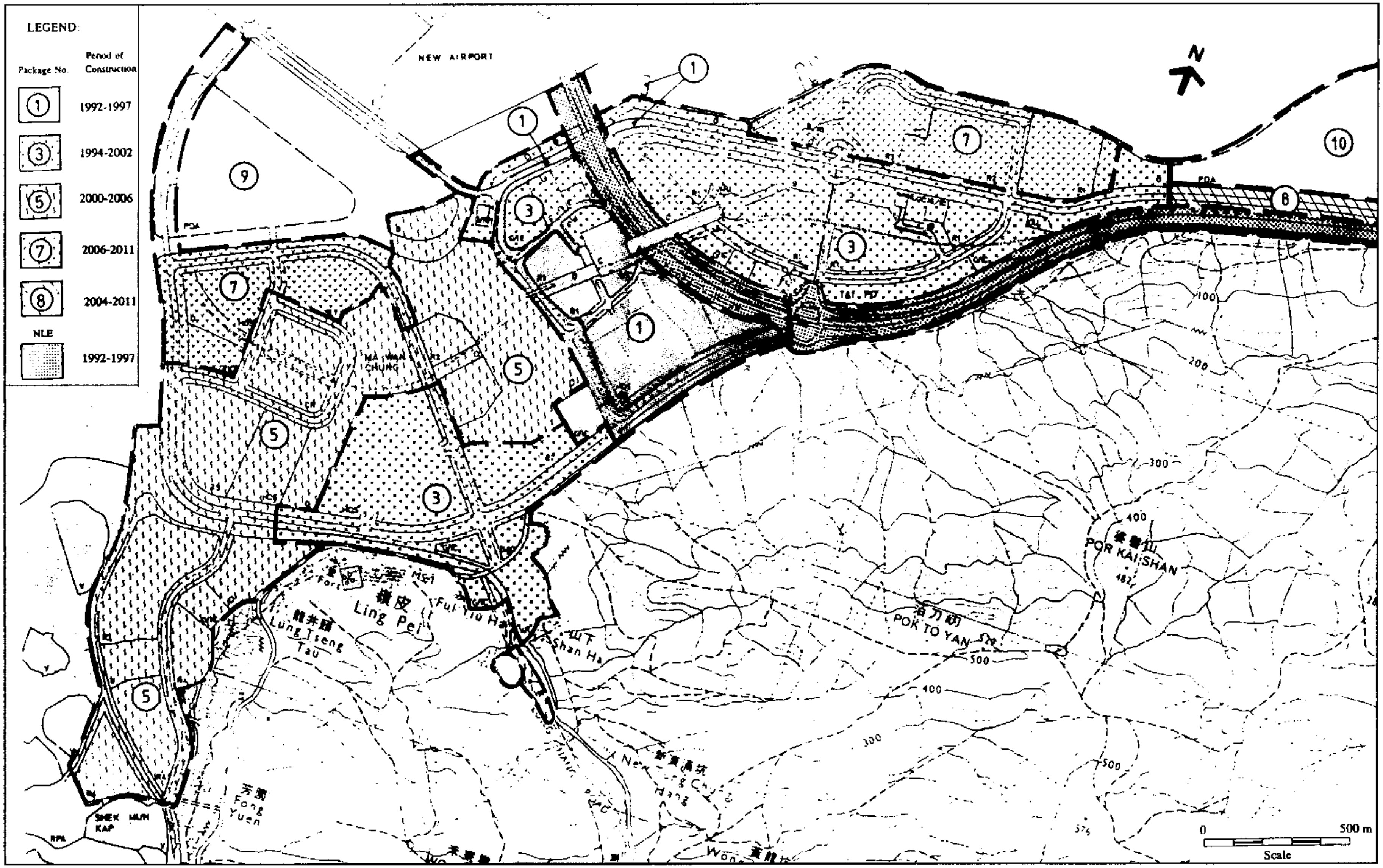

Figure 2 - Plan of the Tung Chung Development Showing Phasing of the Construction (from TDD, 1992)

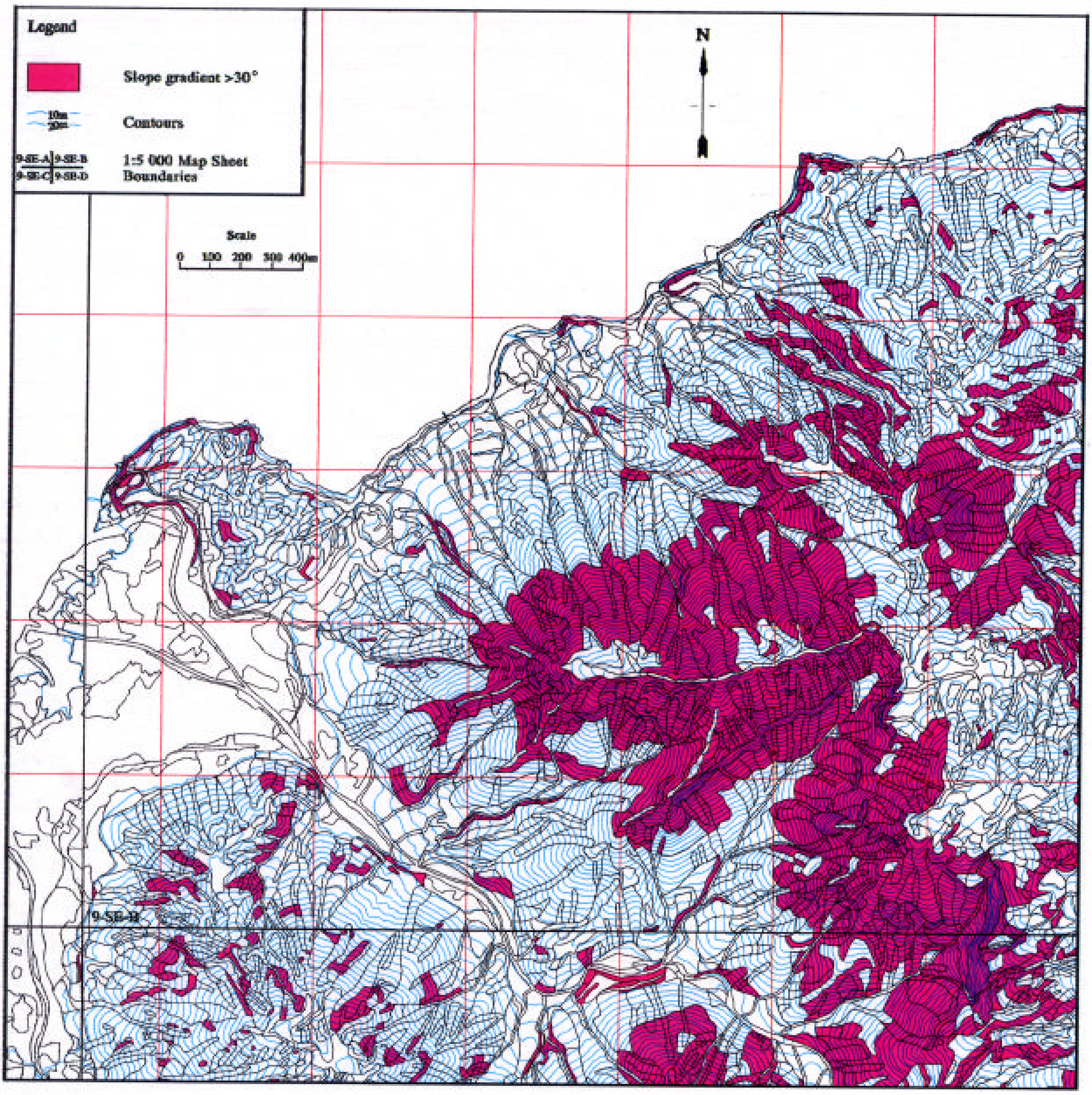

Figure 3 - Land in the Study Area with Steep Terrain (Slope Gradient > 30°)

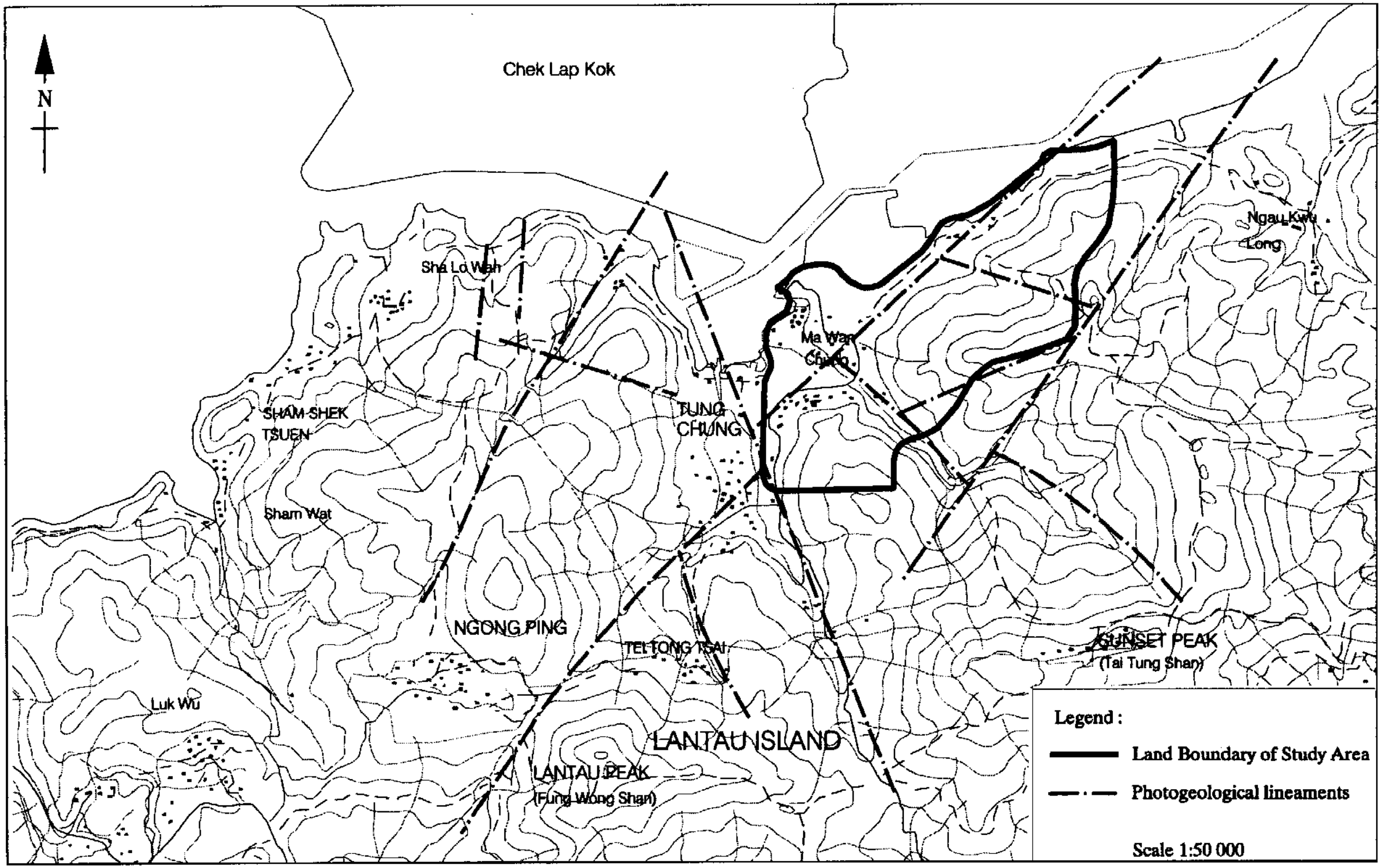

Figure 4 - Photogeological Lineaments in the Tung Chung Area

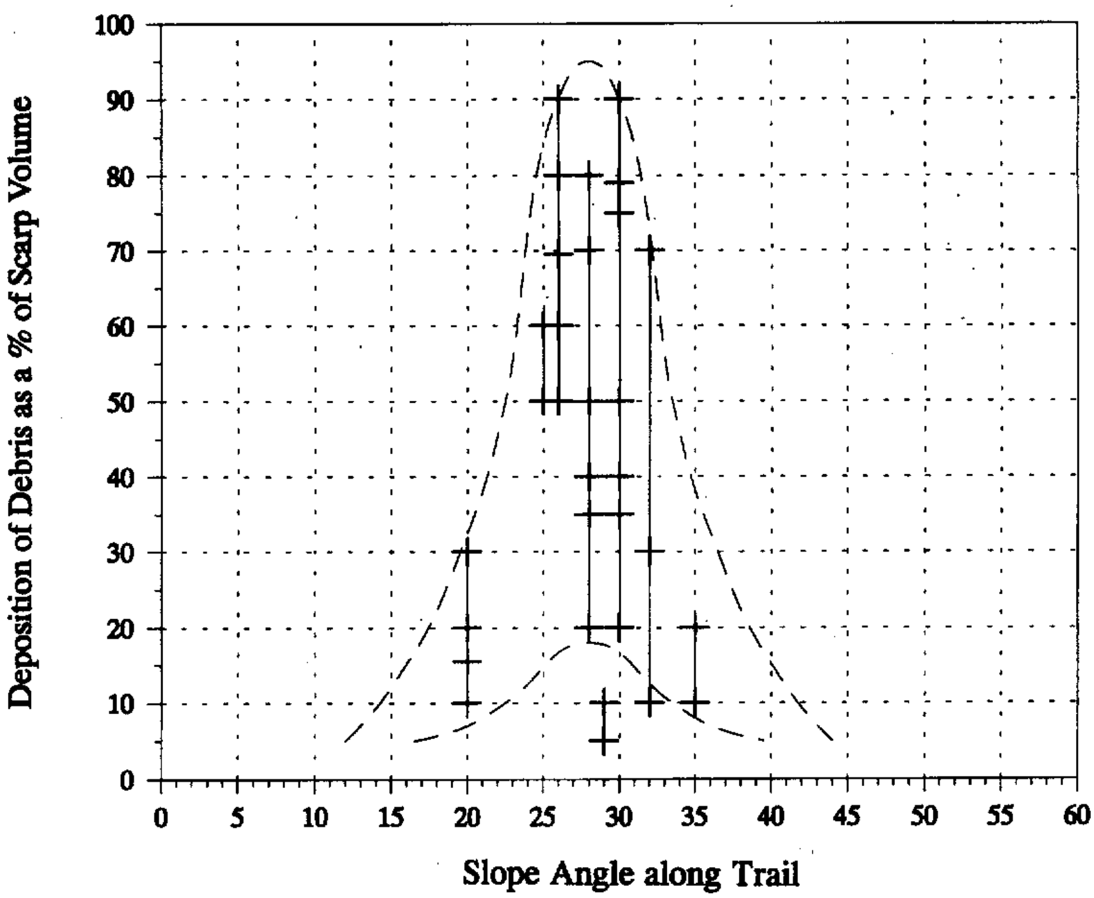

Figure 5 - Slope Angle vs Deposition Volume (as % of Main Scarp Volume)

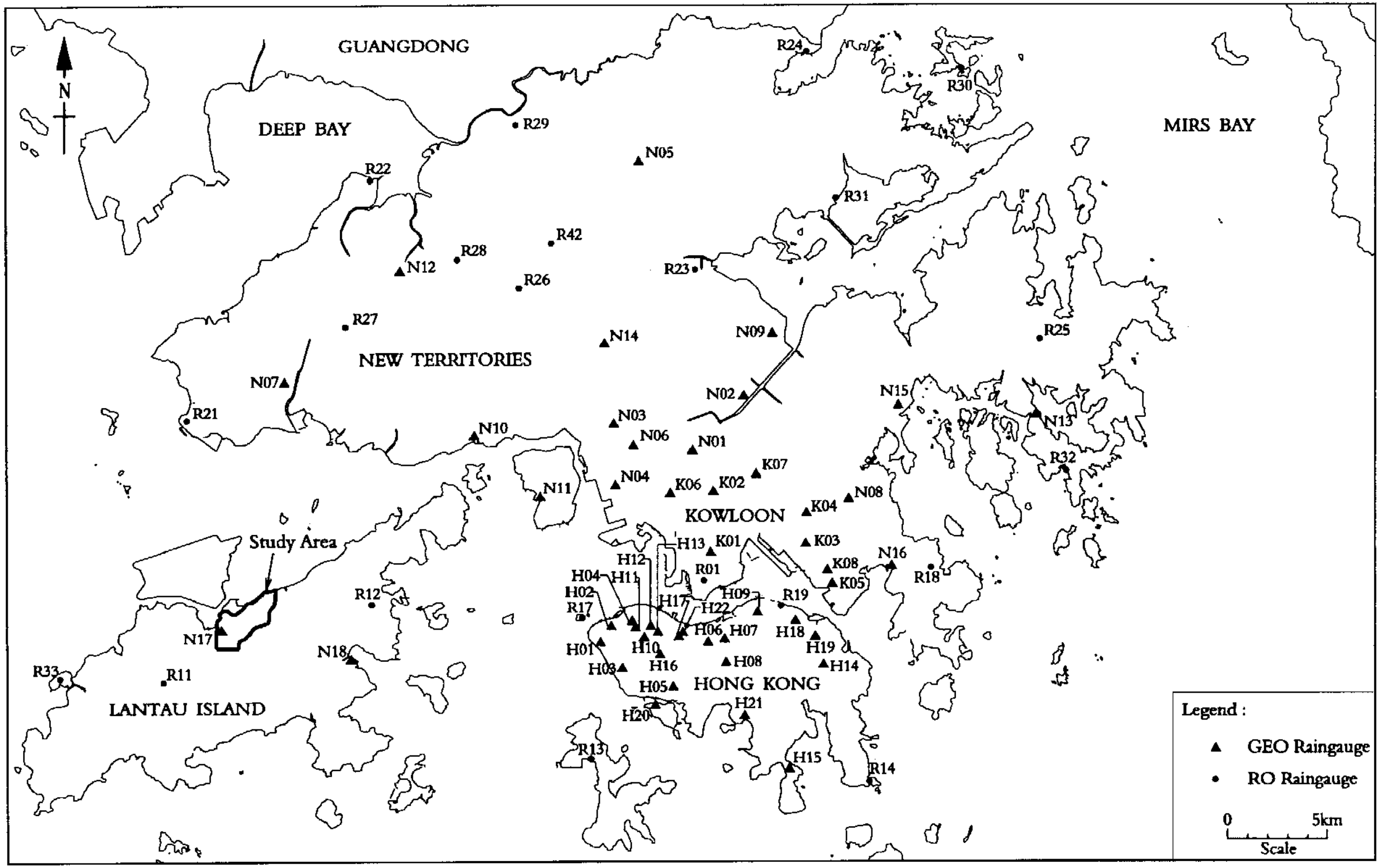

Figure 6 - Location of GEO and RO Automatic Raingauges

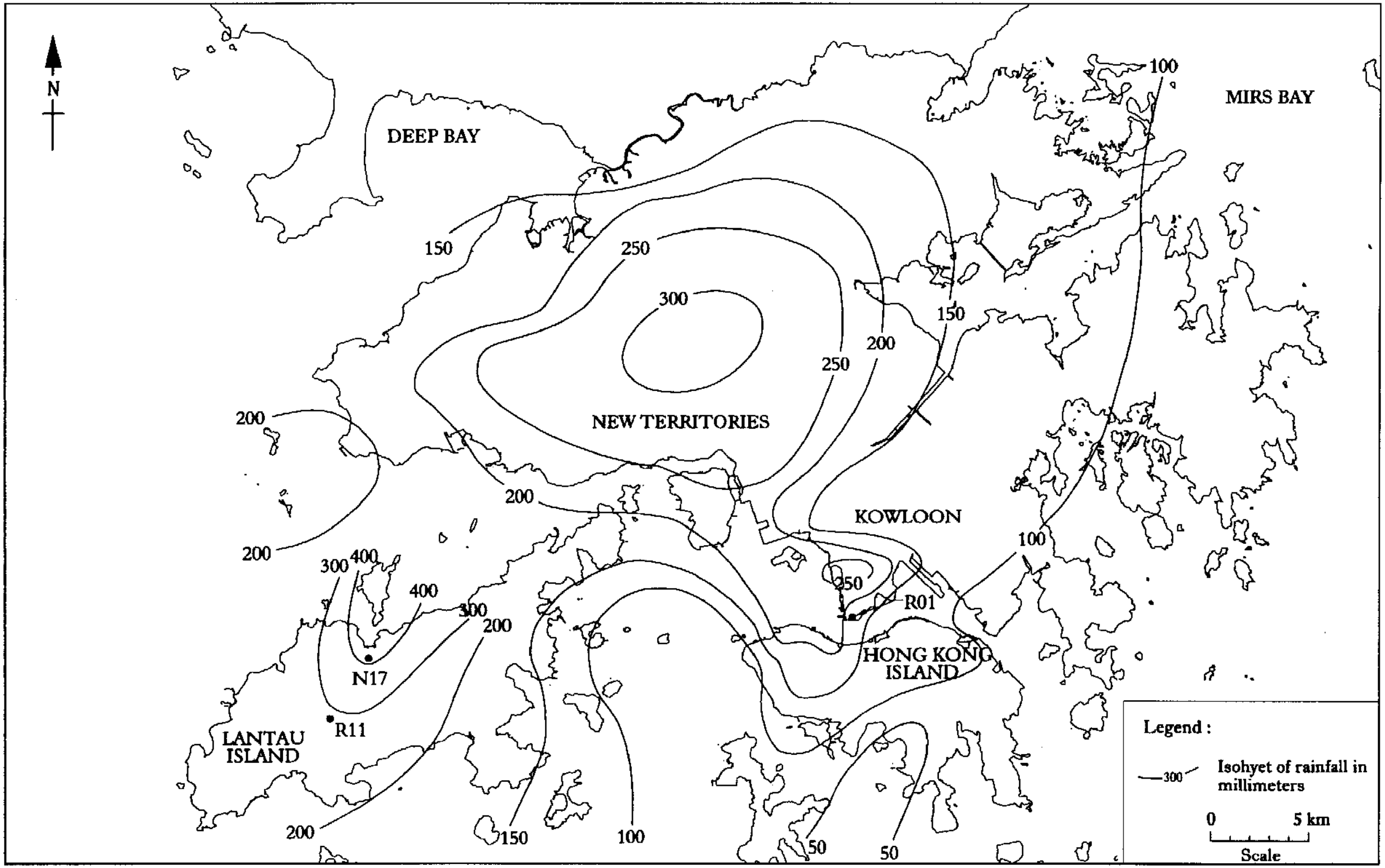

Figure 7 - Rolling 24-hour Rainfall Distribution during the Rainstorm of 18 July 1992

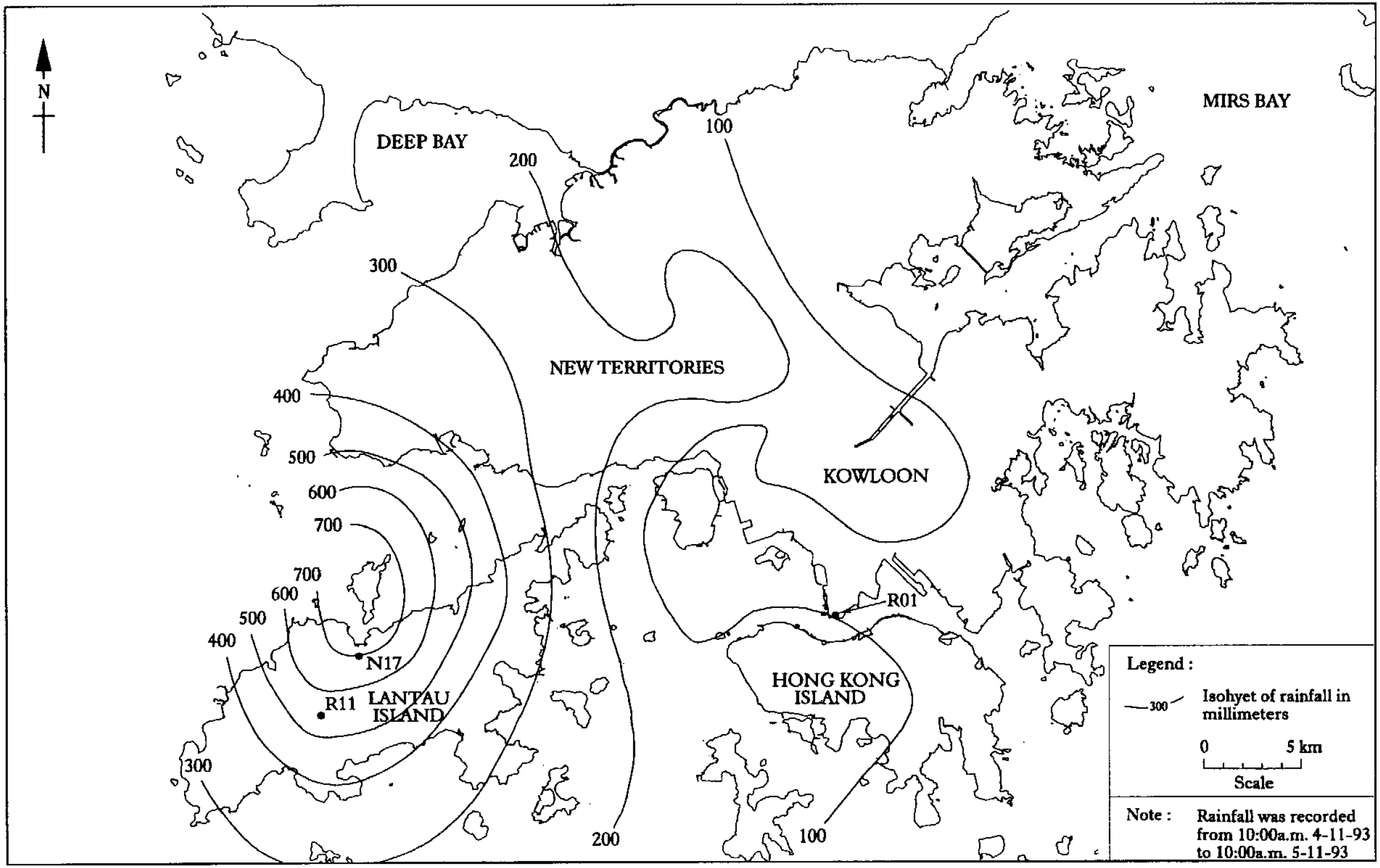

Figure 8 - Rolling 24-hour Rainfall Distribution during the Rainstorm of 5 November 1993

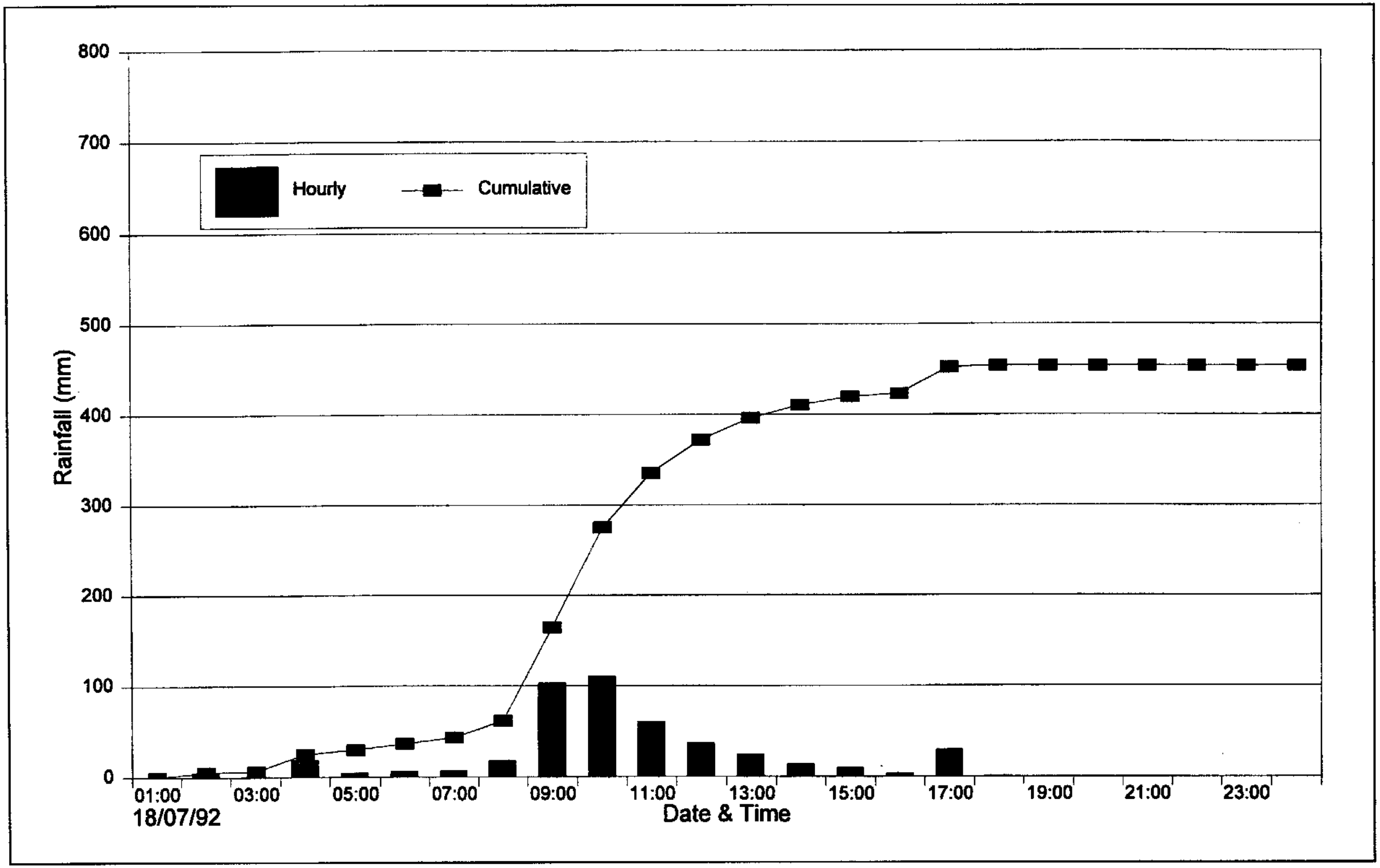

Figure 9 - Hourly Rainfall Recorded by Raingauge N17 during the Storm of 18 July 1992

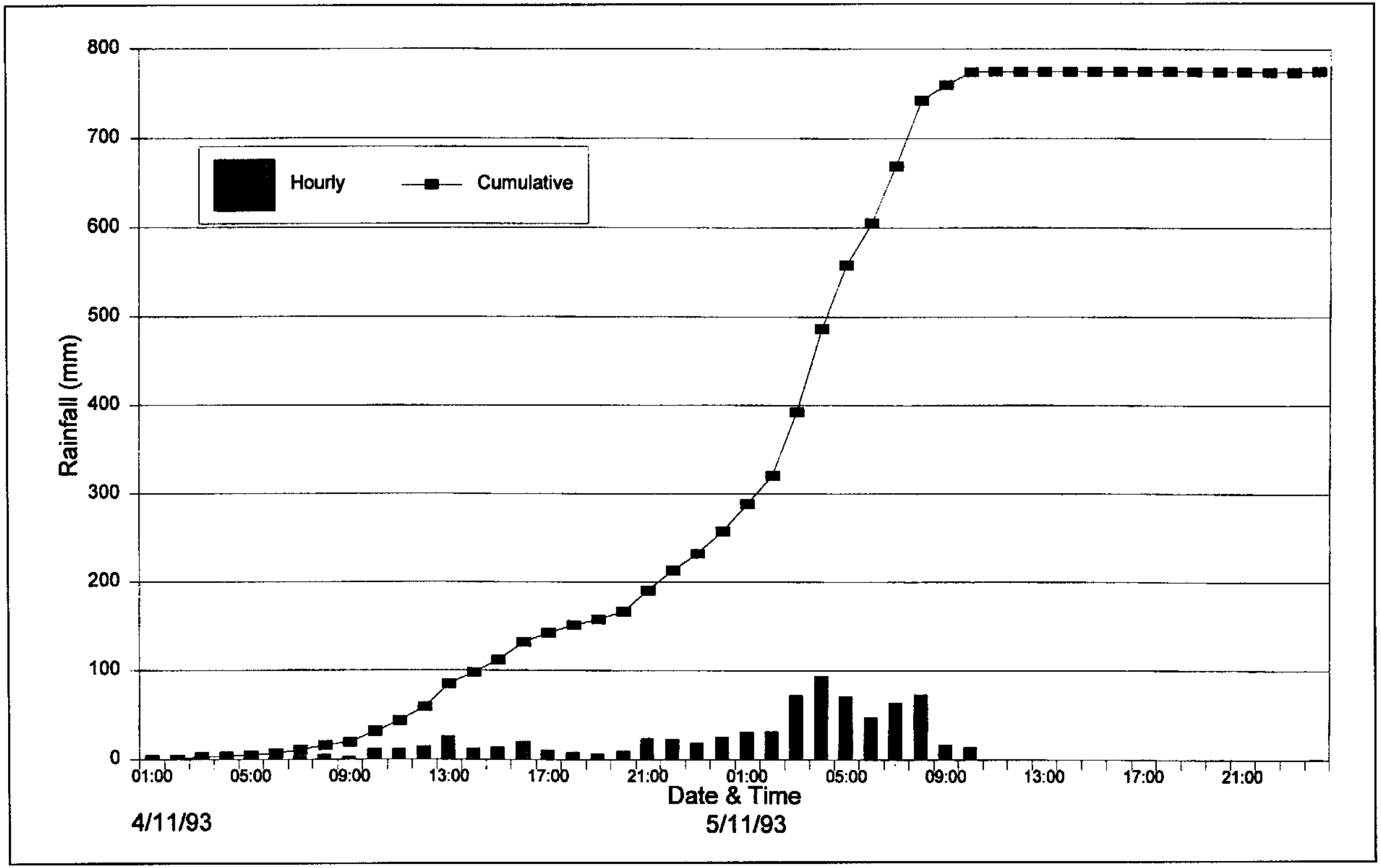

Figure 10 - Hourly Rainfall Recorded by Raingauge N17 during the Storm of 5 November 1993

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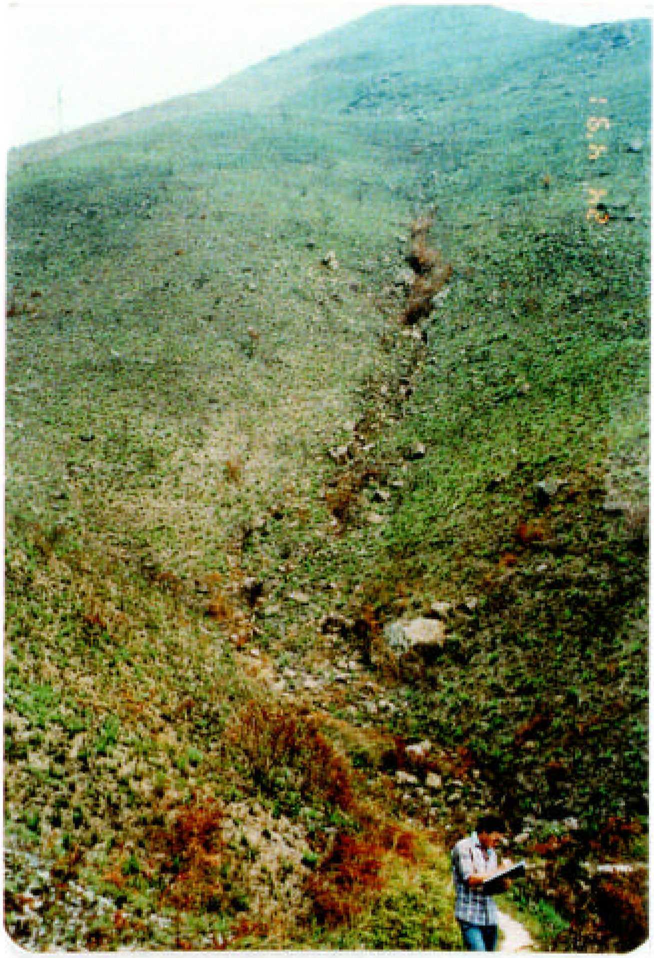
Plate 3 - Well Rounded Ridge Crest on Hill Above Tung Chung Fort



Negative No. EG 91/60/20

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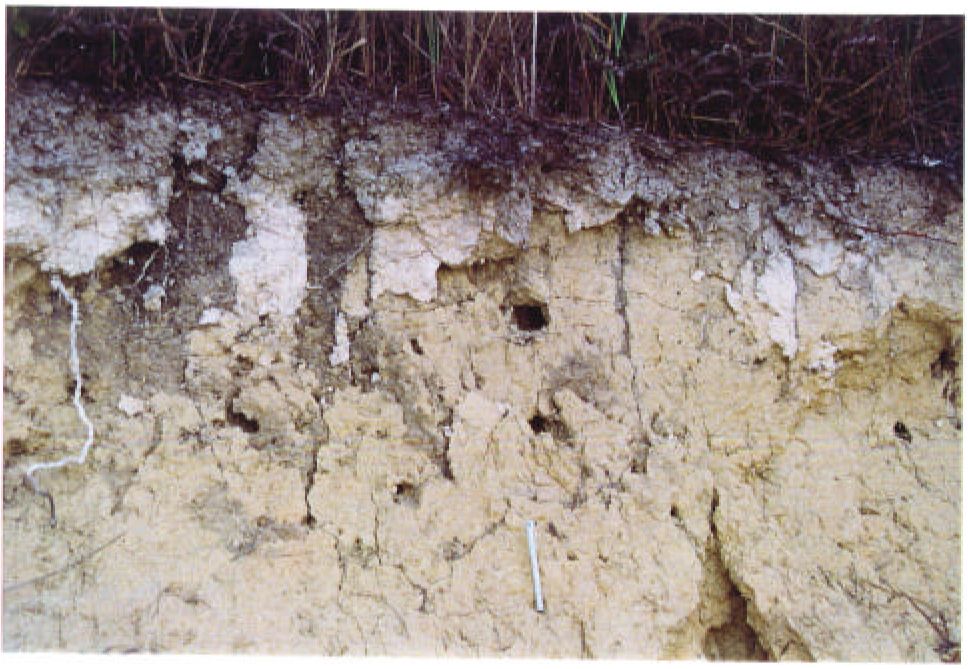

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Plate 23 - Overall View of the Landslide (5A/2) that produced a Landslide Trail Runout Extending into the Tung Chung New Town Development Area, Phase 1

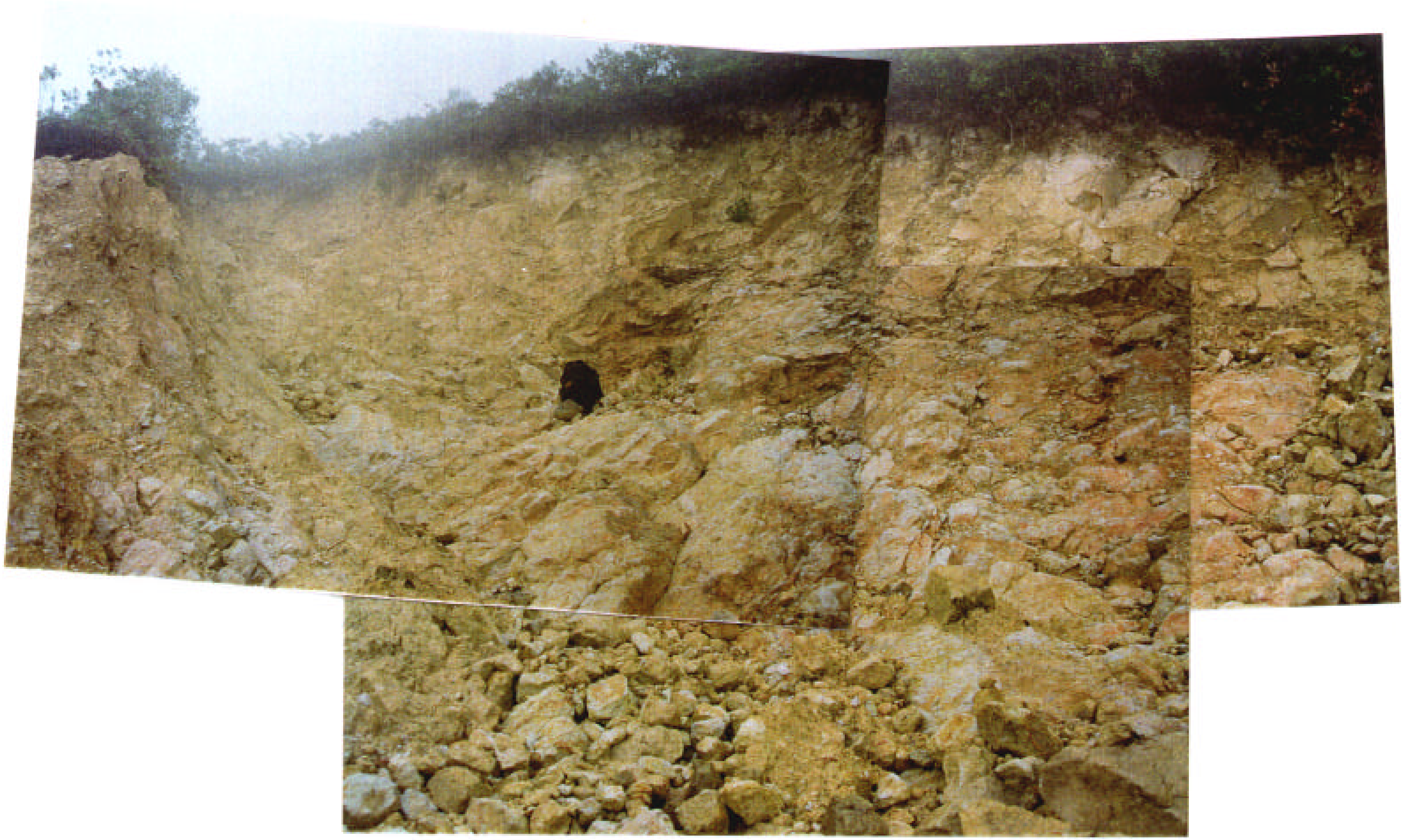

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Plate 24 - Main Scarp in Weathered Bedrock of Landslide 5A/2

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APPENDIX A

LANDSLIDE TERMINOLOGY

Terminology for Study of Natural Terrain in Hong Kong

The terminology presented here is adopted from that suggested by King (in prep.) largely based on Varnes (1978) and Hutchinson (1988). Terms for description of features within a landslide scar are based on IAEG (1990) modified as necessary to accommodate high mobility long run out failures, and for description of sediment-water flows on Pierson and Costa (1987). The proposed terminology is not meant to encompass all terms used when describing landslides, and is biased towards defining those terms which may not be being used in a consistent way at present. The proposed terminology is also biased towards terms used when describing elongate, relatively shallow natural terrain landslides which are dominated by flow and alluvial processes, as there are many such features in Hong Kong and they have not yet been extensively reported or described.

Some of the terms have a strict definition followed by comments that start with "Note" to illustrate its application. When defined terms are used in the definitions of other terms they are underlined.

GENERAL TERMS

Natural terrain : -

Terrain that has not been modified substantially by human activity such as site formation works, agricultural terraces, cemetery platforms or squatter habitation. Note that in most of the Territory natural terrain has been influenced by deforestation and fire and locally may have been influenced by prehistoric agriculture.

Landslide : -

A general, all-encompassing term used to describe an event comprising the downslope movement of a discrete mass of soil and/or rock. Note that the term makes no inference as to process, i.e. : true sliding may not be involved. It is proposed that extremely slow slope movements such as soil creep and gravitational sagging are not included under the general term landslide.

Natural terrain landslide : -

A landslide in which the scar is located entirely within natural terrain. Note that a landslide involving both natural terrain and terrain that has been modified substantially by human activity is not considered to be a natural terrain landslide, e.g. failure immediately above and extending into an excavation or immediately below fill.

Quasi-natural terrain landslide : -

A large failure in predominantly natural terrain triggered by, or possibly triggered by, a relatively small human activity. Landslides for which there is an element of doubt with respect to the importance of human activity are placed in this category.

Natural Slope : -

A sloping section of natural terrain with boundaries defined for geomorphological or administrative purposes.

LANDSLIDE FEATURES

Scar : -

The land surface affected by a landslide. This includes the source, the displaced material and any trail.

Relict scar : -

A scar on which vegetation has re-established but which still has a well-defined main scarp.

Displaced Material : -

Material displaced from its original position on the slope by movement in a landslide. Note that an accumulation of displaced material is a deposit.

Crown : -

The practically undisplaced material still in place and adjacent to the highest parts of the main scarp.

Trail : -

Part of a scar downslope from the main scarp dominated by transport and deposition of debris, although erosion may also occur.

Head : -

The upper parts of a landslide along the contact between the displaced material and the main scarp. Note that an elongate landslide may not have a definable head.

Surface of Rupture : -

A surface on the undisturbed ground caused by movement of the displaced material away from the undisturbed ground.

Main scarp : -

The exposed steep part of the surface of rupture.

Floor : -

Any exposed shallow part of the surface of rupture.

Source : -

The area above the surface of rupture.

Entrained Material : -

Displaced Material from any location other than the source.

Toe : -

The lower margin of the displaced material of a landslide, it is the most distant part of the scar from the main scarp. Note that for a landslide with a trail this will be the distal part of the trail.

Mobility angle : -

The arc tangent of the height (H) over length (L) ratio where; H = elevation difference between the crown and the toe. L = the horizontal distance from the crown to the toe. Note that this is often called the apparent angle of friction (aaf) in technical literature. However aaf has also been used when H and L are defined on the basis of the centre of gravity of the displaced material and to aviod possible misinterpretation this new term is proposed.

TYPES OF DISPLACED MATERIAL

Colluvium : -

A general term applied to any heterogeneous, structureless mass of soil and/or rock material and sometimes organic matter, deposited on and at the base of natural slopes by predominantly mass-wasting processes.

Intact displaced mass : -

The mass of displaced material (soil, colluvium or rock) from a landslide that largely retains its original morphology.

Intact displaced material : -

Displaced material (soil, colluvium or rock) that retains its original structure. Intact displaced material may occur as clasts or slabs within debris.

Debris : -

Displaced material from a specific landslide which has disintegrated and lost its original morphology. Debris may include clasts of intact displaced material. Note that debris is very young colluvium and it is proposed that the term is used to distinguish the debris of a specific landslide from pre-existing in-situ colluvium which may have the same composition. This differs from Varnes' (1978) definition of the term debris, which he uses to describe any deposit of predominantly coarse engineering soil. In Hong Kong this has usually been described as colluvium, or talus. Specific types of debris include:

Blocky Debris : -

Debris comprising loose blocks of intact displaced material, generally rock but possibly soil.

Slurry debris : -

Debris derived from slurry flow. Note that diagnostic characteristics of slurry debris include the formation of steep lobate fronts and lateral levees, and the matrix support of particles of gravel size or larger.

Alluvial Debris : -

Debris transported and deposited by water. Note that diagnostic characteristics include grain size sorting and layering.

Boulder : -

Rock fragment greater than 200 mm diameter that is not part of a rock mass.

TYPES OF LANDSLIDE SCAR

The following typical types of landslide scar have been observed on natural terrain in Hong Kong. The divisions reflect differences in the mobility of the displaced material.

Slump : -

A scar with an intact displaced mass which has only partially mobilised and is mainly on the surface of rupture. Note that a slump has no trail.

Elongate : -

A scar in which some or all of the displaced material has mobilised from the surface of rupture forming debris. Note that an elongate scar has a trail and the source is often a spoon shaped or planar depression.

Elongate channelised : -

Defined as an elongate scar in which the debris has been channelised in a drainage line or depression.

An elongate scar may be further described by the distribution of displaced material within it.

Uniform Deposit : -

Debris deposit comprising a sheet of debris of uniform thickness within the trail.

Lateral Deposit : -

Debris deposit comprising ridges aligned along the trail at or near the lateral margins.

Intermediate Deposit : -

Debris accumulation at some point along the trail between the source and the toe.

Terminal Deposition : -

Debris deposit at the toe. Note that this is commonly lobate or fan shaped.

MOVEMENT TERMS

Sliding : -

Shear displacement along one or several surfaces, or within a relatively narrow zone, which are visible or may be reasonably inferred (Varnes, 1978).

Liquefaction : -

Generation of high positive excess pore water pressures during shearing and hence a substantial reduction of the effective stress and the shearing resistance. Note that in Hong Kong liquefaction is known to have occurred in the rain induced failure of loose fill slopes.

Flow : -

Broadly defined as continuous irreversible deformation of a geologic material that occurs in response to an applied stress that is usually gravity. Types of flow include:

Slurry flow : -

The movement of a saturated sediment/water mixture having sufficient yield strength to exhibit plastic flow behaviour in the field (see slurry debris). When movement ceases, fine and coarse particles consolidate with no interparticle movement.

Streamflow : -

The flow of water with a sufficiently small sediment concentration that its flow behaviour is unaffected by the presence of sediment in transport.

Hyperconcentrated streamflow : -

The flow of a mixture of water and sediment that possesses a small but measurable yield strength but that still appears to flow like a liquid. Particles settling out of a hyperconcentrated streamflow suspension settle independently, giving deposits sorted by grain size.

TYPES OF LANDSLIDE EVENT

SIMPLE : -

A landslide with the same mechanism for detachment and movement of the displaced material.

Slide : -

A landslide in which the movement is by sliding. Note that this may be further qualified by a prefix specifying the material involved, e.g. colluvium/residual soil/weathered rock slide. Slides may be separated into translational or rotational on the basis of their morphology

Translational slide : -

Slide in which the sliding surface is relatively planar or gently undulating in downslope section.

Rotational slide : -

Slide in which the sliding surface is curved and concave upwards and imparts a degree of backward rotation or tilt to the displaced material. Note this is termed a slump by Varnes (1978) and a slip by Hutchinson (1988).

Topple : -

Movement of a detached rock mass by overturning about a pivot point below the centre of gravity of the unit.

Sheet Erosion : -

The removal of soil or decomposed rock by the surface flow of water or a mixture of water and sediment.

Gully Erosion : -

The creation of an incised drainage line by channelised surface flow.

Outwash : -

The redistribution of debris by streamflow and hyper-concentrated streamflow.

COMPLEX : -

A landslide that is a complex geomorphological event in which debris is moved by one or several transport mechanisms that differ from the detachment mechanism. Note that classification is based on the assessed dominant transport mechanism such as falling, sliding, flowing and streamflow, although all of these processes may have occurred to different degrees at different parts of the scar. The morphology of the landslide scar and material type of the displaced material also contribute to the description of the landslide.

Rockfall : -

The displacement of a piece of rock from a rock mass. Much of the movement is through the air by free fall but may include leaps, bounds, rolling and sliding.

Boulderfall : -

The displacement of a boulder where much of the movement is through the air by free fall but may include leaps, bounds, rolling and sliding. Note that boulder falls most commonly result from the undercutting by erosion or landsliding of exhumed corestones or colluvial boulders on steep natural hillsides.

Debris slide : -

A landslide in which debris moves by the dominant mechanism of sliding. Note these often occur on steep hillsides where they typically form an elongate scar and that intact displaced material is normally present.

Debris flow : -

A landslide in which debris moves by the dominant mechanism of flow. Note that these often occur on steep hillsides where they typically form an elongate scar. The presence of slurry debris is a good indication that flow has occurred. Debris flows may be separated into either unconfined hillslope debris flows which form an elongate scar on a relatively planar hillslope or channelised debris flows which form a channelised elongate scar.

Mud flow : -

A landslide with the same characteristics as a debris flow in which the displaced material is predominantly fine grained.

Debris flood : -

The transport of a significant load of sediment by the dominant mechanisms of streamflow or hyperconcentrated streamflow. The load can range in grain size from clay to boulders. A debris flood may originate from outwash or gully erosion.

Debris Torrent : -

The channelised transport of a significant load of sediment, that may include landslide debris, by the mechanisms of flow , hyperconcentrated streamflow and streamflow but none is clearly dominant.

APPENDIX B

LANDSLIDE DATABASE

B.1. LANDSLIDE DATABASE

B.1.1 General

A landslide database was created, using the program DBASE IV, to store manipulate the field data collected during the study.

The complete database comprises two tables; one contains data relating to the landslide scarp (SCRP.DBF), the other contains data relating to the debris trail (TRAILS.DBF) produced downslope of the scarp. The structure of the two database tables is given below:

Structure for database: B:\SCRP.DBF

Number of data records: 86
Date of last update : 07/26/95

Field	Field Name	Type	Width	Dec	Index
1	SLIDE_NO	Character	6		Y
2	OBSERV_N	Character	5		N
3	SLOPE_ANGL	Numeric	2		N
4	SLOPE_DIR	Numeric	3		N
5	HD_SCAR_AN	Numeric	2		N
6	H_SCAR_DIR	Numeric	3		N
7	PIPING	Character	1		N
8	VOLUME	Numeric	5		N
9	DEPTH	Numeric	3	1	N
10	WIDTH	Numeric	4		N
11	LENGTH	Numeric	4		N
12	SLIDE_LONG	Numeric	5		N
13	MATERIAL	Character	5		N
14	DESCRIPT	Memo	10		N
15	ACTIVITY	Numeric	3		N
16	YR1945	Character	3		N
17	YR1963	Character	3		N
18	YR1972	Character	3		N
19	YR1982	Character	3		N
20	YR1992	Character	3		N
21	YR1993	Character	3		N
22	FLOW_MODEL	Character	11		N
23	PHOTOGRAPH	Character	14		N

Structure for database: B:\TRAILS.DBF

Number of data records: 141
Date of last update : 07/26/95

Field	Field Name	Type	Width	Dec	Index
1	SLIDE_NO	Character	6		N
2	SLOPE_ANGL	Numeric	2		N
3	TRAIL_SECT	Numeric	2		N
4	OBSERVE	Character	5		N
5	SUBSTRATE	Character	6		N
6	VOLUME	Numeric	5		N
7	DEPTH	Numeric	4	2	N
8	WIDTH	Numeric	4	1	N
9	LENGTH	Numeric	5	1	N
10	EROSION	Numeric	3		N
11	DEPOSITION	Numeric	2		N
12	DEB_DESCPN	Memo	10		N
13	DRAIN_ORDR	Character	1		N
14	SLP_MPH_XS	Character	10		N
15	SLP_MPH_PF	Character	10		N
16	TRAIL_TYP1	Character	10		N
17	TRAIL_TYP2	Character	10		N
18	CHANNEL_WD	Numeric	4	2	N
19	CHANNEL_DP	Numeric	4	2	N
20	LAT_DEPOSI	Character	10		N
21	LAT_THICK	Numeric	4	2	N
22	VEGETATION	Character	12		N
23	TCM_SLOPE	Character	1		N
24	TCM_TERRA	Character	1		N
25	TCM_SURFAC	Character	1		N
26	TCM_LD_USE	Character	1		N
27	TCM_EROS_N	Character	1		N
28	PHOTOGRAPH	Character	14		N

B.1.2 Description of Fields

A brief description of each of the fields in the landslide database is given below:

Database: B:\SCRP.DBF

SLIDE_NO	-	The landslide slide number
OBSERV_N	-	Source of data (API or FIELD)
SLOPE_ANGL	-	Gradient of natural slope adjacent to scarp
SLOPE_DIR	-	Direction of maximum slope gradient
HD_SCAR_AN	-	Gradient of landslide scarp

H_SCAR_DIR	-	Direction of maximum gradient of scarp
PIPING	-	Piping present (Y or N)?
VOLUME	-	Estimated volume in m^3 of scarp
DEPTH	-	Depth in metres of scarp
WIDTH	-	Maximum width of scarp
LENGTH	-	Maximum length of scarp
SLIDE_LONG	-	Total length of debris slide including debris trail and scarp
MATERIAL	-	Dominant material type exposed in the scarp RS - residual soil, Co - Colluvium, WR - weathered rock.
DESCRIPT	-	Description of the material exposed in the scarp
ACTIVITY	-	Previous landslide activity
YR1945	-	Year of previous activity (from API), Y - yes or blank if no
YR1963	-	Year of previous activity (from API), Y - yes or blank if no
YR1973	-	Year of previous activity (from API), Y - yes or blank if no
YR1982	-	Year of previous activity (from API), Y - yes or blank if no
YR1992	-	Year of previous activity (from API), Y - yes or blank if no
YR1993	-	Year of previous activity (from API), Y - yes or blank if no
FLOW_MODEL	-	Code depicting the complexity and type of debris trail associated with the scarp
PHOTOGRAPH	-	Photographic record negative reference number

Database: B:\TRAILS.DBF

SLIDE_NO	-	The landslide slide number
SLOPE_ANGL	-	The average slope gradient in degree's along the section of the debris trail described
TRAIL_SECT	-	The section of the debris trail described in the record starting from the section closest to the landslide scarp and working downslope. The number system used is 1, 2, 3 etc.
OBSERVE	-	The observation source (either API or FIELD)
SUBSTRATE	-	The nature of the substrate ground material below the debris trail. The code use is CO for colluvium, RS for residual soil, WR for weathered rock.
VOLUME	-	The estimated volume of
DEPTH	-	The depth of the debris trail
WIDTH	-	The width of the debris trail
LENGTH	-	The length of the debris trail

EROSION	-	The estimated volume of erosion within the debris trail section
DEPOSITION	-	The estimated deposition within the debris trail section as a percentage of the original scarp volume
DEB_DESCPN	-	Description of the debris material
DRAIN_ORDR	-	Description of the drainage order of the debris trail (0 for none, 1 for, 2 for)
SLP_MPH_XS	-	Description of the slope morphology along the slope contour
SLP_MPH_PF	-	Description of the slope morphology down the slope profile
TRAIL_TYP1	-	Description of the dominant debris trail transport mechanism
TRAIL_TYP2	-	Description of the secondary debris trail transport mechanism
TRAIL_TYP1	-	Description of the dominant debris trail transport mechanism
TRAIL_TYP2	-	Description of the secondary debris trail transport mechanism
CHANNEL_W	-	Width of channel (in metres) if channelised debris flow
CHANNEL_DP	-	Depth of channel (in metres) if channelised debris flow
LAT_DEPOSI	-	Lateral deposition (Y - yes, N - none)
LAT_THICK	-	Thickness (in metres) of lateral deposit if any
VEGETATION	-	Type of vegetation present (SCRUB, TREES, GRASS, etc)
TCM_SLOPE	-	Terrain Classification Mapping (TCM) code for slope class
TCM_TERRA	-	TCM code for terrain type
TCM_SURFA	-	TCM code for surface type
TCM_LD_USE	-	TCM code for land use type
TCM_EROS_N	-	TCM code for erosion
PHOTOGRAPH	-	Photographic record negative reference number

B.1.3 Linked Database Tables

Each of the database tables contains a common field (SLIDE_NO) against which they can be linked during queries of the complete data set. This method of data storage reduces the size of the database as repeated fields of scarp data for each debris trail section are not required.

Linking the database tables in this way allowed a number of queries to be made and reports generated relating to :

1) Scarp characteristics, where the data were grouped ;
   i) according to a scarp width range criterion, and,

   ii) according to a scarp volume range.

2) Debris trail characteristics, where the data were grouped ;
   i) according to the dominant debris trail transport, and,
   ii) according to the debris trail complexity.

LIST OF DRAWINGS