SECTION 3: DETAILED STUDY OF THE LANDSLIDES AT KAU WA KENG SAN TSUEN ON 4 JUNE 1997

Halcrow Asia Partnership Ltd

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FOREWORD

This report presents the findings of a detailed study of four landslides (GEO Incident Nos. MW97/5/14, MW97/6/49, MW97/6/50 and MW97/6/56) which occurred on slopes adjacent to Kau Wa Keng San Tsuen on 4 June 1997. Debris from the landslides affected the squatter village, but no fatalities or injuries were reported.

The key objectives of the detailed study were to document the facts about the landslides, present relevant background information and establish the probable causes of the landslides. The scope of the study was generally limited to site reconnaissance, desk study and analysis. Recommendations for follow-up actions are reported separately.

The report was prepared as part of the 1997 Landslip Investigation Consultancy (LIC), for the Geotechnical Engineering Office (GEO), Civil Engineering Department (CED), under Agreement No. CE 68/96. It is one of a series of reports produced during the consultancy by Halcrow Asia Partnership Limited (HAP). The report was written by Dr M Swales and reviewed by Dr R Moore and Mr H Siddle. The assistance of the GEO in the preparation of the report is gratefully acknowledged.

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1. INTRODUCTION

Four landslides, referred to as landslides A to D in this report (GEO Incident Nos. MW97/5/14, MW97/6/49, MW97/6/50 and MW97/6/56), occurred on the morning of 4 June 1997 on separate slopes along the western boundary of Kau Wa Keng San Tsuen (Figure 1 and Plate 1). The failures involved two soil cut slopes (landslides A and B) and two fill slopes (landslides C and D), with estimated volumes ranging from 15 m^3 to 500 m^3. The landslides affected building lots in the village, but no fatalities or injuries were reported.

Following the landslides, Halcrow Asia Partnership Limited (the 1997 Landslip Investigation Consultants), carried out a detailed study of the failures for the Geotechnical Engineering Office (GEO), Civil Engineering Department (CED), under Agreement No. CE 68/96. It is one of a series of reports produced during the consultancy by Halcrow Asia Partnership Limited (HAP).

The key objectives of the detailed study were to document the facts about the landslides, present relevant background information and establish the probable causes of the landslides. The scope of the study was limited to site reconnaissance, desk study and analysis. Recommendations for follow-up actions are reported separately.

This report presents the findings of the study which comprised the following key tasks :

(a) a review of relevant documents relating to the history of the site,

(b) analysis of rainfall records,

(c) interviews with witnesses and persons affected by the landslides,

(d) detailed observations and measurements of the landslide sites, and

(e) diagnosis of the probable causes of the landslides.

2. THE SITE

2.1 Site Description

Landslides A to D were located on the west side of the village of Kau Wa Keng San Tsuen (Figure 2). The village is located in a narrow, northwest trending valley that contains a minor river within a concrete channel. The west side of the village comprises up to four rows of one and two storey terraced houses located on the valley floor.

The west side of the densely vegetated natural hillside above the village was inclined at about 30° to the horizontal and extended from an elevation of about 20 mPD to about 100 mPD at the slope crest. Extensive rock outcrops are present throughout the hillside. Several developments were present at the slope crest, including residential buildings, a service reservoir and several registered fill slopes (Figure 2).

Five natural streamcourses, referred to as Nos. 1 to 5 (Figure 2), drain the natural terrain within the study area. Stream Nos. 3 and 5 contained permanently flowing water that discharged into the river. Water from stream No. 3 is conveyed through the village within a spillway. Local residents confirmed that the other three streams are ephemeral.

A man-made drainage channel, constructed to intercept surface water stream flows and run-off, traverses the natural hillside upslope of the village for about 280 m (Figure 2). On inspection by HAP in June 1997, the standard of construction and maintenance was found to vary along the length of the channel. Where it was founded on rock, the channel tended to be properly formed (Plate 3) whereas in soil terrain, it was typically shallow and infilled with foreign material (Plate 4).

Landslides A and B involved the failure of cut slopes located behind house Nos. 69A and 85 respectively (Figures 3 to 7). Both cut slopes were concave in section, being inclined at about 45° at the toe and steepening to around 75° towards the crest; they were up to 7 m high and around 12 m wide. Before the landslides, the slopes were covered with relatively well maintained chunam and drained by 50 mm diameter weepholes spaced at about 2 m centres.

Landslide C occurred on a man-made slope behind house No. 73. The slope comprised a fill body retained by a 3.5 m high masonry retaining wall. The slope above was terraced and supported by four more retaining walls that were constructed from brick and covered by chunam (Figures 6, 8 and 9). The uppermost retaining wall was around 2 m high, 11 m long and supported a concrete-covered fill platform which was used as a recreational area. The concrete covering of the platform was in poor condition. A steeply inclined rock face is situated above the platform over which water was observed to flow even during periods of dry weather.

Prior to failure, the slope in the vicinity of landslide D (Figures 10 and 11) comprised an unretained granitic fill body of about 1 000 m^3. The upper part of the fill body was about 15 m wide and formed an almost level platform, whilst its flanks sloped at about 40° to the horizontal. House No. 139C was located some 15 m downslope of the toe of the fill, on a small cut and fill platform. Scattered remains of old building materials on the upper part of the fill body suggest that other squatter premises may have been present at sometime in the past.

The four landslides shown in Figure 2 affected areas to the rear of house Nos. 69A, 85, 73 (landslides A to C) and to the side of house No. 139C (landslide D). Landslides A, B and D occurred entirely within unallocated Government land (District Lands Office, 1997; Housing Department, 1997a; GEO, 1997a). In the case of landslide C, the main scarp of the landslide was located on unallocated Government land while the debris affected land under Government Land Licence No. W9480 (District Lands Office, 1997).

2.2 Site History

2.2.1 Site Development

The historical development of the site was determined from a sequential series of aerial photographs and from a review of available documentary information.

Prior to 1945 the valley was undeveloped except for low agricultural terraces. Aerial photographs show that the majority of the buildings and associated man-made slopes on the west side of the valley were in place by 1954. In 1961 a major cutting about 30 m wide by 10 m high was being formed to provide terracing behind village houses located between stream Nos. 3 and 4 (Figure 2). Aerial photographs indicate that during construction a failure occurred in the northern part of the cutting, immediately below a large sheeting joint surface exposed in the natural terrain. Evidence of water seepage on the sheeting joint surface may be seen in the 1961 aerial photographs. The material from the excavation appears to have been end-tipped on the natural terrain to the north of the excavation to create two fill slopes (Figure 2), the larger of which was later affected by landslide D. Aerial photographs indicate that minor terracing took place between 1961 and 1963 above the cut slope to the rear of house No. 85.

2.2.2 Previous Landslides

According to GEO's Landslide Incident Report database, there have been eleven previous reported landslides on the west side of the village (i.e. west of the river) since 1978 (Table 1 and Figure 2). They involved estimated volumes of 10 m^3 to 50 m^3 comprising colluvium or "weathered rock" and were reported to be caused by "infiltration". All involved damage to property or affected footpaths and access lanes. A serious landslide occurred on 16 August 1982 (GCO Incident No. NT 82/8/8) which involved the collapse of two, 3 m high masonry retaining walls and part of the platform in front of house Nos. 39 and 41. Several squatter huts were buried and two people were killed as a result of this landslide.

The Landslide Incident Report database indicates that the man-made slope on which landslide A occurred was affected by previous landslides (GEO Incident Nos. MW94/7/9 and MW95/7/8) on 22 July 1994 and 14 July 1995. From the distribution of landslide incidents, it appears that failures most commonly take place on the upslope boundary of the village where man-made slopes meet the natural terrain. Some clustering of incidents is apparent, particularly where there are sources of surface water flow. For example, three incidents behind house Nos. 43 and 45 (MW89/5/88A, MW89/5/88B and MW93/9/21) occurred on a cut slope located downslope of stream No. 1. Inspection of aerial photographs taken in 1963 also indicates that two pre-existing landslide scars are present within the catchments of stream Nos. 2 and 5 (Figure 2). The latter of these landslides extends about 40 m downslope, the toe of which was later covered by the body of granitic fill involved in the recent landslide D.

The GEO's Natural Terrain Landslide Inventory shows no landslides on the natural hillside overlooking the west side of Kau Wa Keng San Tsuen.

2.3 Previous Studies

2.3.1 Slope Registrations and Stage 1 Studies

The man-made slopes affected by the recent landslides were not registered in the 1977/78 Catalogue of Slopes (Binnie & Partners, 1978a and 1978b). The natural hillside above the village was assigned Slope No. 11NW-A/N7 and was included in a Phase 1 Landslide Study Report by consultants to the Geotechnical Control Office (GCO) in 1978 (Binnie & Partners, 1978b). Potential landslides on the hillside were assessed to pose "high risk" to life and a recommendation was made to "warn inhabitants of possible danger from landslips and boulders."

The cut slope behind house No. 69A affected by landslide A was registered by GEO's consultants as slope No. 11NW-A/C233 in the New Catalogue of Slopes in December 1995. In the Stage 1 Study carried out at the time, no signs of seepage nor distress of the slope were observed, and no emergency action on the slope was considered necessary.

The retaining wall and fill slope behind house No. 73 were registered as slope No. 11NW-A/FR202 in the New Catalogue of Slopes in October 1996. At that time, no signs of seepage nor distress of the slope were observed, and no emergency action on the slope was considered necessary.

2.3.2 Previous Assessments

In the early 1980s, the Tsuen Wan New Town Development Office (TWNT) prepared an Outline Development Plan (Kau Wa Keng ODP No. TWNT/17) for Kwai Chung Planning Area 43. The village and natural hillside fell within Planning Areas 43B and 43F respectively. In 1981, the GCO "raised no objection to the proposed use on the planning area" and made comments which were intended to be of use in detailed design (GCO, 1981). In these comments the GCO noted that "a few landslides have been observed; mostly on the steep slopes of Area 43F, western side." In relation to Area 43B, the GCO also noted that, "the western boundary of the area is formed by very steep slopes" and that "the API plan indicates the presence of a landslide scar along this boundary."

The area affected by landslides A to D has not been subject to a Non-Development Clearance programme (GEO, 1997a).

2.4 Subsurface Conditions

The Hong Kong Geological Survey Map Sheet No. 11 (GCO, 1986) shows a uniform distribution of fine-grained granite on the west side of the village and the hillside above. However, according to field reconnaissance and aerial photographic interpretation conducted by HAP two types of granite have been identified in the area. A pronounced lineament running down the hillside in an east to west direction separates predominantly medium-grained granite to the south from predominantly megacrystic coarse-grained granite to the north (Figure 2). This interpretation was confirmed by the Hong Kong Geological Survey (GEO, 1998b).

The predominant geology at the sites of landslides A and B comprised moderately weak to weak, dry to moist, light yellowish brown spotted grey, dark brown and white, moderately to completely decomposed, medium- to coarse-grained granite of mass weathering grade PW 0/30 to PW 30/50. This was overlain by loose to medium dense, moist, orangish brown, clayey silty gravelly sand (residual soil). Landslides C and D primarily involved fill which comprised loose, moist to wet, greyish to orangish brown, slightly clayey silty gravelly sand.

The orientations of discontinuities were measured in outcrops of predominantly PW 90/100 weathered granite exposed on the hillside above the village. The dominant discontinuity set comprised sheeting joints with an average dip/dip direction of 46/075. Two further joint sets, orthogonal to the sheeting joints, had average dips/dip directions of 85/350 and 61/265 respectively. The contact between mass weathering zones PW 0/30 to PW 30/50 and PW 90/100 coincided with the sheeting joints, with occasional steps occurring along orthogonal joints (Figures 4 and 6).

Kau Wa Keng San Tsuen is situated near the Lai Chi Kok Tolo Channel Fault Zone. According to the Hong Kong Geological Survey Memoir No. 2 (GCO, 1986), there are two major faults in the area trending northwest to southeast at both the crest and toe of the natural slope (Figure 2). Minor faulting in the area trends northeast to southwest.

Some information on the geology is also provided by the boreholes and trial pits (Figure 2) associated with three previous investigations (Lam Geotechnics, 1985; Enpack, 1996; P & T Geotechnics, 1981). These indicate that the soil layer is typically between 2 m and 6 m thick and that joint spacing increases with depth.

3. THE LANDSLIDES

3.1 Time of the Landslides

Local residents confirmed that the time of failure for all four landslides was about 07:00 hours on 4 June 1997. Landslide A was preceded by a small failure which, according to the GEO Incident Report, occurred at 11:00 hours on 8 May 1997.

3.2 Description of the Landslides

3.2.1 Landslide A

A plan and cross-section of the landslide are shown in Figures 4 and 5 respectively.

A minor landslide (GEO Incident MW97/5/14) with an estimated volume of 5 m³ occurred on the lower half of the northern part of the cut slope behind house No. 69A during heavy rainfall on 8 May 1997 (Plate 5). Inspections by HAP after the incident revealed cracking of the chunam cover extending laterally across the unfailed, upper part of the cut slope. A larger landslide subsequently affected the entire cut slope on 4 June 1997 (Plate 6).

The landslide of 4 June 1997 was about 8 m wide and 5 m long, with an estimated volume of 80 m^3, the debris of which came to rest against the rear wall of house No. 69A. The landslide was about 2.5 m deep and exposed granitic residual soil overlying highly to completely decomposed, medium- to coarse-grained granite. In places, a fabric of closely spaced discontinuities aligned parallel to the slope was present in the soil. The failure took place along the discontinuities and the debris slipped downslope in a single translational sliding movement. Several erosion pipe holes were observed in the main scarp, about 1 m below ground level. The debris comprised loose to firm, moist to wet, slightly clayey gravelly sand with occasional angular shaped cobbles. The travel angle of the landslide debris was estimated to be in excess of 30°, despite the debris having come to rest against the rear wall of house No. 69A. This angle is within the typical range for rain-induced failures in Hong Kong (Wong & Ho, 1996).

The inclination of the natural terrain above the landslide was typically about 30° to the horizontal. Topsoil and residual soil was present immediately above the crest of the cut slope whilst an extensive sheeting joint outcropped further upslope, dipping parallel to the natural terrain at about 45° to the horizontal. Inspections by HAP over a three-week dry period after the landslide, revealed that water flowed continuously over much of the sheeting joint surface. The source of the water could not be identified, but the extensive nature of the water flow suggested the presence of a springline within the natural hillside close to the village.

House No. 69A was unoccupied at the time of the landslide, following permanent evacuation of the property on 30 April 1990. After the landslide, arrangements were made for the Highways Department to carry out urgent repair works (GEO, 1997a).

3.2.2 Landslide B

A plan and cross-section of the landslide (GEO Incident MW97/6/49) are shown in Figures 6 and 7 respectively.

The landslide involved the full height of the cut slope (Plate 7) and exposed a 2 m thick layer of residual soil overlying completely decomposed medium-grained granite. The failure was about 9 m wide, 5m long and 1 m deep. The main scarp of the landslide was inclined at 50° to 70° to the horizontal. The estimated volume of the landslide was 15 m^3, the debris from which accumulated against the rear wall of house No. 85. The travel angle of the landslide debris was estimated to be in excess of 30° which is within the typical range for rain-induced failures in Hong Kong (Wong & Ho, 1996).

The chunam-covered cut slope behind house No. 85 was composed of two sections characterised by different grades of mass weathering (Figure 6). The south side of the slope comprised a sheeting joint surface in PW 90/100 granite, with an average inclination of about 50° to the horizontal. The north side comprised residual soil and PW 0/30 weathered granite (completely decomposed) which was underlain by a sheeting joint which daylighted near the toe of the slope. The landslide occurred on the north side of the slope and involved translational sliding of the residual soil and weathered granite on the sheeting joint. The landslide debris comprised gravelly silty sand with slabs of the chunam. A layer of moderately to highly decomposed granite up to 0.1 m thick, with a fabric of extremely closely spaced discontinuities orientated parallel to the sheeting joint, was present at the interface between the soil and rock. During the course of the landslide, some spalling of the chunam cover (an area of about 20 m^3)

also occurred adjacent to the north flank of the landslide but without further failure of the soil in the slope (Figure 6).

Two days after the failure, water was observed flowing over the entire exposure of the sheeting joint. This remained the case on repeated site visits over the following two weeks, even during dry weather. Over this period, water was also issued from an erosion pipe hole located in the main scarp, about 2 m below ground level (Plate 8).

Following the landslide, the GEO recommended permanent evacuation of house No. 85 (GEO 1997b).

3.2.3 Landslide C

A plan of the landslide (GEO Incident MW97/6/50) is shown in Figure 6 and cross-sections of the landslide are shown in Figures 8 and 9.

The landslide involved part of a terraced fill slope comprising three brick retaining walls (Plates 9 and 10) and produced an estimated 60 m^3 volume of debris. The failure was about 9 m wide, 6 m long and had a maximum depth of 2 m. The bulk of the landslide debris was derived from the uppermost terrace platform, which was retained by a 2 m high cemented brick wall. The landslide exposed highly and completely decomposed medium-grained granite.

The brick wall at the crest of the fill body was 300 mm thick (Plate 11). The fill exposed in the main scarp comprised loose to very loose, wet, pale orangish and greyish brown, silty gravelly sand with angular cobbles and small boulders of highly decomposed granite, pieces of brick and concrete, and numerous voids.

According to the residents of house No. 73, most of the landslide occurred in one sudden rapid movement at about 07:00 hours on 4 June 1997. At this time, the main scarp was likely to have been located about 12 m from the house, cutting into the front part of the fill platform and leading to failure of the retaining wall. A washout channel, about 2 m deep, extended the main scarp a further 6 m into the fill platform forming a secondary washout scarp. It is likely that the washout channel developed between 07:00 hours and 11:00 hours during continued heavy rainfall after the landslide.

During inspection by HAP, water from an unknown source was observed flowing over a sheeting joint surface at the back of the platform upslope of house No. 73. Water was also being directed to the crest of the landslide from the adjacent house No. 85. Most of the landslide debris was deposited over the masonry wall at the toe of the slope and very wet debris filled the yard behind the house. The masonry wall itself was undamaged by the landslide. The travel angle of the landslide debris was estimated to be around 26°, taking account of the fact that the debris came to rest behind house No. 73. The travel angle is at the lower end of the typical range for rain-induced failures in Hong Kong (Wong & Ho, 1996). The involvement of loose fill in this case probably gave rise to the lower travel angle than for landslides A and B.

Following the landslide, the GEO recommended permanent evacuation of house No. 73 (GEO, 1997c).

3.2.4 Landslide D

A plan and cross-section of the landslide (GEO Incident MW97/6/56) are shown in Figures 10 and 11 respectively. A general view of the landslide is shown in Plate 12.

The landslide mostly involved the failure of a fill slope and was 35 m long, 11 m wide and 4 m deep, with an estimated volume of about 500 m^3. The geometry of the main scarp suggests there were two phases of failure. An initial failure most likely occurred at the front of the fill slope where the gradient was steep, which was later followed by a washout caused by surface water flow from an ephemeral stream (Figures 10 and 11). The travel angle of the initial landslide debris was slightly in excess of 30° and within the typical range for rain-induced failures in Hong Kong (Wong & Ho, 1996).

During inspections by HAP several weeks after the landslide, a dry streamcourse containing cobbles, small boulders and flattened vegetation was identified above the crest of the landslide. The fill adjacent to the main scarp was also found to be in a saturated condition. Interviews with residents in the vicinity of the landslide have confirmed that on the day of the failure, water was seen flowing over the crest of the main scarp. The washout phase of the landslide cut a deep, stepped erosion channel (Plate 13) and extended the main scarp further up the hillside.

The washout channel exposed four layers of material (Plate 14). The upper layer comprised 1 m to 2 m of relatively homogeneous, loose, sandy gravel fill with small pieces of old chunam. The second layer was up to 1 m thick and composed of heterogeneous loose, granitic fill with small boulders. The fill was underlain by a thin layer of topsoil comprising firm, moist, dark greyish brown, slightly gravelly, slightly clayey, sandy silt which in turn was underlain by decomposed granite. The landslide debris was mainly composed of fill material.

Following the landslide, the GEO recommended permanent evacuation of house No. 139C and urgent repair works to the slope (GEO, 1997d). The resident was re-housed and the Highways Department were requested by the Housing Department to "liase with DLO/Kwai Tsing for commencement of the urgent slope repair works as recommended by CGE/MW, GEO" (Housing Department, 1997b).

4. RAINFALL

The nearest GEO automatic raingauge to Kau Wa Keng San Tsuen is raingauge No. N04, located at Cho Yiu Estate, about 500 m southwest of the village (Figure 1). The daily rainfall recorded between 8 April and 8 June 1997 and hourly rainfall intensities for the periods between 3 May to 8 May and 1 June to 6 June 1997 are presented in Figure 12. Prior to the minor failure on 8 May 1997, the 24-hour and 12-hour rainfall totals were 210 mm and 204.5 mm respectively. The landslides on 4 June 1997 were preceded by 24-hour and 12-hour rainfall totals of 263 mm and 252.5 mm respectively. Isohyets of rainfall for the period between 00:00 hours to 07:00 hours on 4 June 1997 are shown in Figure 13.

The estimated return periods for maximum rolling rainfall of various durations based on historical rainfall data at the Hong Kong Observatory (HKO) are presented in Table 2 and

Table 3. The maximum rolling 1-hour rainfall recorded between 09:45 hours and 10:45 hours on 8 May 1997, and between 06:00 hours and 7:00 hours on 4 June 1997, was 128.5 mm. This rainfall intensity has an estimated return period of about 40 years and is the most severe of the rainstorm durations considered.

The maximum rolling rainfall for the rainstorms on 8 May 1997 and 4 June 1997 have been compared with the most extreme rainstorms recorded at the raingauge since it began operation in 1982 (Figure 14). The maximum rolling rainfall prior to 11:00 hours on 8 May 1997 and 07:00 hours on 4 June 1997 exceeded the intensities of previous rainstorms for durations up to 6 hours and 8 hours respectively. The maximum rolling rainfall for longer durations was less intense than for previous rainstorms.

5. PROBABLE CAUSES OF FAILURE

The close correlation between the peak intensities of the rainfall events and the reported time of failure indicates that intense short duration rainfall most probably triggered the landslides. The causes are mostly attributable to saturation of the man-made soil cut and fill slopes. The probable major contributory factors of the landslides are considered to be :

(a) the concentrated discharge of surface water,

(b) the rapid saturation of the soil layers by concentrated infiltration of surface water,

(c) the development of transient groundwater pressures following intense rainfall, and

(d) the fact that the man-made soil cut slopes, fill slopes and retaining wall, having been formed before 1978, were not designed and constructed to current geotechnical standards.

The above contributory factors may generally be applicable to many landslides in squatter areas. Although the 1997 landslides at the site are clustered, it should be noted that the slope types, mechanisms of failure and the relative importance of the various contributory factors are different for the individual landslides, as described below.

The contributory factors and their relative importance for each landslide are summarised in Table 4. Many of the factors are common to more than one landslide. Excessive surface water was directed to the landslide sites by several means, including run-off on steep sheeting joint surfaces, flow from ephemeral streams and overflow from an ineffective drainage channel. As the ground mass comprised relatively thin soil layers overlying comparatively impermeable rock, saturation of the soil parts of the slopes and reduction in soil suction would have been relatively rapid. In all cases, transient perched water tables most probably developed. Potential instability would have been compounded by the inadequate design and detailing of the man-made slopes, including inadequate drainage provisions, oversteep slope angles and the poor compaction of fill material. These factors are considered further in the discussion below.

The geological and topographical settings of landslides A to D are similar. In all cases, the relatively impermeable sheeting joints outcropping in the natural terrain would have impeded or even prevented downward infiltration. These conveyed surface water downslope as surface run-off. This is likely to have caused concentration of surface water flow at each of the landslide sites. Immediately above landslides A to C, running water was observed on the rock surfaces several weeks after the failures had occurred. The large quantity of water observed may indicate the presence of natural springs in the hillside. During the rainstorm of 4 June 1997, further surface water discharged above landslides B, C and D from the ephemeral streams, so that the volume of water directed to the man-made slopes which failed would have been greater than the typical amounts normally associated with direct infiltration. Landslides C and D also involved washout of loose fill due to erosion by concentrated surface water flow leading to the formation of washout channels in the main scarps. Poor detailing and lack of maintenance of the drainage channel above the village also led to overtopping of water on to the slopes below.

The geometry of the man-made slopes also contributed to the failures. The upper parts of the fill slopes were essentially level, allowing ponding and concentrated water ingress into the loose fill. For landslides A and B, the cut slopes were oversteep and it is thought that instability was caused by the build-up of water pressure in the weathered granite behind the chunam cover. The build-up of water pressures probably developed due to inadequate provision of drainage weepholes.

The likely formation of transient perched water tables is considered to be the principal contributory factor for all the landslides. With the exception of landslide D, the groundwater probably perched above the rock/soil interface, given that the rock is relatively impermeable. In the case of landslide D, the loose fill would have been more permeable relative to the underlying top soil and weathered granite allowing perched ground water to develop in the fill. Erosion pipe holes in the main scarps of landslides A and B would have served as water conduits, allowing rapid groundwater flow, saturation and development of transient water pressures during heavy rainfall.

The man-made slopes involved in the recent landslides were not designed and constructed to current geotechnical standards. As a result, the cut slopes involved in landslides A and B were oversteep and, although the chunam cover was maintained in a good condition, there was inadequate drainage provisions for the chunam cover. The fill slopes were poorly compacted and inadequately sealed against infiltration.

6. CONCLUSIONS

Landslides A to D were triggered by intense short duration rainfall. Surface water was directed to the landslide sites through run-off on steep rock surfaces, flow from ephemeral streams and overflow from an inadequate drainage channel leading to saturation of relatively thin soil and fill layers overlying impermeable rock. The hydrogeological conditions were conducive to the development of perched water tables in the soil causing reduction in shear strength and slope failure.

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Table 1 - Previous Landslide Incidents at the Site

GEO Incident No.	Location	Date of Failure	Estimated Volume (m^3)	Type of Failure	Failed Materials	Consequence
K82/2	Kau Wa Keng San Tsuen, Kwai Chung	NA	NA	NA	NA	Squatter huts affected
MW86/5/3	No. 21 Kau Wa Keng San Tsuen	May 14, 1986	NA	Washout	Weathered rock : soil	Squatter huts affected
MW89/5/88A	Nos. 45 and 43, Kau Wa keng San Tsuen	May 21, 1989	10	Landslide	Weathered rock : decomposed granite	Backlane affected
MW89/5/88B	Nos. 45 and 43, Kau Wa Keng San Tsuen	May 21, 1989	10	Landslide	Weathered rock : decomposed granite	Backlane affected
MW93/9/21	No. 45, Kau Wa Keng San Tsuen	September 26, 1993	25	Landslide and subsidence	Weathered rock : decomposed granite	Building lot affected
MW94/7/8	No. 5, Kau Wa Keng San Tsuen	July 22, 1994	15	Landslide	Weathered rock	Building lot affected
MW94/7/9	No. 69A, Kau Wa Keng San Tsuen	July 22, 1994	45	Landslide	Weathered rock	Building lot affected
MW95/7/8	No. 69A, Kau Wa Keng San Tsuen (Hut No. RTW/4AA/118)	July 14, 1995	35	Landslide	Colluvium and weathered rock	Squatter huts affected
NT82/201	Squatters : Kau Wa Keng San Tsuen	May 29, 1982	NA	Landslide	NA	Squatter huts affected
NT82/8/63	No. 23 Kau Wa Keng San Tsuen	August 16, 1982	< 50	Landslide	NA	Building lot affected
NT82/8/68	Nos. 186-189 Kau Wa Keng San Tsuen	August 16, 1982	<50	Spalling of slope surface protection	NA	Building lot affected

Table 2 – Maximum Rolling Rainfall at GEO Raingauge No. N04 for Selected Durations Preceding the 8 May 1997 Landslide and The Corresponding Estimated Return Periods

Duration	Maximum Rolling Rainfall (mm)	End of Period	Estimated Return Period (Years)
5 minutes	16	10:35 Hours on 8 May 1997	6
15 minutes	43	10:40 Hours on 8 May 1997	26
1 hour	128.5	10:45 Hours on 8 May 1997	41
2 hours	170	11:00 Hours on 8 May 1997	23
4 hours	180.5	11:00 Hours on 8 May 1997	8
12 hours	204.5	11:00 Hours on 8 May 1997	3
24 hours	210	11:00 Hours on 8 May 1997	2
2 days	230	11:00 Hours on 8 May 1997	2
4 days	266	11:00 Hours on 8 May 1997	2
7 days	302	11:00 Hours on 8 May 1997	2
15 days	306	11:00 Hours on 8 May 1997	1
31 days	418	11:00 Hours on 8 May 1997	1

Notes: (1) Return periods were derived from the Gumbel equation and data published in Table 3 of Lam & Leung (1994).

(2) Maximum rolling rainfall was calculated from 5-minute data for durations up to one hour and from hourly data for longer rainfall durations.

Table 3 – Maximum Rolling Rainfall at GEO Raingauge No. N04 for Selected Durations Preceding the 4 June 1997 Landslide and The Corresponding Estimated Return Periods

Duration	Maximum Rolling Rainfall (mm)	End of Period	Estimated Return Period (Years)
5 minutes	14	10:35 Hours on 8 May 1997	3
15 minutes	38	10:40 Hours on 8 May 1997	10
1 hour	128.5	07:00 Hours on 4 June 1997	41
2 hours	162.5	07:00 Hours on 4 June 1997	18
4 hours	205	07:00 Hours on 4 June 1997	14
12 hours	252.5	07:00 Hours on 4 June 1997	6
24 hours	263	07:00 Hours on 4 June 1997	3
2 days	294	07:00 Hours on 4 June 1997	3
4 days	294	07:00 Hours on 4 June 1997	2
7 days	295	07:00 Hours on 4 June 1997	2
15 days	297	07:00 Hours on 4 June 1997	1
31 days	788	07:00 Hours on 4 June 1997	4

Notes: (1) Return periods were derived from the Gumbel equation and data published in Table 3 of Lam & Leung (1994).

(2) Maximum rolling rainfall was calculated from 5-minute data for durations up to one hour and from hourly data for longer rainfall durations.

Table 4 - Probable Causes of the Landslides

<table>
<tr><th>Landslide A</th><th>Landslide B</th><th>Landslide C</th><th>Landslide D</th></tr>
<tr><td colspan="4">Description of Man-made Slope</td></tr>
<tr><td>Soil cut
(Chunam covered and inclined at 45° to 70°)</td><td>Soil cut
(Chunam covered and inclined at 45° to 70°)</td><td>Fill slope
(Fill platform and retaining wall)</td><td>Fill slope
(End tipped fill platform on natural slope)</td></tr>
<tr><td colspan="4">Trigger Mechanism for Landslide</td></tr>
<tr><td>Intense short duration rainfall on 8 May and 4 June 1997</td><td>Intense short duration rainfall on 4 June 1997</td><td>Intense short duration rainfall on 4 June 1997</td><td>Intense short duration rainfall on 4 June 1997</td></tr>
<tr><td colspan="4">Probable Causes</td></tr>
<tr><td>Surface water flow to the site on steeply inclined sheeting joint surfaces</td><td>Surface water flow to the site on steeply inclined sheeting joint surfaces</td><td>Surface water flow to the site on steeply inclined sheeting joint surfaces</td><td rowspan="2">Water flow from a major ephemeral stream</td></tr>
<tr><td>Inadequate drainage channel upslope from site</td><td>Water flow from an ephemeral stream</td><td>Water flow from an ephemeral stream</td></tr>
<tr><td>Infiltration and formation of transient perched water table above the soil/sheeting joint interface</td><td>Inadequate drainage channel upslope from site (Overtopping)</td><td>Surface water flow diverted from an adjacent fill platform</td><td>Ponding of water on level area</td></tr>
<tr><td>Saturation of thin soil layer above a sheeting joint surface</td><td>Infiltration and formation of transient perched water table above the soil/sheeting joint interface</td><td>Inadequate drainage channel upslope from site (Overtopping)</td><td rowspan="4">Infiltration and formation of transient perched water table in fill above weathered granite</td></tr>
<tr><td>Instability induced along inclined and daylighting geological fabric</td><td>Saturation of thin soil layer above a sheeting joint surface</td><td>Ponding of water on level fill platform</td></tr>
<tr><td rowspan="2">Increase in water pressure behind chunam cover</td><td>Instability induced along inclined and daylighting geological fabric</td><td>Infiltration and formation of transient perched water table</td></tr>
<tr><td>Increase in water pressure behind chunam cover</td><td>Saturation of fill</td></tr>
<tr><td>Oversteep cut slope angle</td><td>Oversteep cut slope angle</td><td>Increase in water pressure behind retaining wall (due to lack of weepholes)</td><td>Saturation of fill</td></tr>
<tr><td colspan="4">Failure Mode</td></tr>
<tr><td>Small sliding failure (8 May 1997)</td><td>Secondary spalling of the chunam cover after failure</td><td>Sliding failure of fill platform and retaining wall (4 June 1997)</td><td>Sliding failure of fill from the front of the platform (4 June 1997)</td></tr>
<tr><td>Sliding failure of the soil (4 June 1997)</td><td>Secondary spalling of the chunam cover after failure</td><td>Secondary washout after Failure</td><td>Secondary washout after failure</td></tr>
</table>

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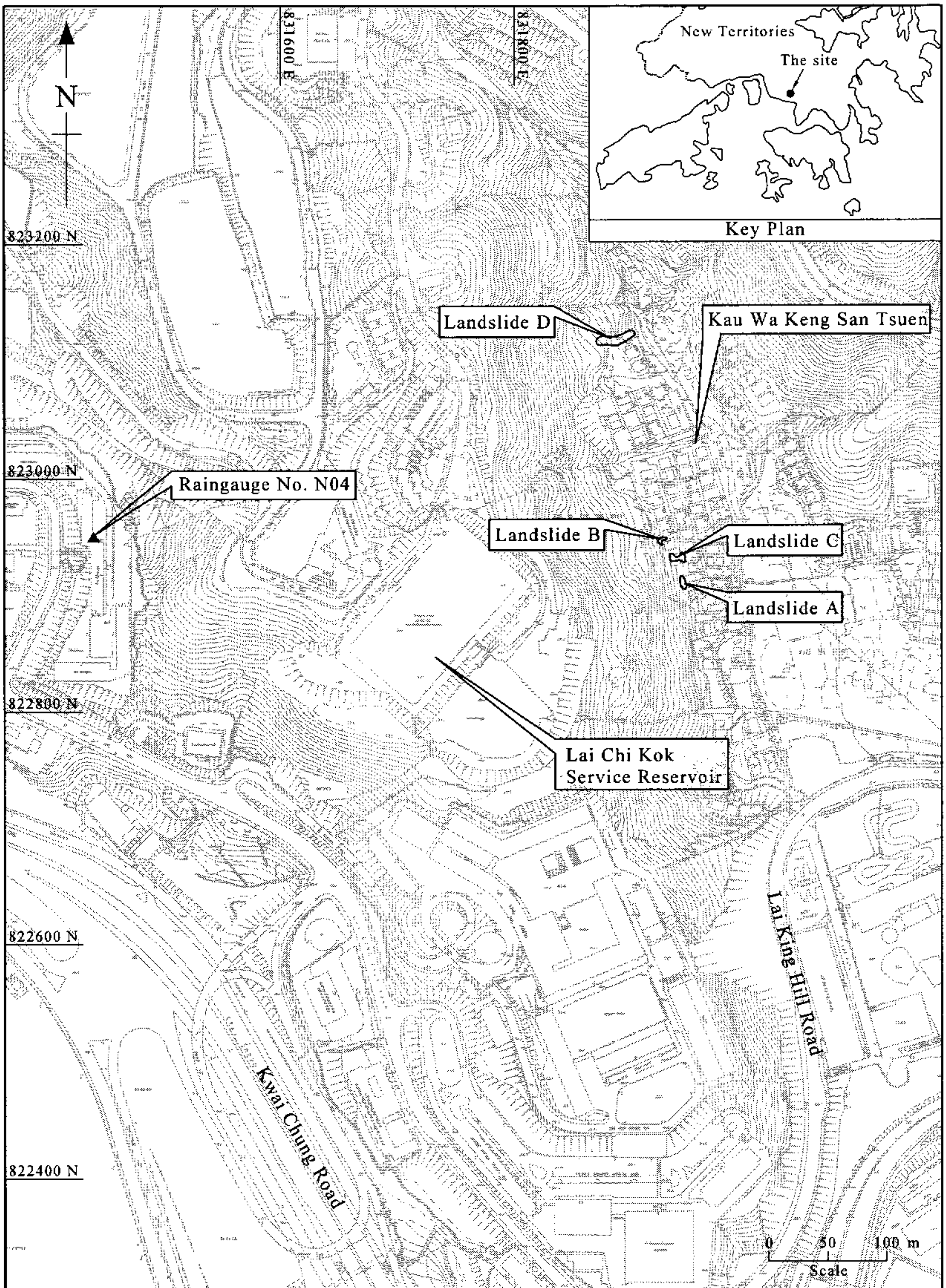


Note : Base map is extracted from Survey Sheet Nos. 11NW-1D, 11NW2C, 11NW6B & 11NW-7A, dated October 1992 (Original scale 1:1 000).

Figure 1 - Site Location Plan

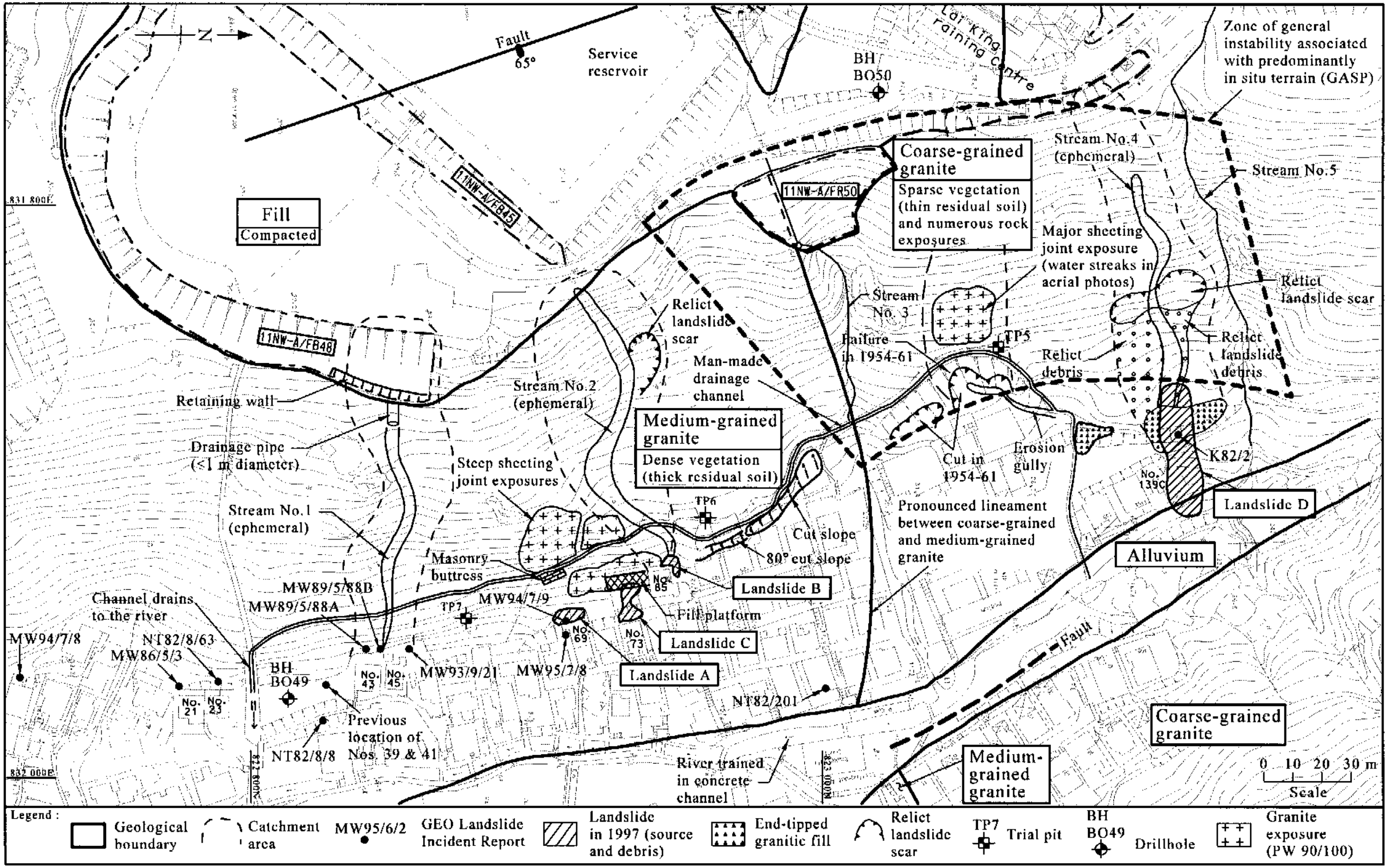
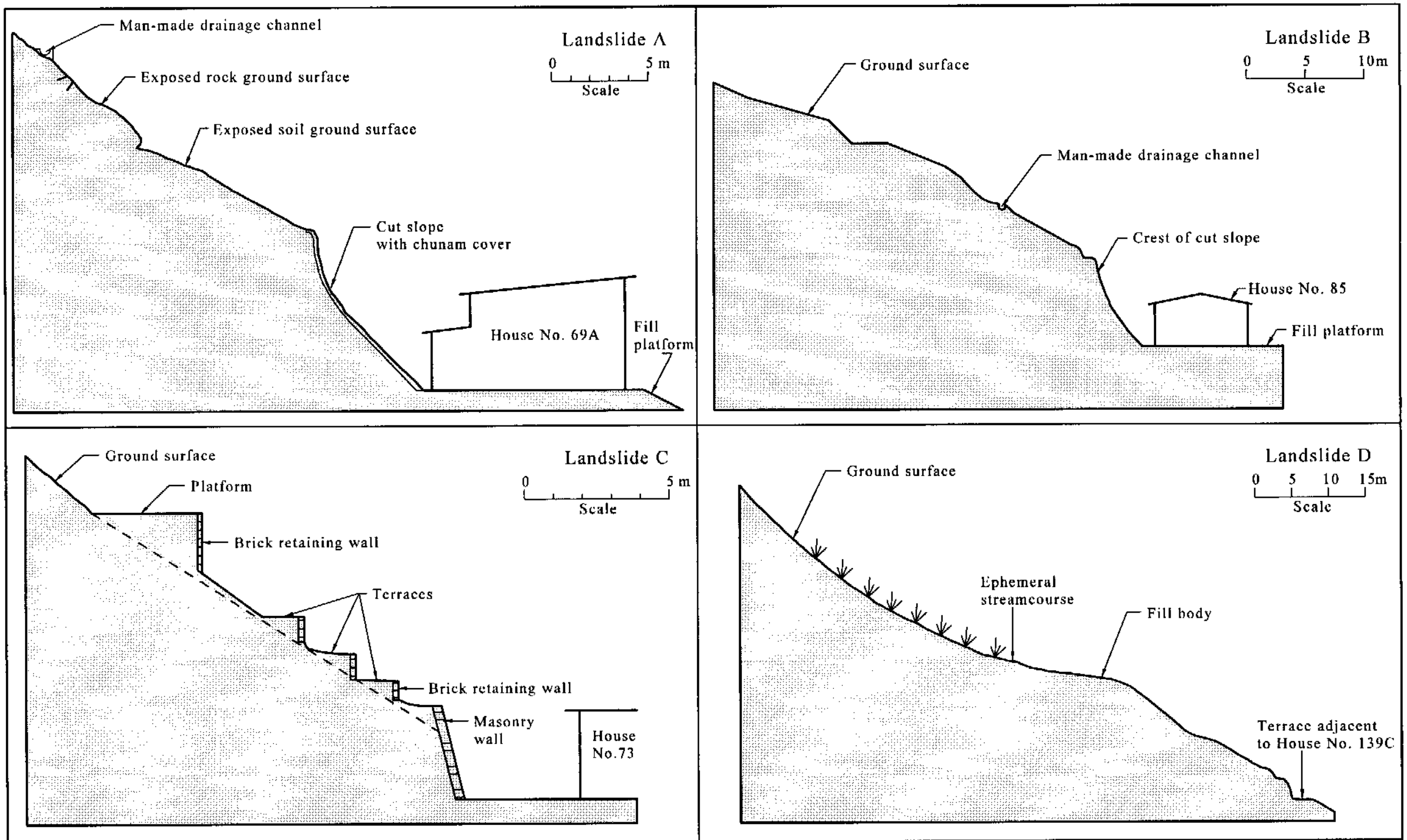
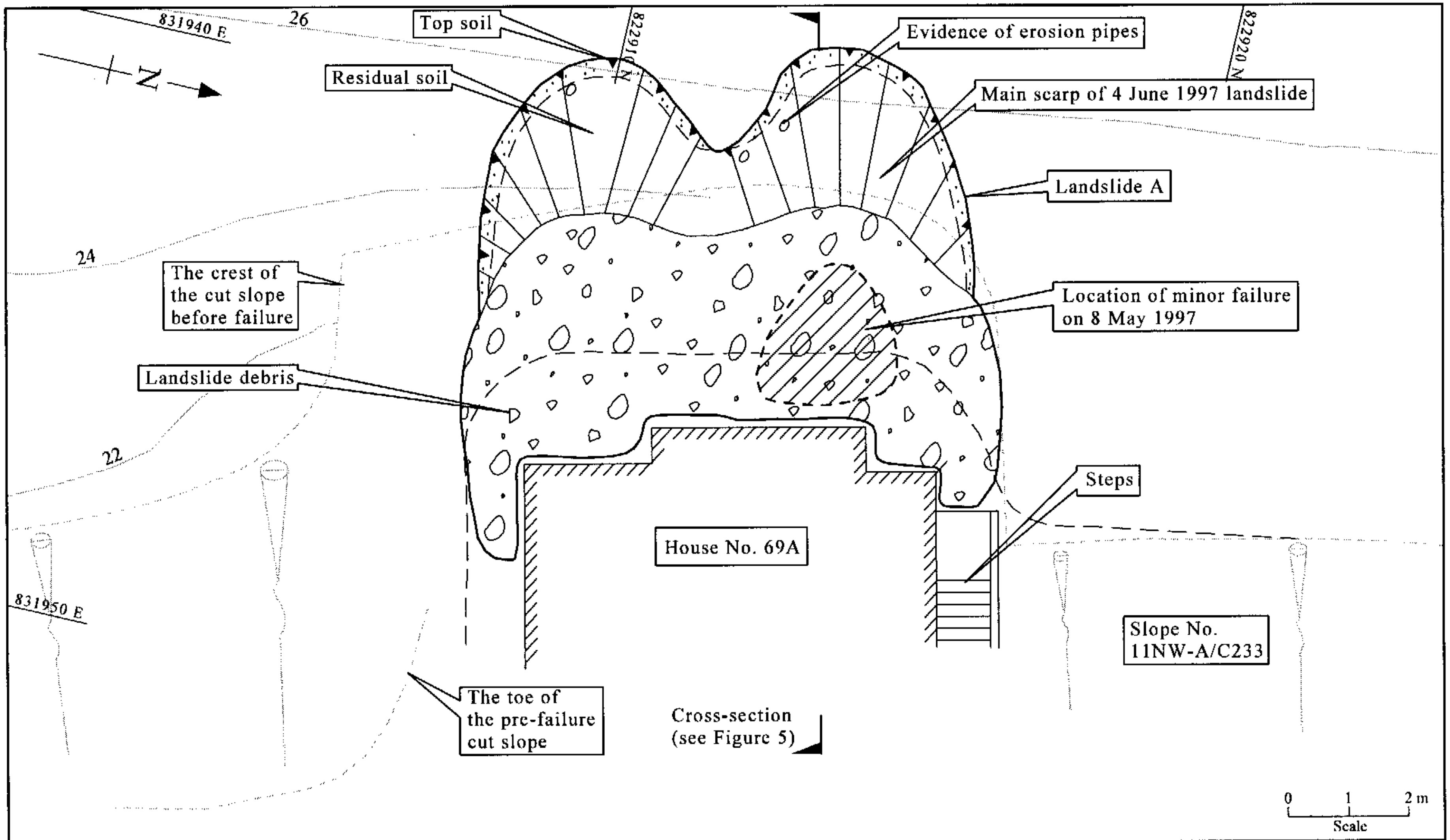


Figure 2 - Plan of the Landslide Sites



Note : See Figure 2 for locations of the landslide sites.

Figure 3 - Ground Profile Before the Landslides



Note : Base map is extracted from Survey Sheet No. 11NW-2C dated October 1992 (Original scale 1:1 000).

Figure 4 - Plan and Details of Landslide A

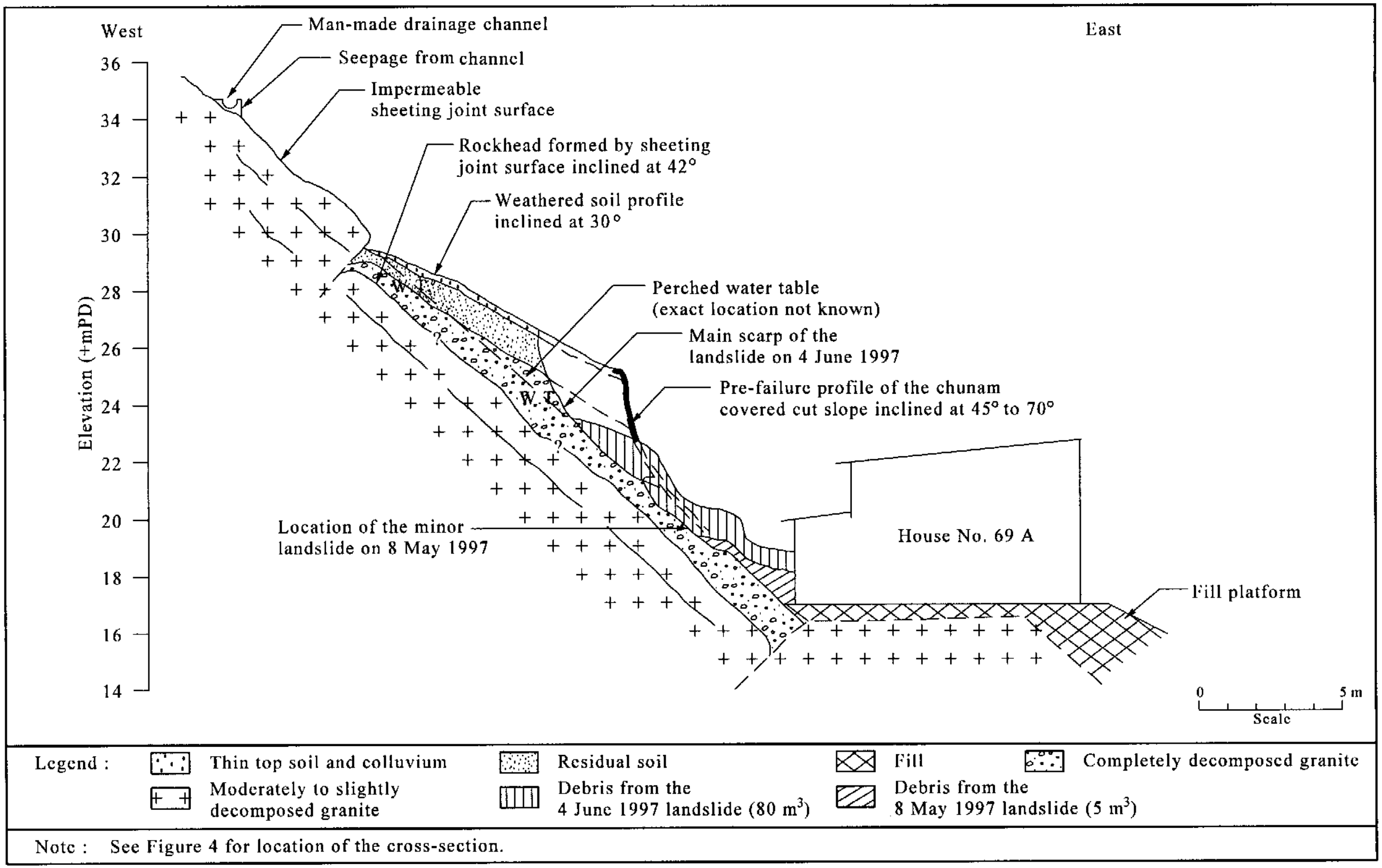


Figure 5 - Cross-section Through Landslide A

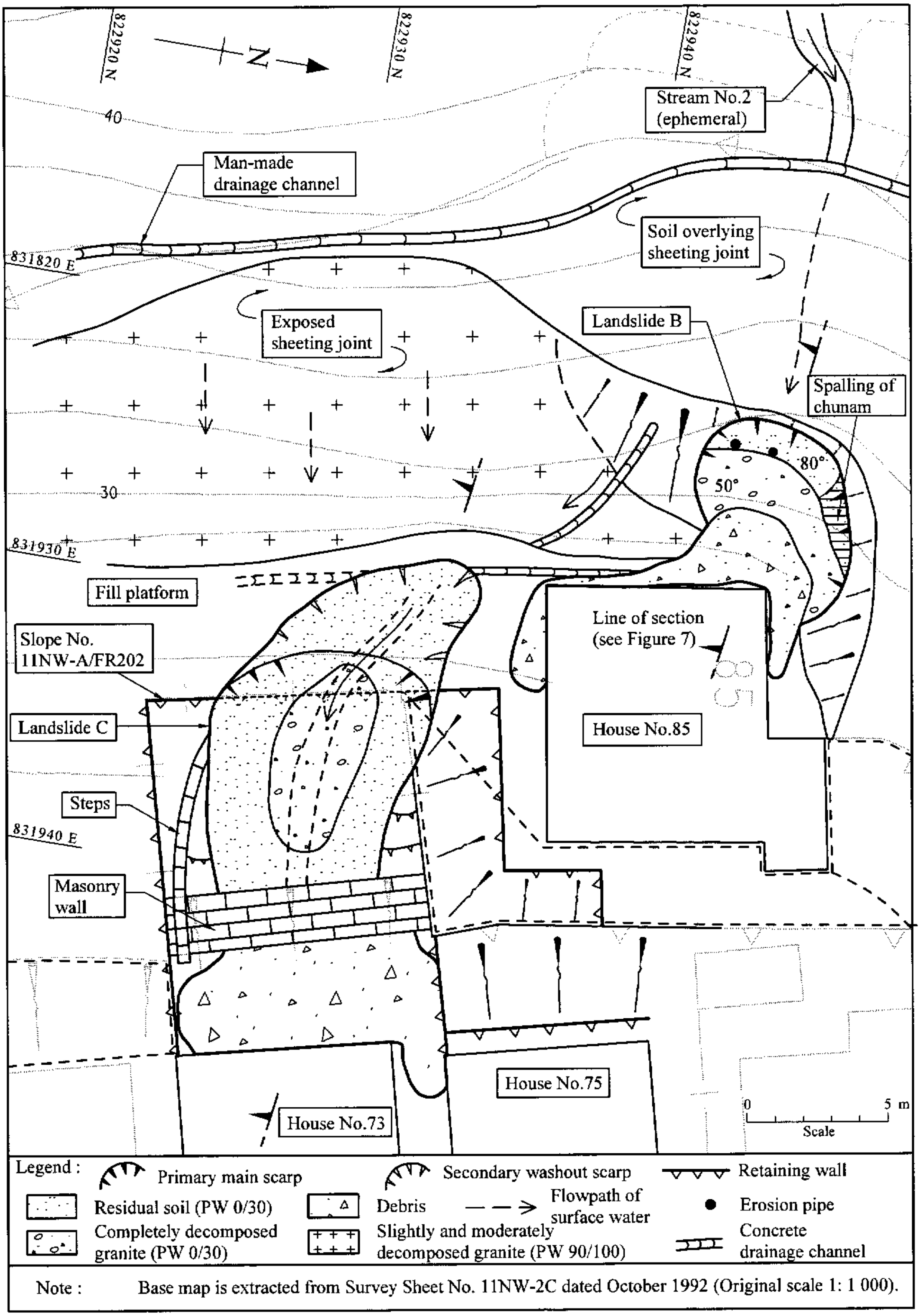


Figure 6 - Plan and Details of Landslides B and C

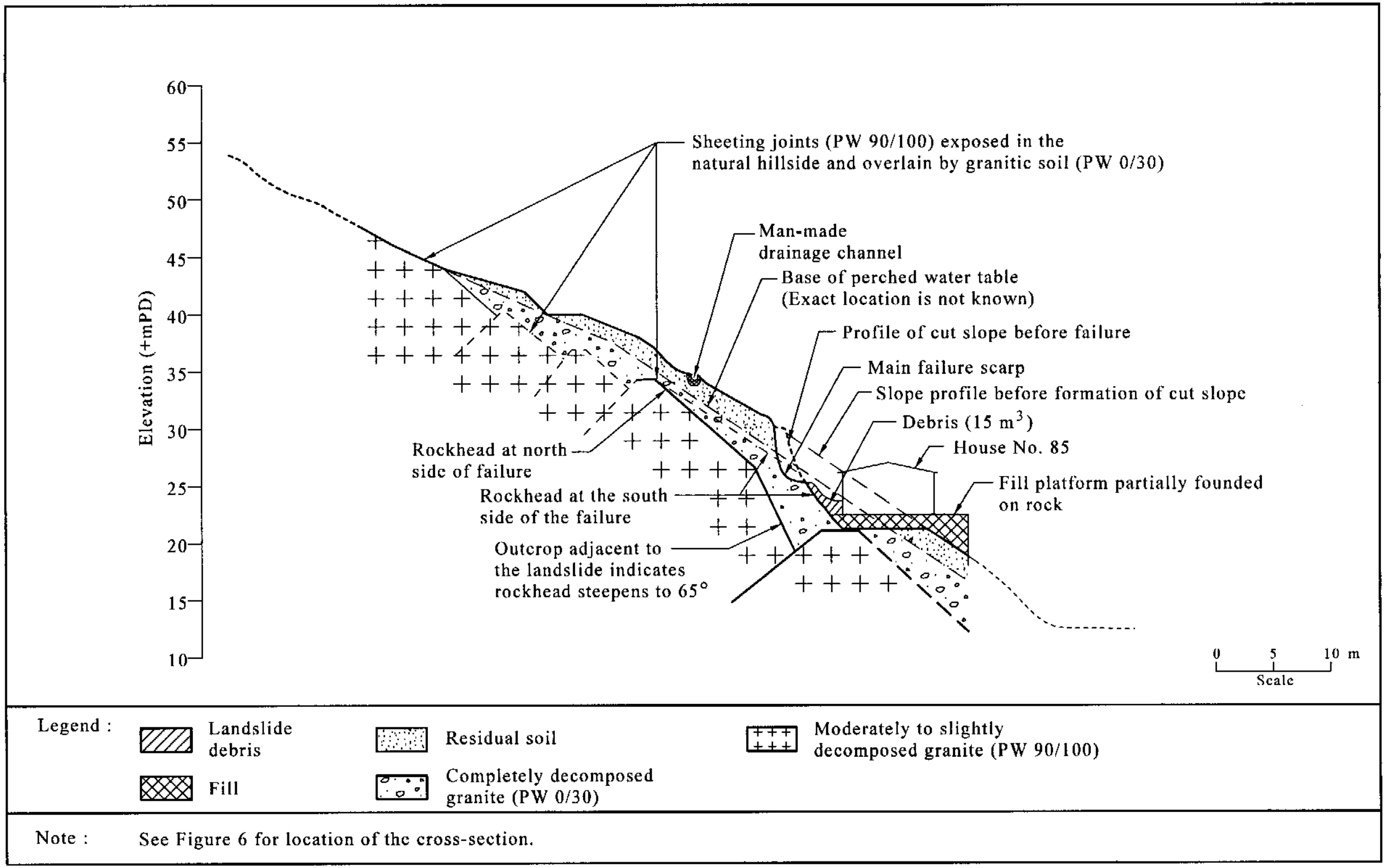


Figure 7 - Cross-section Through Landslide B

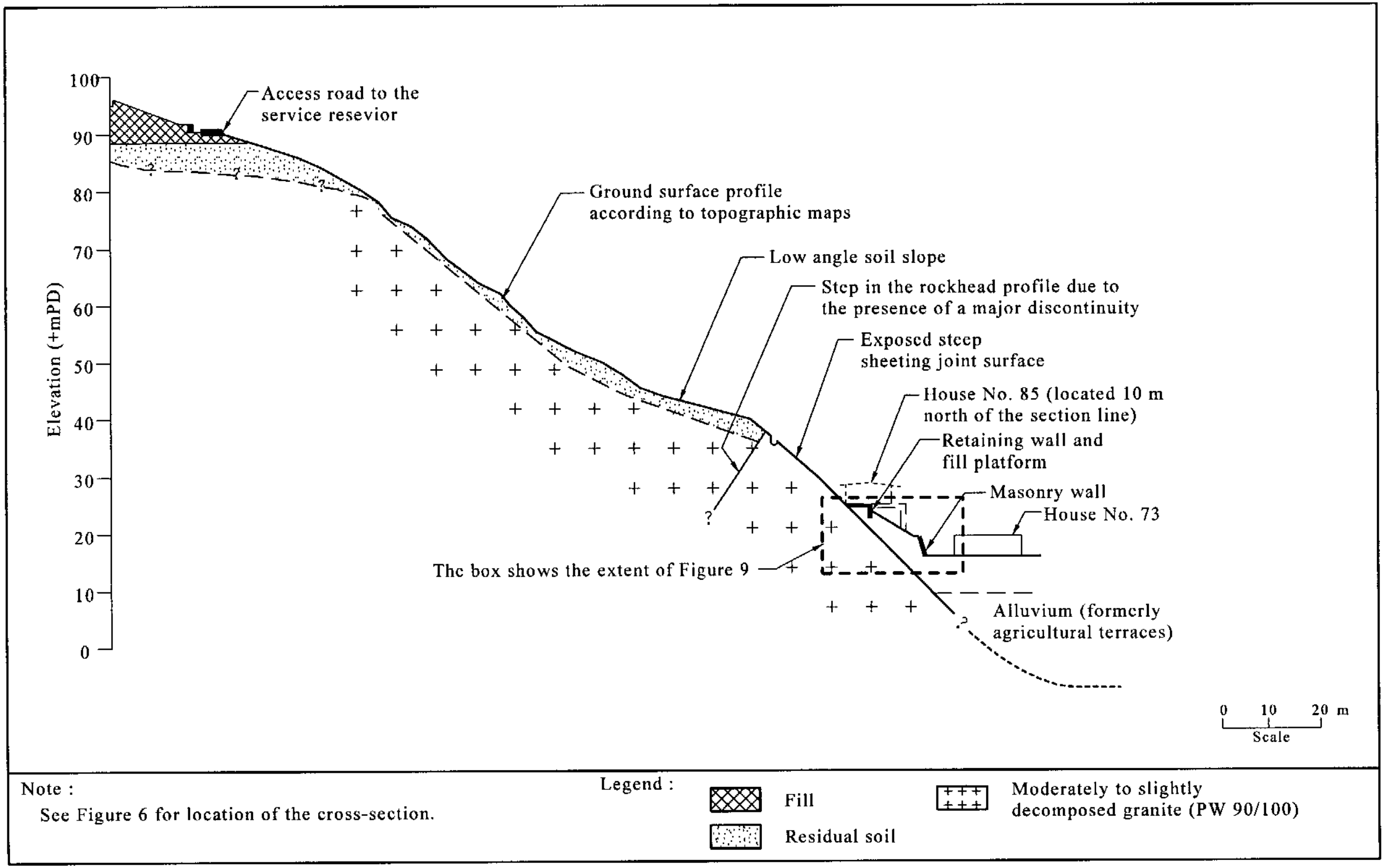


Figure 8 - General Cross-section Through Landslide C

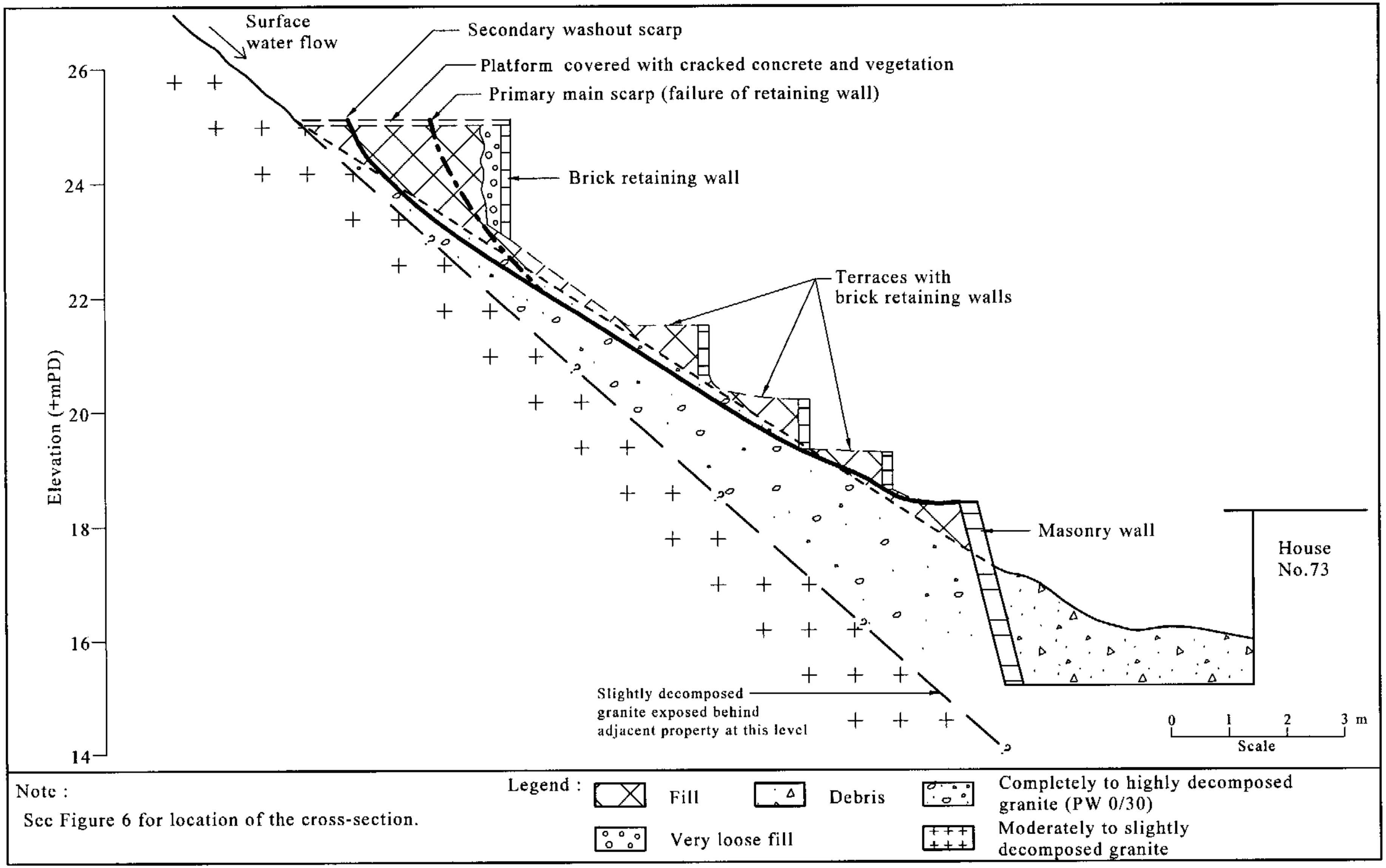


Figure 9 - Detailed Cross-section Through Landslide C

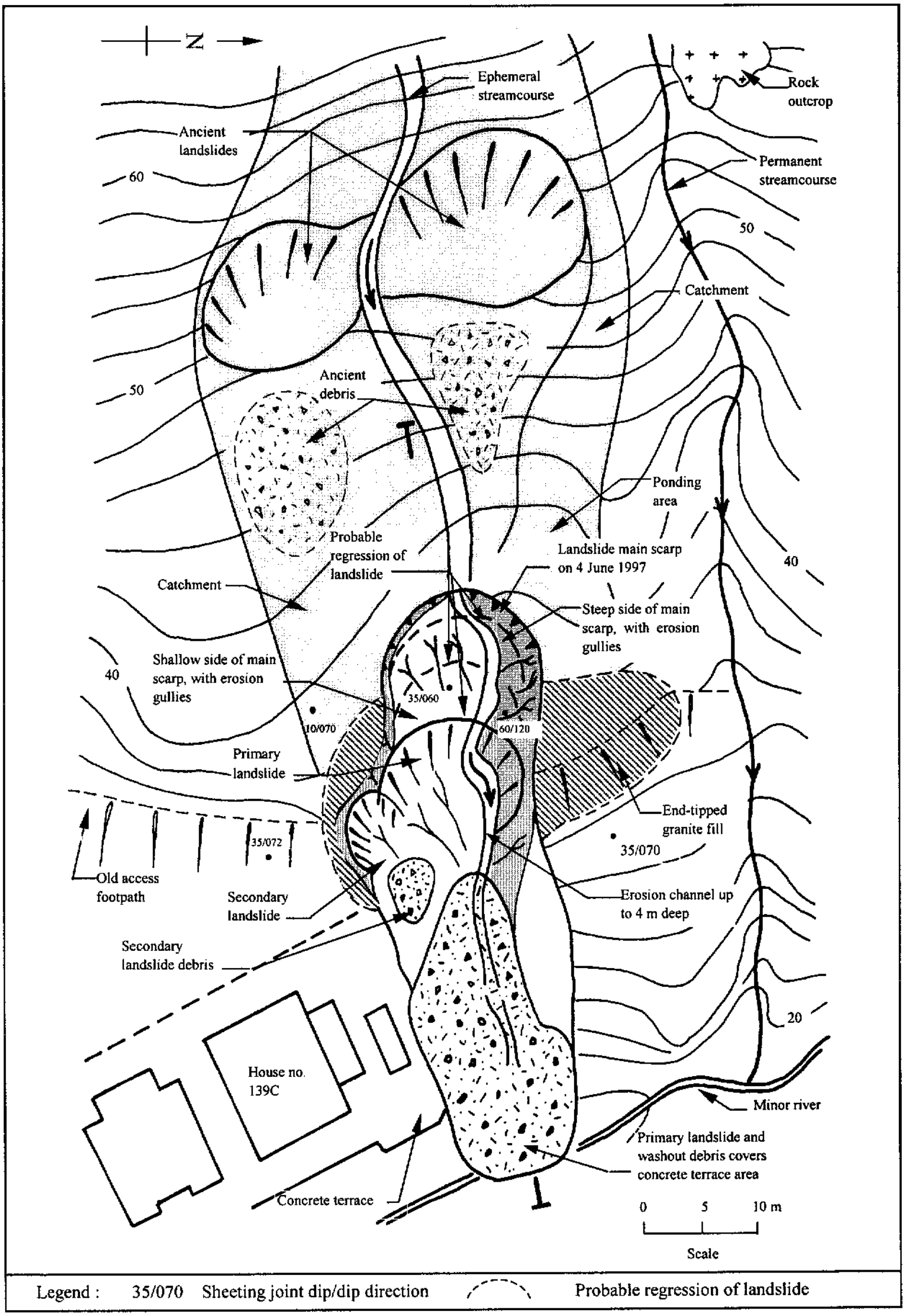


Figure 10 - Plan and Details of Landslide D

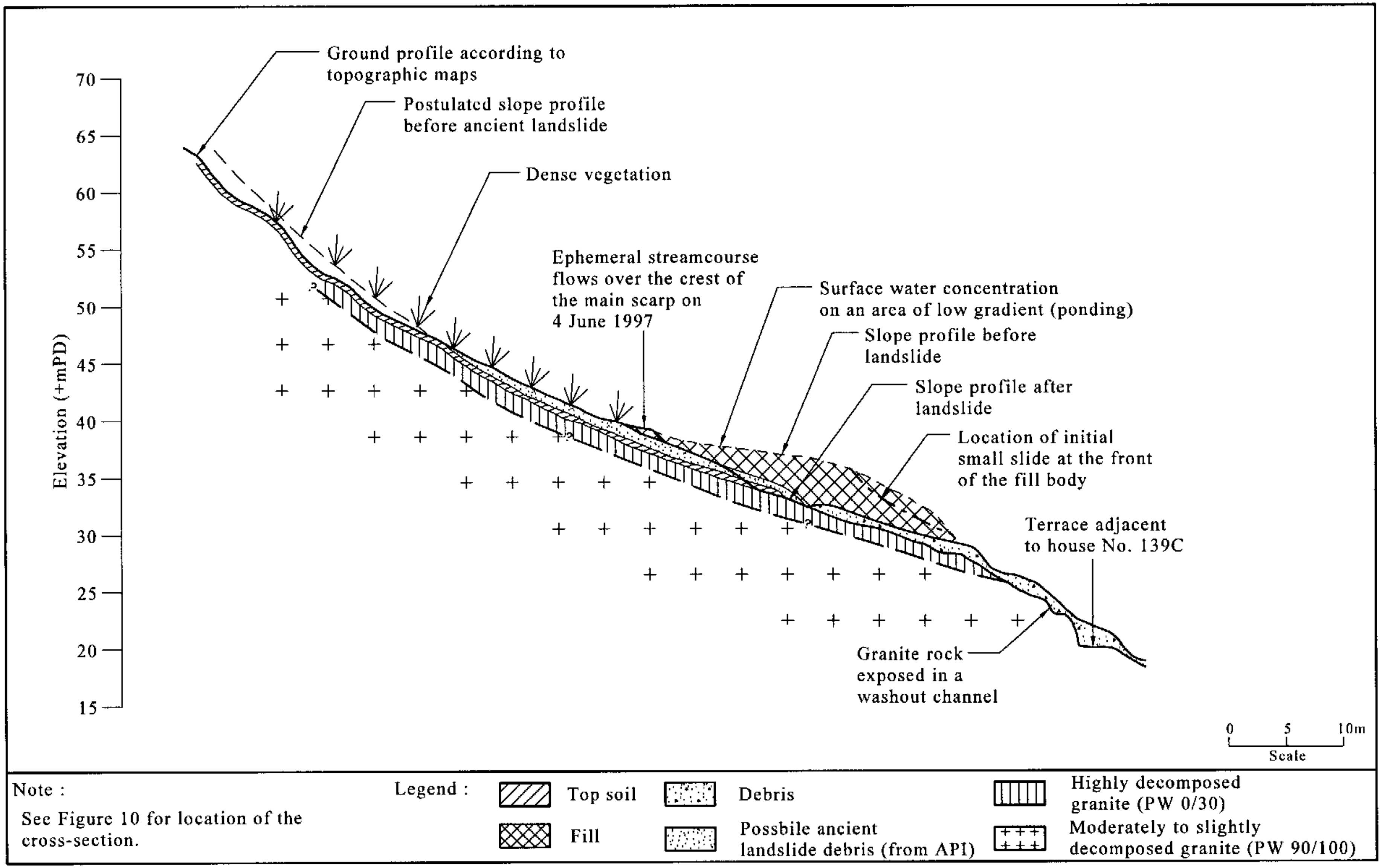
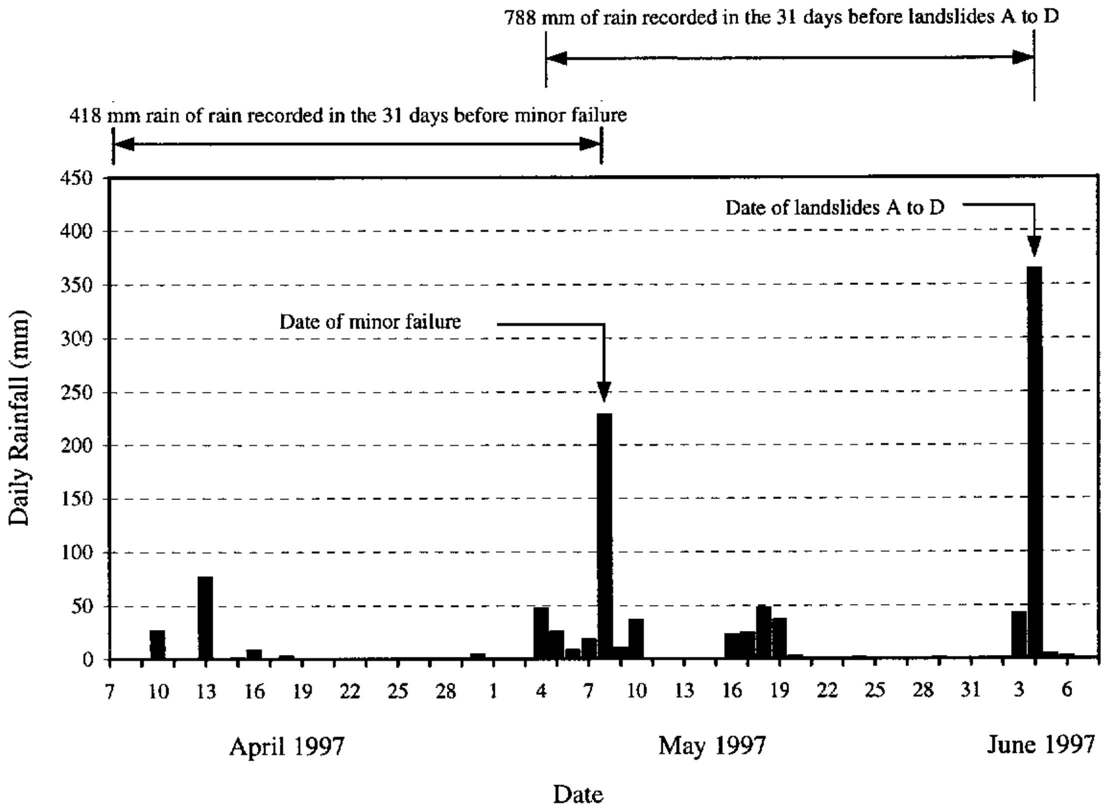
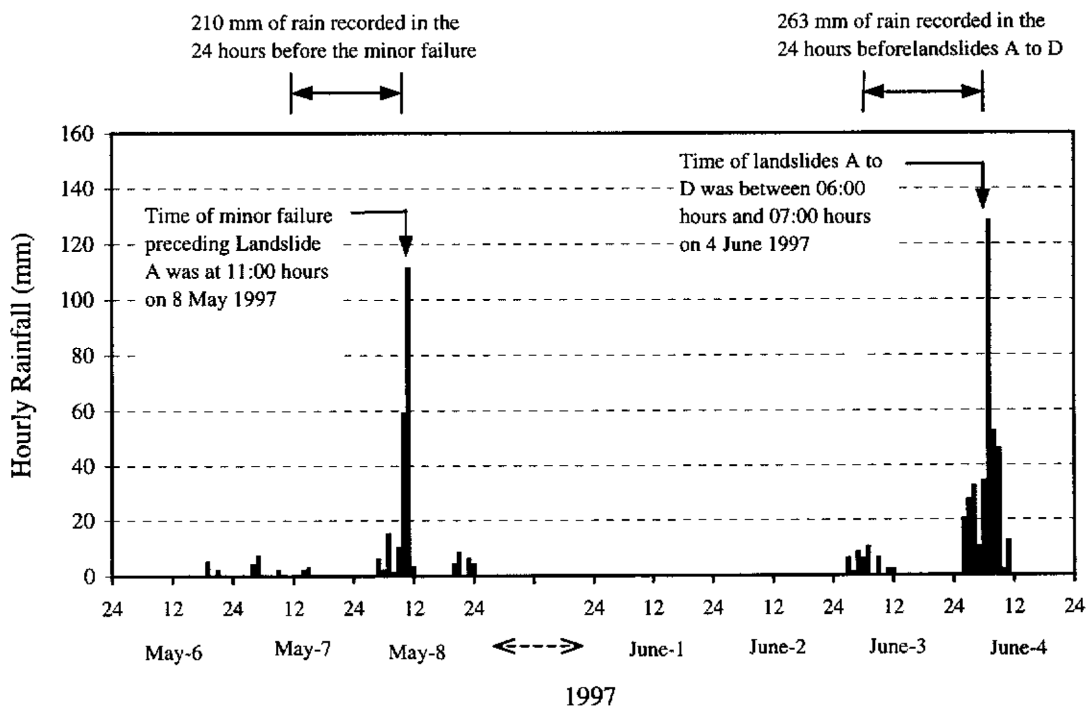


Figure 11 - Cross-section Through Landslide D

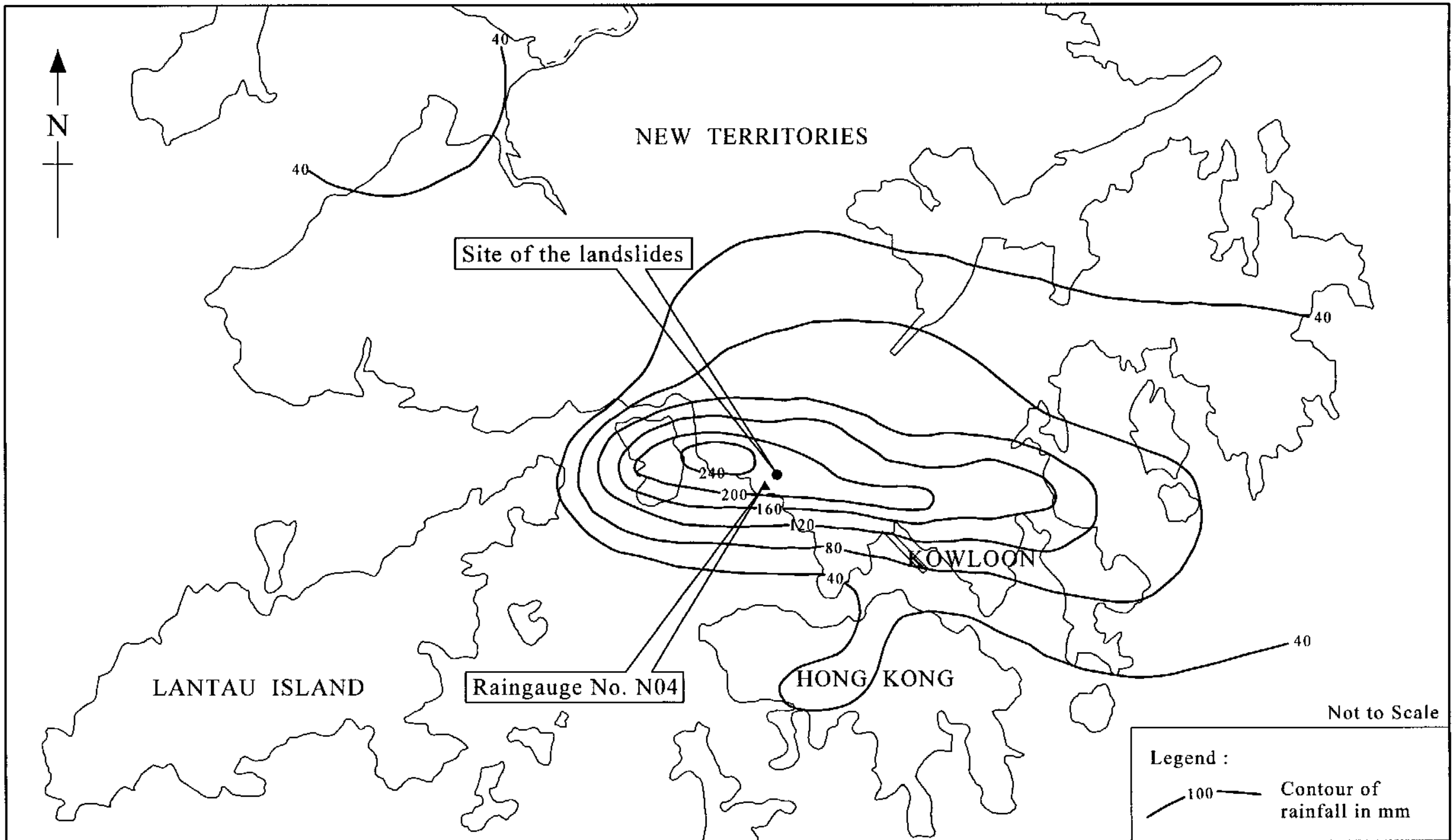


(a) Daily Rainfall Recorded between 7 April and 6 June 1997



(b) Hourly Rainfall Recorded between 6 May and 4 June 1997

Figure 12 - Rainfall Recorded at GEO Raingauge No. N04



Note : Isohyets prepared by the Hong Kong observatory.

Figure 13 - Isohyets of Rainfall between 00:00 Hours and 07:00 Hours on 4 June 1997

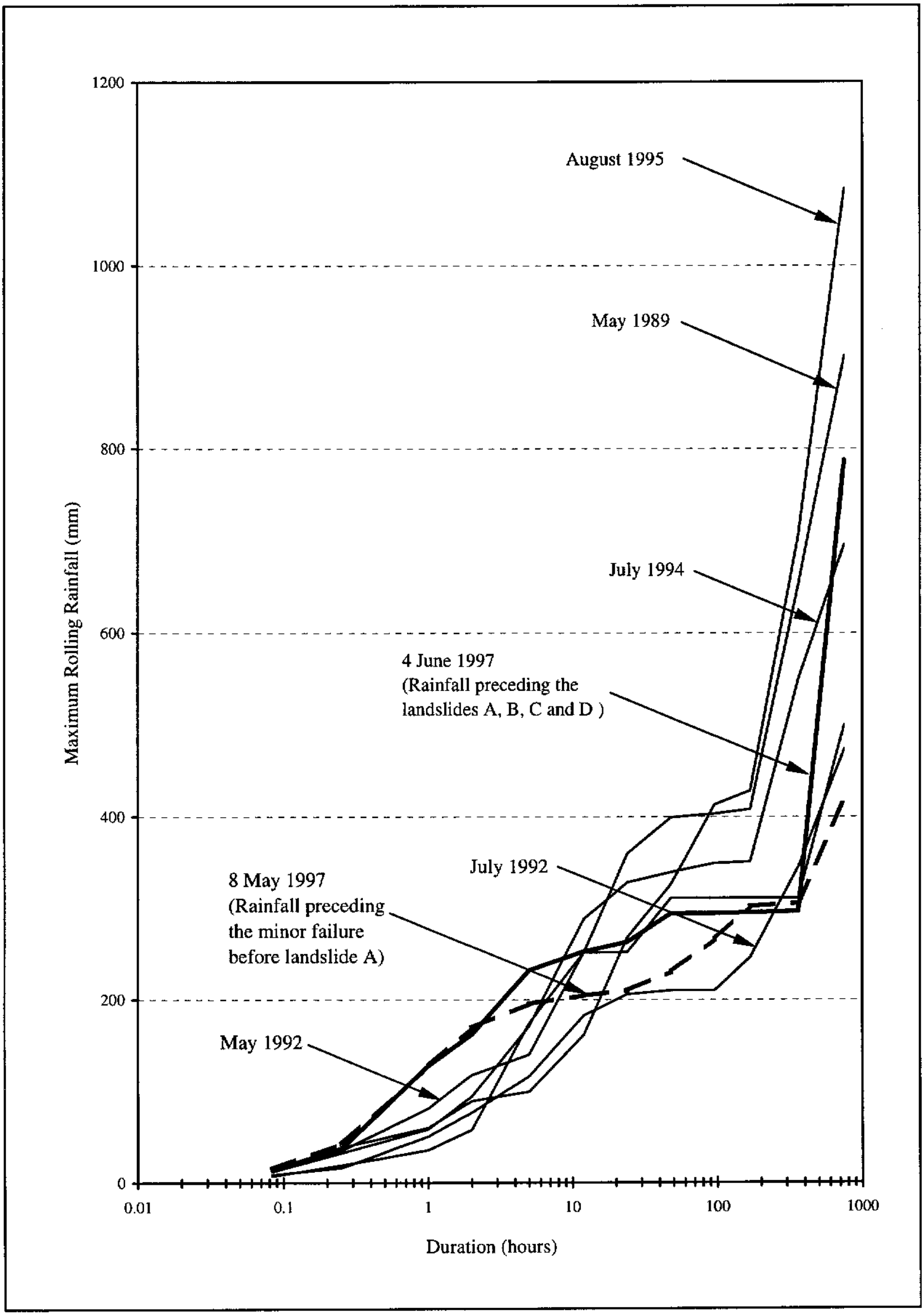


Figure 14 - Maximum Rolling Rainfall at GEO Raingauge No. N04 for Major Rainstorms

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Plate 2 - A Sheeting Joint Rock Surface Above Landslide A (Photograph Taken on 20 June 1997)

Plate 3 - View of the Surface Water Run-off Channel Above the Village (Photograph Taken on 3 March 1998, Between House Nos. 45 and 69)

Plate 4 - View of the Surface Water Run-off Channel Above the Village (Photograph Taken on 20 June 1997)

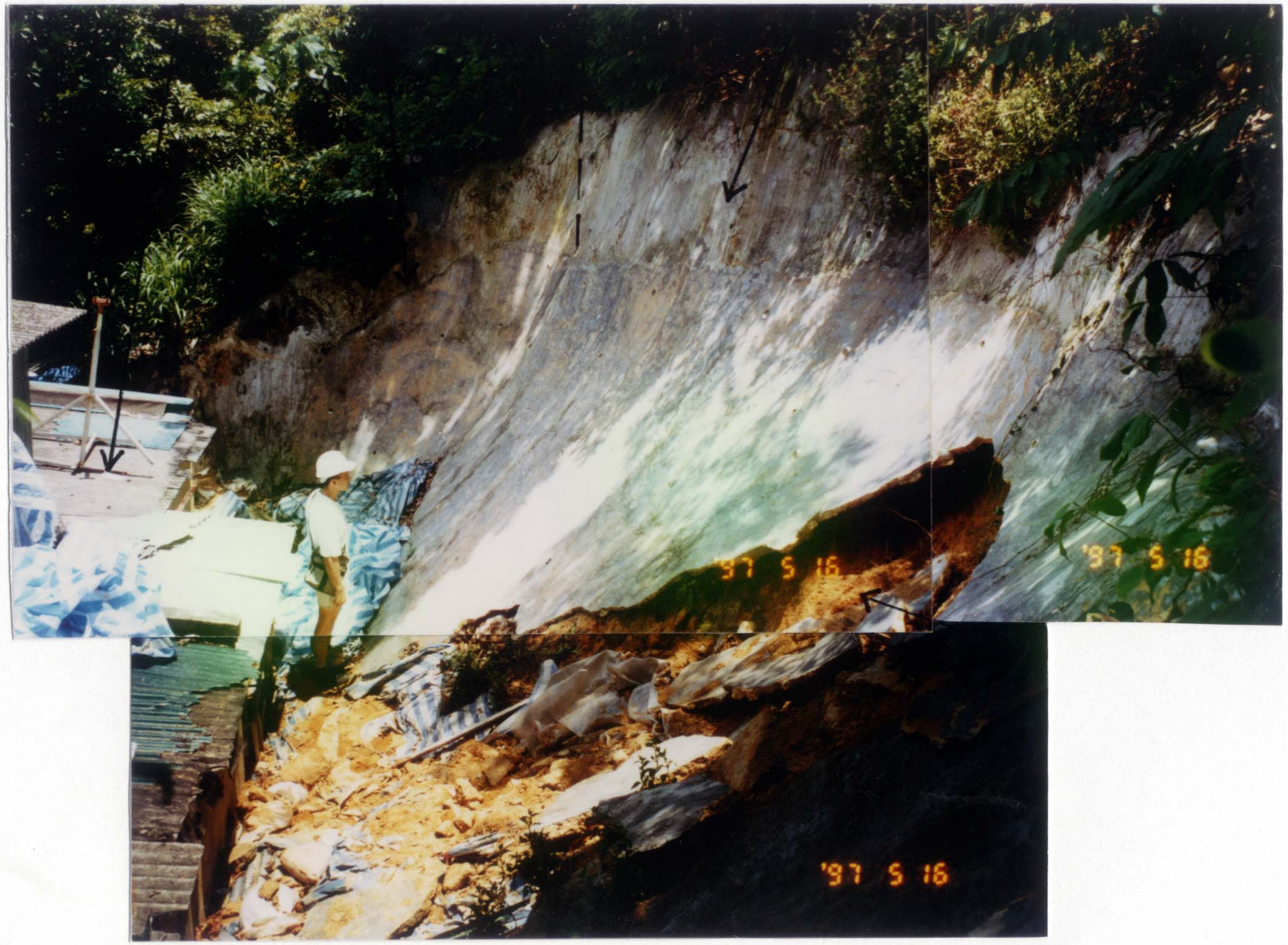

Plate 5 - View of the Small Failure Before Landslide A (Photograph Taken on 5 May 1997)

Plate 6 - View of Landslide A (Photograph Taken on 20 June 1997. Note the Entire Slope Shown in Plate 2 has Failed)

Plate 7 - View of Landslide B (Photograph Taken on 6 June 1997. Note the Water Flowing on the Steep Sheeting Joint Surface Below the Failed Soil Cut Slope)

Plate 8 - An Erosion Pipe in the Main Scarp of Landslide B (Photograph Taken on 6 June 1997. Note the Arrow Points to Flowing Water Issuing from the Pipe in the Centre of the Photograph)

Plate 9 - View of Landslide C (Photograph Taken on 6 June 1997. Note that the Fill Platform was Located Near the Top of the Landslide Scar)

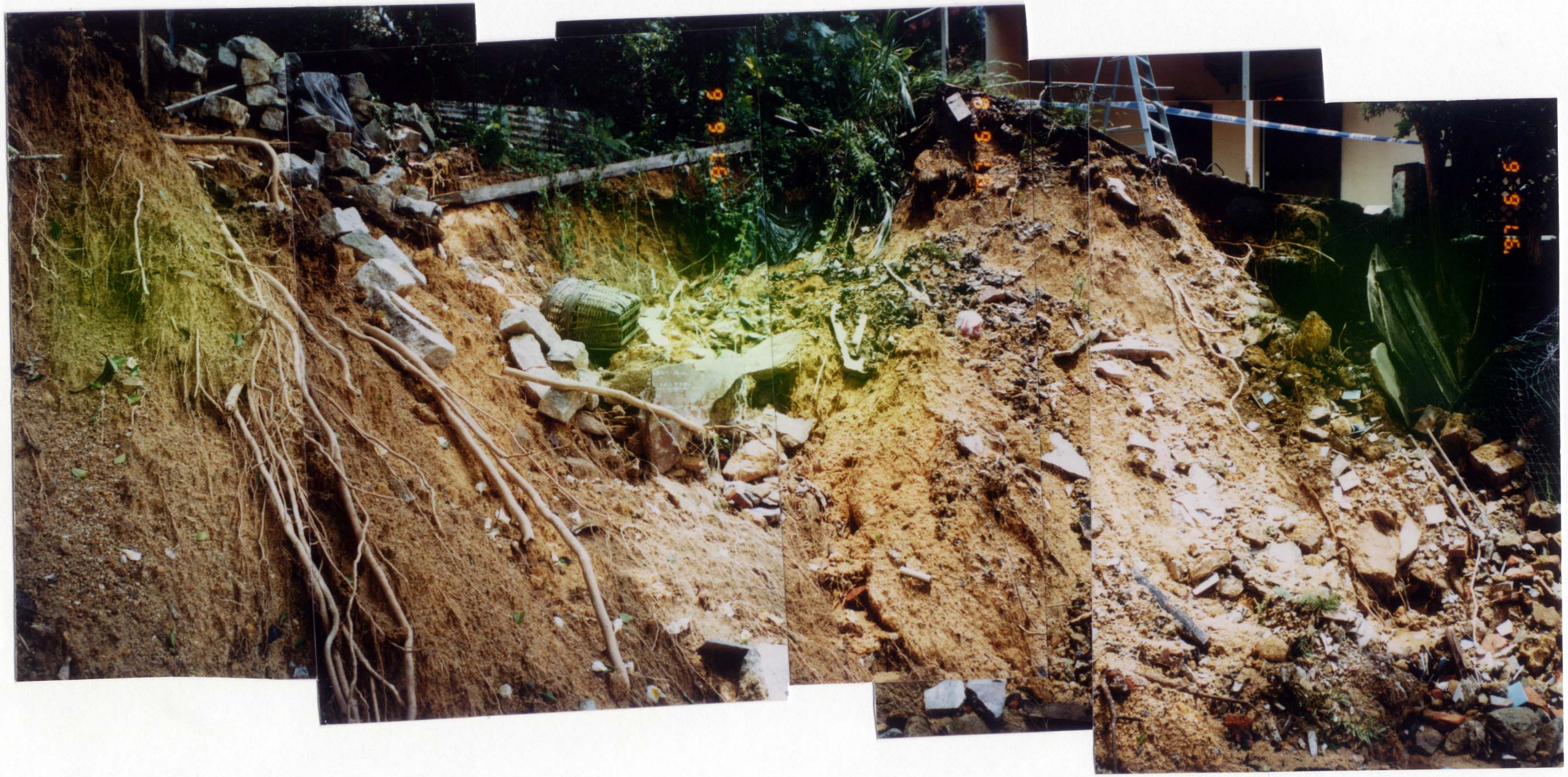

Plate 10 - View of the Upper Part of Landslide C (Photograph Taken on 6 June 1997. Note the Secondary Washout Channel Extending to the Back of the Full Platform)

Plate 11 - View of the Thin Brick Retaining Wall Involved in Landslide C (Photograph Taken on 6 June 1997)

Plate 12 - View of Landslide D (Photograph Taken on 23 June 1997.
Note the Deep Channel in the Upper Part of the Landslide)

Plate 13 - View of the Erosion Channel in the Upper Part of Landslide D (Photograph Taken on 23 June 1997)

Layer 1 - (Homogeneous fill)

Layer 2 - (Heterogeneous fill)

Layer 3 - (Topsoil)

Layer 4 - (Highly decomposed granite)

Plate 14 - Detailed View of the Four Layers of Material
Exposed in the Erosion Channel of Landslide D (Photograph Taken on 23 June 1997.
Note the Upper Two Layers are Fill. The Layers Below are Topsoil and Highly Decomposed Granite)