INVESTIGATION OF SOME SELECTED LANDSLIDES IN 1998 (VOLUME 6)

GEO REPORT No. 113

Fugro Scott Wilson Joint Venture

GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING DEPARTMENT

THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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PREFACE

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. A charge is made to cover the cost of printing.

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

R.K.S. Chan
Head, Geotechnical Engineering Office
August 2001

EXPLANATORY NOTE

This GEO Report consists of two Landslide Study Reports on the investigation of selected slope failures that occurred in 1998. The investigations were carried out by Fugro Scott Wilson Joint Venture (FSW) for the Geotechnical Engineering Office as part of the 1998 Landslide Investigation Consultancy.

The LI Consultancies aim to achieve the following objectives through the review and study of landslides:

(a) establishment of an improved slope assessment methodology,

(b) identification of slopes requiring follow-up action, and

(c) recommendation of improvement to the Government's slope safety system and current geotechnical engineering practice in Hong Kong.

The Landslide Study Reports prepared by FSW are presented in two sections in this Report. Their titles are as follows:

The Landslip Investigation Division of the Geotechnical Engineering Office worked closely with the LI Consultants and provided technical input and assistance to the landslide studies.

SECTION 1 : DETAILED STUDY OF THE LANDSLIDE AT TATE'S RIDGE, FEI NGO SHAN ROAD ON 9 JUNE 1998

Fugro Scott Wilson Joint Venture

This report was originally produced in November 1999 as GEO Landslide Study Report No. LSR 16/99

FOREWORD

This report presents the findings of a detailed study of the landslide (GEO Incident No. K 98/6/5) that occurred on 9 June 1998, at Slope No. 7SE-C/C42 below the Police Post at Tate's Ridge along Fei Ngo Shan Road, Kowloon. Debris from the landslide travelled downslope for a horizontal distance of about 170 m from the crown of the landslide, completely blocking Fei Ngo Shan Road. There were no casualties as a result of the landslide.

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

The report was prepared as part of the 1998 Landslide Investigation Consultancy (LIC), for the Geotechnical Engineering Office (GEO), Civil Engineering Department (CED), under Agreement No. CE 74/97. This is one of a series of reports produced during the consultancy by Fugro Scott Wilson Joint Venture (FSW). The report was written by Mr M Hughes and reviewed by Mr Y C Koo. The assistance of the GEO in the preparation of the report is gratefully acknowledged.

Y C Koo
Project Director/Fugro Scott Wilson Joint Venture

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1. INTRODUCTION

At sometime between the early morning and 12:30 p.m. on 9 June 1998, a landslide (GEO Incident No. K 98/6/5) occurred at Slope No. 7SE-C/C42 below the Police Post at Tate's Ridge, Fei Ngo Shan Road, Kowloon (Figure 1 and Plates 1 and 2). Debris from the landslide travelled downslope for a horizontal distance of about 170 m from the crown of the failure, completely blocking Fei Ngo Shan Road. There were no casualties as a result of the landslide.

Following the landslide, Fugro Scott Wilson Joint Venture (FSW), the 1998 Landslide Investigation Consultants, commenced a study of the failure on 10 June 1998 for the Geotechnical Engineering Office (GEO), Civil Engineering Department (CED) under Agreement No. CE 74/97. This is one of a series of reports produced during the consultancy by FSW.

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

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

(a) desk study, including a review of relevant documentary records relating to the history of the site,

(b) aerial photograph interpretation (API),

(c) topographic survey, geological and geomorphological mapping and detailed observations and measurements at the landslide site,

(d) limited ground investigation works and laboratory testing of soil samples collected from the landslide site,

(e) analysis of rainfall data,

(f) engineering analyses of the failed slope, and

(g) diagnosis of the probable causes of the landslide.

2. THE SITE

2.1 Site Description

A general location plan of the landslide site is shown in Figure 1, and a more detailed site plan and typical cross-sections through the landslide site are shown in Figures 2 to 4.

The landslide occurred below the Police Post on the south-facing side of the ridgeline that forms Tate's Ridge, northeast of Kowloon. The surrounding area generally comprises moderately to steeply-sloping (30^o to 45^o) terrain that is vegetated with grass and small shrubs. A single-lane country road (Fei Ngo Shan Road) has been cut into the hillside roughly parallel with the ridgeline and about 60 m south of it. Also, a rough track traverses the hillside above Fei Ngo Shan Road about 30 m south of the ridgeline. Formation of the road and track has created a series of soil and rock cut slopes. Of particular interest is the cut slope, Slope No. 7SE-C/C42, directly above Fei Ngo Shan Road, and the cut slope, Slope No. 7SE-C/C570, above the track, as the landslide affected both of these features, together with the hillside above. For the purpose of this report, these will be referred to as the lower and upper cut slopes respectively.

Based on observations made on site and information retrieved during the desk study, it appears that immediately prior to the current failure the lower cut slope extended to the edge of the rough track at the base of the upper cut slope. A 1 m-wide berm separated the lower cut slope into two batters that stood at angles of between 35^o and 40^o. At the crest of the lower cut slope the rough track formed a level area approximately 3 m to 4 m wide. The entire lower slope and track section were protected by shotcrete, forming a rectangular plan profile that extended upslope from Fei Ngo Shan Road for a distance of about 35 m, with a typical width of 30 m and an overall height of 18 m. The upper cut slope extended along the track for approximately 60 m, with a height of about 2 m to 3 m, and was not covered by surface protection.

Surface drainage over the landslide site appears to have comprised a number of surface U-channels descending from the platform at the Police Post and around the flanks of the lower cut slope to discharge into culverts along Fei Ngo Shan Road.

According to the "Systematic Identification of Maintenance Responsibility of Slopes in the Territory" (SIMAR) project undertaken by the Lands Department, maintenance responsibility for the lower cut slope, Slope No. 7SE-C/C42, lies with the Highways Department (HyD). No SIMAR report was available for the upper cut slope, but desk study records indicate that the Architectural Services Department (ArchSD) had previously carried out maintenance works to the area below the Police Post.

2.2 Water-carrying Services

Private and Government utility owners were contacted for details of their installations. This revealed that no water-carrying services are present within the immediate vicinity of the landslide area.

2.3 Site History

2.3.1 General

The site history has been established from API, together with a review of the available documentary records, and is summarised in the following section and illustrated in Figure 5.

A detailed account of the API is presented in Appendix A, along with a series of plans (Figures A1 to A3) showing the development of the site.

2.3.2 Site History and Development

The earliest available aerial photographs, taken in 1956, show that the lower cut slope above Fei Ngo Shan Road and the upper cut slope adjacent to the track had already been formed. The lower cut slope appears to have originally been about 14 m high by 25 m wide and stood at an angle of approximately 45° to the horizontal. The upper slope was typically 3 m high by 60 m wide and in the vicinity of the landslide stood at an angle estimated at between 35° and 50° to the horizontal. There was natural terrain between the crest of the lower cut slope and the edge of the rough track (Figures 5 and 6). The Police Post and concrete platform was in place along the ridgeline and an area, identified by a lighter tone, was evident below the platform, which may represent fill material tipped onto the slope during construction of the Police Post.

In the 1963 photographs the rough track above and to the east of the lower cut slope had been cleared of vegetation and a dark line, which has been identified on site as an unlined drainage ditch, can be seen along the inside edge of the track. The vegetation clearance works had only been carried out as far as the western edge of the lower cut slope and it would seem that the unlined drainage ditch discharged into a natural drainage line descending the hillside at this location.

Subsequent photographs, taken between 1963 and 1977, show the layout of both cut slope features. A fence traverses the hillside above the crest of the lower cut slope. A number of old failure scars are visible in the area surrounding the 1998 failure, but these are comparatively small in the immediate vicinity of the landslide site. A number of lines that could be possible indications of tension cracks are visible over the area above and below the rough track. In particular, there are indications of tension cracks in the vicinity of the northeastern boundary of the 1998 landslide. These traverse the hillside in a northwest to southeast direction forming right-stepping en echelon tension cracks. Desk study records indicate that a prominent tension crack was identified in this area following the failure in 1993 and observations on site following the 1998 landslide suggest that in part the landslide failed along this tension crack. Regarding the other possible tension cracks, observations made on site did not reveal any obvious signs of cracking and no desk study records relating to cracking in this area were found.

The drainage system at the crest of the landslide site comprises a surface channel along the southern edge of the concrete platform forming the Police Post. This appears to discharge directly onto the slope below its western end, whereas a concrete channel further east directs surface water downslope into what appears to be a natural drainage line (Appendix A, Figure A1).

The 1967, 1976 and 1977 photographs show that the lower cut slope is divided into two portions by a small masonry stub wall. The wall does not appear to be very high (less than 1 m), and crosses at just above the mid-point of the slope. What appears to be a broad lens of material, possibly colluvium, can be seen in the shallow depression forming the landslide site, which may be indicative of relict instability (Appendix A, Figure A1). This feature appears to be relatively thin and has a lateral extent that approximately coincides with the eastern and western boundaries of the 1998 landslide. A natural drainage line is apparent above and along the western flank of this broad strip feature, where individual and groups of boulders have accumulated. Individual boulders can also be seen projecting from the surface of the lower cut slope along the western side.

There was little change in the layout of the area in subsequent years up to 1992, but in the 1993 photographs, the shape of the lower cut slope has changed significantly. A new layer of surface protection covers the slope, which now extends as far as the edge of the rough track and has a generally constant width that spans between the two culverts at the toe of the slope. The fence line has locally been realigned so that it now bounds the upper portion of the newly protected area. Construction activity is visible in the natural hillside above the upper cut slope. The channel descending from the Police Post, that previously discharged into a natural drainage line, has been extended so that it connects into the stepped channel running down the eastern flank of the lower cut slope. Also, a new section of surface drainage channel extends diagonally across the natural ground above the upper cut slope. This would appear to be the surface channel placed above the tension crack, as recommended by the Mainland East Division of the GEO, following the failure in 1993. From the aerial photographs, it appears that the channel does not join into the crest channel along the southern edge of the platform along the Police Post, as no connection is visible. Below this channel an arcing line can be seen cutting through the natural slope, which could possibly be the location of a tension crack. These observations (summarised in Appendix A, Figure A2) are consistent with information arising from the desk study, as discussed in Section 2.3.3.

There was little change in the profile of the upper and lower cut slopes in the 1994 photographs, but from desk study records it is evident that the lower cut slope had new surface protection applied following signs of instability at the toe of the slope.

In 1995 and 1996 it is possible to identify extensive cracking in the surface protection at the crest of the lower cut slope (Appendix A, Figure A2). The cracking is more prominent along the western side and there appears to be a break in the surface protection, suggesting the possible presence of tension cracking in this location. No records relating to these observations were recovered during the desk study.

The 1997 photographs show that the lower cut slope has undergone further changes. The area of surface protection now extends slightly further upslope, such that it adjoins the toe of the upper cut slope. Along the outer edge of the rough track, which coincides with the crest of the lower cut slope, a drainage channel has been constructed. A narrow drainage berm is also present at approximately the mid-point of the lower slope and stepped channels connecting with these drainage channels descend both sides of the slope (Appendix A, Figure A3). The line previously identified as a possible tension crack in the natural terrain above the rough track to the northeast of the landslide site can still be seen, but its extent appears to have increased further upslope. The profile of this line is similar to that of the eastern side of the 1998 landslide.

2.3.3 Previous Landslides

The Natural Terrain Landslide Inventory (NTLI) prepared using high level aerial photographs by the GEO, does not record any natural terrain failures in the vicinity of the landslide site. API has indicated the presence of old failure scars and possible tension cracks in the vicinity of the 1998 landslide. File records reviewed during the desk study phase show that the area of the current landslide has a documented history of instability since 1993. As a consequence of this and as evidenced by API, the lower cut slope has undergone several phases of modification.

The earliest recorded incidence of failure was that on 27 September 1993, when a major landslide occurred in the vicinity of the upper cut slope (GEO, 1993) following a rainstorm. The recorded volume of the failure was 1000 m^3, and debris from the landslide blocked Fei Ngo Shan Road (Plate 3). Following the incident a tension crack bounding the upper portion of the landslide was identified in the natural ground approximately 5 m to 10 m above the upper cut slope (Figure 5 and Plate 4). No interpretation as to whether the crack was new or old or details regarding the depth and extent of the tension crack were recorded in the incident report or GEO's files. However, from photographs it is estimated that the maximum movement of the main body of material was less than 0.5 m both horizontally and vertically (Plate 4), although the western side of the landslide appeared to have displaced by a greater extent (Plate 3).

Remedial works recommended by the Mainland East Division of the GEO following the failure comprised cutting back the lower slope to a gradient of 1:2, covering the area with surface protection and construction of new surface drainage. Also, a 300 mm U-channel was to be installed on the uphill side of the tension crack (Plate 5). Additionally, control points were to be installed to monitor the movement of the tension crack during construction of the remedial works. A memo from the GEO to the Highways Department, dated 6 October 1993, stated that "As your monitoring indicates no further movement at the upper part of the slope please fill the tension cracks with well rammed soil to prevent surface water ingress".

Following the failure in September 1993, the failed slope was nominated by the Mainland East Division for inclusion into the Landslip Preventive Measures (LPM) Programme. However, due to the lower priority ranking of the slope in comparison with other slopes being considered, it was not included in the LPM Programme at the time.

In July 1994, further instability in the form of extensive cracking and slope movement was noted at the toe of the cut slope directly above Fei Ngo Shan Road (GEO, 1994). Cracking was most notable at the corners of the slope and there was also some spalling of the shotcrete at the western side (Plate 6). In the central portion of the slope, the shotcrete cover was recorded as having moved out by some 100 mm, and steady seepage was noted along the toe. Remedial measures recommended by the Mainland East Division involved the removal of the existing surface protection and any loose material below, followed by the application of a new shotcrete layer.

In July 1997, cracking and bulging was again observed at the toe of the cut slope directly above Fei Ngo Shan Road with water seeping out from the weepholes about 10 m upslope from the road (GEO, 1997). Also, extensive cracking and spalling of the shotcrete was present at the eastern corner (Plate 7). Two sets of tension cracks were recorded in the

GEO's landslide incident report. One set was recorded immediately below the track at a height of about 18 m above the road, and the other set about 5 m above the track, which was probably the same tension crack identified following the 1993 failure. There was no mention of the extensive cracking along the crest of the lower cut slope identified in the API.

Following these observations, more extensive remedial measures were recommended by the Mainland East Division. The 18 m-high section of slope directly above Fei Ngo Shan Road was to be formed into two batters (35° for the lower portion and 40° for the upper portion) separated at the mid-point by a 1 m-wide berm. A new layer of shotcrete was to be applied to the trimmed slope, and three rows of 12 m-long soil nails and eleven 10 m-long horizontal drains were to be installed in the lower 6 m of the slope (Figure 6).

A site inspection was undertaken by the Planning Division of the GEO in September 1997, while urgent repair works were ongoing. The Planning Division identified that "The lower part of the slope had been cut into weathered tuff" and "The upper part of the slope exposes bouldery colluvium estimated to be up to about 2 m thick overlying the bedrock". A lens of material with an "irregular strike and form" was observed to daylight from the lower portion of the slope (Plate 8). This material comprised a reddish brown silty clay that was considered to be "a thermally altered mudstone or dyke (possible lamprophyre)". The outcrop was about 2 m wide and was "generally low dipping into the slope and is likely to form a relatively impermeable barrier to groundwater flow compared to the decomposed bedrock". Previous signs of seepage from above this band were observed in the form of "small pipes and erosion rills up to about 3 m above the contact".

Signs of distress at the toe in the form of "bulging" were also recorded. Instability above and adjacent to the site was observed in the form of "numerous small scarps and tension cracks", in particular, a previously unidentified tension crack was noted higher up the natural terrain (Plate 8). However, no details regarding the depth, extent and age of the tension cracks were recorded. Also visible in some of the photographs taken during this site visit was a longitudinal strip descending from the platform area at the Police Post. This feature appears to have been formed by water flowing downslope, suggesting the possibility of overtopping of the crest channel along the platform.

Following the initial recommendations for urgent repair works discussed on site between HyD and the Mainland East Division of GEO on 14 October 1997, further recommendations were made to the ArchSD by the Mainland East Division concerning the natural ground above the cut slopes. These recommendations involved clearance, repair and upgrading the existing surface drainage along the slope, and "Fill the tension crack in the slope which is about 10 m below the slope crest using suitable fill materials and hand compact the fill". These filling works appear to refer to the existing tension crack identified following the 1993 failure. No records were recovered to establish whether these works were carried out.

2.4 Previous Inspections and Studies

The cut slope features affected by the landslide were not registered in the 1977/78 Catalogue of Slopes.

In mid-1992, the GEO initiated a consultancy agreement, entitled "Systematic Inspection of Features in the Territory" (SIFT), to search systematically for slopes not included in the 1977/78 Catalogue of Slopes and to update information on previously registered features, by limited site inspections and studying aerial photographs. Both cut slopes were categorised as Class C1 features under the SIFT project, i.e. "Assumed formed pre-1978 or illegally formed", and allocated the Feature Nos. 7SE-C/C42 and 7SE-C/C570 for the lower and upper cut slopes respectively.

In 1994, the GEO commenced a consultancy agreement, entitled "Systematic Identification and Registration of Slopes in the Territory" (SIRST), to systematically update the 1977/78 Catalogue of Slopes and to prepare the New Slope Catalogue. The GEO's consultants for the SIRST project inspected both features between 5 and 9 September 1997. The SIRST report for the lower cut slope noted that site works were in progress. The report identified the slope to be in a fair condition with no signs of seepage or distress and it also recorded inferred past instability as being "none". The SIRST report for the upper cut slope stated that there was "No proper access to the slope feature". Inferred past instability was "minor" and "Signs of Distress" were recorded as being "Reasonable", with possible old scars on the eastern end of the slope.

A Stage 1 Study Report, dated 10 June 1994, prepared by the Design Division of the GEO noted signs of distress over the slope, but no details were provided to indicate what form the distress took.

The first recorded landslide on 27 September 1993 was referred to in GEO Report No. 43 (Chan, 1995). The report recorded that the 1993 landslide "involved mainly colluvium" and that the failure was "probably due to prolonged rainfall and water infiltration as well as the blockage of drains resulted from lack of maintenance".

3. DESCRIPTION OF THE LANDSLIDE

3.1 Time of the Landslide

The exact time of the landslide is not known, as there were no eyewitness accounts of the failure. The first sighting of the landslide was by a staff member of the Fire Services Department, who reported the incident at 12:30 p.m. on 9 June 1998. The security guards responsible for patrolling the area surrounding the Police Post were interviewed, but they were not able to give a more precise time of occurrence of the landslide.

When studying the rainfall pattern of the storm on 9 June 1998, it is evident that it reached its highest local intensity between 5:30 a.m. and 8:30 a.m. on the morning of 9 June 1998. Therefore, it is considered that the failure probably occurred between 5:30 a.m. and 12:30 p.m. on 9 June 1998.

3.2 Description of the Landslide

A plan and section of the landslide are shown in Figures 2 and 4 respectively. Photographs of the landslide are shown in Plates 1 to 2 and 9 to 15.

The first inspection of the landslide by FSW was on the afternoon of 10 June 1998. The landslide debris at that time was still completely wet and small surface flows were evident along sections of the failed mass. Initial observations of the mainscarp showed no clear indications of seepage from the exposed surface, but a thorough inspection was not possible due to poor access. As more than 24 hours had elapsed between the first report of the landslide and the initial inspection, it is possible that such signs would have disappeared.

The landslide occurred in a natural depression below an east-to-west trending ridgeline. The landslide had an asymmetrical plan profile and comprised four morphological units (Figure 2 and Plate 1), namely:

(a) an upper, shallow concave scar within the hillside above the upper cut slope,

(b) the main concave scar (mainscarp) affecting the hillside and both the upper and lower cut slopes that appears to have been partially controlled by a locally persistent planar discontinuity along the eastern side dipping at an angle of 50^{o} in a south-southwesterly direction and a zone of finer-grained material, probably siltstone, outcropping along the western side of the surface of rupture,

(c) the landslide debris trail covering part of the lower cut slope and the natural ground below Fei Ngo Shan Road, and

(d) a small localised area along the western side of the landslide where material appears to have moved only a relatively small distance and as a largely intact raft.

The estimated volume of the failure based on survey of the failure scar was about 2 500 m^3.

The crown of the shallower upper portion of the landslide occurred about 4.5 m downslope from the edge of the platform of the Police Post. Within this area, the rupture surface was typically 1.5 m to 2 m deep, 15 m long and between 8 m wide at the crown and 20 m wide at the boundary with the mainscarp. Approximately 500 m^3 of failed material originated from this source. The inclination of the rupture surface was typically between 25^{o} and 35^{o} in a south-southeasterly direction. Locally towards the edges of the failure the rupture surface was steeper.

Within the mainscarp, the rupture surface was typically 3 m to 4 m deep, 30 m long and between 20 m and 40 m wide. Approximately 2 000 m^3 of failed material originated from this source. The inclination of the rupture surface was between 30^{o} and 40^{o}, but locally steeper towards the edges of the failure.

No seepage or soil pipes were observed over the exposed portion of the rupture surface, neither were there signs of slickensiding that can be attributed to the 1998 landslide.

Debris from the landslide formed a sub-horizontal deposit at the head of the debris trail approximately 20 m to 25 m from the crown. Material in this area was thought to be approximately 2 m to 3 m thick and was very wet and covered by displaced vegetation (Plates 2 and 12). The vegetation appeared largely intact giving the impression that this section of the slope failed as an intact raft that broke up slightly under movement. Occasional large boulders and broken U-channel sections were evident over the surface.

To the west of this sub-horizontal area was a small raft of material that appeared largely intact and that had apparently moved a significantly smaller distance (approximately 5 m) than the main body of failed material. This feature may represent an area that failed as a result of (i.e. subsequent to) the main landslide.

The fence line that formerly bounded the upper portion of the lower cut slope moved downslope by approximately up to 15 m during the landslide. It marked the break between the sub-horizontal and sloping portions of the debris trail.

Debris from the landslide accumulated at the toe of the lower cut slope, blocking Fei Ngo Shan Road (Plate 13). This material was estimated to have a thickness of between 3 m to 4 m above the road.

Below Fei Ngo Shan Road the failed material entered a natural drainage gully and became channelised, travelling downslope unobstructed until it reached Jat's Incline. The material in this portion of the debris trail appeared coarser, probably due to the effects of surface water (Plate 14). The travel angle of the landslide debris (Wong & Ho, 1996a), measured from the crown of the landslide to the distal end of the failure was 30^o (Figure 3), which is within the range of typical values for rain-induced landslides.

Based on the two distinct portions of the failure scar, it is considered that the 1998 landslide involved two phases of movement with material from the mainscarp failing first. The distribution of failed sections of shotcrete across the debris trail suggests there was a greater degree of mobility down the western flank of the landslide, in the vicinity of where a natural drainage line and colluvial deposits were identified by API. The semi-intact nature of the vegetation cover across the sub-horizontal platform at the head of the debris trail suggests that material from the shallower portion of the landslide moved as a 'raft'.

Inspection of the platform at the crest of the landslide revealed a number of minor cracks through the concrete surfacing, but these were randomly orientated and were not considered to be associated with the current failure. It was noted that a baffle wall had been constructed along the crest channel along the southern edge of the platform, as per recommendations from the Mainland East Division of the GEO following the 1997 failure. The surface U-channel placed above the tension crack (as identified from the desk study records) was connected into the crest channel. This section of channel descended directly downslope from the crest channel for a distance of approximately 4.5 m, where it had been severed by the landslide. Along the western flank of the failure, below the severed portion of drainage channel an area of vegetation had been flattened in a downslope direction.

Following clearance of the failed material from the slope above Fei Ngo Shan Road, it was possible to establish the extent of the failed area. Approximately the lower half of the slope remained intact with only a slight area of bulging, approximately 5 m square, in the central portion (Figure 7). About 10 m upslope from the road, three soil nail heads, approximately 1 m square in dimension, were exposed (Figure 7 and Plate 15). The positions of these nails are consistent with information revealed during the desk study, and they would appear to be the top row of nails installed in 1997.

Directly below the nail heads the shotcrete had failed sub-horizontally creating a boundary above which there was no shotcrete and below which the shotcrete remained intact. Adjacent to the westernmost nail head, this boundary arced upwards sub-vertically, and similarly formed a boundary to the east of which was no shotcrete, but to the west of which was intact shotcrete (Plate 15).

The area of slight bulging referred to above occurred directly below the exposed nail heads, and towards the lower western corner of this a fourth nail head was partially exposed. On inspection, voids were identified beneath the shotcrete in the vicinity of this nail, but the nail head itself did not appear to have moved, suggesting that only the rigid surface protection had moved/distorted.

Also uncovered following the clearance of debris deposited on the lower slope were ten raking drains (a total of eleven were indicated by the desk study records, but only ten were identified on site). Seven of these remained largely intact within the originally shotcreted surface, but the remaining three were overlain by what appeared to be failed material and had significantly flattened profiles from the circular section. These three drains were located in the central portion of the slope at about the same elevation as the top row of soil nails.

Elsewhere across the lower slope minor cracks were present through the shotcrete layer, but these did not appear to follow any regular pattern. Further signs of distress included an area of spalling, approximately 1 m square, at the lower western corner of the slope, where the drainage channel descended into the culvert.

Following clearance works it was evident that the landslide had severed the small bund on the downhill side of Fei Ngo Shan Road. Also, several large indents were present in the road surface, presumably formed when boulders had impacted on the road during the landslide.

4. SUBSURFACE CONDITIONS

4.1 Geology and Geomorphology

With reference to the published geological map (GCO, 1986), the landslide site is mapped as comprising thermally altered crystal and lithic tuff, tuff breccia and tuffite of the Shing Mun Formation (Figure 8). A granite intrusion lies directly northeast of the site and an outcrop of siltstone and mudstone occurs about 300 m to the east.

Although no geological structures are shown as intersecting the site, a possible fault is mapped approximately 200 m east of the landslide site, trending north-northeast to south-southwest. A photogeological lineament with a similar trend is also mapped approximately 240 m northwest of the site.

Three sub-vertical feldsparphyric rhyolite intrusions are mapped approximately 120 m, 180 m and 230 m to the southeast of the landslide site, trending northwest to southeast, and another approximately 200 m northeast of the site, to the north of Tai Lo Shan.

Several lobes of "debris flow deposits" are indicated about 100 m south of the landslide site, below Jat’ s Incline.

The GEO's Geotechnical Area Studies Programme (GASP) Report I (GCO, 1987), produced for regional appraisal and outline and strategic planning purposes at a scale of 1:20 000, designated the terrain in the area of the 1998 landslide as an area of "general instability", that denotes "insitu terrain where many failures and other evidence of instability occur" which "provides an indication of the inherent weakness of the terrain and/or the occurrence of unfavourable groundwater conditions".

The area surrounding the landslide site comprises a broad shallow depression that is bounded on either side by spurs that project out from the ridgeline in a southerly direction. The broad depression can further be divided into two smaller drainage depressions separated by a wide, but less prominent spur. The boundaries to these features are not sharp or well defined and it is not possible to discern whether they are relict landslide scars or erosion features. The two smaller depressions form natural drainage paths that feed into a deeper single gully further downslope. The landslide occurred in the easterly gully, directly below the Police Post (Figure 1).

Relict landslide scars and more recent instability can be observed on site in the surrounding area. Some of these are concentrated along the upper cut slope above the track that traverses the mid-portion of the hillside (Figure 2). These are small-scale, shallow failures (typically less than 5 m wide and 1 m in depth) and can be identified as circular-shaped mainscarps. Larger failure scars (typically 15 m to 20 m wide by 25 m to 35 m long) are evident adjacent to the spur lines below Fei Ngo Shan Road. These appear as prominent depressions (approximately 2 m to 3 m deep), with sharp well-defined boundaries. These lie outside the boundary of the 1998 landslide and are not related to the incident.

In the easterly depression forming the landslide site a lens of material (identified from API) appears to have existed prior to the landslide. This feature may represent an area of colluvium (see also Section 4.3 below). Also, large boulders, either as individual pieces or as groups, cover much of the hillside. This coarse material, where evident along drainage lines, may be a further indication of colluvial deposits.

4.2 Previous Ground Investigations

No previous ground investigation records were recovered during the desk study. Subsequently, the geology has been assessed principally through field mapping and observations made on site, as discussed in the following section.

4.3 Current Investigation

Limited investigation works were carried out following the landslide in an attempt to obtain specific details about the failure. These included localised soil strips in the mainscarp and a shallow trial pit in the lower cut slope, the locations of which are shown in Figure 7. The purpose of the trial pit was to establish the position of the toe of surface of rupture, as well as to identify the existence, layout and condition of remedial works installed following the July 1997 failure. A number of bulk disturbed samples were taken so that grading and Atterberg Limits tests could be carried out. The results of these tests are summarised in Table 1.

The soil strips and mapping of the landslide identified the principal material exposed in the mainscarp as a thermally altered fine to coarse ash tuff, with a rock mass weathering zone rating of PW 0/30. This material comprised a stiff, reddish brown and mauve, occasionally pink and white, fine gravelly very sandy very clayey silt, with an extensive network of manganiferous and kaolin veins (completely decomposed thermally altered fine to coarse ash tuff (CDT) with closely spaced and randomly orientated discontinuities). Towards the ground surface, this material was further decomposed to residual soil (approximately 2 m thick).

Outcrops of dark blue grey, moderately and moderately-to-slightly decomposed tuff (MDT and M-SDT respectively) were irregularly spaced within the more weathered matrix. These appeared to be more prominent over the eastern portion of the rupture surface, and over the lower eastern portion an area of M-SDT formed a locally persistent outcrop with a planar surface that dipped at an angle of 50^{o} approximately due south (Plates 9 and 12). A slickensided black manganiferous deposit was observed over parts of this outcrop. This plane appears to have partially controlled the eastern side of the landslide in this area.

Above the locally persistent planar outcrop and forming an apparent projection of it, was a boundary differentiating between recently exposed material below and a more decomposed and discoloured material above was observed. Vegetation was noted as growing from the discoloured portion, and fill material, comprising fine to coarse gravel-sized fragments of weathered tuff, was identified in the upper portion of this zone (Plate 10). This feature could be traced over an area approximately 15 m long by 1 m deep, and is thought to be a part of the tension crack/mainscarp identified following the 1993 landslide, that was subsequently filled with "well-rammed soil".

The kaolin veins identified in the tuff were typically 1 mm to 2 mm thick, but locally up to 10 mm to 15 mm thick, and had a predominant northwest-to-southeast strike within the CDT. The mechanism of formation of the kaolin veins is not fully understood. Kaolin minerals could possibly have been deposited along discontinuities within the CDT by the precipitation of minerals leached out of overlying materials by percolating groundwater and/or formed by in-situ weathering of minerals deposited along discontinuities during hydrothermal activity associated with the granite intrusion to the northeast of the site.

The manganiferous veins were typically between 0.5 mm and 1 mm thick and are considered to be infill material deposited along discontinuities during the weathering process. In the CDT, the manganiferous deposits were wet and smeared easily under finger pressure, but on the surface of the M-SDT outcrop over the eastern side of the site, it was harder.

Slickensides were identified over the surface of some of these deposits. These are considered to be the result of minor, localised movements that may have occurred due to tectonic activity and/or creep movements associated with removal of overburden over a considerable period of time (Koo, 1982).

The presence of the veins gives an indication of the distribution of relict structure within the tuff.

Along the western side of the landslide, soil strip S2 revealed a band of fine-grained material in the mainscarp (Figure 9 and Plate 11). In the upper cut slope an exposure of a strong, slightly decomposed, dark grey fine-grained rock formed an extension of the band of completely decomposed material exposed in the mainscarp. Based on the fine grain size and the local outcrop of mudstone and siltstone to the east of the site as indicated on the geological map and identified on site, it is considered that this material is probably siltstone. In the mainscarp, the siltstone was weathered to a stiff, orangish brown and greenish grey, slightly sandy (fine grained), clayey to very clayey silt with some kaolin veining and was finer grained than the surrounding weathered tuff. The exposure in the cut slope indicates the band of siltstone to be of the order of 3 m thick, with a variable dip of between 25° and 55° in a predominantly east-north-easterly direction into the slope.

Also along the western side of the landslide, in the vicinity of the track and upper cut slope soil, strip S3 revealed a layer of colluvium. This comprised angular to sub-rounded, gravel, cobble and occasional boulder-sized material in a matrix of firm, orange brown speckled blue grey, slightly sandy, slightly gravelly, clayey silt. The thickness of this layer is uncertain, but it is thought to be relatively thin. The position of this material is consistent with findings from the API, which noted a broad lens of material, possibly colluvium, over the lower portion of the landslide site, and bouldery material along what appeared to be a natural drainage line descending the western flank of the landslide site.

Inspection of the unprotected cut slope along Fei Ngo Shan Road immediately west of the landslide also revealed a layer of colluvium, typically 1.0 m to 2.0 m thick, overlying CDT (Figure 9). The layer of colluvium was observed to diminish in thickness in a westerly direction.

At the crown of the failure a small amount of fill was exposed (maximum thickness 1.5 m), that was probably derived from end-tipped material originating from the cutting required for the Police Post, as noted from the API. The presence of this material is not thought to be significant in the context of the current instability.

A shallow trial pit (TP1) was dug in the lower cut slope directly upslope of the westernmost nail head where the toe of surface of rupture was suspected (Figure 7 and Plate 16). In the upslope face of the trial pit a layer CDT was exposed that was similar in colour, structure and composition to that identified in the mainscarp. The thickness of this layer thinned from a maximum of 250 mm at the eastern corner of the trial pit to nothing at the westerly corner. At the base of the CDT a thin seam of remoulded material, typically 50 mm thick, could be seen. This seam was softer and wetter than the surrounding material and based upon hand examination, comprised material with a similar grain size to that of the CDT above, but lacked the visible structure. Beneath the seam lay an area of MDT over the easterly half of the trial pit and a lens of completely decomposed siltstone over the westerly half of the trial pit. All three materials were distinctly different from the remoulded seam from the point of view of structure, grain size, texture and strength (Plate 17).

In the westerly face of the trial pit the seam of remoulded material daylighted from the slope above the siltstone (Plate 18). This position of the daylighting seam was coincidental with the sub-vertical sheared shotcrete boundary discussed in Section 3.2. In the easterly face of the trial pit the structure within the CDT that was present in the upslope face was not as distinct. This made it difficult to identify the exact alignment and inclination of the remoulded seam, but it is estimated that it dips out of the slope at an angle of about 25^{o} in a southerly direction. Despite the uncertainty regarding the exact alignment of the remoulded seam, it is clear that in the lower easterly face of the trial pit the seam daylighted above the nail heads exposed following clearance of the landslide debris (Section 3.2). This, together with the sub-horizontal sheared shotcrete boundary identified just below the nail heads, provides a strong indication that this is the area where the toe of the rupture surface daylighted from the slope.

Excavation works to uncover the raking drains along the top row of soil nails also exposed completely decomposed siltstone approximately 5 m east of the trial pit, suggesting that the silstone daylights out of the slope at this location. These observations are in line with findings of the site visit undertaken by the Planning Division of GEO in September 1997 (Section 2.3.3 and Plate 8).

Localised vegetation clearance works were also undertaken along the track on both sides of the landslide, and further up slope in the vicinity of the drainage ditch (Figure 7). The purpose of these was to investigate the presence of tension cracks, but on completion of the clearance works no evidence was revealed to indicate additional signs of instability linked to the current failure.

The need to complete the urgent repair works did not allow sufficient time to further investigate this area, and it is not possible to be conclusive about these findings. The feature has been included in the LPM Programme, under which ground investigation works will be undertaken. During these works it would be prudent to investigate whether possible old tension cracks as indicated from API (Section 2.3.2) are present in the area adjoining the 1998 landslide site.

4.4 Deduced Ground Conditions

Based on the available information the dominant material involved in the landslide was CDT, which has an extensive network of kaolin and manganiferous veins through the fabric of the material. These veins are thought to be infills deposited along discontinuity surfaces within the body of the material, and their presence indicates the distribution of relict structure, which is interpreted as being closely-spaced and randomly orientated.

Along the lower eastern portion of the landslide, an area of M-SDT was identified that forms a locally persistent planar discontinuity. This feature is coincidental with the location of the tension crack identified following the 1993 landslide and may therefore have been a controlling factor in the history of instability of the landslide site.

It was noted that outcrops of less weathered material were present on the flanks of the natural hillside bounding the landslide, but that in the main body of the landslide the material was predominantly completely weathered. This suggests a deeper and more advanced weathering profile exists in the shallow depression where the landslide occurred. This is corroborated by the fact that API identified the presence of an old drainage line along the western side of the shallow depression.

A band of fine-grained material, probably siltstone, cuts along the western flank of the landslide site and appears to daylight in the mid-portion of the lower cut slope, approximately at the same elevation as the top row of soil nails. Locally the outcrop has a variable dip and orientation, but overall it appears to dip in a northeasterly direction at about 50^o (i.e. into the slope). It is estimated that this band of material is about 3 m thick in the main body of the failure, where the material has been weathered to a completely decomposed state and comprises a clayey to very clayey silt, as described on site and supported by a single PSD test (Table 1). Consequently, it is possible that this band forms a relatively impermeable barrier to percolating groundwater.

A pervasive layer of colluvium, about 2 m thick, is thought to have overlain the landslide site, areas of which were removed during cutting operations associated with the formation of Fei Ngo Shan Road, the rough track and subsequent remedial works to the slopes. Based on API and field observations, the colluvium is considered to have been predominantly within the boundary of the 1998 landslide, and consequently much of the physical evidence of the existence of this material has been removed.

The fill identified on site is considered to be of a shallow localised nature and not significant in the context of the current failure.

The thin seam of reworked material and the cracked shotcrete boundary provide a possible indication that the toe of the surface of rupture daylighted the slope just above the top row of soil nails installed in 1997.

4.5 Groundwater Conditions

The topography of the area surrounding the depression in which the landslide occurred is such that the catchment serving this area is relatively small, and it is unlikely to be large enough to sustain a permanent high groundwater table.

The poor drainage provisions at the Police Post and across the hillside above the cut slopes would have led to increased surface water flows within the shallow depression forming the landslide site, resulting in a higher degree of infiltration across the unprotected portion of the hillside. This setting is conducive to the formation of transient elevated water pressures within the tuff during heavy rainfall. The presence of tension cracks in the unprotected natural terrain would have exacerbated this process. The unlined drainage ditch at the toe of the upper cut slope could also potentially have resulted in concentrated water ingress into the ground leading to wetting up and possible localised high groundwater pressure.

The presence of a natural drainage line down the western side of the landslide site suggests possible concentrated subsurface groundwater flow in the past. However, in the absence of detailed ground investigation using drillholes and piezometers it is not possible to verify the hydrogeology and groundwater conditions of the landslide site.

It is possible that the band of finer-grained material cutting across the lower cut slope may have had a local influence on the direction of groundwater flow at the interface with the tuff due to the permeability contrast between the two. Photographs show seepage issuing from the mid to upper-portion of the lower cut slope, suggesting the possible presence of high localised groundwater pressure (Plate 7). This is corroborated by observations made on site by the Planning Division of GEO following the failure in 1997 (Plate 8), as discussed in Section 2.3.3.

5. ANALYSIS OF RAINFALL RECORDS

The nearest GEO automatic raingauge No. K07 is located at Oi Wai House, Tse Oi Estate, about 1 800 m southwest of the landslide. The raingauge records and transmits rainfall data at 5-minute intervals via a telephone link to the GEO. These records have been analysed to determine the characteristics of the rainstorm associated with the landslide.

For the purposes of this analysis, it is assumed that the landslide occurred at 12:30 p.m. on 9 June 1998.

The daily rainfalls recorded by the raingauge in May and June 1998, together with the hourly rainfalls from 8 to 9 June 1998, are shown in Figure 10. The storm was concentrated around the day of 9 June 1998, with particularly heavy rainfall experienced in the morning between 05:30 hrs. and 09:30 hrs.

Isohyets of rainfall for the 24-hour period prior to the reported time of the landslide (12:30 hrs on 9 June 1998) for the whole of the SAR are shown on Figure 11.

Table 2 shows the maximum rainfall intensities and their estimated return periods for different durations for the main storm of 9 June 1998. The maximum 2 hour rainfall of 137.5 mm was the most severe, which corresponded to a return period of about 8 years (Lam & Leung, 1994).

A comparison of the patterns of previous heavy storms affecting the landslide site is shown in Figure 12. It is evident that the short-duration rainfall was comparable to the maximum previously experienced by the area for the records analysed since 1983, but the long-duration rainfall was comparatively less severe than that experienced previously.

Whilst return periods for various durations of the storm have been assessed based on Lam & Leung (1994), it is recognised that this method does not necessarily give the true return period for a particular site (Wong & Ho, 1996b). However, it does provide an objective ranking of the relative severity of the rainfall characteristics of different rainstorms.

6. DISCUSSION

The close correlation between rainfall and the landslide suggests that the failure was triggered by rainfall.

Based on documentary records the site has a history of instability since at least 1993 and possibly from as early as 1963 based on API. Following the failure in 1993, which involved ground movement without full detachment of material, deformation was noted at the slope toe and a significant tension crack was observed in the hillside above the cut slope. These observations suggest the progressive development of a deep-seated instability within the CDT, which is estimated to have had a maximum depth of about 9 m (Figure 6). Subsequent instabilities in 1994 and 1997 were accompanied by further deformation at the slope toe as well as the development of additional tension cracks further upslope.

While the 1998 landslide was not a “surprise” given the presence of tension cracks due to progressive ground movement, it is not certain as to the cause of the original instability leading to the formation of tension cracks in the hillside, which has a deep weathering profile. This could have been the result of the formation of the cut slopes into a section of marginally stable hillside and/or the presence of weak material and adverse geological features. API has identified the presence of a natural drainage line down the western side of the shallow depression forming the landslide site with the potential for a locally depressed weathering profile and the presence of weak decomposed material overlain by colluvium.

It is unknown whether the hillside was affected by concentrated subsurface groundwater flows, but following the formation of tension cracks, which in accordance with site observations and desk study records were never effectively sealed, a direct point of infiltration was provided to surface water flows. This is considered to have led to the formation of transient elevated groundwater pressure within the hillside together with the development of cleft water pressure in the tension cracks. The development of tension cracks with time can be viewed as an overall deterioration with regard to the stability of the hillside.

The poor detailing of the drainage provisions (i.e. no properly engineered downhill drainage path for surface runoff from the concrete platform at the crest) probably led to increased surface water flow over the landslide site, which might have been a contributory factor to instability and the 1998 landslide.

The available information suggests that the 1998 failure daylighted a short distance above area of the lower cut slope where soil nails were installed in 1997. Therefore, the slip plane over the lower portion of the landslide (item (b), Section 3.2) was at a shallower depth than previous incidents of instability. The upper portion of the landslide (item (a), Section 3.2) may be the result of a retrogressive type failure.

A noteworthy characteristic of the 1998 landslide was that it involved a “brittle” failure mode with detachment of debris in an uncontrolled manner, whereas the previous instabilities were apparently “ductile” with no significant disintegration of the displaced material. Based on the available information, it is postulated that previous instabilities involved the progressive development of a large-scale deep-seated failure, estimated to have a maximum depth of about 9 m and an estimated volume of about 5 000 m^3. The

1998 landslide was not as deep-seated, with a maximum depth of about 5 m and an estimated volume of 2 500 m^3.

The reason why the deeper-seated instability should exhibit "ductile" behaviour is not certain, but it may be linked to the geometry of the sliding surface and the operational shear strength of the material. It is possible that the average dip of the sliding surface was close to the critical state strength of the ground mass, such that overall equilibrium of the unstable mass could be regained following some slope deformation and corresponding changes in the slope geometry. Also, dilation along the sliding surface and the formation of tension cracks during slope deformation probably resulted in a reduction in water pressure acting on the slip plane, which would further contribute to the limited mobility of the debris.

The installation of soil nails within the bottom 10 m of the lower cut slope suppressed further movement along the pre-existing deep-seated slip plane and effectively forced the unstable mass upslope to fail along a slip plane that daylighted above the soil nailed zone. This shallower failure involved ground that had cracked and opened up as a result of movement associated with the deeper-seated instability. This would have promoted rapid water ingress with the development of cleft water pressure and localised groundwater pressure during heavy rainfall. The failure mechanism may therefore be different to that of the deeper-seated instability. The margin of safety against the failure mode in 1998 was reduced by the removal of toe support from the lower cut slope (Figure 7) due to trimming works undertaken following the 1993 and 1997 instabilities.

It is postulated that the shallower failure mechanism was unable to regain equilibrium in the same way as the previous deeper-seated instability, because upon failure the unstable mass tended to "overshoot" from about the middle portion of the cut slope where the toe of the slip surface daylighted. This may have been exacerbated by the rapid build-up of water pressure in the near-surface material. The above is a credible explanation for the failure mode apparently switching from a 'slow-moving' failure to an uncontrolled failure with fast-moving debris in 1998.

7. CONCLUSIONS

It is concluded that the 9 June 1998 landslide was triggered by heavy rainfall with an estimated return period of about 8 years.

The hillside has a history of instability and exhibited signs of distress that can be traced back to at least 1993, with soil nails and horizontal drains installed over the bottom 10 m of the lower cut slope following further instability in 1997. The available information suggests that the previous instabilities involved intermittent movements along a deep-seated slip plane (up to 9 m below ground surface) daylighting near the toe of the lower cut slope.

The 1998 landslide involved failure at shallower depth (up to 5 m below ground surface) and detachment of debris in an uncontrolled and fast-moving manner. The principal cause of the landslide was the development of transient elevated groundwater pressures in the distressed ground and the build-up of cleft water pressures in tension cracks (that had not been properly sealed against water ingress) during heavy rainfall.

The potential presence of a deeper-seated slip plane together with possible tension cracks in the area adjoining the landslide site as deduced from API, should be examined in detail during the ground investigation under the LPM Programme.

8. REFERENCES

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LIST OF TABLES

Table 1 - Summary of Classification and Index Test Results

Laboratory Sample No.	Material Type	Sample Location	Depth below ground level (m)	Sample Type	Particle Size Distribution				Liquid Limit (%)	Plastic Limit (%)	Moisture Content
					Gravel (%)	Sand (%)	Silt (%)	Clay (%)			
A1	Residual Soil	S1	0 - 1.2	Bulk	3	23	57	17	56	36	33
A2	Residual Soil	S1	1.2 - 2.7	Bulk	7	27	38	28	69	35	29
A3	CDT	S1	2.7 - 4.4	Bulk	10	27	43	20	53	33	27
A4	CDT	S1	5.9 - 10	Bulk	3	31	55	11	53	37	33
A5	CDB	S2	0 - 0.5	Bulk	2	5	79	14	63	41	42

Legend : CDT Completely Decomposed Tuff S1 Soil Strip No. 1
CDB Completely Decomposed Basalt

Note: Visual descriptions of Soil Samples A1-A5 are summarized as follows:

Sample A1 - Slightly gravelly, very clayey, very sandy SILT
Sample A2 - Gravelly, very clayey, very sandy SILT
Sample A3 - Gravelly, very clayey, very sandy SILT
Sample A4 - Slightly gravelly, clayey, very sandy SILT
Sample A5 - Slightly gravelly, slightly sandy, clayey SILT

Table 2 - Maximum Rolling Rainfall Records at GEO Raingauge No. K07 for Selected Durations Preceding 9 June 1998 Landslide and the Corresponding Return Periods

Duration	Maximum Rolling Rainfall (mm)	End of Period	Estimated Return Period (Years)
5 minutes	12	05:50 hours on 9 June 1998	2
15 minutes	31	05:55 hours on 9 June 1998	4
1 hour	83.5	06:40 hours on 9 June 1998	4
2 hours	137.5	06:55 hours on 9 June 1998	8
4 hours	166	08:45 hours on 9 June 1998	6
12 hours	227.5	10:00 hours on 9 June 1998	5
24 hours	270	12:30 hours on 9 June 1998	4
48 hours	285	12:30 hours on 9 June 1998	2
4 days	320	12:30 hours on 9 June 1998	2
7 days	385	12:30 hours on 9 June 1998	3
15 days	483.5	12:30 hours on 9 June 1998	2
31 days	740.5	12:30 hours on 9 June 1998	3

Notes: (1) Return periods were derived from Table 3 of Lam & Leung (1994).

(2) Maximum rolling rainfall was calculated from 5-minute data for durations up to 48 hours, and from hourly rainfall data for longer durations.

(3) The use of 5-minute rainfall data between 2 hours and 48 hours results in better data resolution, but may slightly over-estimate the return periods using Lam & Leung (1994)' s data, which are based on hourly rainfall for these durations.

LIST OF FIGURES

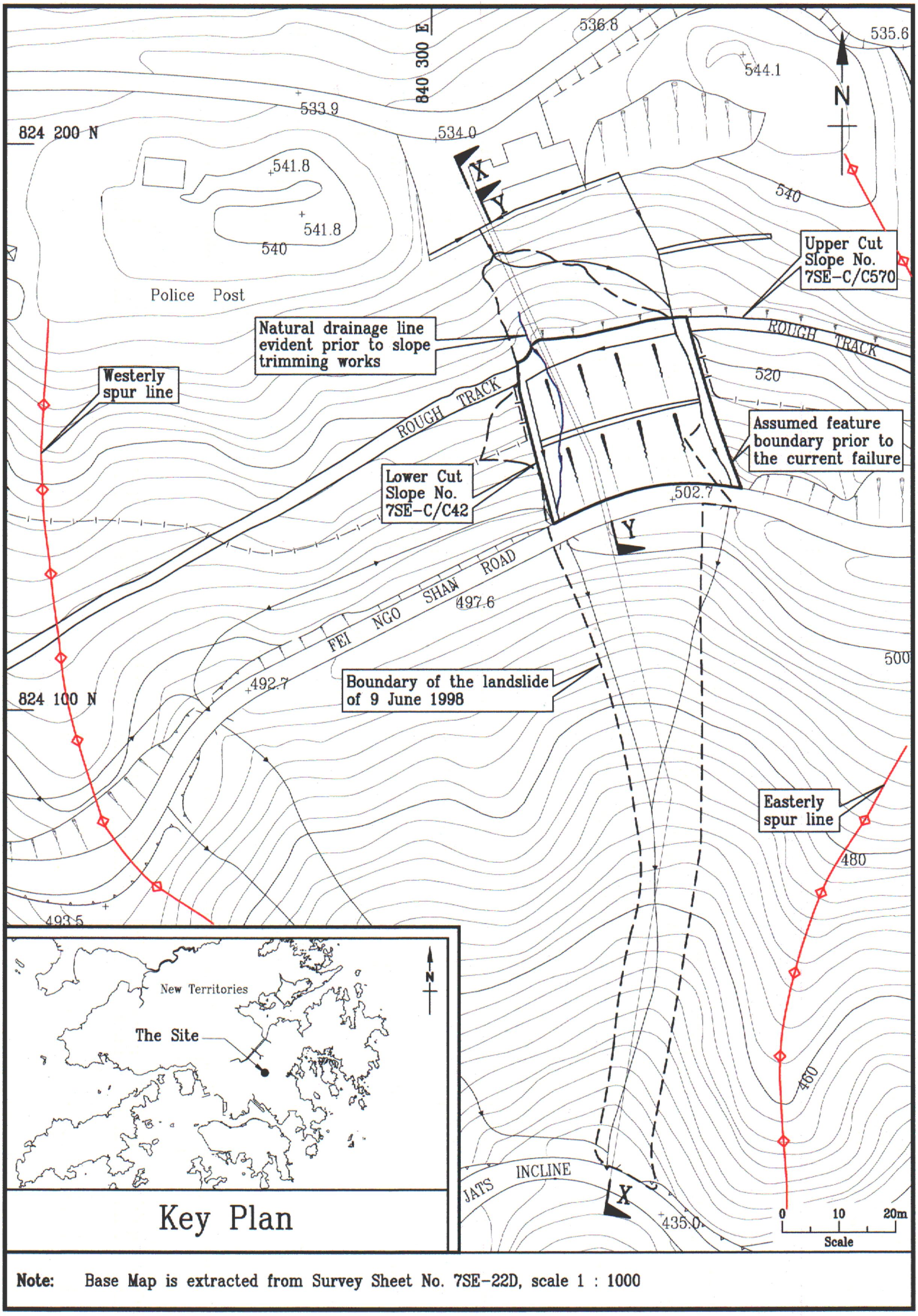


Figure 1 - Site Location Plan

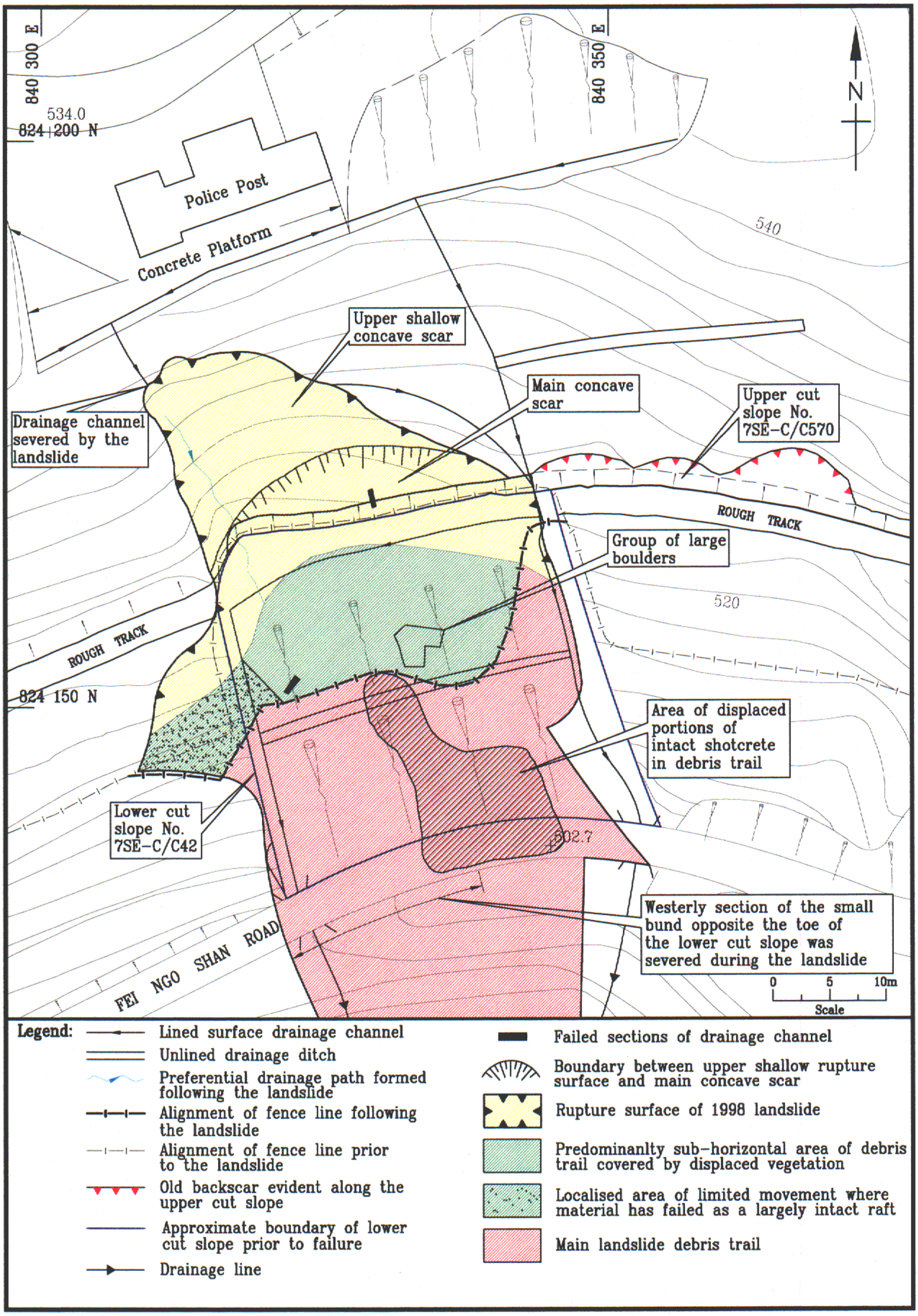
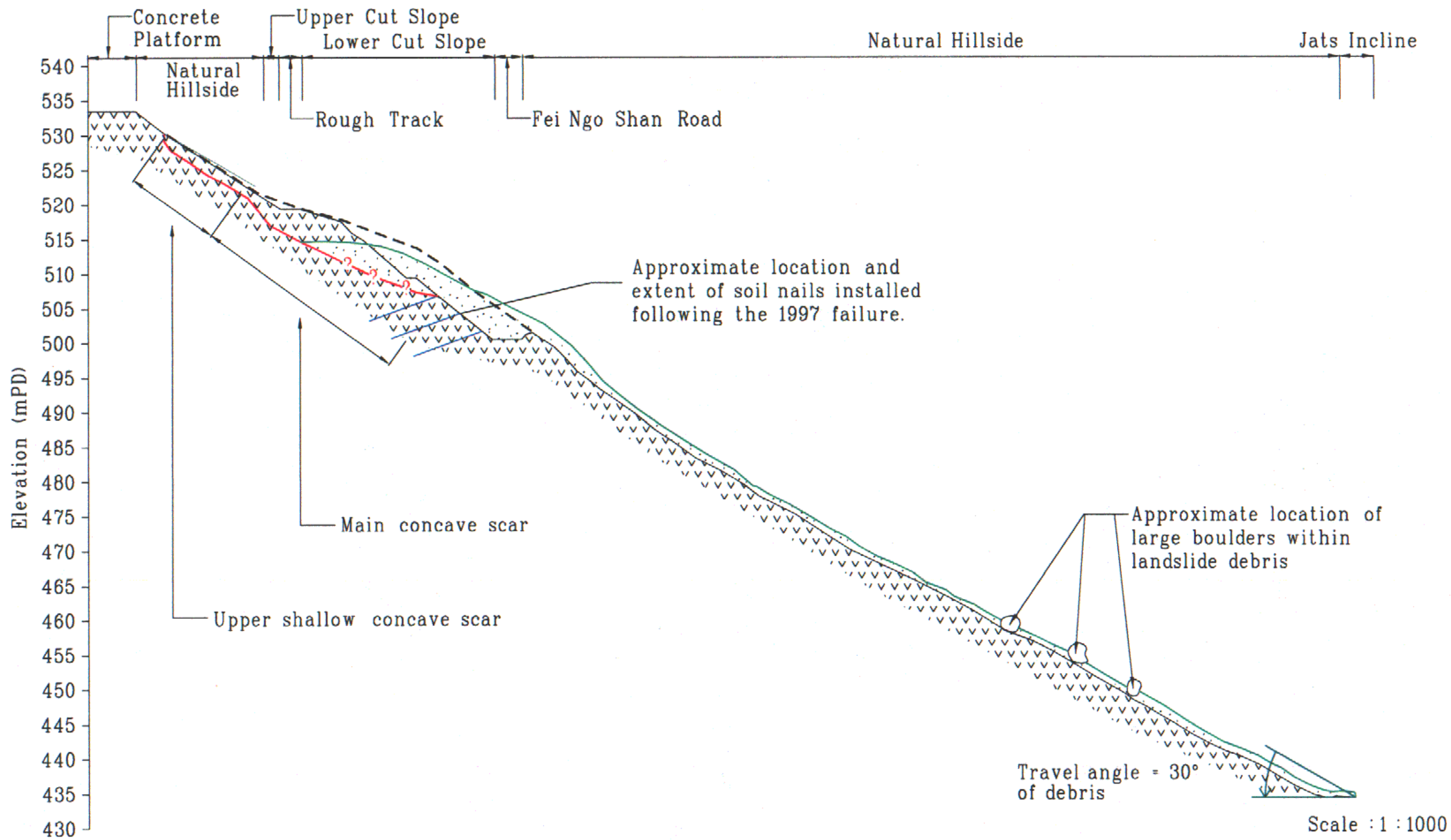


Figure 2 - Plan of the 1998 Landslide Site



Legend :

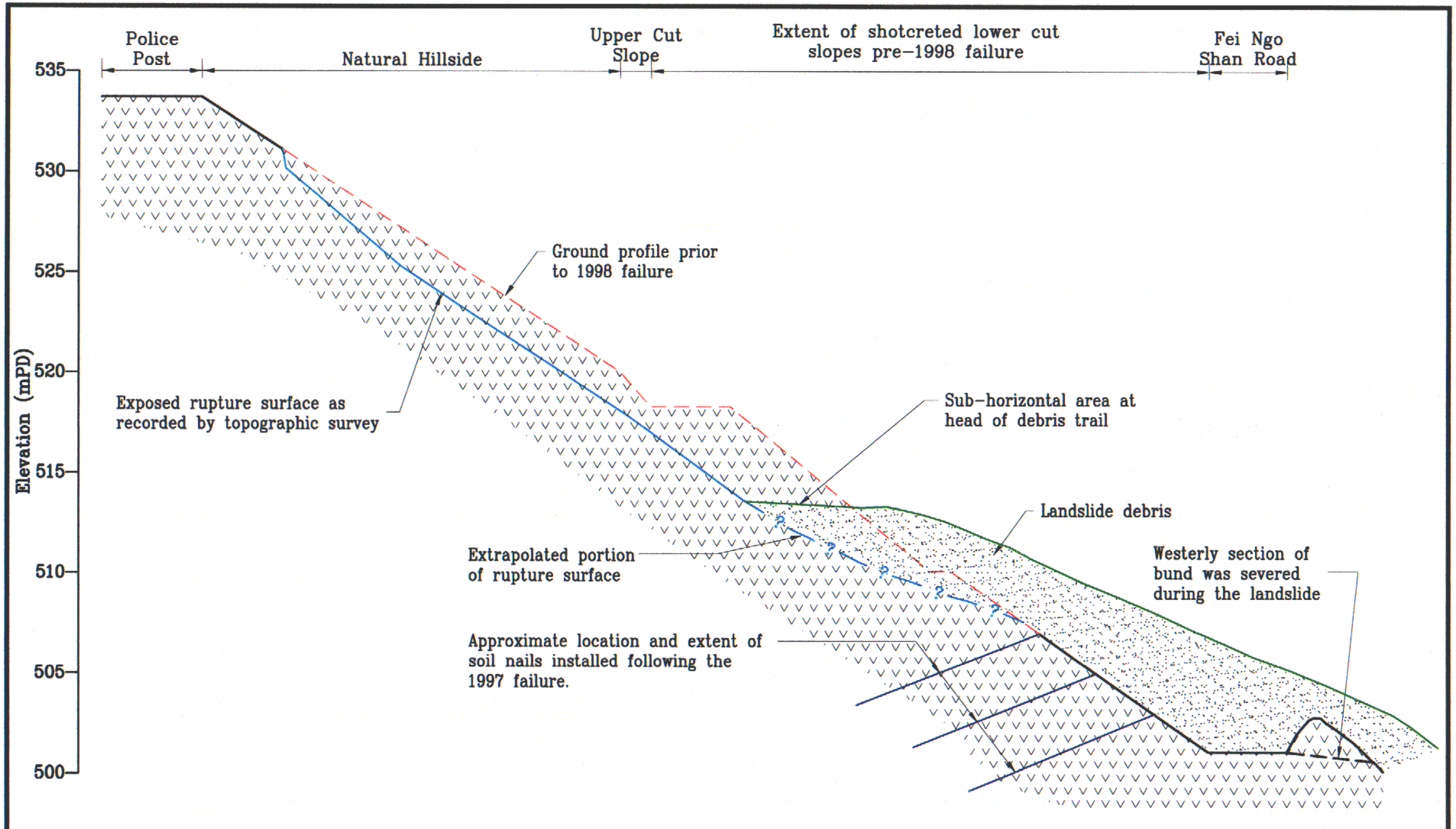
- - - - - Ground profile prior to formation of Fei Ngo Shan Road and the rough track.
——— Approximate profile of existing ground surface prior to the landslide.
——— Exposed surface of rupture.
— ? — Extrapolated surface of rupture beneath failed material.
——— Approximate surface profile of landslide debris.

Completely decomposed tuff

Landslide debris

Note : See Figure 1 for location of section

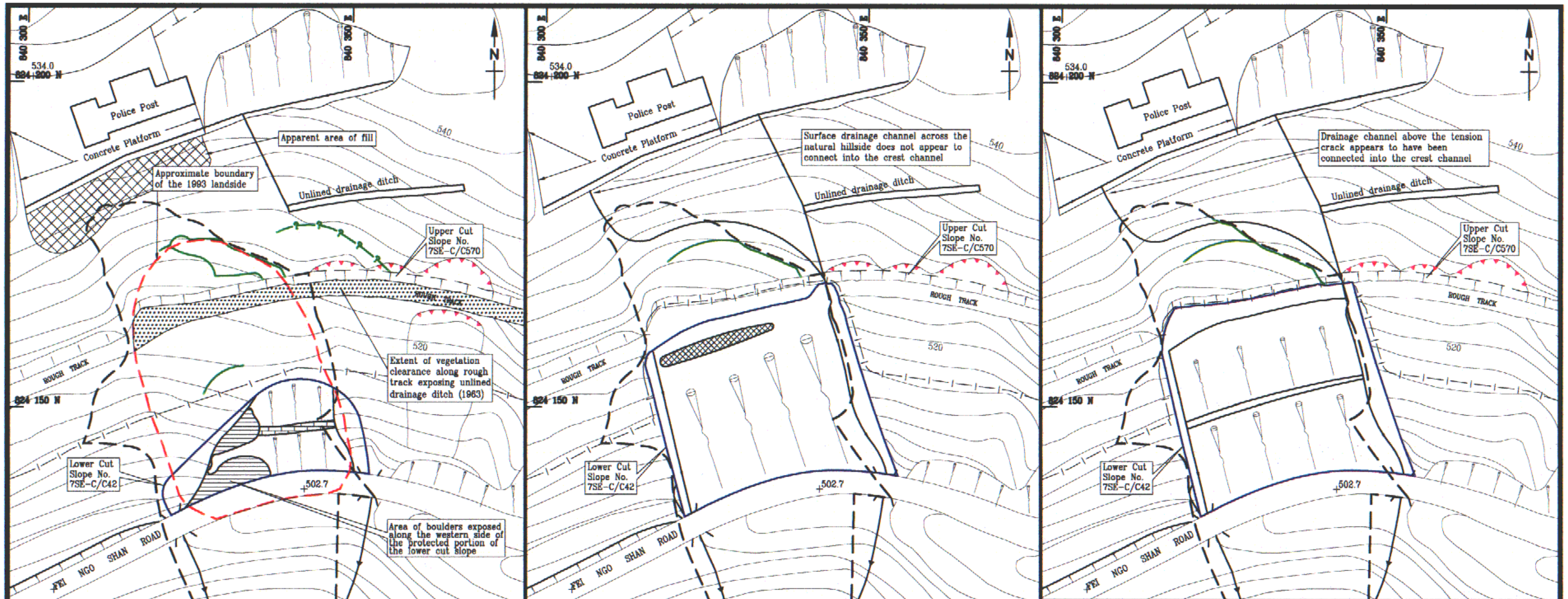
Figure 3 - Cross-section X-X through the Landslide Site



Legend: Completely decomposed tuff Landslide debris

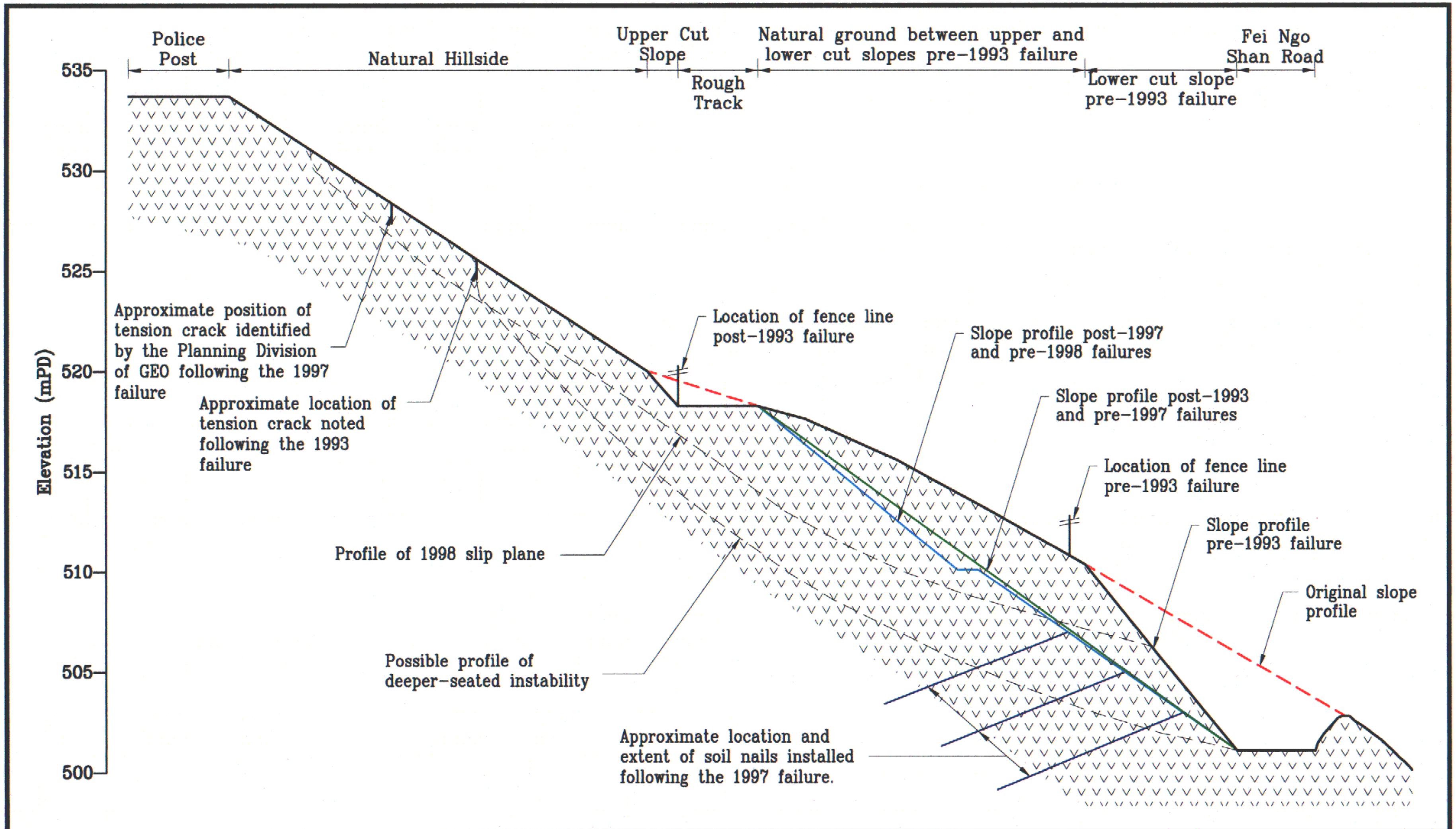
Note: See Figure 1 for location of section.

Figure 4 - Cross-section Y-Y through the Landslide Site



Layout of the Landslide Site Pre-1993 Failure	Layout of the Landslide Site Post-1993, and Pre-1997 Failure	Layout of the Landslide Site Post-1997, and Pre-1998 Failure
Legend: Boundary of lower cut slope Lined surface drainage channel Fence line Possible tension crack Possible tension crack (only prominent in 1963 aerial photographs and no indications of cracking observed on site) Backscar evident along upper cut slope Boundary of 1998 landslide, including debris trail	**Legend:** Boundary of lower cut slope Lined surface drainage channel Fence line Possible tension crack Backscar evident along upper cut slope Boundary of 1998 landslide, including debris trail Area of extensive cracking and possible tension crack	**Legend:** Boundary of lower cut slope Lined surface drainage channel Fence line Possible tension crack Backscar evident along upper cut slope Boundary of 1998 landslide, including debris trail
Notes: (1) Natural ground lies between the upper and lower cut slope. (2) A masonry retaining wall cuts along the mid-point of the lower cut slope.	Notes: (1) The lower cut slope has been trimmed back so that the slope crest adjoins the rough track. (2) New surface drainage has been constructed in the natural ground above the crest.	Notes: (1) The lower cut slope has been trimmed slightly and a berm formed at the mid-point of the lower cut slope. (2) The tension crack in the natural ground appears to have extended upslope.

Figure 5 - Plan Showing the History of Development of the Landslide Site



Legend: Completely decomposed tuff

Note: See Figure 1 for location of section.

Figure 6 - Cross-section Y-Y Showing the History of Development of the Landslide Site

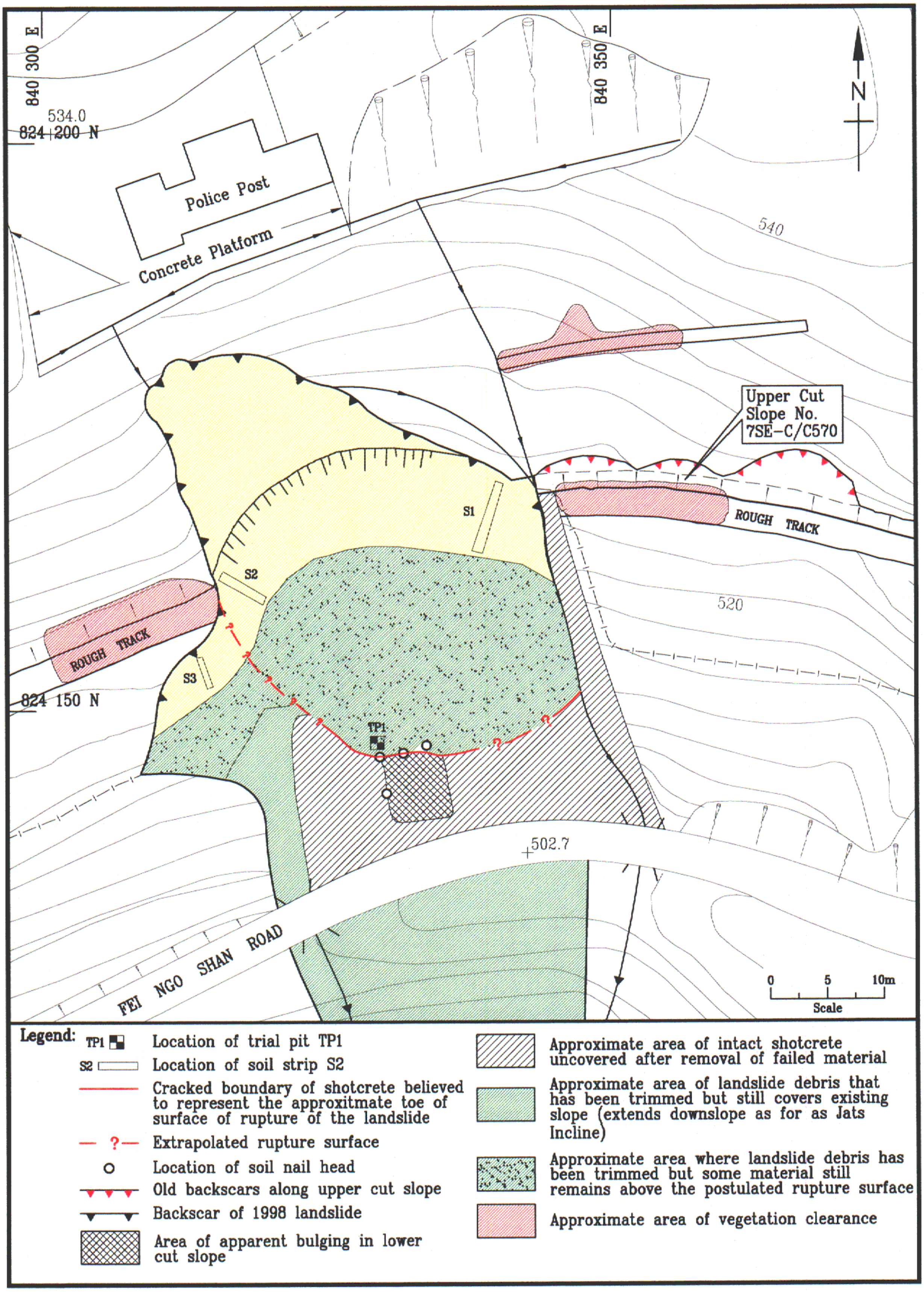
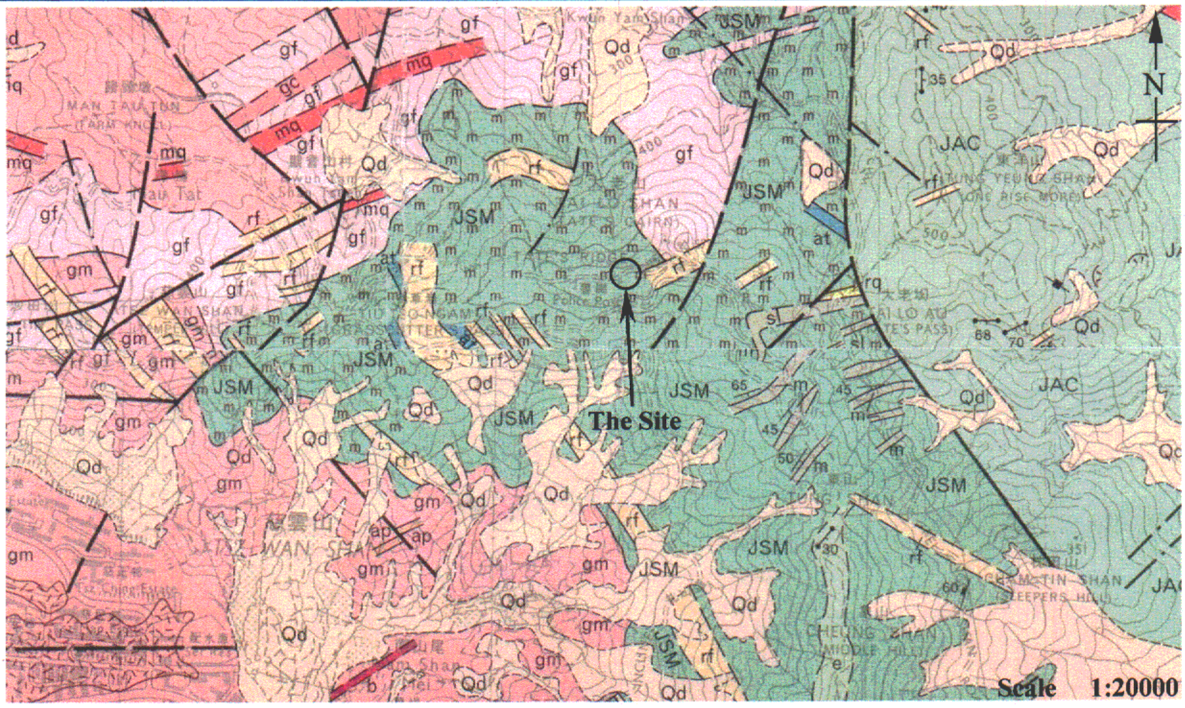


Figure 7 - Layout of Investigation Works and Details of the Site Following Clearance Works



Legend :

QUATERNARY SUPERFICIAL DEPOSITS (Onshore)

Qd	Unsorted sand, gravel, cobbles and boulders; clay/silt matrix

SOLID GEOLOGY

JAC	Vitric tuff with fiamme
JSM	Crystal and lithic tuff, tuff-breccia and tuffite
sl	Siltstone and mudstone
gf	Fine-grained granite, <2 mm
gm	Medium-grained granite, 2-6 mm
gc	Coarse-grained granite, >6 mm
mq	Quartz monzonite
gd	Granodiorite
rq	Quartzphyric rhyolite
rf	Feldsparphyric rhyolite
m m m	Hornfels
at	Altered tuff and sedimentary rock

GEOLOGICAL LINES

- Geological boundary, superficial deposits
- * Geological boundary, solid rock (* Broken lines denote uncertainty)
- * Mineral vein
- Photogeological lineament
- * Broken lines denote uncertainty

STRUCTURAL SYMBOLS

- 20 Flow fabric
- 20 Jointing

Note: Extract from Sheets 7 and 11 of the Hong Kong Geological Survey 1:20,000 Scale Map Series HGM20 (GCO, 1986)

Figure 8 – Solid and Superficial Geology of the Site

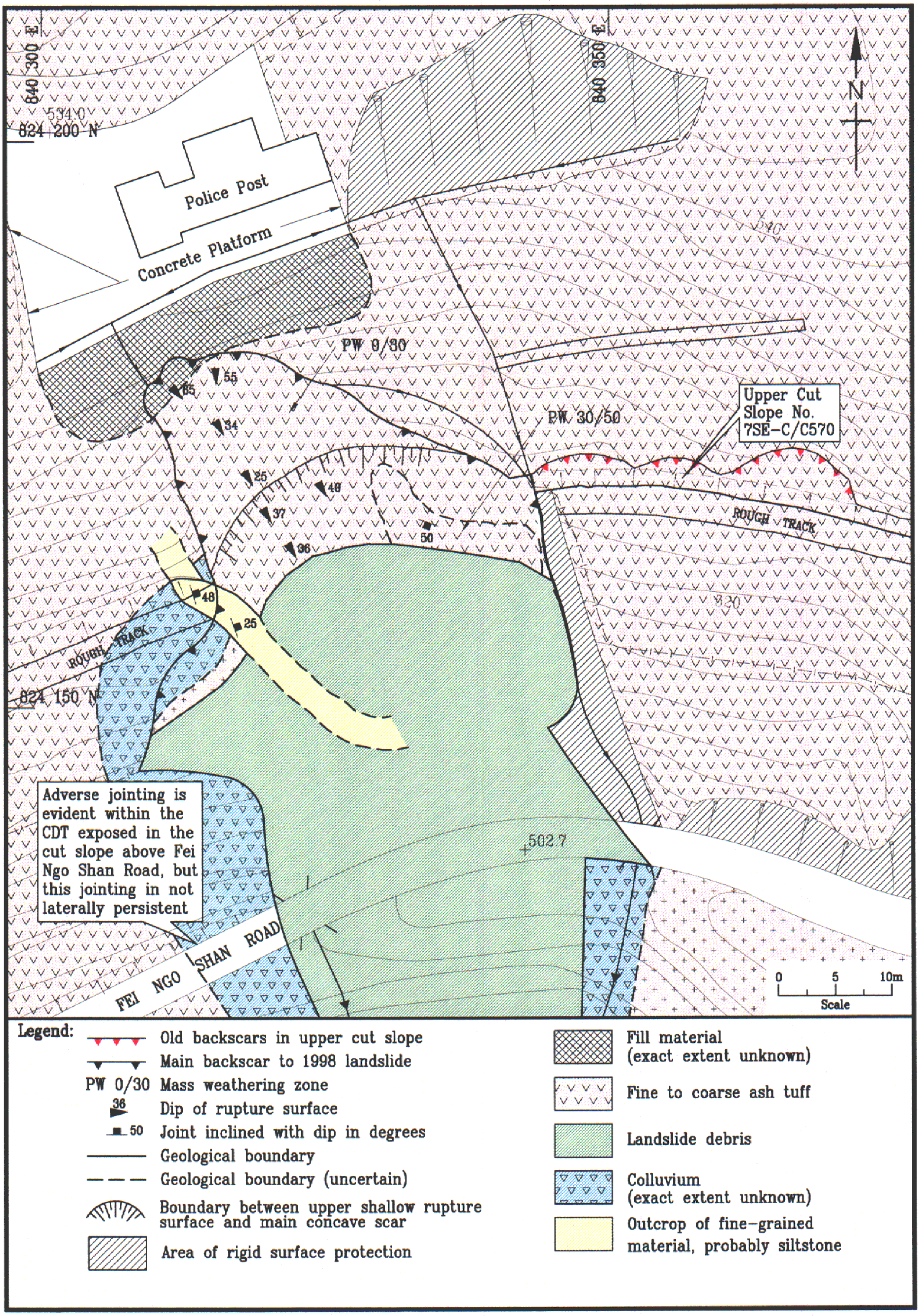
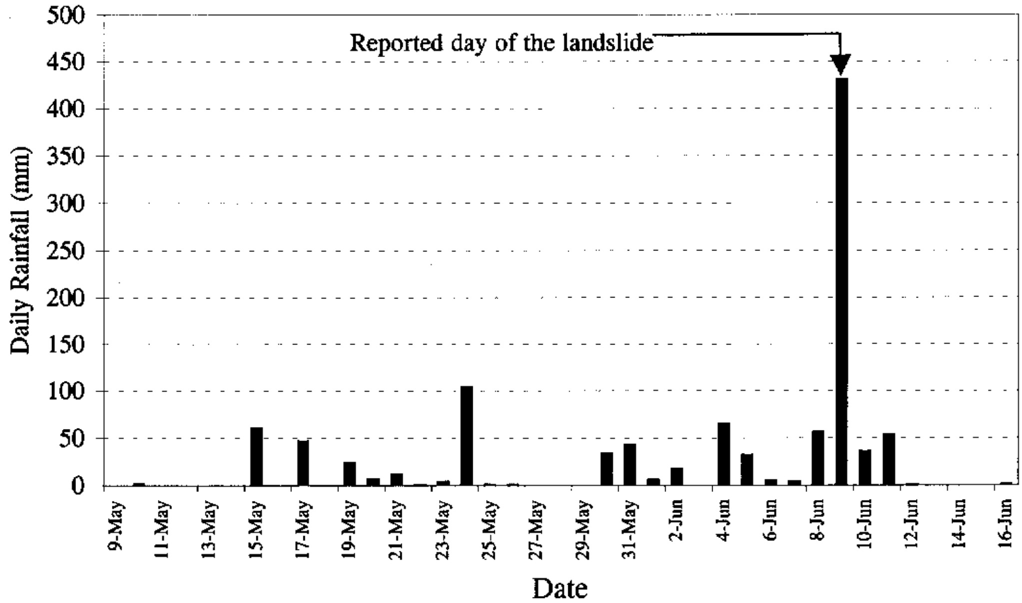
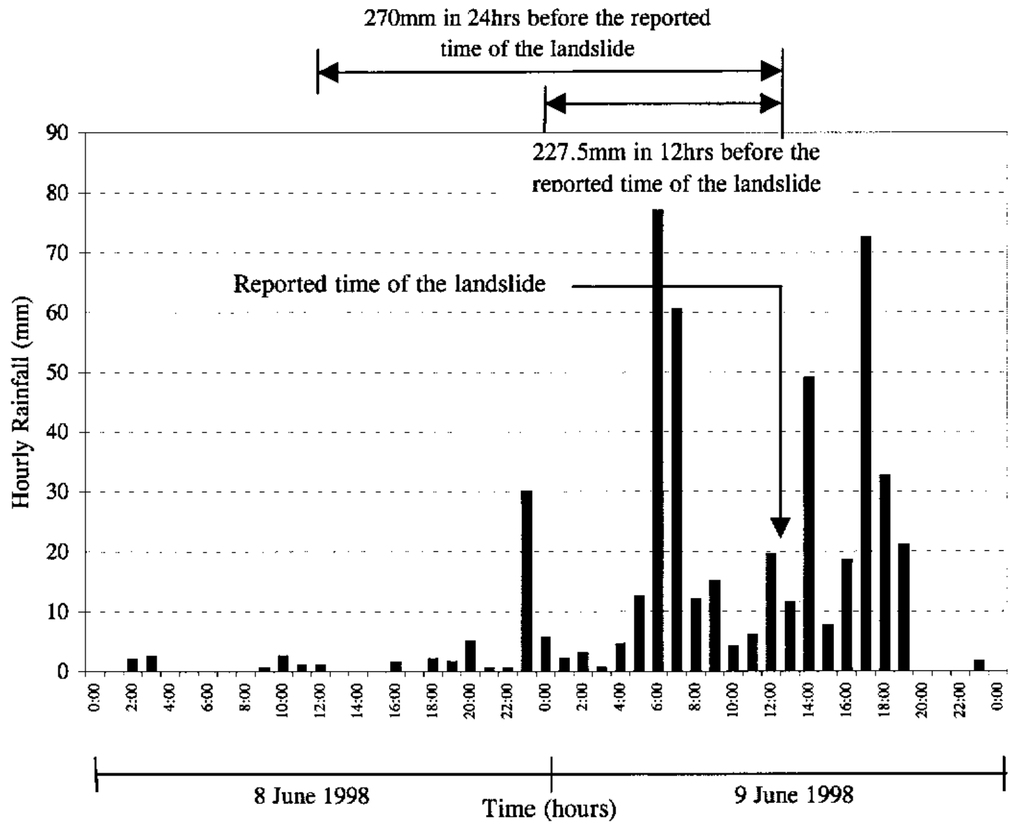


Figure 9 - Geology of the Landslide Site Based on Field Mapping

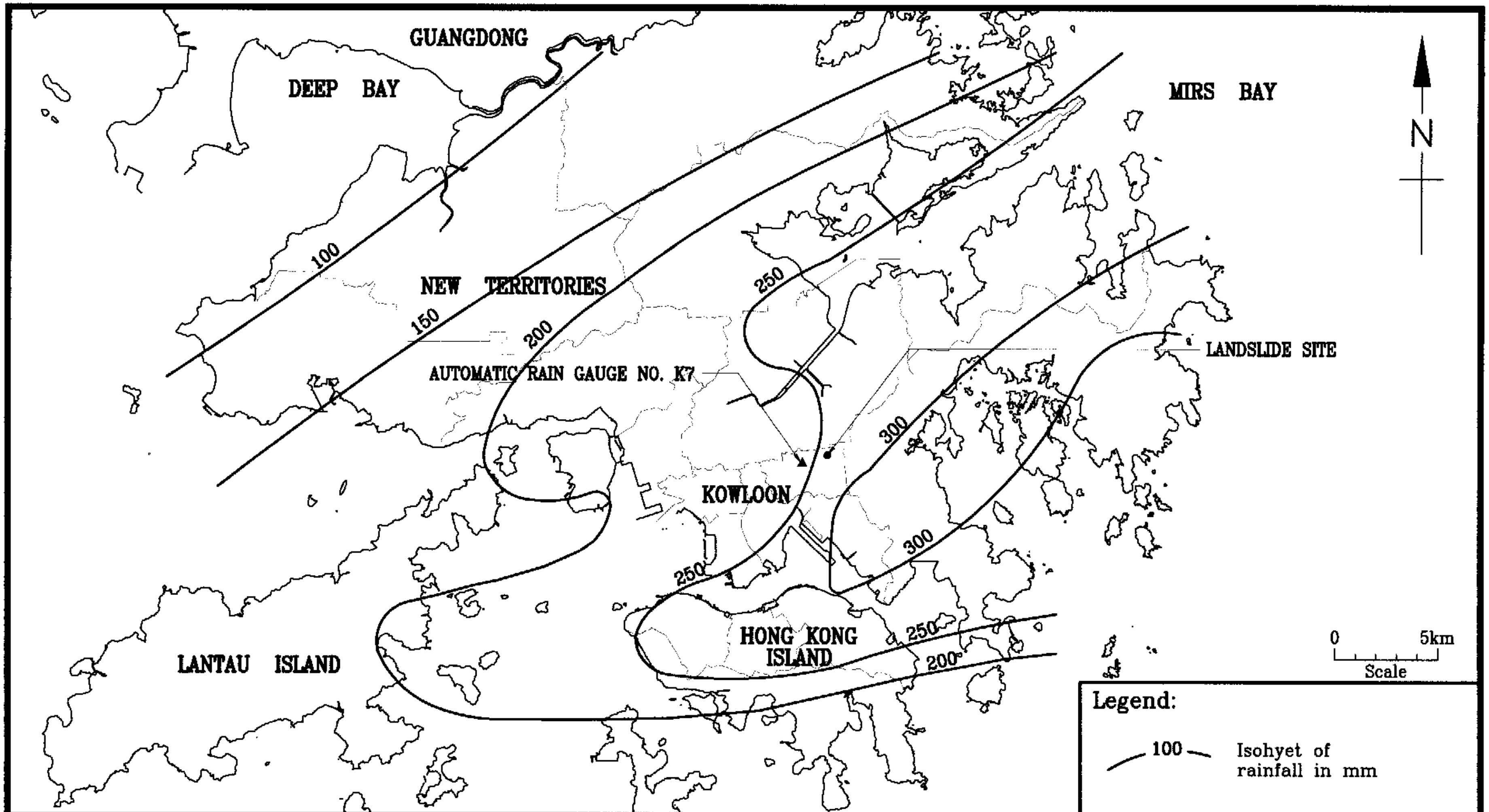


(a) Daily Rainfall Recorded at GEO Raingauge K07 from 9 May to 16 June 1998



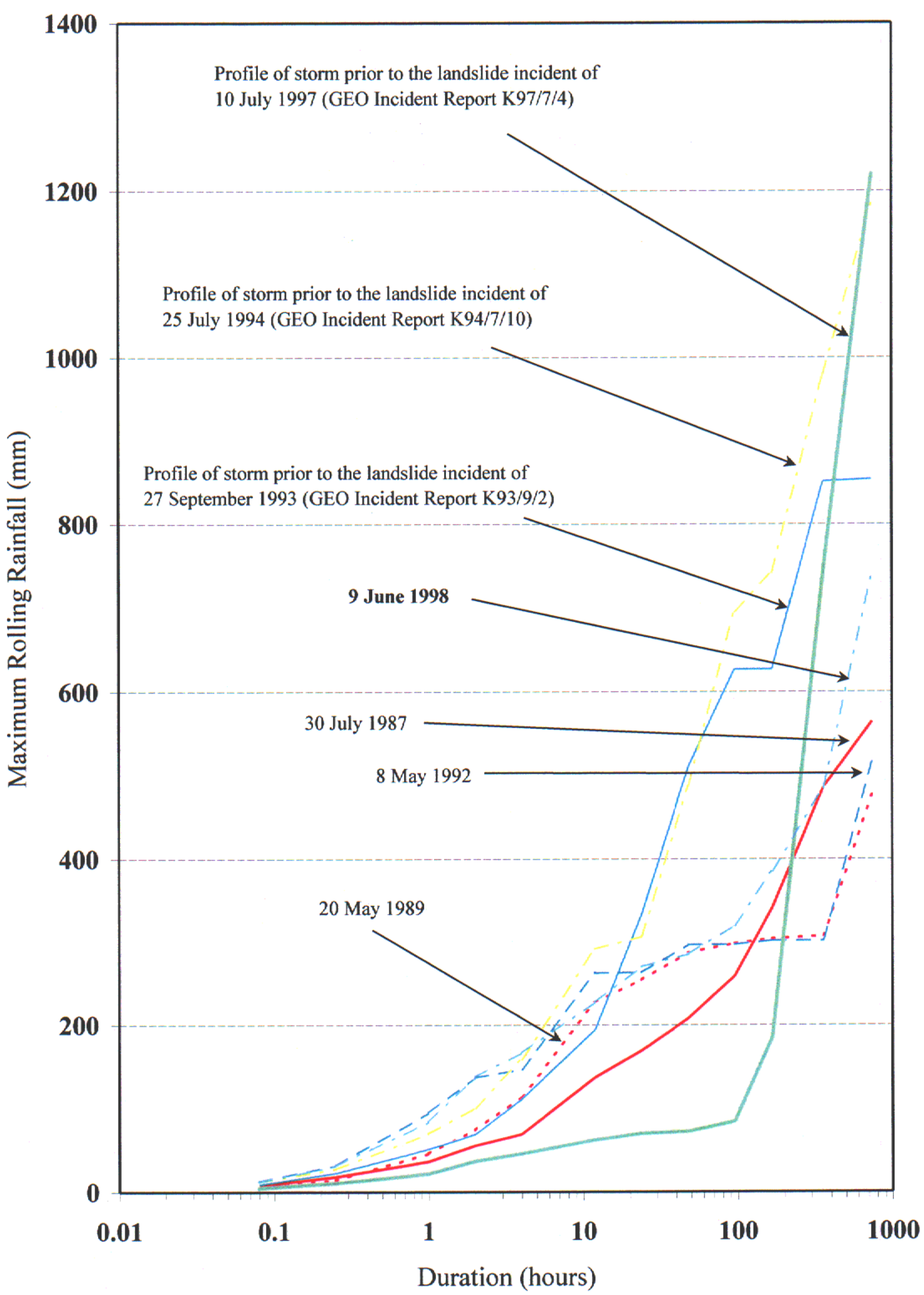
(b) Hourly Rainfall Recorded at GEO Raingauge K07 from 8 June to 9 June 1998

Figure 10 - Daily and Hourly Rainfall Recorded at GEO Raingauge No. K07



Note: Isohyet prepared based on data from GEO raingauges

Figure 11 - Isohyet of 24-hour Rainfall Prior to the Landslide



Note: Rainfall data are 5-minute statistics from GEO raingauge No. K07

Figure 12 - Maximum Rolling Rainfall at GEO Raingauge No. K07 for Major Rainstorms

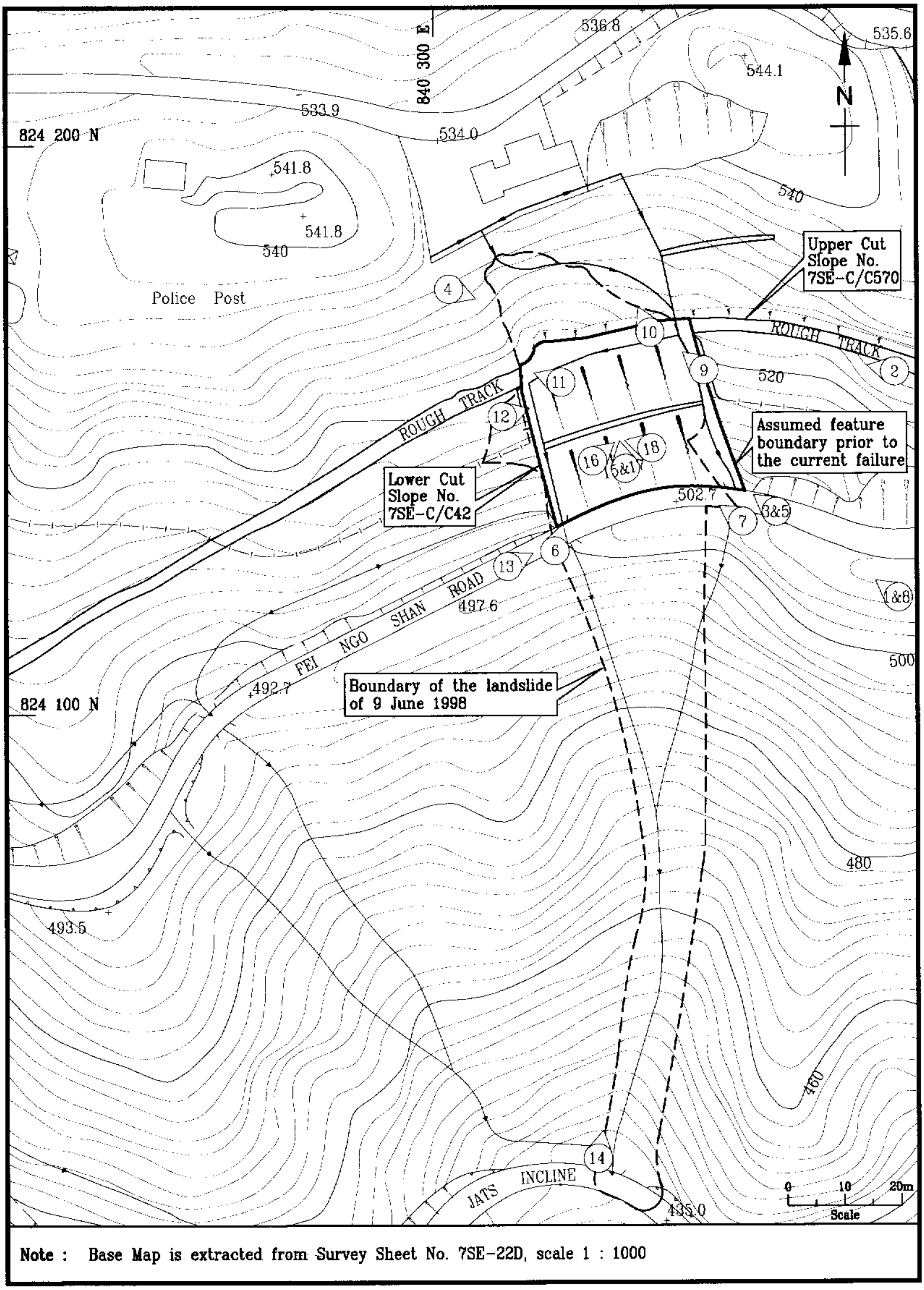


Figure 13 - Plan of the Landslide Site Showing the Location and Direction of Photographic Plates

LIST OF PLATES

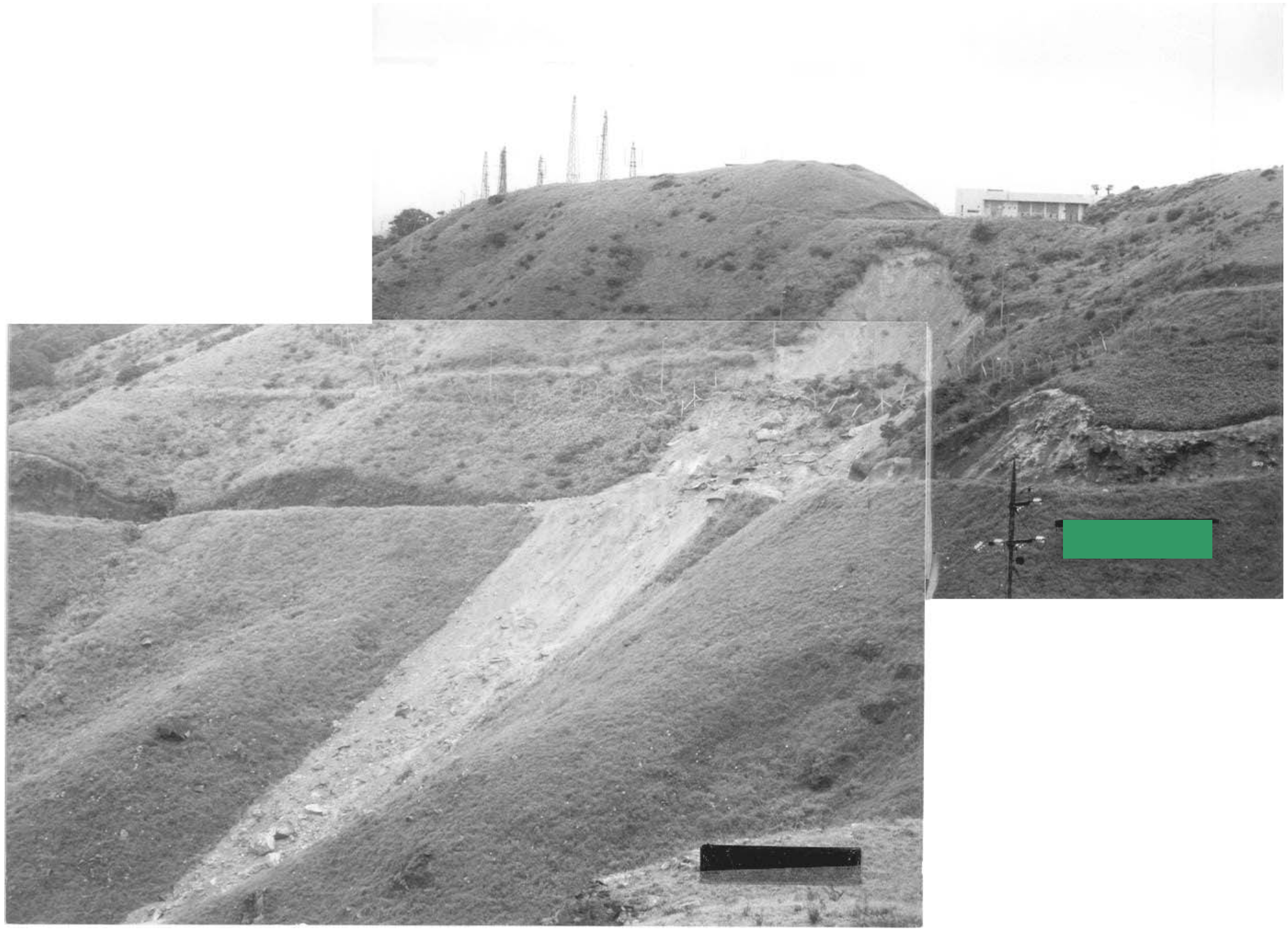


Plate 1 – Front View of 9 June 1998 Landslide
(Photographs taken on 12 June 1998)

Note : See Figure 13 for Location of Photographs.

Plate 2 – Side View of 9 June 1998 Landslide
(Photographs taken on 12 June 1998)

Note : See Figure 13 for Location of Photographs.

Plate 3 – General View of the September 1993 Landslide
(Photographs taken on 27 September 1993)

Note : See Figure 13 for Location of Photographs.

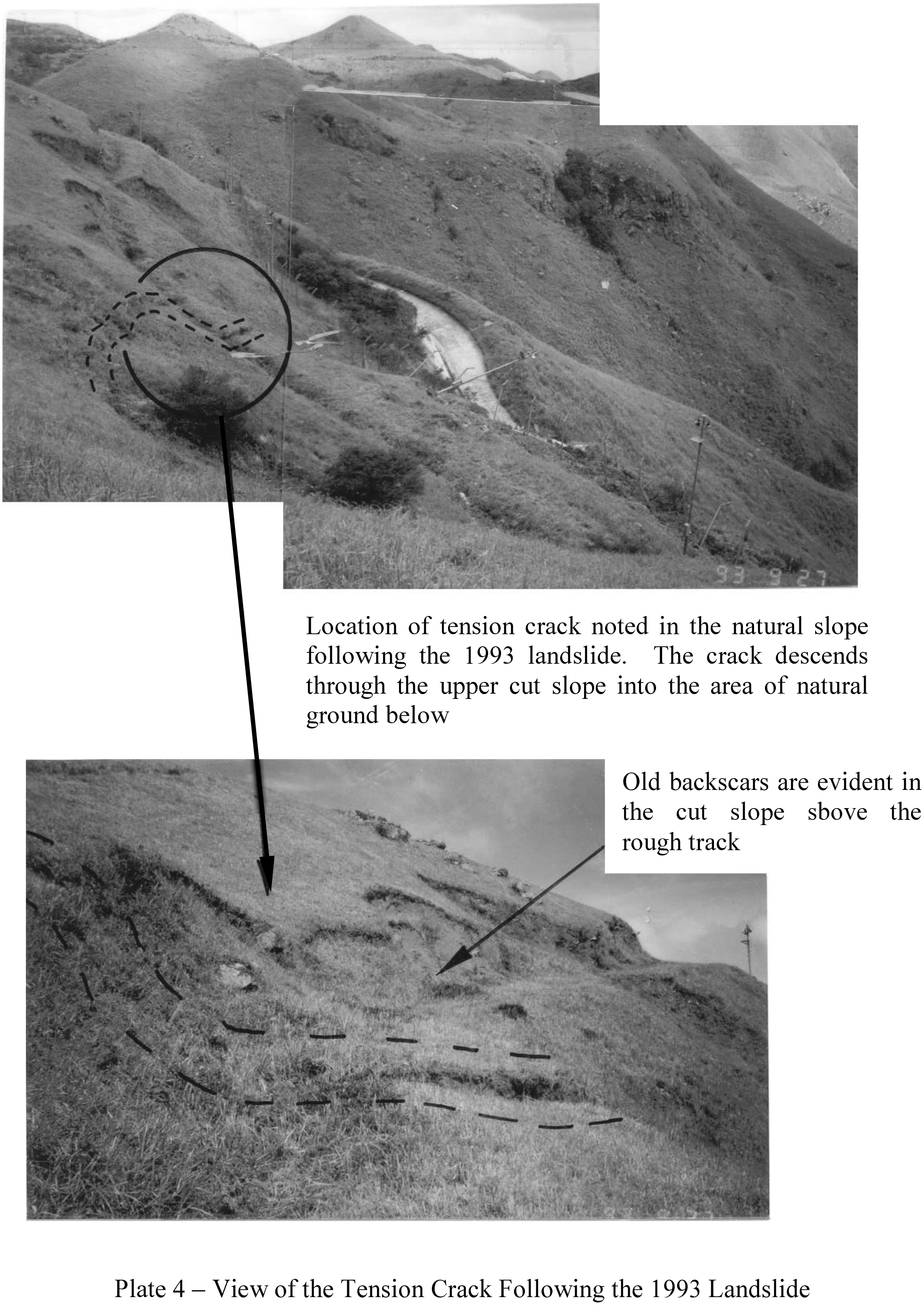


Plate 4 – View of the Tension Crack Following the 1993 Landslide
(Photographs taken on 27 September 1998)

Note: See Figure 13 for Location of Photographs.

Plate 5 – View of Slope Following Remedial Works in 1993
(Photographs taken on 21 December 1993)

Note : See Figure 13 for Location of Photographs.

Plate 6 – View of Slope Distress in July 1994
(Photographs taken on 25 July 1994)

Note : See Figure 13 for Location of Photographs.

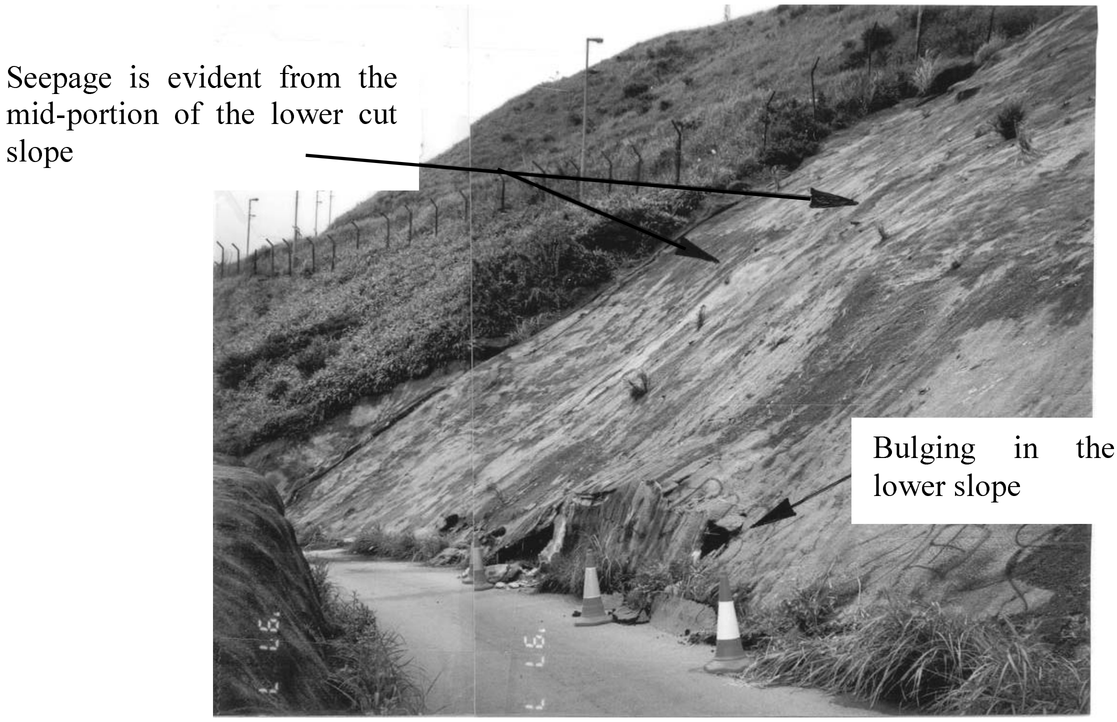


Plate 7 – View of Slope Distress in July 1997
(Photographs taken on 11 July 197)

Note: See Figure 13 for Location of Photographs.

Legend:

Tension cracks

Line of drainage channel cutting diagonally across the natural hillside above the main tension crack

Area of fine-grained material exposed in the lower cut slope

Seepage noted above the contact with the dyke

Plate 8 – View of Site Showing Observations Made by the Planning Division of GEO after Instability in 1997
(Photographs taken on 24 September 1997)

Note : See Figure 13 for Location of Photographs.

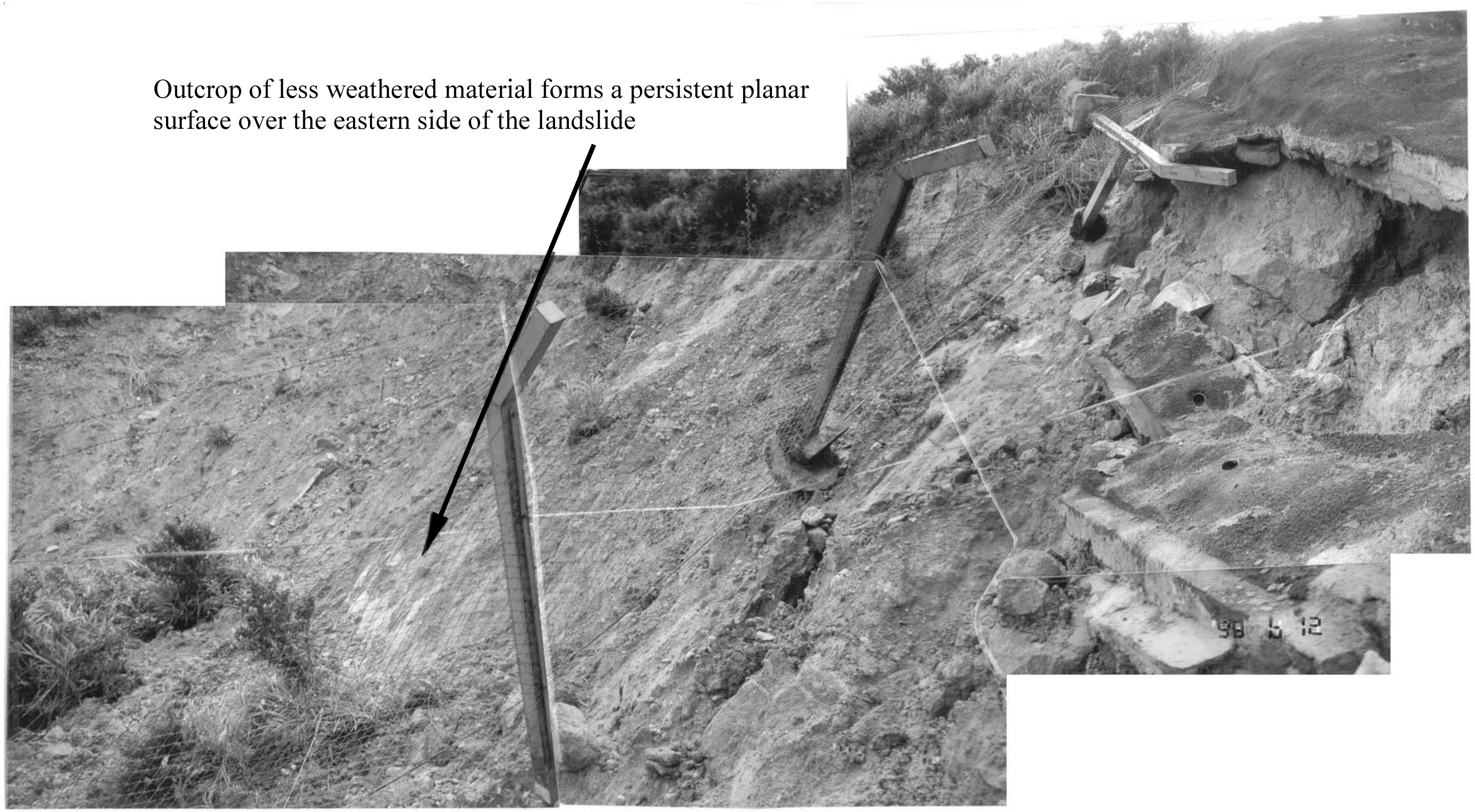


Plate 9 – View of the Planar Discontinuity along the Eastern Side of the Landslide
(Photographs taken on 12 June 1998)

Note : See Figure 13 for Location of Photographs.

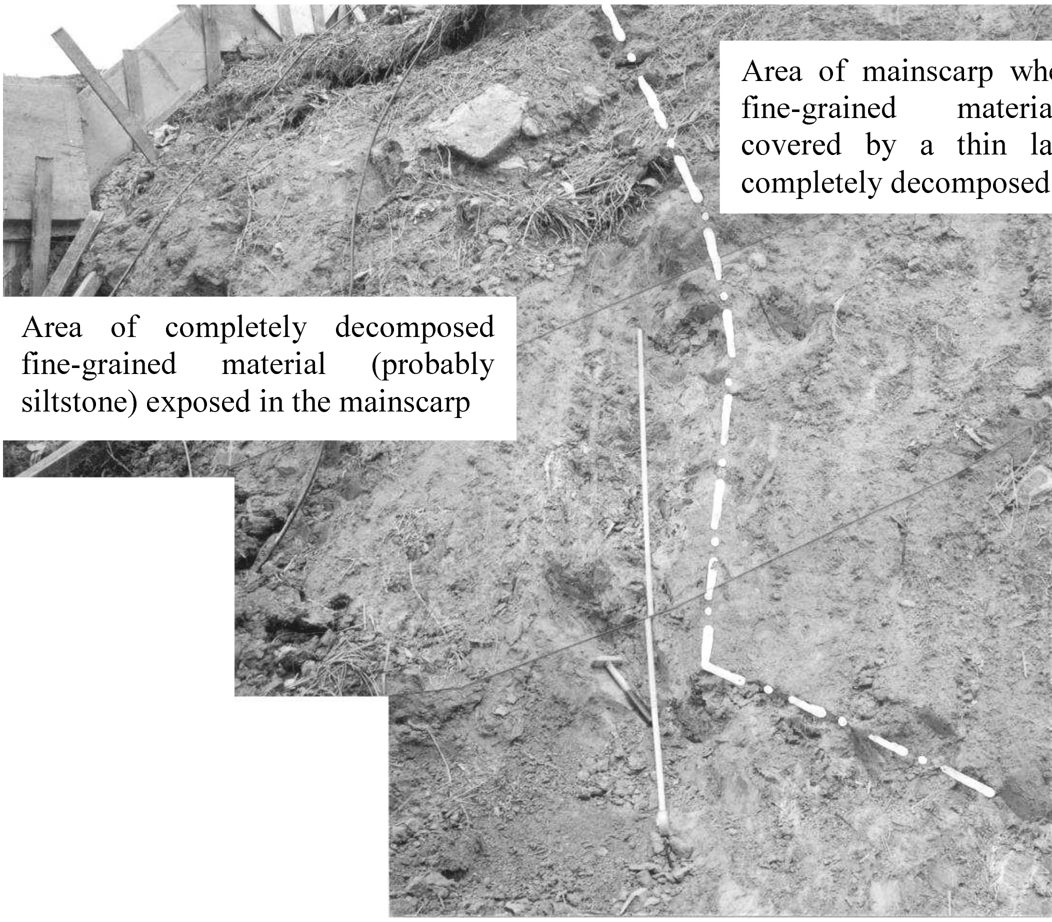
a) In-part the 1998 landslide failed along the existing tension crack formed following the 1993 landslide

b) The depth of the tension crack appears to be about 1 m deep

c) In-part the tension crack was filled with granular material

Plate 10 – View of Tension Crack Formed prior to the Landslide on 9 June 1998
(Photographs taken on 7 July 1998)

Note : See Figure 13 for Location of Photographs.



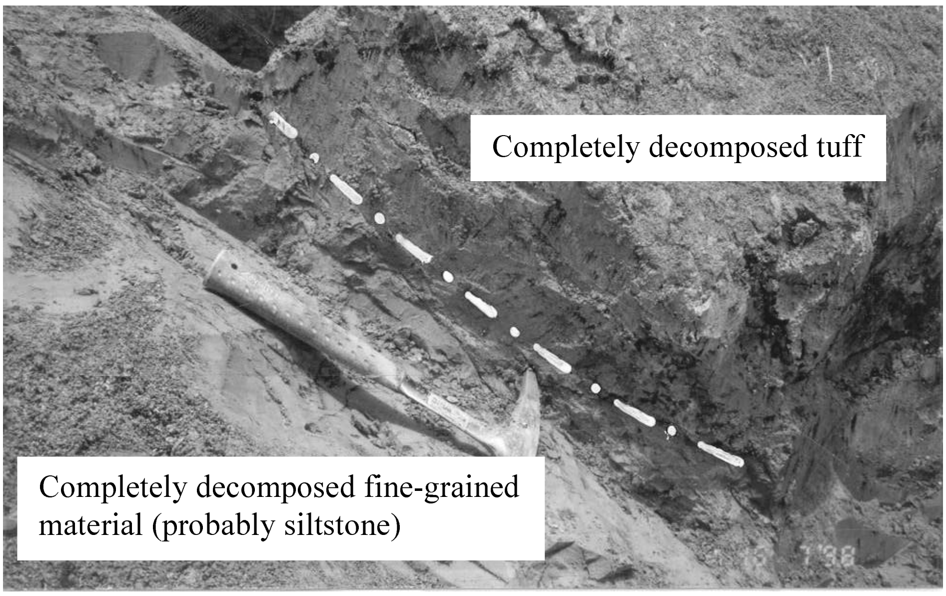


Plate 11 – View of Fine-grained Material (Probably Siltstone) Exposed along the Western Side of the Landslide
(Photographs taken on 16 July 1998)

Note: See Figure 13 for Location of Photographs.

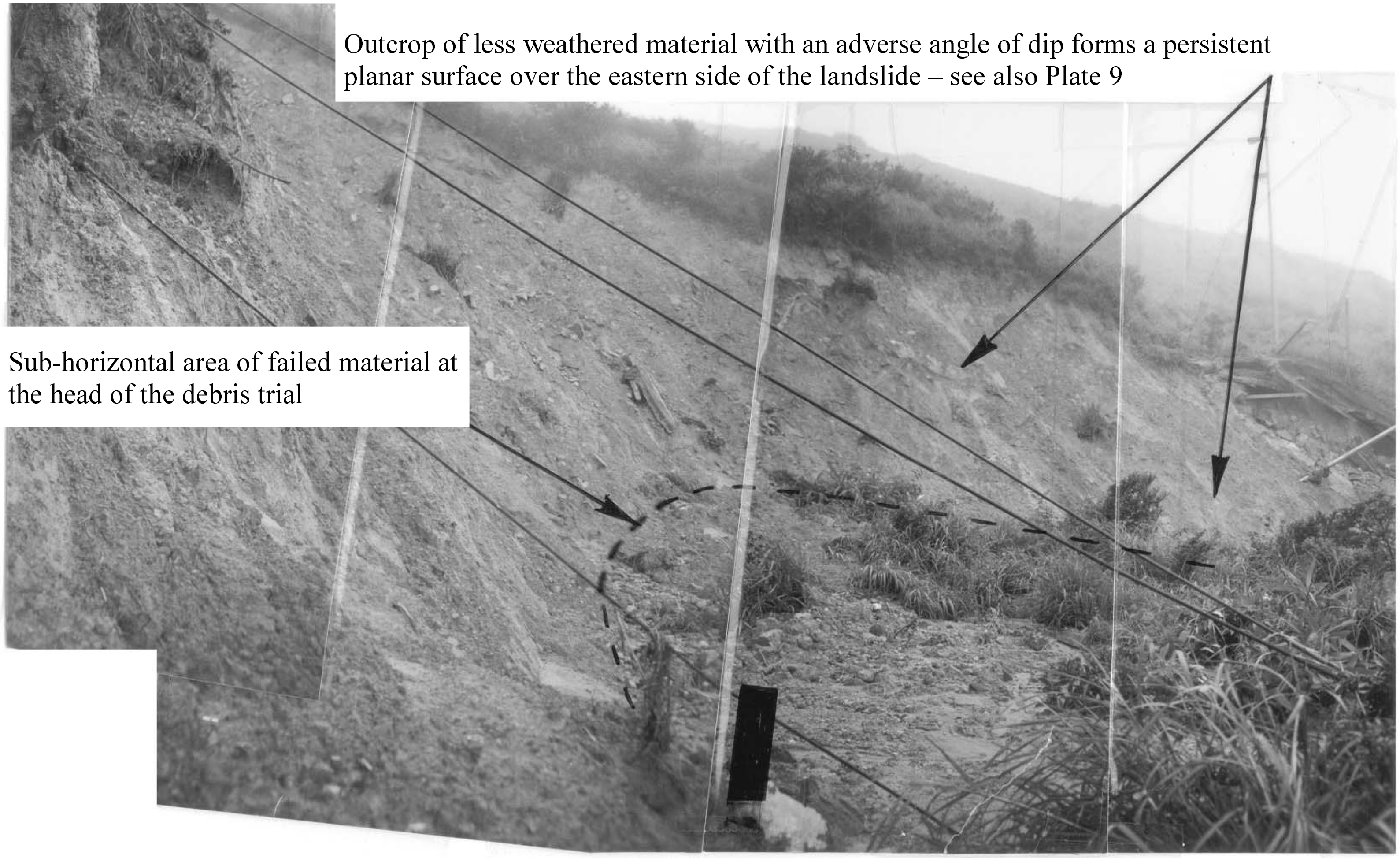


Plate 12 – View of Head of Failed Material Following 9 June 1998 Landslide
(Photographs taken on 10 June 1998)

Note : See Figure 13 for Location of Photographs.

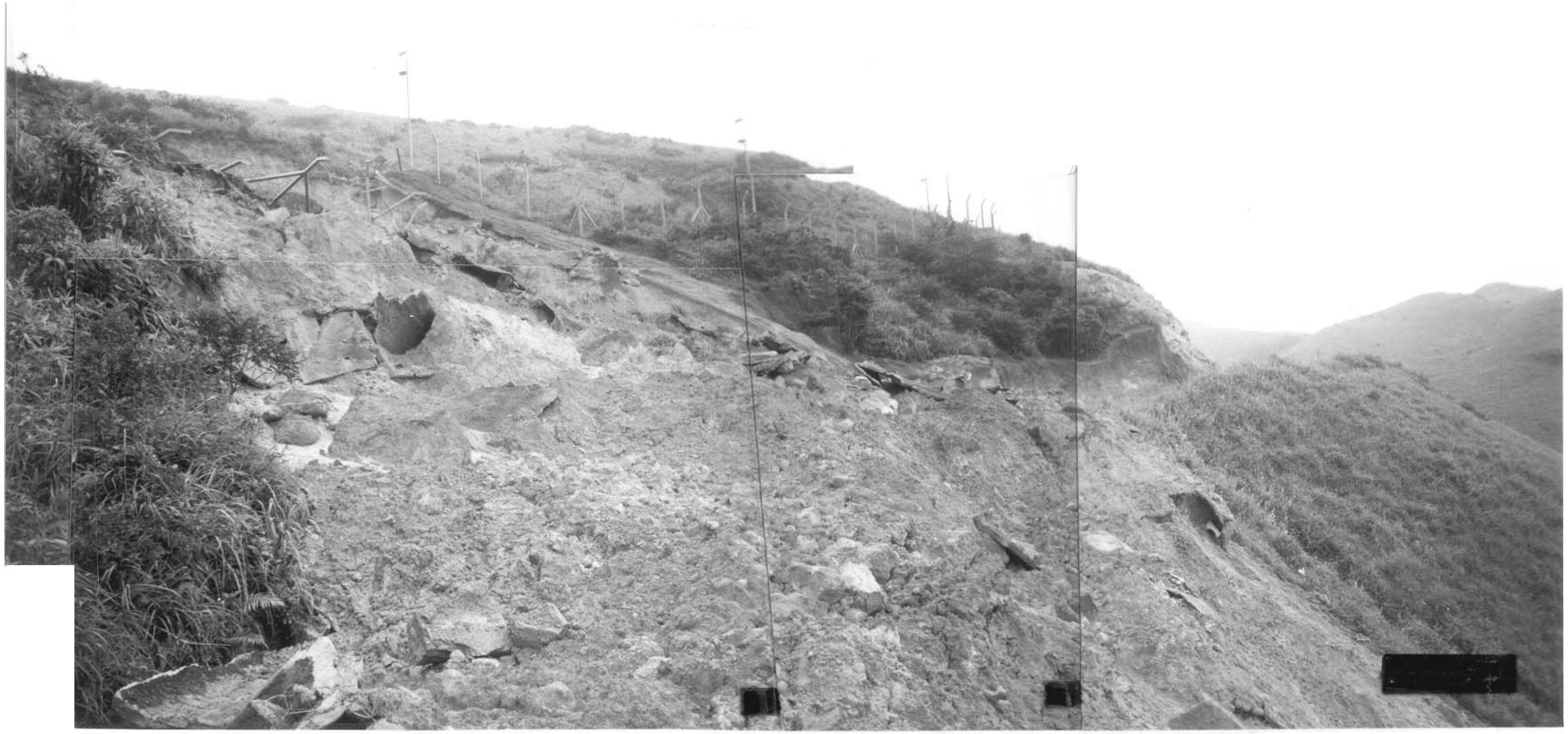


Plate 13 – View of Landslide Debris above Fei Ngo Shan Road Following 9 June 1998 Landslide
(Photographs taken on 10 June 1998)

Note : See Figure 13 for Location of Photographs.

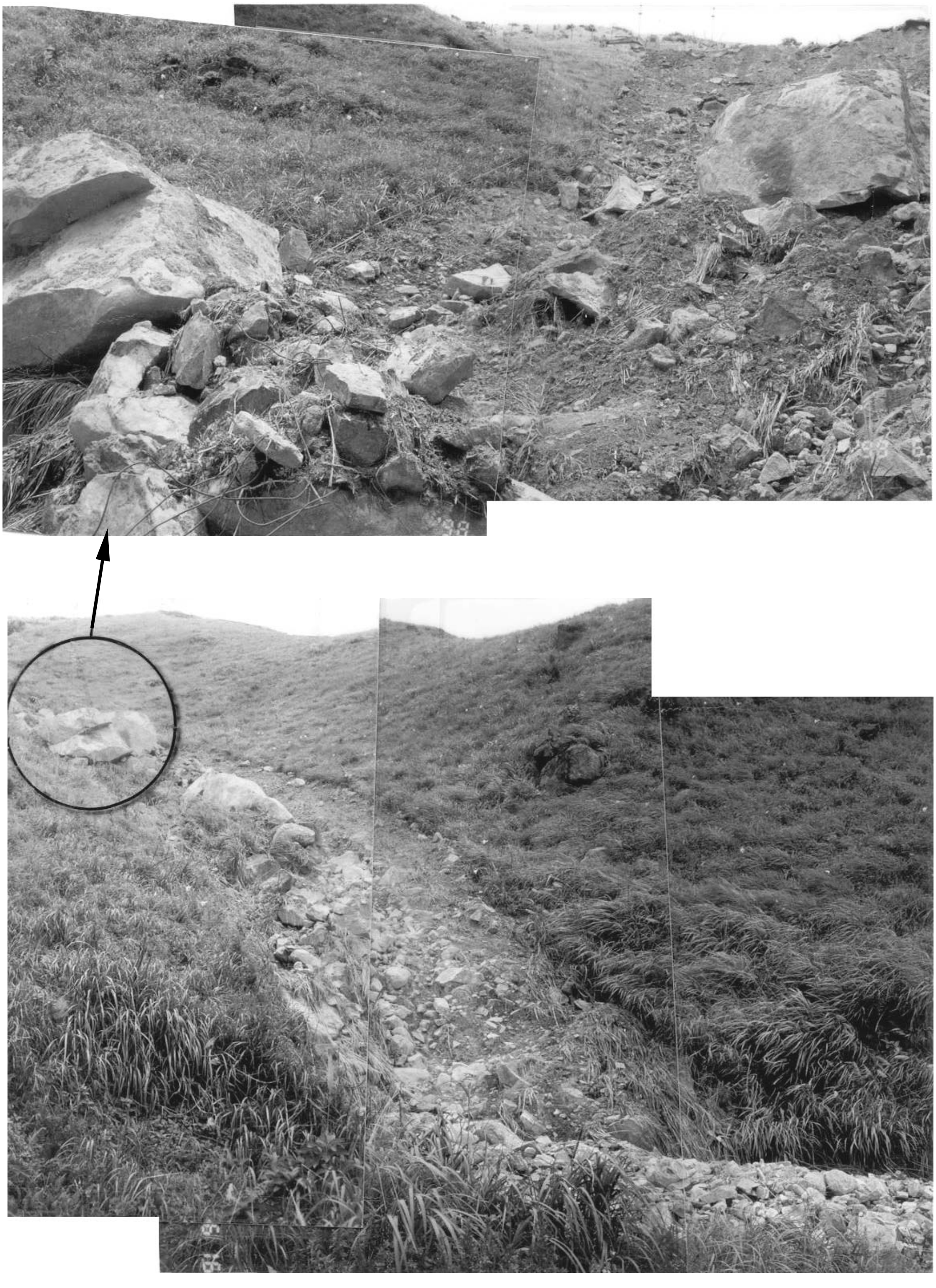


Plate 14 – View of Bouldery Material in the Lower Debris Trail Following 9 June 1998 Landslide
(Photographs taken on 10 June 1998)

Note: See Figure 13 for Location of Photographs.

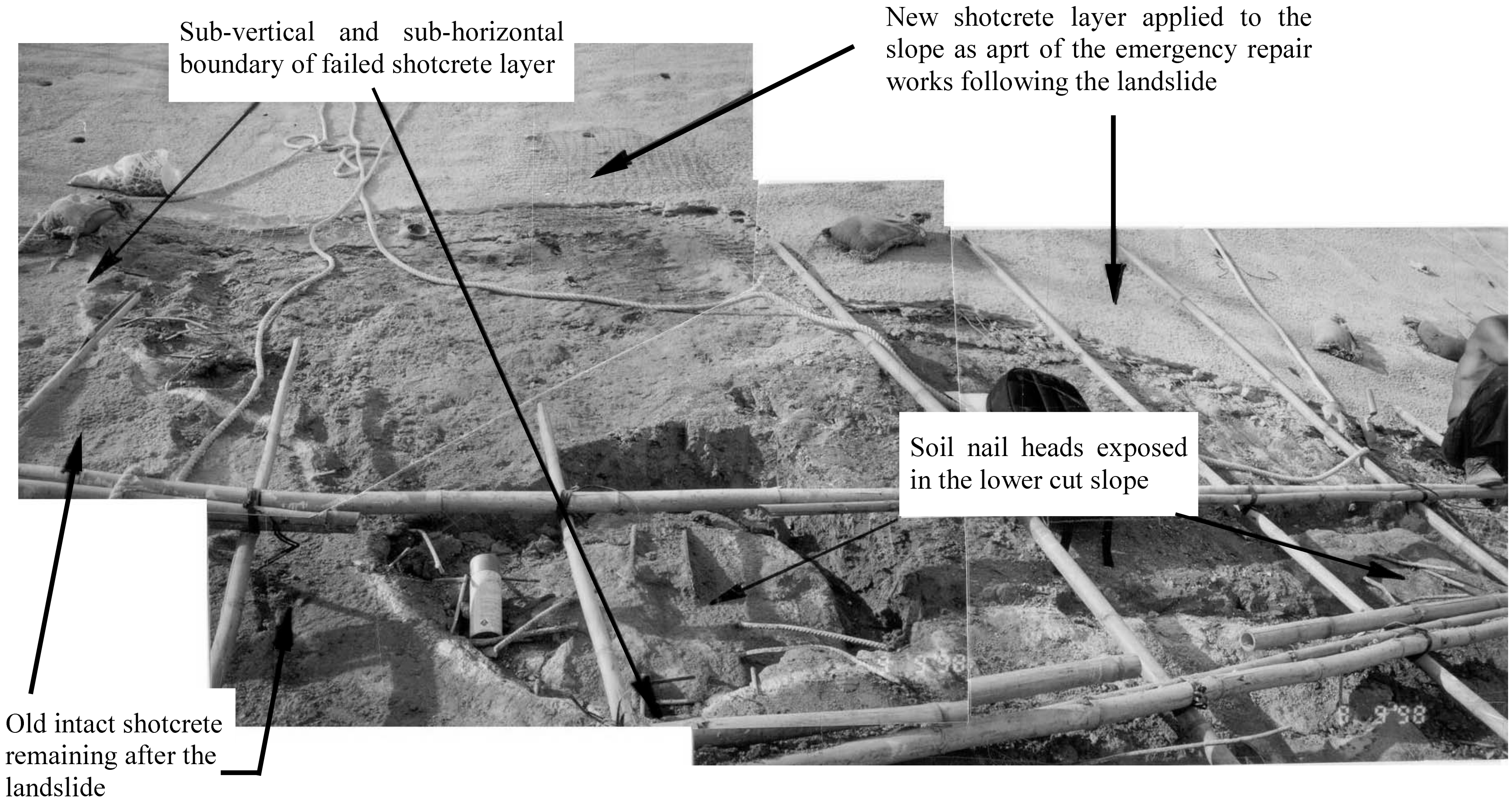


Plate 15 – View of Soil Nail Heads Exposed in the Lower Cut Slope Following 9 June 1998 Landslide
(Photographs taken on 10 June 1998)

Note : See Figure 13 for Location of Photographs.

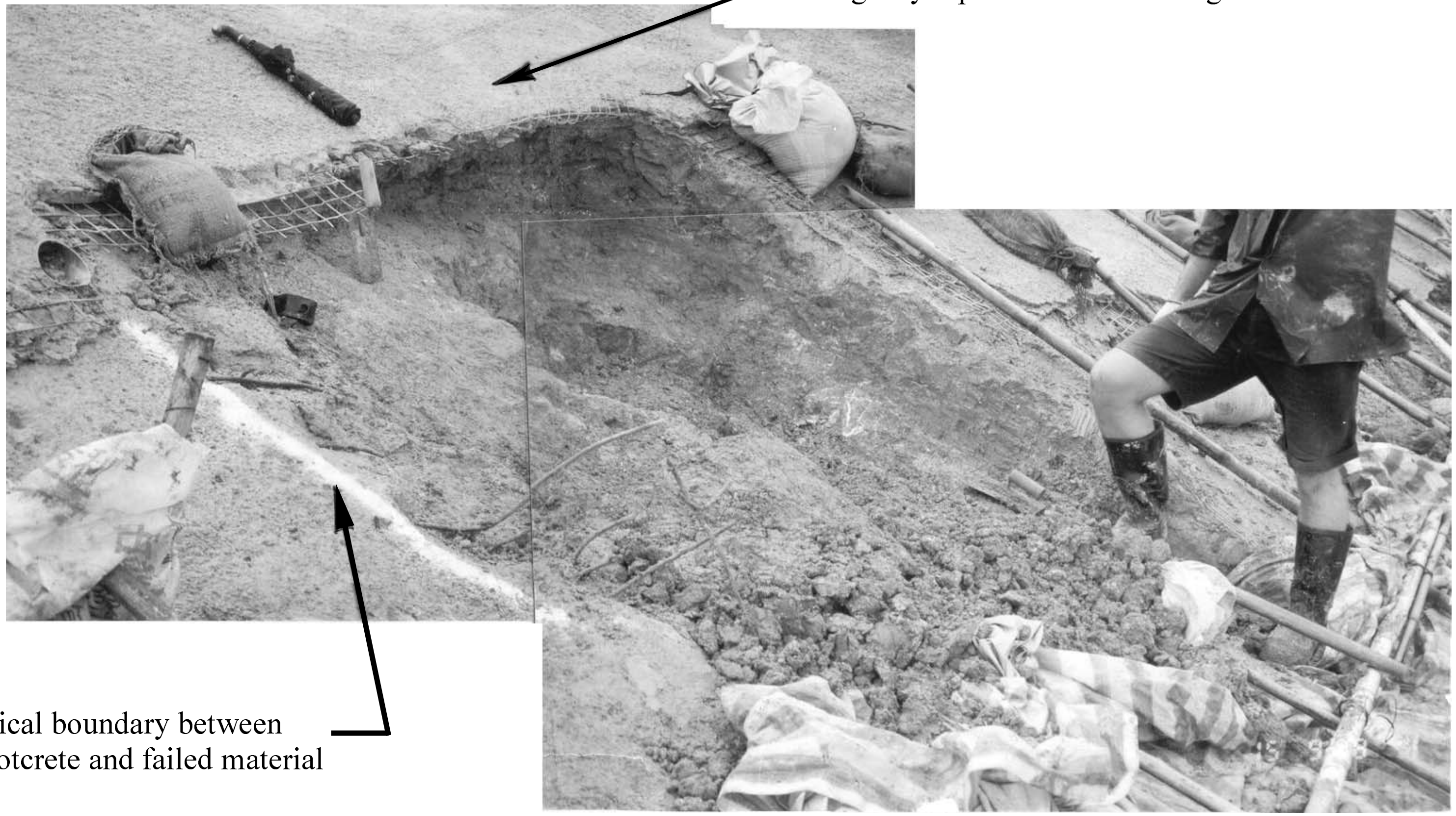


Plate 16 – General View of Trial Pit (TP1) in the Lower Cut Slope
(Photographs taken on 9 September 1998)

Note : See Figure 13 for Location of Photographs.

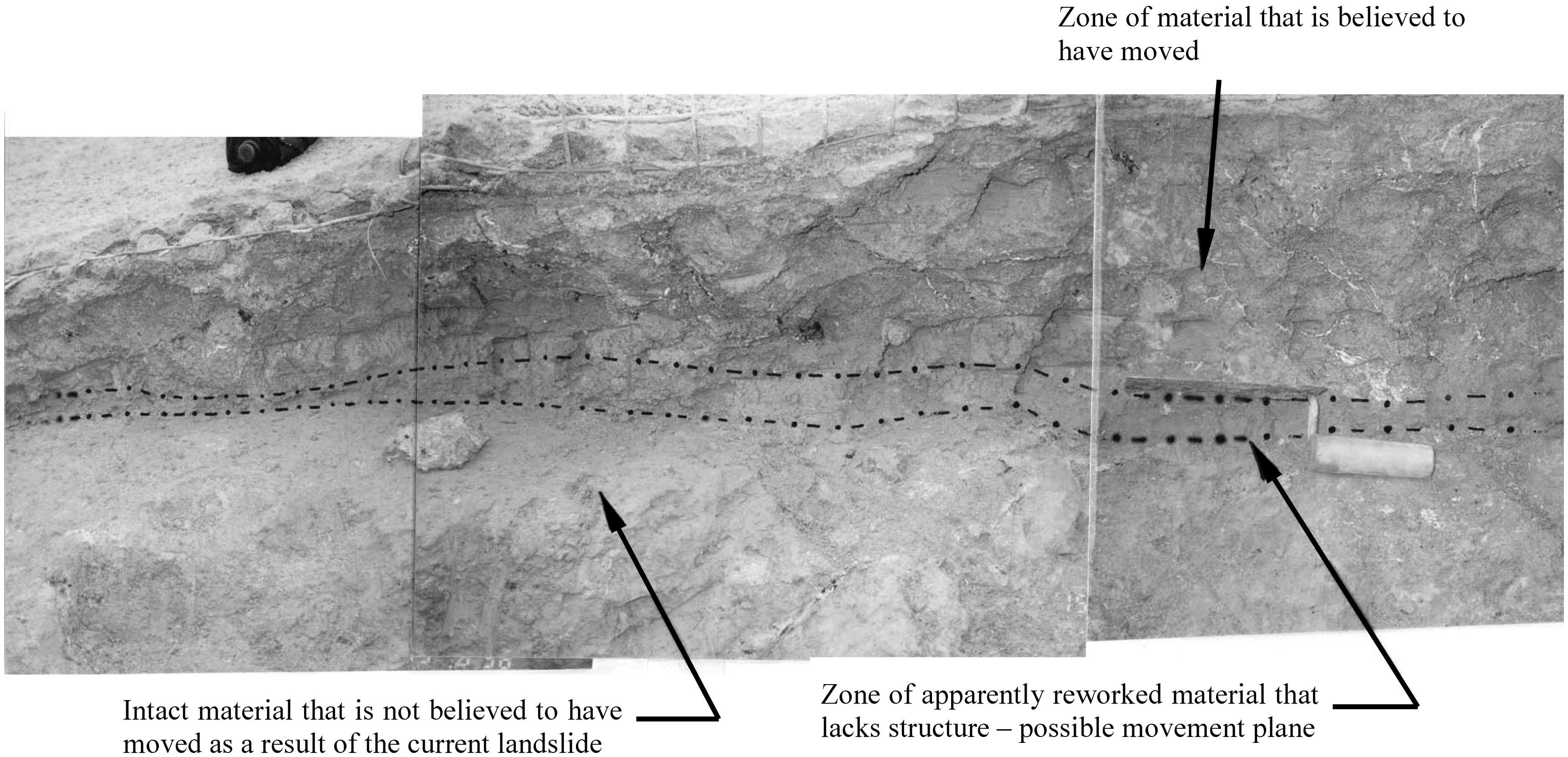


Plate 17 – View of Disturbed Seam Exposed in the Trial Pit (TP1)
(Photographs taken on 9 September 1998)

Note : See Figure 13 for Location of Photographs.

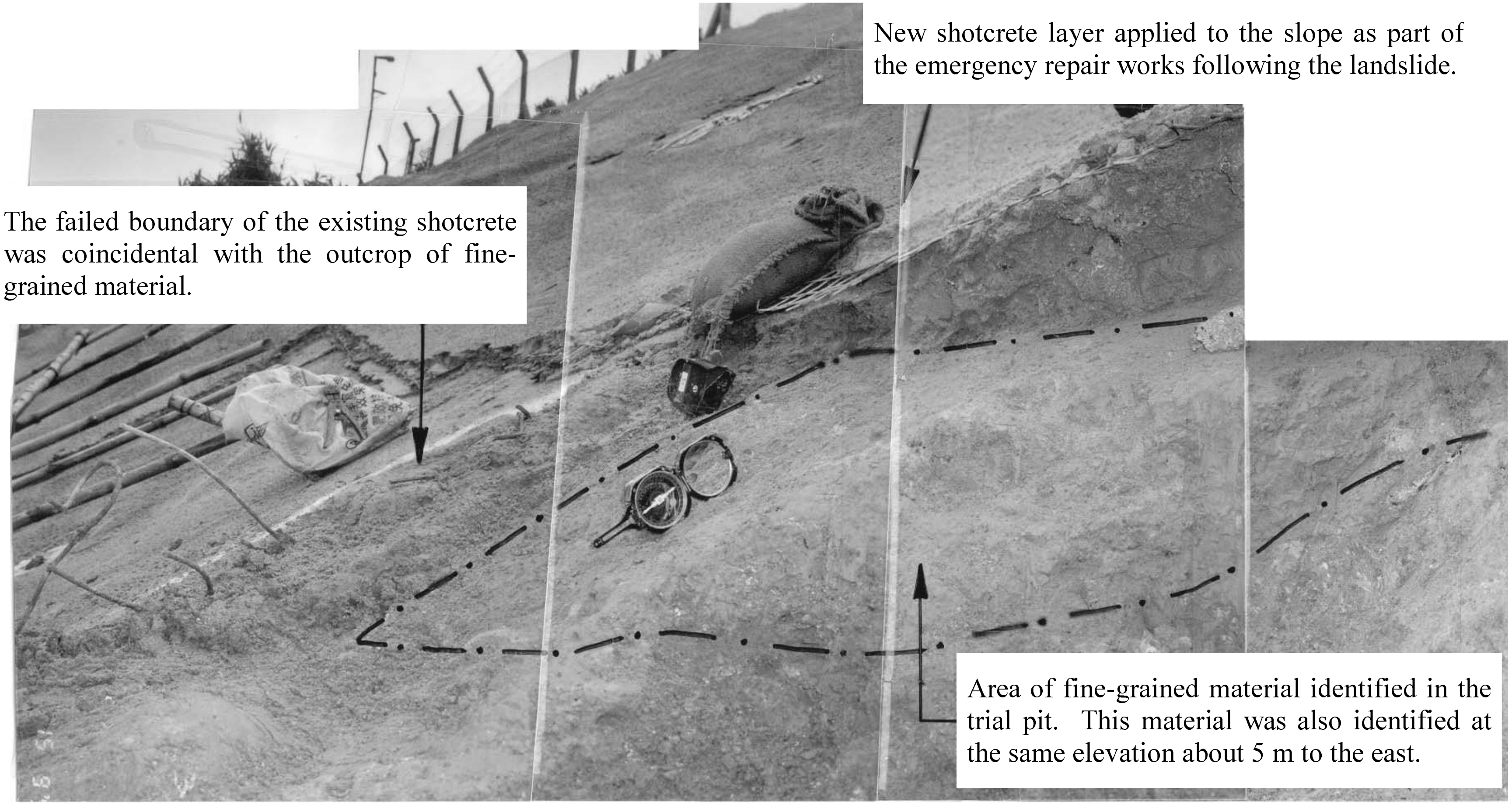


Plate 18 – View of Lens of Fine-grained Material (Probably Siltstone) Exposed in the Trial Pit (TP1)
(Photographs taken on 9 September 1998)

Note : See Figure 13 for Location of Photographs.

APPENDIX A

AERIAL PHOTOGRAPHIC INTERPRETATION

A1. SITE HISTORY

The following site history has been interpreted from aerial photographs dating from 1956 to 1997. The development of the site is illustrated on Figures A1 to A3 inclusive.

YEAR	OBSERVATIONS
1956	Fei Ngo Shan Road and Jat's Incline have both been formed below Tate's Ridge. A Police Post has been formed partly in cut on a platform along the ridgeline. A fan shaped area can be identified by a lighter tone below the platform, which may represent the extent of fill material tipped onto the slope during construction of the Police Post. A rough track has been excavated along the mid-point of the slope between Fei Ngo Shan Road and the Police Post forming a cut slope above the track. Another cut slope is located directly above Fei Ngo Shan Road. These form the upper and lower cut slopes respectively. A linear feature trending east-west is identified on the eastern side of the slope below the Police Post, which appears to connect with a natural drainage line that descends down the western flank of the lower cut slope. Observations made on site indicate that the feature is an unlined, man-made drainage ditch.
1963	Along the southern boundary of the platform, at the rear of the Police Post, a linear feature is identified which was observed during a site visit as a surface drainage channel. From the photographic evidence, this channel discharges directly onto the slope at the western end of the platform, where a strip, characterised by a lighter tone, descends the slope towards the road. The strip may represent a preferential surface water flow path. The eastern end of the surface channel is connected to a rectangular feature identified on site as a sediment trap. Below the trap, the channel descends southwards into the unlined drainage ditch noted in the 1956 photographs.
	The cut slope above the rough track, which is not covered by surface protection, has an irregular profile and a number of failure scars are visible along its length. The portion of the rough track above and to the east of the lower cut slope appears to have been recently cleared and a dark, narrow line is visible along the inside edge of the track. This feature has been identified on site and is thought to be an unlined, man-made drainage channel. Below the track, two light coloured areas are visible, the first directly above the crest of the lower cut slope, and the second approximately 20 m east of the cut slope. The area to the east has been identified on site, and is interpreted from the photographs as a relict landslide scar, which has affected part of the track. The area above the crest of the lower cut slope could represent local instability, surface erosion, or may simply be an area of local ground disturbance or end-tipping associated with clearance of the track.
	The lower cut slope has a more regular profile and is bounded by a surface drainage channel that connects into two culverts at either side of the feature. A protective surface cover has been applied to about two thirds of the feature, with narrow sections along the western, and to a lesser extent, the eastern sides, remaining vegetated. These vegetated strips do not appear to have been cut. The

area of surface protection appears darker along the western side possibly caused by rock/boulder outcrops. Immediately above the mid-point of the slope a linear feature can be seen, the nature of which is unclear.

Directly below Fei Ngo Shan Road, in the vicinity of the culvert and drainage channel at the western side of the lower cut slope, areas denoted by a lighter tone (similar to those noted below the track), are visible. These could be representative of end-tipped material, possibly associated with the general slope works or due to surface erosion.

A number of lines can be identified over the area forming the landslide site that could be possible tension cracks. Two of these are evident in the natural hillside between the upper cut slope and drainage ditch identified in the 1956 photographs. Another can be seen above the western side of the lower cut slope. Also, a semi-circular feature above the upper cut slope on the eastern side of the landslide site gives the impression of a possible tension crack.

The natural ground surrounding the landslide area appears to be covered with grass and small shrubs and bushes with an absence of large trees.

A rock outcrop can be seen along the eastern ridgeline and what appear to be large discrete boulders are present within a slight surface depression adjacent to the western edge of the lower cut slope. These may represent coarse colluvial deposits and /or toppled corestones.

A fence line traverses the slope directly above the crown of the lower cut slope.

1967 The semi-circular line, thought to be a tension crack, above the upper cut slope on the eastern side of the landslide site is not as prominent, but the other lines identified in 1963 are still evident.

What appears to be a wide strip of material, possibly colluvium, can be seen in the shallow depression forming the landslide site. The upper boundary of this deposit starts at about the mid-point of the natural hillside and extends for a distance of about 30 m to 40 m downslope of Fei Ngo Shan Road. The lateral extent of this feature approximately coincides with the western and eastern boundaries of the lower cut slope.

Also evident in the photographs is a break in the ground profile in the vicinity of the rough track, above the western side of the lower cut slope. This appears to be a small localised gully feature and coincides with where fine-grained material (probably siltstone) was identified to outcrop in the slope.

1972-74 There are no obvious changes to the area of interest.

1976 The layout of the area appears to be the same as that shown in previous years, but due to the superior quality of these photographs more detailed observations can be made of several key features.

A more extensive pattern of lines, thought to be possible tension cracks, can be seen in the natural hillside above the upper cut slope. These occur in the location where a tension crack was identified following the landslide in September 1993.

The linear feature identified at the mid-point of the lower cut slope in the 1963 photographs appears to be a small, masonry retaining wall traversing the slope. The darker patches identified along the western edge are interpreted as outcrops of boulder-size material. Other darker patches, which appear to be individual boulders, can be seen in the cut slope below the wall.

Groups of boulders and generally coarse material can also be seen along the western boundary of the wide strip feature identified in the 1967 photographs, where there appears to be a natural drainage line. Leading into this is what appears to be another natural drainage line, which extends from the man-made drainage ditch to the west of the landslide site. The line of this drainage path approximately coincides with the upper boundary of the wide strip feature.

The light strip identified below the western end of the crest channel along the southern edge of the platform in the 1963 photographs, is no longer visible. Although, elsewhere along the crest channel, several strips, denoted by a lighter tone, are present on the slope below the platform. It is possible that these represent areas where surface water has overtopped the crest channel and flowed downhill.

1977-83 No apparent change in the study area, but the lines denoting possible tension cracks are becoming less apparent with time.

1984-88 The lower western corner of the cut slope appears to have a lighter tone than the adjacent surface cover, possibly suggesting recent resurfacing. The same observation is noted up to 1988. In 1988, the western portion of the cut slope appears to be covered with vegetation.

1990 The upper portion of the cut slope has a lighter tone than the adjacent surface cover.

1991-92 No obvious changes are noted

1992 The shape of the lower cut slope has changed significantly. It now extends up slope from the culverts on either side of the feature to the rough track. The fence line has locally been realigned so that it bounds the upper portion of the shotcreted slope. The surface is now more rectangular in shape and has been completely covered with a surface protection layer (probably sprayed concrete). Two lines are observed between the platform and the cut slope, which from desk study records and site visits have been identified as surface drainage channels. The eastern most channel formed a continuation of the existing drainage channel descending from the slope crest, while the western most feature is cut in a diagonal line from the top corner of the northeastern portion of the lower cut slope to a point below the platform. A further two, less prominent, lines are seen descending from the crest platform. These have been interpreted as access tracks formed during construction of the remedial works.

Two small areas, denoted by a lighter tone, are observed to the east of the cut slope. The upper area appears to be related to surface disturbance of the cut slope above the rough track. The nature of the lower area is unclear.

1994	As above. Vegetation growth along the line of the channels noted above.
1995	It is clear from the photographs that the upper portion of the shotcreted area adjacent to the fence line is badly cracked in the western corner. There also appears to be a break in the shotcrete layer in this location suggesting the possible presence of a tension crack. The U-channel cutting diagonally across the natural hillside as identified in the 1993 photograph can be seen. This channel does not appear to join up with the channel at the crest of the slope. An arcuate line can be seen on the down slope side of the channel, which may represent a tension crack. The location of this crack would be consistent with that identified in photographs for the period between 1963 to 1977, and with information retrieved during the desk study.
1996-1997	As above.
Nov. 97	The cut slope has undergone minor remedial works, including reformation of the upper portion of the slope, installation of an intermediate berm and application of a new layer of surface protection (probably shotcrete), such that the lower cut slope extends to the toe of the upper cut slope. The area comprising the cracked surface cover, observed in 1995 and 1996, is no longer visible. New drainage has been constructed along the intermediate berm and along the crest of the upper batter, the location of which appears to coincide with the possible tension crack observed as a break in the surface cover in the 1995 and 1996 photographs. Otherwise the extent of the lower cut slope has not significantly changed. A line, probably representative of a tension crack, is visible along the eastern side of the landslide site, on the downhill side of the diagonal drainage channel. This coincides with the line observed in 1995, but the vertical extent appears to have increased upslope, such that it forms a profile similar to that of the eastern side of the current landslide.

A2. SUMMARY OF SITE HISTORY

The aerial photographs show that the upper and lower cut slopes under investigation were formed prior to 1956. The photographs identify the possibility of colluvium in the area of the 1998 landslide as well as the possibility of tension cracks in the natural ground above the upper cut slope. In 1993, the lower cut slope was trimmed back significantly and new surface cover applied. Following this, the crest of the lower cut slope then adjoined the edge of the rough track. New surface drainage is evident across the site, in particular, a drainage channel can be seen cutting diagonally across the natural hillside above the area where desk study records indicate the presence of a tension crack. In 1995 and 1996 extensive cracking is evident along the upper northwestern edge of the lower cut slope. In 1997 it is apparent that the lower cut slope has been modified further. The shotcreted area now extends to the toe of the upper cut slope and an intermediate berm divides the slope into two parts.

A3. PHOTOGRAPHS

A full list of the photographs studied as part of the API is presented below:

DATE	ALTITUDE (Feet)	PHOTO REFERENCE
1956	-	F42/81A/RAF 0021-0022
02/1963	4200	Y08619-Y08620
24/02/1963	7000	Y8299-Y8300
1967	6250	Y13464-Y13465
03/10/1972	13000	2269-2270
21/11/1974	12500	9785-9786
28/01/1976	4000	12903-12904-12905
21/12/1977	4000	20212-20213
10/02/1981	5500	36605-36608, 36581-36582
10/10/1982	10000	44565-44566
22/12/1983	10000	52142-52143
20/10/1984	11000	56478-56479
09/11/1986	10000 (Oblique)	A7324
21/12/1986	10000	A8196-A8197
03/11/1988	10000	A15167-A15168
03/12/1990	10000	A24375-A24376
29/10/1991	10000	A28819-A28820
14/11/1991	10000	A29239
11/11/1992	10000	A33265-A33266
05/12/1993	10000	CN5415-CN5416
21/10/1994	10000	A39485-A39486
05/09/1995	2500	CN10956-CN10957
23/11/1995	10000	CN12313-CN12314
21/11/1996	10000	CN16190-CN16191
29/01/1997	20000	CN16567-CN16568
01/11/1997	10000	CN19023-CN19024

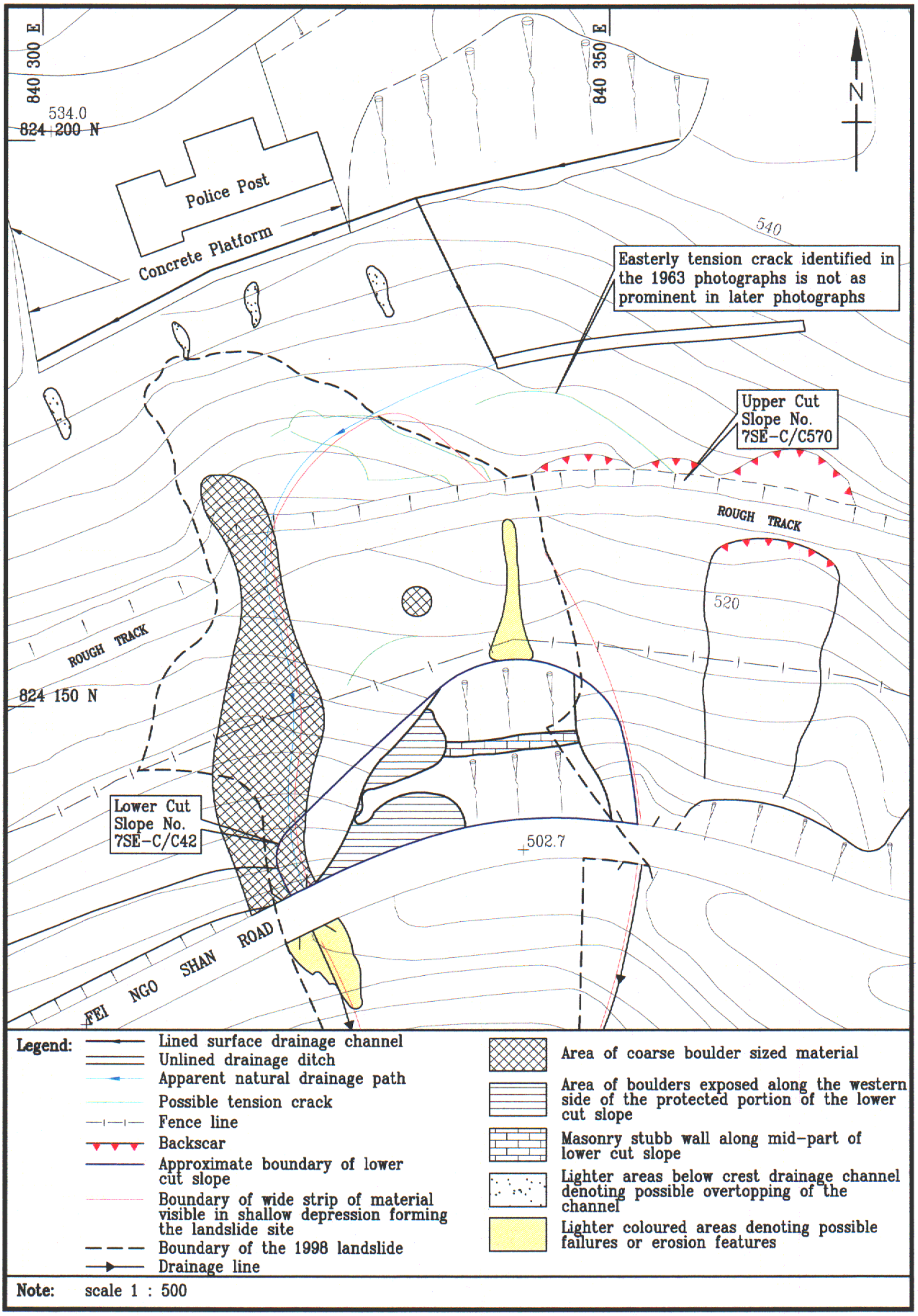


Figure A1 - Layout of the Landslide Site Pre-September 1993 Failure

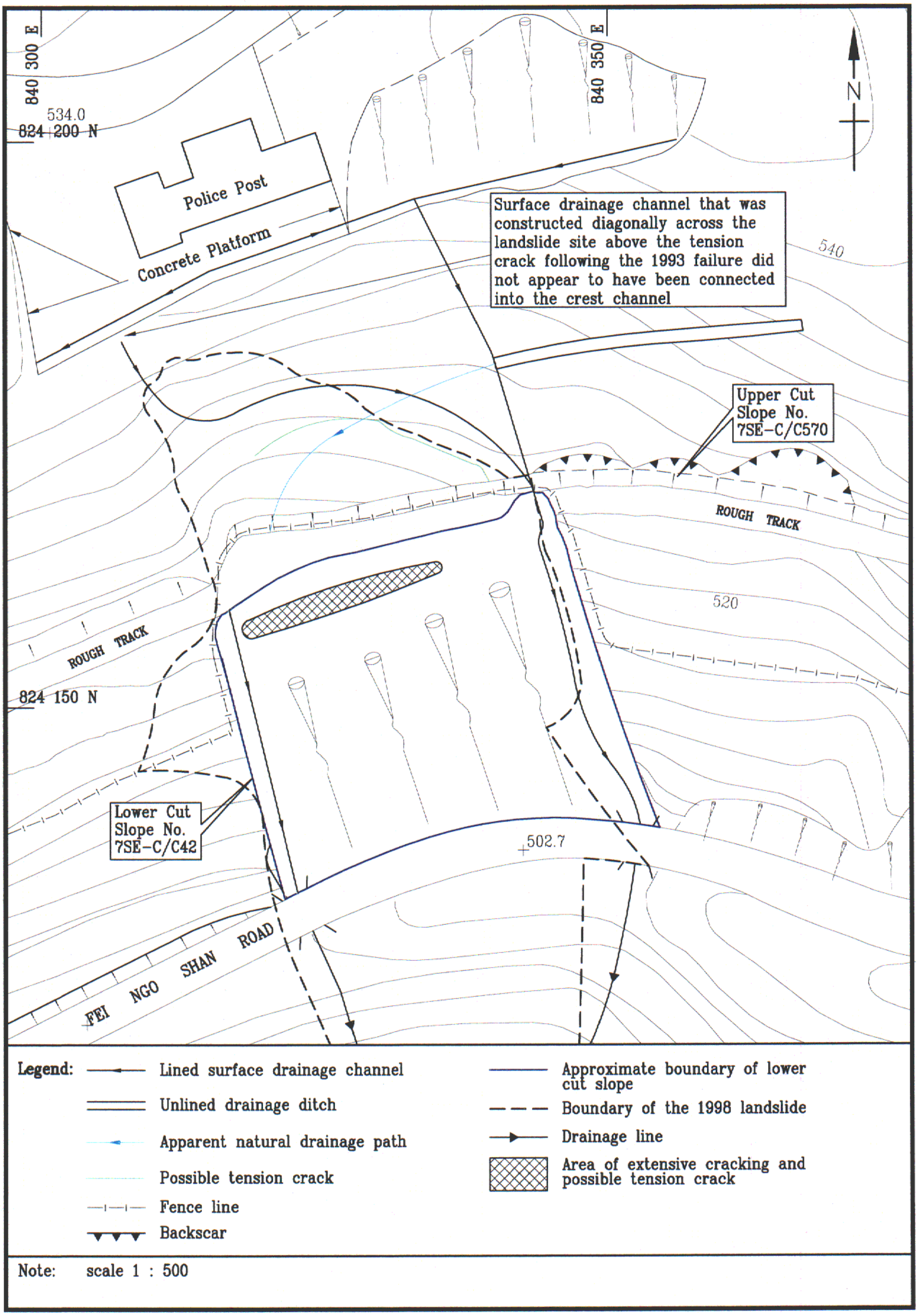


Figure A2 - Layout of the Landslide Site Pre-July 1997 Failure

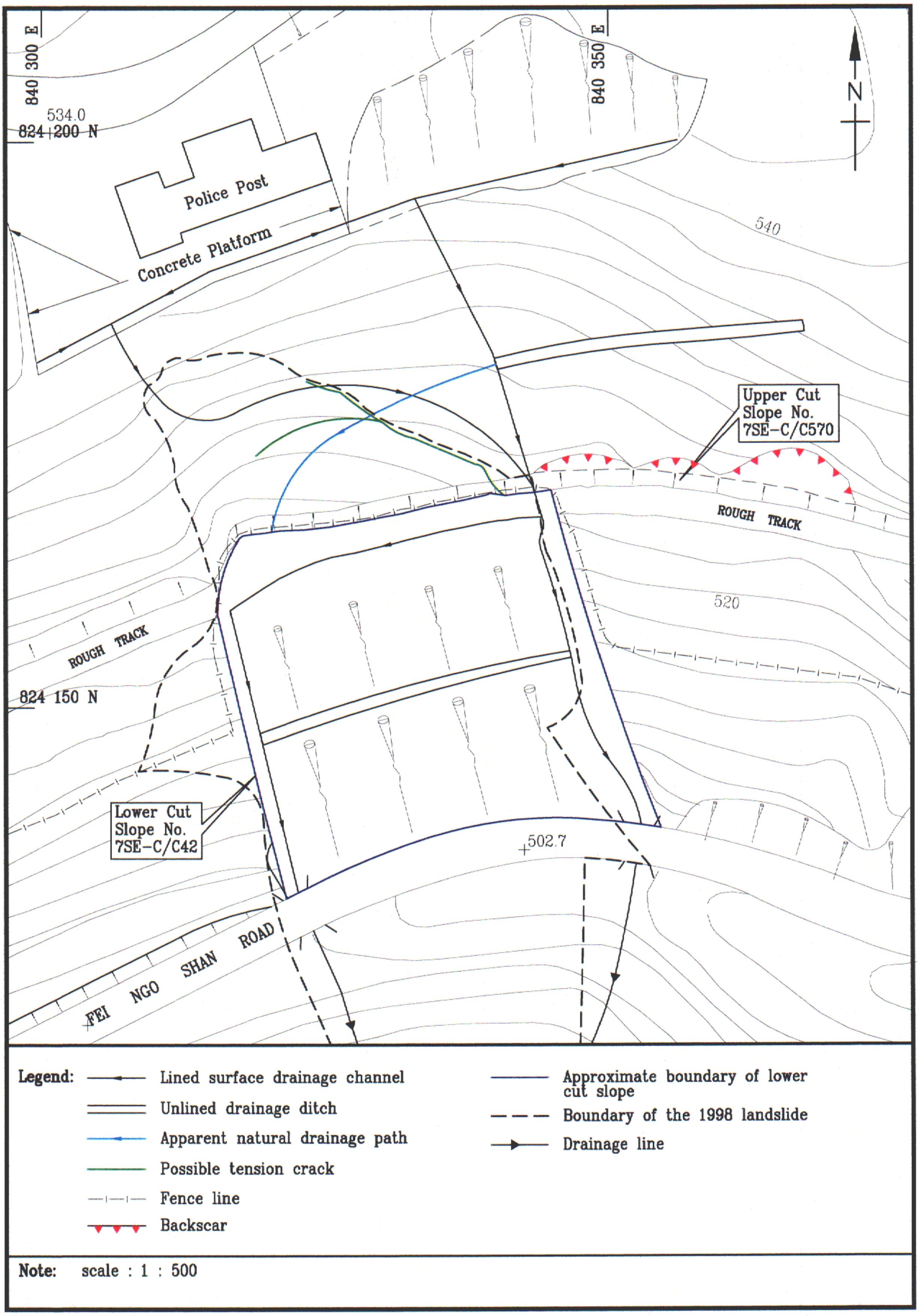


Figure A3 - Layout of the Landslide Site Post-July 1997 Failure