REPORT ON THE SHUM WAN ROAD LANDSLIDE OF 13 AUGUST 1995

Volume 2

FINDINGS OF THE LANDSLIDE INVESTIGATION

Geotechnical Engineering Office
Civil Engineering Department
Hong Kong Government

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This Report is presented in two volumes. Volume 1 contains the independent findings of Sir John Knill on the Shum Wan Road landslide of August 1995 and the lessons to be learnt from it. Volume 2, prepared by the Geotechnical Engineering Office of the Civil Engineering Department, presents the detailed findings of the landslide investigation. The contents of Volume 2 have been reviewed and agreed by Sir John Knill who relies on them in his own assessment given in Volume 1.

Requests for additional copies of this Report should be sent to :

Chief Geotechnical Engineer/Special Projects,
Geotechnical Engineering Office,
Civil Engineering Department,
Civil Engineering Building,
101 Princess Margaret Road,
Homantin, Kowloon,
Hong Kong.

EXECUTIVE SUMMARY

On 13 August 1995, a landslide took place at the hillside above Shum Wan Road, Aberdeen. It caused the collapse of a 30 m long section of Nam Long Shan Road that included a passing bay supported by a fill embankment. The landslide debris crossed Shum Wan Road and damaged three shipyards and a factory near the seafront. The landslide resulted in two fatalities, and five other people were injured.

A comprehensive investigation into the landslide was carried out by the Geotechnical Engineering Office (GEO) during the period August 1995 to March 1996. This detailed study included a desk study, interviews with witnesses, topographic survey, observations and measurements at the landslide site, geological mapping, ground investigation, examination of the condition of drainage systems and water-carrying services, theoretical stability and seepage analyses, and diagnosis of the causes of the failure.

The investigation concluded that the main landslide involved two distinct parts that occurred almost simultaneously. The failure was caused principally by :

(a) the presence of weak layers in the ground, i.e. clay seams and clay-infilled joints,

(b) ingress of water during prolonged heavy rainfall,

(c) a minor failure of the fill embankment below a passing bay on Nam Long Shan Road, and

(d) water flowing along Nam Long Shan Road, because of partial blockage of its drainage system, and discharge of part of this water onto the hillside.

This report presents details of the investigation and its findings.

CONTENTS

1. INTRODUCTION

At about 4:00 a.m. on 13 August 1995, a landslide took place at the hillside above Shum Wan Road, Aberdeen (Plate 1 & Figure 1), causing the collapse of a 30 m long section of Nam Long Shan Road. The landslide debris crossed Shum Wan Road and damaged three shipyards and a factory near the seafront. The landslide resulted in two fatalities, and five other people were injured.

The Geotechnical Engineering Office (GEO) of the Civil Engineering Department commenced an investigation of the landslide on the morning of 13 August 1995. A Progress Report (Geotechnical Engineering Office, 1995) giving an interim account of the landslide was issued on 21 September 1995.

The investigation, which was conducted between August 1995 and March 1996, included the following key tasks :

(a) desk study, including review of relevant documentary records, examination of aerial photographs and old topographic maps of the site, and analysis of rainfall data,

(b) interviews with witnesses to the landslide and with other concerned persons,

(c) topographic surveys and detailed observations and measurements at the landslide site,

(d) geological mapping,

(e) a comprehensive programme of ground investigation by drilling, insitu testing and laboratory testing,

(f) inspection of the condition of drainage systems and water-carrying services, and

(g) theoretical stability and seepage analyses.

This report presents the findings of the investigation. Full details of the investigation work undertaken and the results obtained are contained in a set of documents which have been placed in the Civil Engineering Library of the Civil Engineering Building, and these are accessible by the public.

2. THE LANDSLIDE SITE

The landslide on 13 August 1995 occurred at a hillside between Shum Wan Road and Nam Long Shan Road (Figure 1). Prior to the landslide, the hillside was densely vegetated and had an overall gradient of about 27°.

There were three concrete retaining walls in the vicinity of the landslide area below

Nam Long Shan Road (Figure 1). Two of the walls were about 2 m in height and probably supported the Nam Long Shan Road embankment before the construction of a passing bay. The third wall was about 1.2 m high and was likely to have been constructed to form a squatter platform.

Nam Long Shan Road was about 5 m wide at the location of the landslide, and there was a passing bay on the downhill side of the road. The passing bay, estimated from aerial photographs taken in 1994 to be about 5 m wide, was supported by a fill embankment about 10 m high from toe to crest. The passing bay embankment partly concealed one of the 2 m high retaining walls (the southern concrete retaining wall). There was a 4 m high cut slope on the uphill side of the road. None of the above man-made features were registered in the Catalogue of Slopes prepared by consultants for the Hong Kong Government in 1977 and 1978. It is not known why the 10 m high fill embankment was not registered. The other features did not fulfil the criteria for registration.

At part of the toe of the failed hillside along Shum Wan Road is a steep 7 m high rock cliff. Registered cut slope No. 15NW-B/C77, which did not fail in the incident, is situated to the south of the landslide (Figure 1). Shum Wan Road is 7.5 m wide.

The reclaimed land between Shum Wan Road and the seafront at Po Chong Wan is the site of a temporary industrial area containing a number of shipyards and factories (Figure 1).

Surface water from the hillside above Nam Long Shan Road is collected by natural stream courses and man-made channels and discharges into catchpits leading to cross-road drain pipes buried under the road (Figure 2). Water from these pipes flows into stream courses or man-made channels further downhill, as does surface water discharged from Nam Long Shan Road by drainage openings in the concrete upstand along the downhill side of the road. At the southern side of the landslide, a 1.2 m wide stepped-channel conveyed water from Nam Long Shan Road to Shum Wan Road.

A 225 mm diameter sewer and a 100 mm diameter private fresh-water main run along Nam Long Shan Road.

3. HISTORY OF THE SITE

The site development history has been determined from aerial photographs by expert interpreters, from old maps of the site and from a review of other documentary information.

The earliest available aerial photographs of the site were taken in 1945. Nam Long Shan Road can be seen in these photographs, and it appears that the two 2 m high concrete retaining walls below Nam Long Shan Road had been constructed by that time. Photographs taken in the 1970's show that the passing bay involved in the landslide was added to Nam Long Shan Road between 1976 and 1977. The passing bay was constructed on a new fill embankment.

The photographs show that, by 1977, works had commenced on the reclamation into Po Chong Wan from Shum Wan Road. The cut slopes along Shum Wan Road were formed between 1977 and 1978.

Along with the roadworks at Nam Long Shan Road and Shum Wan Road, squatter activities on the hillside are evident from aerial photographs. A number of squatter huts are shown on Survey Sheet No. 15-NW-4C dated October 1984 (Figure 1). The 1.2 m high concrete wall below Nam Long Shan Road was likely to have been constructed in the 1970's as part of the squatter development. Signs of illegal dumping from Nam Long Shan Road are apparent in photographs taken since 1977.

There is evidence of minor landslips or soil erosion within or close to the collapsed hillside in photographs taken since the 1940's. These were mainly concentrated on the embankments along Nam Long Shan Road. In the 1988 and 1991 photographs, two patches of erosion can be seen on the fill embankment immediately below the passing bay involved in this landslide. The erosion patches are directly above the southern concrete retaining wall, their approximate locations being shown in Figure 1.

A large ground depression in the hillside north of the landslide is apparent in the 1949 aerial photographs. It may indicate an ancient landslide scar (Figure 1).

There are documentary records (Choot, 1993) of two minor landslips in 1983 at the landslide area (Figure 1). The two landslip incidents, which were classified as "erosion of natural slope" and "erosion of fill platform" respectively, occurred on 17 June 1983.

The squatter huts on the hillside were completely cleared in 1988 under Government's Non-development Clearance Programme.

So far as can be established, there have been no previous studies of the unregistered man-made slopes and retaining walls in the vicinity of the landslide area. There is no record of any design documents for these earthworks and retaining walls having been submitted to the GEO for checking.

The GEO carried out a territory-wide Geotechnical Area Studies Programme from 1979 to 1985 to provide a geotechnical basis for the planning and management of land use in Hong Kong. Along with a significant proportion of hillsides elsewhere in the territory, the land in the neighbourhood of the landslide is classified as a "zone of general instability associated with predominantly colluvial terrain" on the 1:20 000 scale Physical Constraints map produced in the Geotechnical Area Studies Programme (Geotechnical Control Office, 1987a) (Figure 3). The areas mapped as "zones of general instability" are those with signs of downslope mass movement at some time in the past.

4. ANALYSIS OF RAINFALL RECORDS

Two GEO automatic raingauges are located close to the landslide (Figure 4). Raingauge No. H20 at Ap Lei Chau Estate is about 1.8 km west of the site, while raingauge No. H05 at Aberdeen Treatment Works is about 2 km to the northwest.

Rainfall records from both raingauges have been analysed. Their rainfall patterns and intensities in the period before the landslide are broadly similar. The record from raingauge No. H05 is presented in Figure 5 to illustrate the probable rainfall pattern and intensity at the landslide area.

There was heavy rain during the hours before the landslide at 4 a.m. The distribution across the territory of the 4-hour and 24-hour rainfall before the landslide is shown in Figure 4. Between 11 p.m. on 12 August and 3 a.m. on 13 August, 159 mm of rain was recorded, with a peak hourly rainfall of 48 mm between 2 a.m. and 3 a.m. (Figure 5). The recorded 30-hour rainfall at raingauge No. H05 before the landslide was 381 mm.

The rainstorm on 12 August 1995 prior to the landslide was preceded by a heavy rainstorm around 3 August 1995. A total of 846 mm of rain was recorded by raingauge No. H05 in the 13 days before the landslide (Figure 5).

A comparison between the pattern of the rainfall before the 1995 landslide and that of previous major rainstorms affecting the area since the installation of raingauge No. H05 in 1979 is shown in Figure 6. It can be seen that the rainfall preceding the landslide is on the high side, being the highest recorded by the raingauge for durations exceeding 15 days and comparable to the highest experienced previously for rainfall durations of 24 hours or less. The only period with similar rainfall intensities was that of 23 July 1994.

Analysis of the return periods of the rainfall intensities of this rainstorm for different durations based on historical rainfall data at the Royal Observatory shows that the 31-day rainfall was the most uncommon, with a corresponding return period of about 75 years.

It is apparent that intense rainstorms, of very long return periods according to the rainfall data at the Royal Observatory, have occurred every year in Hong Kong since 1992. The GEO is reviewing whether the repeated occurrence of such rare rainfall events represents a change in the regional climate.

5. DESCRIPTION OF THE LANDSLIDE

5.1 Field Observations and Measurements

The extent and profile of the landslide and the debris were determined by topographic surveys carried out by the Survey Division of the Civil Engineering Department before the landslide was disturbed by any remedial works. The extent of the landslide is shown in Figure 7, and a cross-section through it is given in Figure 8.

The landslide resulted in a 70 m high scar, with a width varying from about 50 m just below Nam Long Shan Road to about 90 m above Shum Wan Road. The upper part of the landslide surface (Figure 8) was concave in shape and was up to about 12 m in depth below the pre-failure ground surface. The lower part of the landslide surface was planar and was 2 to 3 m below the pre-failure ground surface.

The rock cliff at the toe of the hillside did not fail during the landslide. At the top of the landslide scar, a 30 m section of Nam Long Shan Road collapsed, and the landslide extended a short distance up the slope above the road.

The landslide released about 26 000 m^3 of soil and rock, about 12 000 m^3 of which remained on the landslide surface (Figure 8). The remaining debris was deposited on Shum Wan Road and the reclaimed land to the west, spreading over an area of about 5 000 m^2

(Figure 7). A large volume of debris was also deposited in the slipway of a shipyard. The top surface of the debris on the reclaimed land was almost horizontal.

The landslide at Shum Wan was unusually large in size (26 000 m^3 in volume). A review of the available records shows that this is the largest landslide in Hong Kong over the past twenty years.

The debris can be classified broadly into four major types (Figure 7). On the reclaimed land to the west of Shum Wan Road, the debris was in the form of a relatively intact 'slab' of material, generally about 2 m thick but up to 3 m in places (Plate 2). The 'slab' consisted of partially weathered tuff with disturbed but recognisable joint structures of the original weathered rock mass. The joints were closely spaced and were locally infilled with white kaolinitic clay up to about 10 mm thick. The 'slab' was underlain in places by a thin layer of mainly vegetation and top soil. Clumps of vegetation were common on the top of the 'slab', and some were also deposited around the outer edge of the 'slab' near the sea front.

The debris in the space between the 'slab' debris and the hillside comprised mainly a very soft or loose fluvial deposit of clay, silt, sand, gravel and some cobbles and boulders (Plate 3). The debris was generally about 2 m thick.

The planar part of the landslide surface was generally covered by soil debris up to about 3 m thick. The soil debris was up to about 5 m thick within the concave scar. The debris included fill material and refuse, such as bottles, polystyrene, car tyres and construction waste (Plate 4). Other man-made objects, including concrete retaining wall fragments, broken pieces of bituminous pavement, sections of 225 mm diameter earthenware pipes, 100 mm diameter galvanised iron water pipes and concrete slabs, were also found (Figure 9). It was noted that most of the concrete retaining wall fragments (Plate 5) were deposited in the lower planar scar, whereas the pieces of bituminous pavement (Plate 6) were all within the upper concave scar.

A large amount of rock debris generally about 2 m thick overlaid the soil debris on the concave scar (Plate 7). The largest rock fragment was about 3 m across.

Two trucks parked on Nam Long Shan Road were brought down during the landslide. One remained sitting on a piece of bituminous pavement which dipped at about 14° to the east on top of the debris. The other truck was buried by debris. Another truck and a taxi remained poised on Nam Long Shan Road, overhanging the crest of the landslide scar. A number of cars were buried by debris on Shum Wan Road.

The scouring action of surface water resulted in three prominent erosion channels in the landslide debris (Figure 7). The erosion channels were typically about 1 m deep and 2 m wide. The largest one was up to about 6 m in width over much of its length.

5.2 Witnesses Accounts

GEO officers interviewed eleven persons and reviewed other records which might provide information about the landslide event, such as Police records and the Ocean Park record of the time that water and power supply to the park area were cut off.

According to eye-witnesses, the landslide occurred at about 4 a.m. At that time, the lower part of the hillside was illuminated by security lighting from a building at Shum Wan Road whereas the upper part of the hillside was fairly dark. One eye-witness observed a small white patch on the hillside near the position of Nam Long Shan Road. The patch grew bigger progressively. Suddenly the lower portion of the hillside bulged out and slid down as a whole piece across the full width of the landslide scar. The event was reported to the Police at 4:06 a.m. by another eye-witness. Nam Long Shan Road did not collapse during this main landslide but, according to eye-witnesses, failed about half an hour later in a subsequent slip.

A large volume of water was seen discharging onto the landslide scar from the broken sewer pipe until the early afternoon of 13 August 1995. The private fresh-water main was turned off by staff of the Ocean Park at about 7:30 a.m. on 13 August.

Some witnesses reported that there had been illegal dumping of refuse and construction waste on the hillside downslope of Nam Long Shan Road, and that the road had been used frequently by heavy construction vehicles in the months before the landslide. Witnesses also said that the drainage channels down the hillside in the landslide area were relatively dry even when it was raining in the past few months, and that muddy water was seen on the surface of the hillside. Another witness who walked part way up the 1.2 m wide stepped-channel (Figure 2) on 6 August 1995 did not see any blockage of the channel.

6. SUBSURFACE CONDITIONS AT THE SITE

6.1 General

The subsurface conditions at the landslide area were determined from information obtained from desk and field studies. The desk study comprised a review of existing geotechnical data. The field studies included a ground investigation consisting of eight boreholes, fourteen trial pits, nine trial trenches, 22 GEO probe tests, a seismic refraction survey and geological mapping (Figure 10). Piezometers were installed in boreholes to monitor the groundwater pressures. Information from the ground investigation carried out on the adjoining hillside in relation to remedial works design was also used in determining the subsurface conditions at the landslide area.

6.2 Geology

The geology at the landslide area comprised a thin mantle of colluvium overlying partially weathered fine-ash to coarse-ash crystal tuff. A typical geological section through the landslide is given in Figure 11. The colluvium, as exposed on the adjoining hillside, is predominantly a silt/clay with gravel and cobble clasts, forming an impersistent layer up to about 1 m thick. The age of the colluvium determined from laboratory dating of three samples, by the Guangdong Institute of Geochemistry using the thermoluminescence technique, is in the range of 35 000 to 48 000 years before present (Guangdong Institute of Geochemistry, 1995).

Rock fabrics in the partially weathered tuff dip mainly northeast. On the adjoining hillside either side of the landslide, they dip at 10° to 40° to the horizontal. However, the dip is steep (70° to 90°) within the concave scar area.

Two sub-vertical joint sets and at least two gently dipping (20° to 35°) joint sets were exposed in the landslide and confirmed by measurements in boreholes. The joints were generally closely to widely spaced. However, the sub-vertical joints within the concave scar were very closely spaced within a zone about 6 m wide striking in a northwesterly direction. These sub-vertical joints would have permitted relatively easy downward passage of water through the partially weathered tuff.

Weathering within the rock mass was more pervasive within the area of very closely spaced sub-vertical joints than elsewhere. Over the area of the concave scar, the completely to highly decomposed tuff was up to about 20 m thick prior to the landslide (Figure 11). This compares with the more typical thickness of about 5 m for a similar zone of completely to highly decomposed tuff with wider joint spacings in the area of the planar scar and in the adjoining ground to the north of the landslide.

Joints within the partially weathered tuff were commonly coated with manganese oxide and infilled with white clay up to about 15 mm thick. An extensive clay seam formed part of the base of the concave scar, the approximate extent of which is shown in Figures 7 & 8. It comprised a soft yellowish brown clay layer, typically 100 mm thick (but locally up to about 350 mm) with highly decomposed tuff fragments, underlain in places by a thin soft white clay with manganese coating. The clay seam contained slickensiding and black staining. Another soft yellowish brown clay layer was also encountered in borehole BH3 adjacent to the landslide backscarp at a depth of about 7.7 m below ground surface. The slickensiding indicates possible ancient slope movement, although no surface expression of such movement at the location of the clay seam can be seen from aerial photographs.

The landslide backscarp was structurally controlled by a series of variably clay-infilled joints (Figure 8). In the lower planar part of the scar, the landslide surface was in partially weathered tuff with some clay-infilled joints.

Fourteen samples of the yellowish brown clay and the white clay in the landslide area were sent to the British Geological Survey for mineralogical determination by X-ray diffraction. The results of the examination show that both clays contain kaolinite and probably halloysite as well (Merriman & Kemp, 1995). The white clay and the yellowish brown clay are mineralogically similar.

Before the landslide, an area of fill covered the upper part of the hillside. The fill was estimated from aerial photographs to be up to about 5 m thick.

Rock fill, predominantly between 200 mm and 300 mm in size, was found immediately behind the remaining sections of the 2 m high concrete retaining walls below Nam Long Shan Road . The fill material behind the 1.2 m high concrete wall was a loose yellowish brown sandy silt/clay with some gravel.

6.3 Material Properties

Twelve block samples were collected for laboratory testing to determine the engineering properties of the materials at the landslide area. The testing was carried out in the Public Works Central Laboratory. This included classification and index tests in accordance with the methods described by Chen (1994), and consolidated undrained triaxial compression tests with porewater pressure measurements and direct shear tests based on the methods of Head (1986) and Head (1982) respectively. The results of the classification and index tests are summarised in Table 1.

The effective shear strength parameters of the completely decomposed tuff obtained from triaxial compression tests (Figure 12(a)) are within the common range of similar material in Hong Kong (Geotechnical Engineering Office, 1993).

Two series of strength tests were carried out for the white clay and the yellowish brown clay. The peak shear strength of the clay given by the triaxial compression test results is shown in Figure 12(b). These results are consistent with the Atterberg Limits of the clay. The results of direct shear tests on a slickensided surface in clay are shown in Figure 12(c).

None of the fill below the collapsed passing bay remained after the landslide. It is therefore not possible to test the original state of the fill. To infer the possible state, insitu tests were carried out on the embankment supporting the passing bay about 60 m north of the landslide area. The results of the density tests, together with laboratory tests on maximum dry density, are summarised in Table 2. It can be seen that the fill generally had a degree of compaction less than 80% of the Standard Proctor maximum dry density, measured in accordance with the procedures of Chen (1994). The current compaction standard for fill embankments requires a degree of compaction of 95% or greater (Geotechnical Control Office, 1984). Therefore, had the two passing bays been constructed at the same time, the fill at the landslide site could have been loose. However, the state of compaction of the fill cannot now be established with certainty.

Results of permeability tests in boreholes carried out by means of falling head tests and packer tests (Geotechnical Control Office, 1987b) are given in Table 3. The test results show that the coefficient of permeability of the partially weathered tuff with very closely-spaced joints was of the order of 10^{-5} m/s. The coefficient of permeability of moderately to slightly decomposed tuff with widely-spaced joints was significantly lower.

6.4 Groundwater Conditions

During the investigation of the landslide, persistent water seepage from the ground was observed at a number of points on the landslide scar (Figures 9 & 11). The elevations of the seepage points at mid-height of the failed hillside (35 to 50 m above Principal Datum) are compatible with the groundwater levels recorded in boreholes nearby and are considered to be a surface expression of the base groundwater level. The groundwater levels at these locations are about 1 to 3 m below the pre-failure ground surface.

The ground investigation also showed that the base groundwater level within the concave scar was about 5 m below the landslide surface. However, seepage was observed from the ground in the concave scar just above the exposed clay seam (Figures 9 & 11). This seepage persisted for about one week after the landslide and reappeared after subsequent rainstorms. This suggests the presence of a transient perched water condition.

By December 1995, the base groundwater level recorded in boreholes within the concave scar had fallen by about 2 m on average from the level recorded in October 1995. This shows a trend of falling base groundwater level.

7. CONDITION OF DRAINAGE AND WATER-CARRYING SERVICES

During heavy rainfall on the morning of 14 August 1995, a large volume of surface water was seen flowing out of catchpits along Nam Long Shan Road south of the landslide area. The surface water flowed onto the road pavement, down Nam Long Shan Road and into the landslide scar. Based on measured depth, width and velocity of water flow, the rate of the water flow down Nam Long Shan Road was estimated to be about 350 litres per second. Subsequently, the drainage channels and catchpits at Nam Long Shan Road were examined. It was noted that some of the catchpits and cross-road drains along Nam Long Shan Road were partly blocked by old soil, vegetation and refuse.

The 1.2 m wide stepped-channel carrying water down the hillside between Nam Long Shan Road and Shum Wan Road was partly broken and buried by debris after the landslide (Figure 7). The condition of the broken portion of the stepped-channel before the landslide cannot be ascertained. However, a witness who walked part way up the stepped-channel one week before the landslide did not see any blockage of the channel. Some 20 m portion of the stepped-channel adjacent to the concave scar remained intact and clear after the landslide.

The water-carrying services along Nam Long Shan Road in the vicinity of the landslide were examined after the failure. The condition of the remaining sections of the sewer adjacent to the landslide was inspected by means of a closed-circuit television survey. The sewer was found to have cracked at a number of locations, and some joints were found to be displaced (DSD Survey, 1995). Subsequently, a section of the sewer with cracks and displaced joints was exposed by trenching (No. TT9). The sewer was found to comprise 0.7 m long earthenware pipes connected by rigid socket-and-spigot joints infilled with cement mortar. The pipes were haunched in concrete. A little brown staining was observed in the soil around the displaced joints, and there were no signs of erosion of the soil. The cracks in the pipes were tight. These observations indicated that, if the section of sewer within the landslide area was of similar condition, only minor leakage would have occurred from it prior to the landslide.

The private fresh-water main consisted of thread-coupled galvanised iron pipes. It was laid on the ground surface along the downhill side of the Nam Long Shan Road. No evidence of previous leakage from the remaining part of the water main, e.g. staining or erosion of adjacent ground, was observed in the investigation.

8. LIKELY MODE AND SEQUENCE OF FAILURE

The shape of the landslide surface, which comprises an upper concave scar and a lower planar scar, suggests that the failure consisted of two parts : an approximately spoon-shaped slip in the upper part of the hillside and a planar slip in the lower part of the hillside. Crucial to the reconstruction of the mode and sequence of failure are :

(a) the eye-witness accounts of the landslide (Section 5),

(b) concrete retaining wall fragments in the debris within the planar scar (Figure 9),

(c) fallen trucks, previously parked at the passing bay before the landslide, and pieces of bituminous pavements at the concave scar (Figure 9), and

(d) the 'slab' of debris of relatively intact weathered rock mass on the reclaimed land to the west of Shum Wan Road (Section 5).

Based on the available information, the most likely mode and sequence of the landslide have been reconstructed and are illustrated schematically in Figure 13.

The segregation of concrete retaining wall fragments in the landslide debris from other man-made objects from Nam Long Shan Road, including the fallen trucks and pieces of bituminous pavement and sewer (Figure 9), is best explained by a minor failure of the fill embankment below the passing bay before the main landslide (Figure 13(a)). The minor failure could either have been a shallow slip in the fill or erosion of the fill surface. Although signs of such erosion can be seen on the surface of the fill embankment in aerial photographs taken in 1988 and 1991, a shallow slip might also have been possible, However, sufficient evidence could not be found to establish the nature of the failure. The intense rainfall from 11 p.m. on 12 August to 3 a.m. on 13 August triggered this first failure.

This first failure would have displaced the concrete upstand at the downhill side of the passing bay but probably did not involve the southern concrete retaining wall. However, once the concrete upstand had been displaced, a large amount of surface water would have flowed from Nam Long Shan Road onto the fill embankment, scouring and infiltrating the fill and developing a perched water level in it, particularly in the rock fill (Section 6.2) behind the southern concrete retaining wall. This would have caused the collapse of the wall and the material behind it, probably in the form of a rapid flow. In the process, fragments of the southern concrete retaining wall would have been transported some distance down the hillside.

The main landslide occurred at about 4 a.m. The upper part of the hillside slipped partly on a clay seam in the partially weathered tuff. This failure was approximately spoon-shaped and took with it the passing bay (Figure 13(b)). Movement of the ground associated with this failure was reported by an eye-witness to be not rapid but continuous. It resulted in the deposition of pieces of bituminous pavement and utility pipes on the concave scar. Fragments of the southern concrete retaining wall that were deposited earlier on the upper part of the hillside would have moved with the debris further downhill.

The debris from this spoon-shaped failure loaded the lower part of the hillside and disturbed its equilibrium. The lower part of the hillside failed along a shallow planar surface sub-parallel to the ground surface (Figure 13(c)). This planar failure released a relatively thin layer of partially weathered tuff that slipped largely as an intact unit or 'slab' down the hill. The 'slab' pushed vegetation and top soil in front of it. Some of the pushed material and the front part of the 'slab' were deposited at the toe of the hillside (Figure 13(d)). The remaining portion of the 'slab' then overrode the deposited material and continued its journey towards the sea. The front of this 'slab' finally came to rest at a maximum distance of about 70 m from the toe of the hillside (Figure 13(e)).

A substantial part of the failed ground from the spoon-shaped slip in the upper part of the hillside was deposited on the planar scar in the lower part of the hillside. The southern concrete retaining wall fragments moved with the ground to rest on the planar scar some distance below the concave scar in the lower part of the hillside.

According to eye-witness accounts, Nam Long Shan Road did not collapse in the main landslide. The main landslide was followed by a few small slips cutting retrogressively up the hillside. A notable slip occurred about half an hour after the main event, resulting in the collapse of Nam Long Shan Road and deposition of debris onto the concave scar. The large zone of rock debris that rested on top of the remains of Nam Long Shan Road on the concave scar would have come from a later slip (Figure 13(f)).

After the main landslide at about 4 a.m., water from the broken water-carrying services and Nam Long Shan Road flowed down the landslide area. It eroded channels on the landslide and resulted in deposition of debris on the level ground at the foot of the hillside.

The above sequence of events is consistent with eye-witness accounts, the observed depositional sequence and characteristics of debris, and the estimated volume of material released in the landslide.

Other possible alternatives have also been considered, including initiation of the main landslide by the lower planar slip and occurrence of the upper spoon-shaped slip some time before the main landslide at 4 a.m. These alternatives are discounted because they would not match the eye-witness accounts and physical evidence from the locations of man-made objects.

9. THEORETICAL STABILITY AND SEEPAGE ANALYSES

9.1 General

To check that the mechanism proposed in Section 8 is theoretically admissible, two sets of limit equilibrium slope stability analyses, one for the spoon-shaped slip in the upper part of the hillside and the other for the planar slip in the lower part of the hillside, were carried out. The representative cross-sections for the analyses are shown in Figure 14. Limit equilibrium slope stability analyses were also carried out to assess the stability of the fill embankment below the collapsed passing bay. In addition, a set of seepage analyses were conducted to examine the effects of various water sources on the groundwater conditions at the upper part of the hillside.

9.2 Upper Part of Hillside

Theoretical analysis of the fill embankment by the method of slices, using the rigorous solution given by Morgenstern & Price (1965), confirms that a shallow slip is possible when the fill is saturated by water.

In the concave scar area, the post-failure base groundwater level was well below the landslide surface (Section 6.4). Theoretical analyses by the method of slices show that this part of the hillside would be stable under such a deep base groundwater condition. Perched water, however, was observed on the clay seam which formed part of the landslide surface of the concave scar (Section 6.2). The associated porewater pressure could have rendered the ground unstable. The theoretical perched water level needed for limit equilibrium depends on the shear strength of the clay seam. The ground could theoretically have failed under a high perched water level of 4 to 5 m coupled with the peak shear strength for the clay seam, or alternatively under a low perched water level of 1 to 2 m if the clay seam had a shear strength close to that of the clay with slickensiding (Figure 15(a)).

The four sources of perched water that can be postulated are :

(a) direct infiltration of incident rainfall into the ground in the hillside below Nam Long Shan Road,

(b) subsurface water flow from the natural ground above Nam Long Shan Road,

(c) water discharged from Nam Long Shan Road, and

(d) leakage from water-carrying services along Nam Long Shan Road.

About 380 mm of rain had fallen directly on the landslide area during the 30 hours prior to the main landslide. Water could have infiltrated the fill embankment below the passing bay and seep through the underlying partially weathered tuff. Seepage analysis using a finite element computer program (Figure 16) shows that this incident rainwater alone could have caused a low head (about 1 m) of perched water to build up on the clay seam.

Subsurface water flow associated with the rainstorm in early August could have reached the landslide area from the natural ground further uphill by 13 August. Seepage analysis using the finite element program suggests that such recharge would have contributed largely to the base groundwater but little to the perched water level on the clay seam at the site. The level of perched water that could have built up cannot be assessed reliably, but the result suggests that it is likely to be low (about 1 m).

The above theoretical assessments suggest that rainfall infiltration alone would not have resulted in a significant perched water level. Theoretical calculations also show that any minor leakage from the sewer or the water main could not have caused the build up of a significant perched water level.

It is estimated that, upon displacement of the concrete upstand at the passing bay by the minor failure of the fill embankment, hundreds of cubic metres of water would have discharged from Nam Long Shan Road at the landslide location in one hour. This amount of water far exceeded the amount of rain falling directly on the fill embankment. Some of the water would have infiltrated the relatively permeable partially weathered tuff. Seepage analyses show that a high perched water could have developed, the height of which depends on the duration of the water flow. For example, a perched water level of about 5 m could theoretically have developed with three hours of water flow from Nam Long Shan Road.

9.3 Lower Part of Hillside

At the location of the planar scar, ground investigation showed that the base groundwater level was closer to the pre-failure ground surface than in the concave scar. Theoretical stability analyses by the limit equilibrium method, using the infinite slope solution, show that the ground could theoretically have become unstable under a range of base groundwater levels between zero and 1 m below ground, depending on the proportion of clay-infilled joints along the landslide surface (Figure 15(b)).

The failure mass from the upper spoon-shaped slip would have loaded the lower part of the hillside and reduced its factor of safety.

10. DIAGNOSIS OF THE CAUSES OF THE LANDSLIDE

It is known from the location of debris from the retaining wall that the main landslide at about 4 a.m. was preceded by a minor failure at the fill embankment below the passing bay. Results of stability analyses show that a shallow slip could have occurred in the fill embankment when the fill was saturated by water. The minor failure could also be the result of erosion of the fill surface. However, there was insufficient evidence to establish which mode of failure was more likely. In either case, the water that triggered the minor failure could have been rainwater falling directly on the fill or water spilling from Nam Long Shan Road, or a combination of both.

The main landslide comprised two parts, an upper spoon-shaped slip and a lower planar slip. The upper spoon-shaped slip was triggered by perched water pressure on a weak clay seam. At this location, the base groundwater level was well below the landslide surface (Section 6.4). Field monitoring of groundwater pressures and theoretical analyses do not support a hypothesis that the slip was caused by a significant rise (more than 6 m) of the base groundwater level. The clay seam was much weaker than the adjacent partially weathered tuff, and it formed a weak plane for a substantial part of the base of the upper spoon-shaped slip.

From the results of theoretical analyses, the upper spoon-shaped slip could have resulted from a high perched water level (4 to 5 m) coupled with an operational shear strength of the clay without slickensiding, i.e. $c' = 8$ kPa, $\phi' = 26°$. A high perched water level was possible based on seepage analyses (Section 9.2), given the large amount of water that would have discharged from Nam Long Shan Road after the minor failure of the fill embankment (Section 8) and the measured permeability of the partially weathered tuff with closely-spaced joints (Table 3). The high perched water hypothesis is therefore credible.

Slickensiding was observed in a small area in the clay seam (Section 6.2). The shear strength of the slickensided clay was found to be low ($\phi' = 21°$). Had the slickensiding been extensive, a relatively low perched water level could have triggered the landslide (1 to 2 m for $\phi' = 21°$). Such a low perched water level could be developed by direct rainfall infiltration and subsurface water recharge from the natural ground uphill. A similar infiltration condition is likely to have occurred regularly in the past, and the low perched water hypothesis could therefore not explain why the hillside did not fail in past rainstorms. This hypothesis also suggests that the fill embankment failure would have been immaterial to the landslide, and that the timing of the fill embankment failure and the main landslide were coincidental. The high perched water hypothesis is much more likely than the low perched water hypothesis.

The base groundwater level at the location of the lower planar slip was high, attributed to the prolonged heavy rainfall in July and early August, and it was about 1 to 3 m below the pre-failure ground surface in October 1995. From the falling trend in the period of October to December 1995 (Section 6.4), the base groundwater level in August 1995 would have been higher, especially during the intense rainfall in the 30 hours before the landslide when the water level could have been very close to the pre-failure ground surface. Theoretical stability analyses show that the 'slab' of partially weathered tuff in this area could have failed, partly along clay-filled joints, under such groundwater conditions (Section 9.3). The loading associated with the debris from the spoon-shaped slip above would have triggered the failure.

11. OTHER CONCEIVABLE FACTORS

After the landslide, witnesses reported observations of factors which might have contributed to the landslide. These include previous squatter activities, illegal dumping and passage of heavy construction vehicles. The effects of these factors have been examined in the investigation and were found to be not significant, as discussed below.

Previous squatter activities in the area of the planar slip had modified the landform, e.g. cutting of the hillside for squatter platforms. This could have affected the stability of the 'slab' of partially weathered tuff by weakening its toe support in the lower part of the hillside. However, this is insignificant compared to the resistance against sliding provided by the base of the 'slab'.

Illegal dumping of refuse and construction waste on the hillside downslope of Nam Long Shan Road might have resulted in ponding of water and might have promoted infiltration. However, the rainfall prior to the minor failure of the fill embankment was not heavy enough to exceed the rate of infiltration, and rainwater would therefore have infiltrated the ground without much surface runoff and ponding. After the failure of the fill embankment, the large amount of water from Nam Long Shan Road would have allowed continuous infiltration even without ponding. Illegal dumping would also have imposed an additional surcharge, but this would have been insignificant to the stability of the large hillside and is therefore not considered to have been a contributory factor.

The passage of heavy construction vehicles on Nam Long Shan Road would have imposed a surcharge on the road embankment and might have damaged the concrete upstand at the edge of the passing bay. The surcharge effect was negligible compared to the mass of the soil. It is not known whether the concrete upstand had been damaged by vehicles but, if it had, water from Nam Long Shan Road would readily have discharged onto the fill embankment. It is not possible to obtain evidence on the state of the concrete upstand immediately before the landslide to judge whether the passage of heavy construction vehicles contributed to the failure in this manner.

12. CONCLUSIONS

The main landslide involved two distinct parts that occurred almost simultaneously. The failure was caused principally by :

(a) the presence of weak layers in the ground, i.e. clay seams and clay-infilled joints,

(b) ingress of water during prolonged heavy rainfall,

(c) a minor failure of the fill embankment below a passing bay on Nam Long Shan Road, and

(d) water flowing along Nam Long Shan Road, because of partial blockage of its drainage system, and discharge of part of this water onto the hillside.

13. REFERENCES

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LIST OF TABLES

Table 1 - Summary of Classification and Index Test Results

Material Type	Sample Location	Depth (m)	Sample Type	Particle Size Distribution				LL (%)	PL (%)	PI (%)	Moisture Content (%)	Specific Gravity
				Gravel (%)	Sand (%)	Silt (%)	Clay (%)					
CDT	S2	Near ground surface	Block	1	17	44	38	67	30	37	29.4 29.2 29.6 30.6	2.64
CDT	S4	Near ground surface	Block	0	8	64	28	48	33	15	30.3 38.6 38.4	2.64
CDT	S5	Near ground surface	Block	1	17	63	19	48	28	20	30.0 35.2 33.4	2.63
CDT	BH3	1.78 - 1.98	Mazier	2	34	42	22	-	-	-	27.4	2.62
Yellowish brown clay	S8	Near ground surface	Block	0	8	28	64	99	39	60	45.6 53.3 52.3	2.63
Yellowish brown clay	S9	Near ground surface	Block	0	12	48	40	123	48	75	63.0	2.62
Fill	TP10	0 - 1 m	Bulk	6	26	54	14	35	21	14	-	-
Fill	TP11	0 - 1 m	Bulk	21	17	42	20	39	22	17	-	-
Fill	TP12	0 - 1 m	Bulk	37	13	38	12	35	21	14	-	-
Fill	TP13	0 - 1 m	Bulk	5	17	49	29	57	24	33	-	-
Fill	TP14	0 - 0.5 m	Bulk	6	29	42	23	41	23	18	-	-

Legend :

CDT	Completely Decomposed Tuff	LL	Liquid Limit	PL	Plastic Limit
PI	Plasticity Index	BH3	Borehole No.3	S2	Block sample No.2
TP10	Trial pit No.10				

Note : Tests were carried out in accordance with Chen (1994).

Table 2 - Results of Density Tests on Fill Material

Trial Pit	Depth (m)	Materials	Insitu Dry Density (Mg/m^3)	Insitu Moisture Content (%)	Laboratory Maximum Dry Density (Mg/m^3)	Optimum Moisture Content (%)	Relative Degree of Compaction (%)
TP10	0	Yellowish brown gravelly sandy silt/clay	1.26	22	1.75	18	72.0
	0.5		1.30	21			74.3
	1.0		1.34	21			76.6
TP11	0	Yellowish brown slightly gravelly sandy silt/clay	1.25	24			71.4
	0.5		1.29	24			73.7
	1.0		1.27	25			72.6
TP12	0	Yellowish brown gravelly sandy silt/clay	1.39	20			79.4
	0.5		1.33	23			76.0
	1.0		1.25	24			71.4
TP14	0.5	Yellowish brown gravelly sandy silt/clay	1.18	15	1.65	21	71.5
	0.5		1.35	14			81.8
Note :	See Table 1 for classification and index properties of fill.						

Table 3 - Results of Permeability Tests

Material	Type of Test	Coefficient of Permeability (m/s)
Completely to highly decomposed tuff	Falling head test in boreholes	1.3×10^{-5} to 8.0×10^{-5}
Moderately to slightly decomposed tuff with closely spaced joints	Packer test and falling head test in boreholes	1.2×10^{-5} to 6.4×10^{-5}
Slightly decomposed tuff with closely spaced joints	Packer test in boreholes	1.3×10^{-5} to 1.8×10^{-5}
Slightly decomposed tuff	Packer test in boreholes	6.6×10^{-9} to 4.3×10^{-7}

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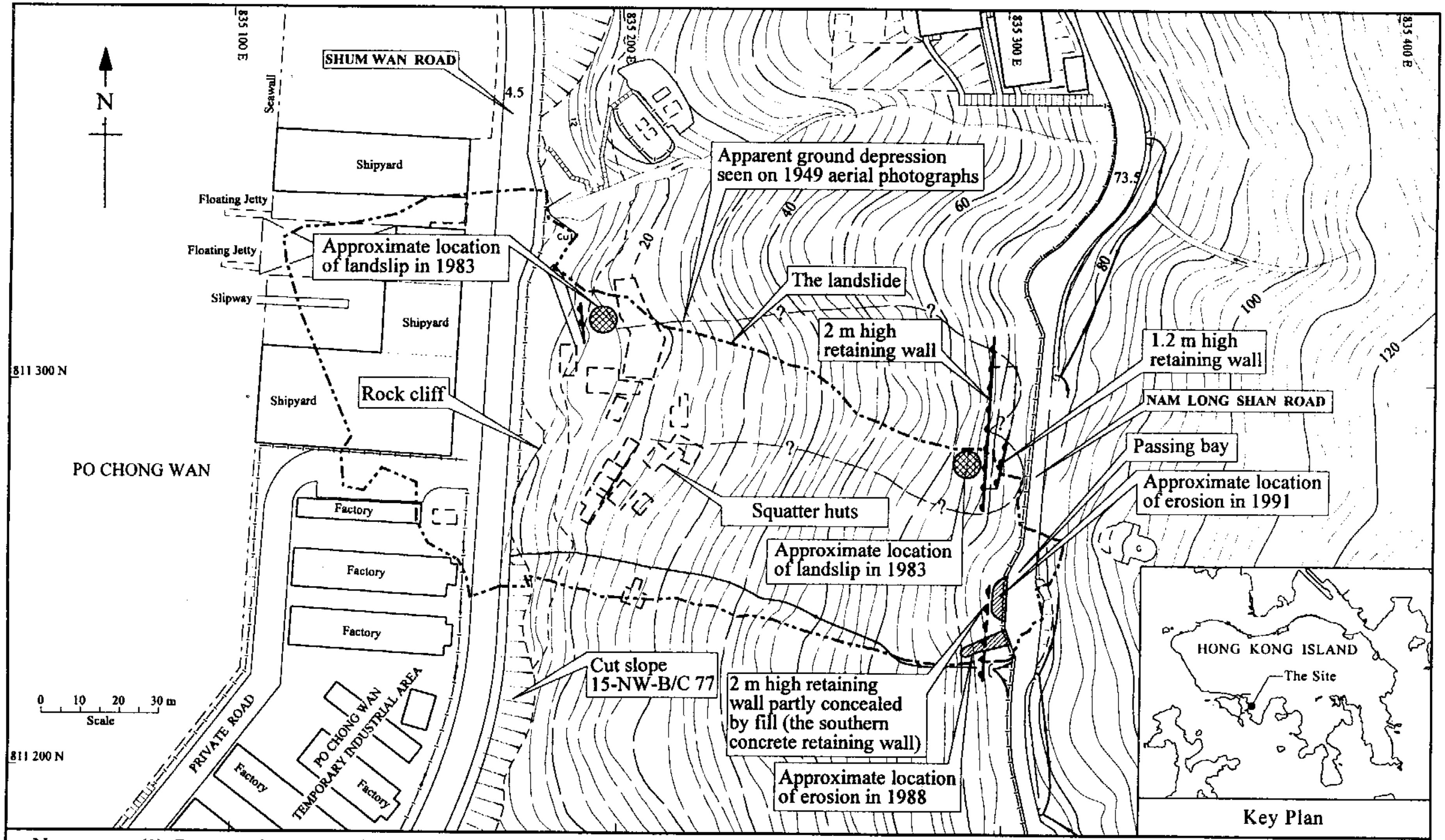


Notes : (1) Base map is extracted from Survey Sheets No. 15-NW-4C & No. 15-NW-4D, dated August 1992 & September 1992 respectively, scale 1 : 1000.
(2) Locations of squatter huts are based on Survey Sheet No. 15-NW-4C, dated October 1984, scale 1 : 1000.

Figure 1 - Site Plan

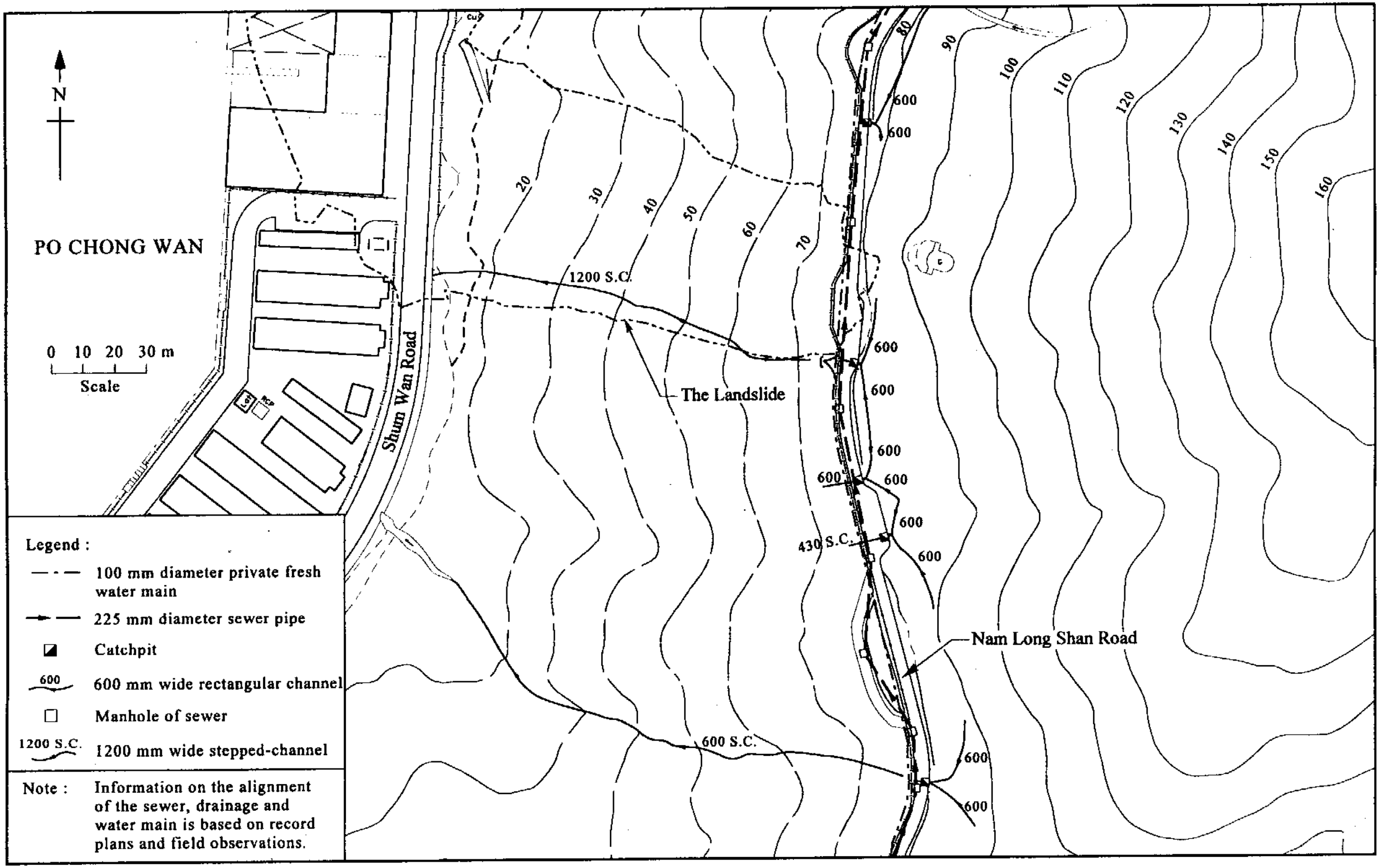
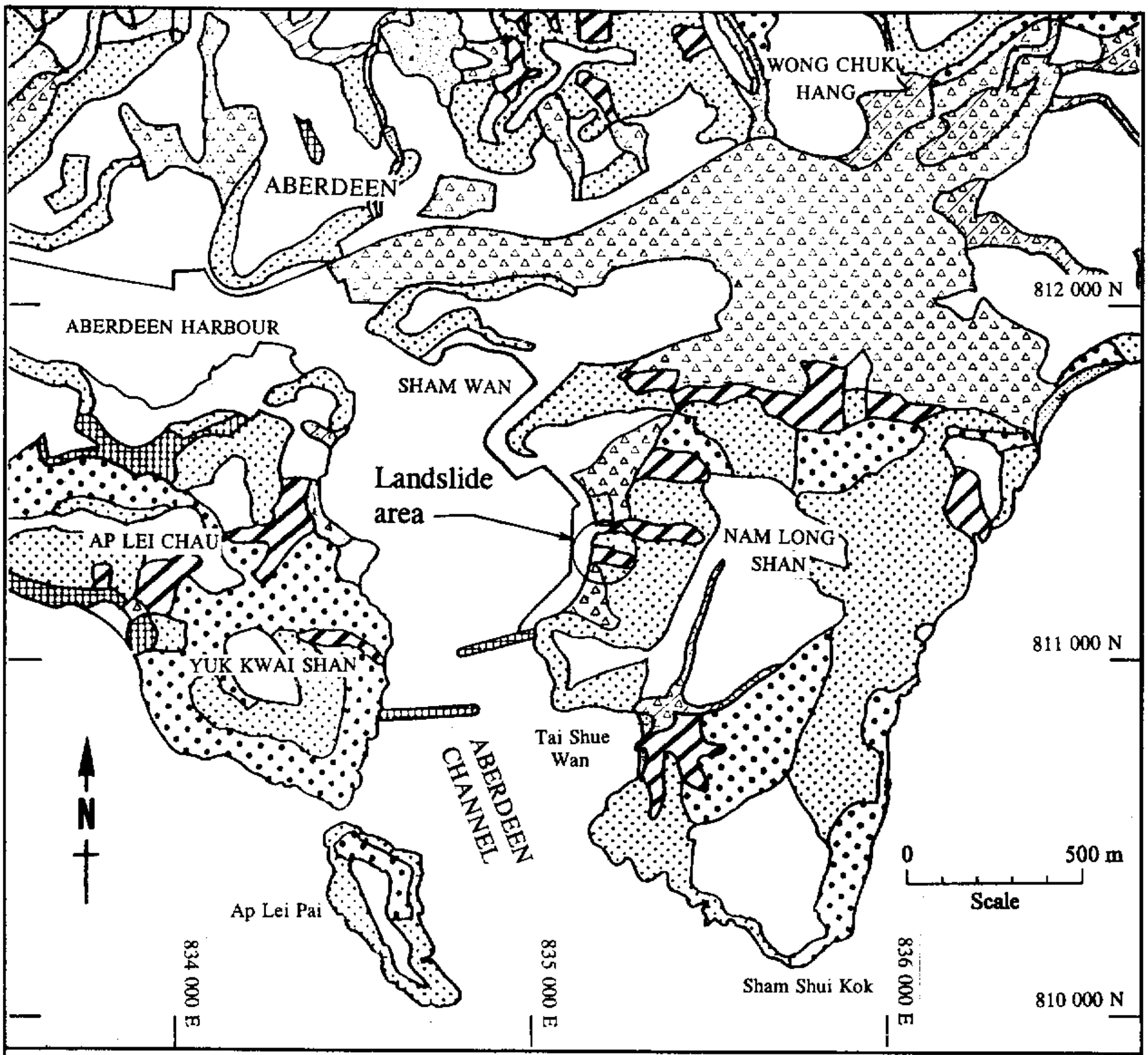


Figure 2 - Layout of Drainage and Water-carrying Services at Nam Long Shan Road



Legend :

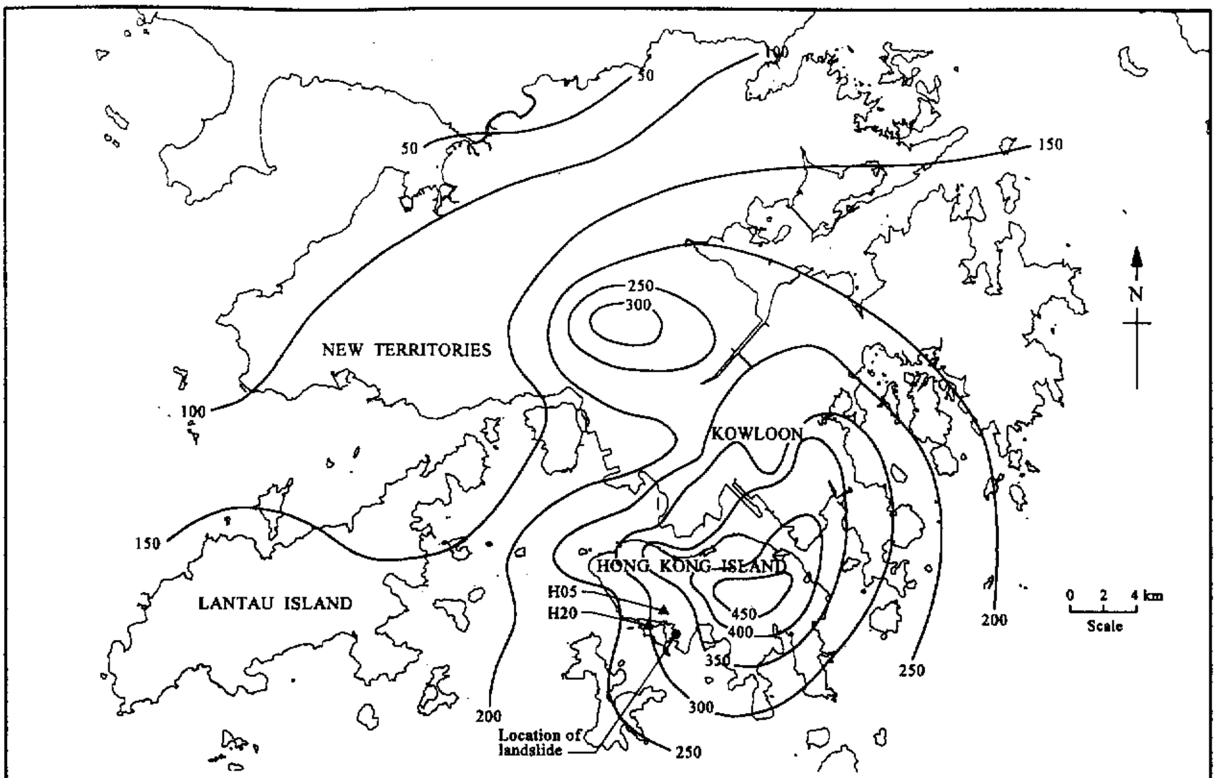
△	Colluvium
△▧	Zones of colluvium which are subject to overland flow and periodic inundation. Evidence of unusual groundwater regime (delineated as drainage plain on Landform Map)
▧	Floodplain - subject to overland flow and regular inundation. Evidence of unusual groundwater regime (delineated as floodplain on Landform Map)
▨	Zones of general instability associated with predominantly colluvial terrain
●	Zones of general instability associated with predominantly insitu terrain
░	Slopes on insitu terrain which are generally steeper than 30 degrees (other than those delineated as colluvial or unstable)

Notes :

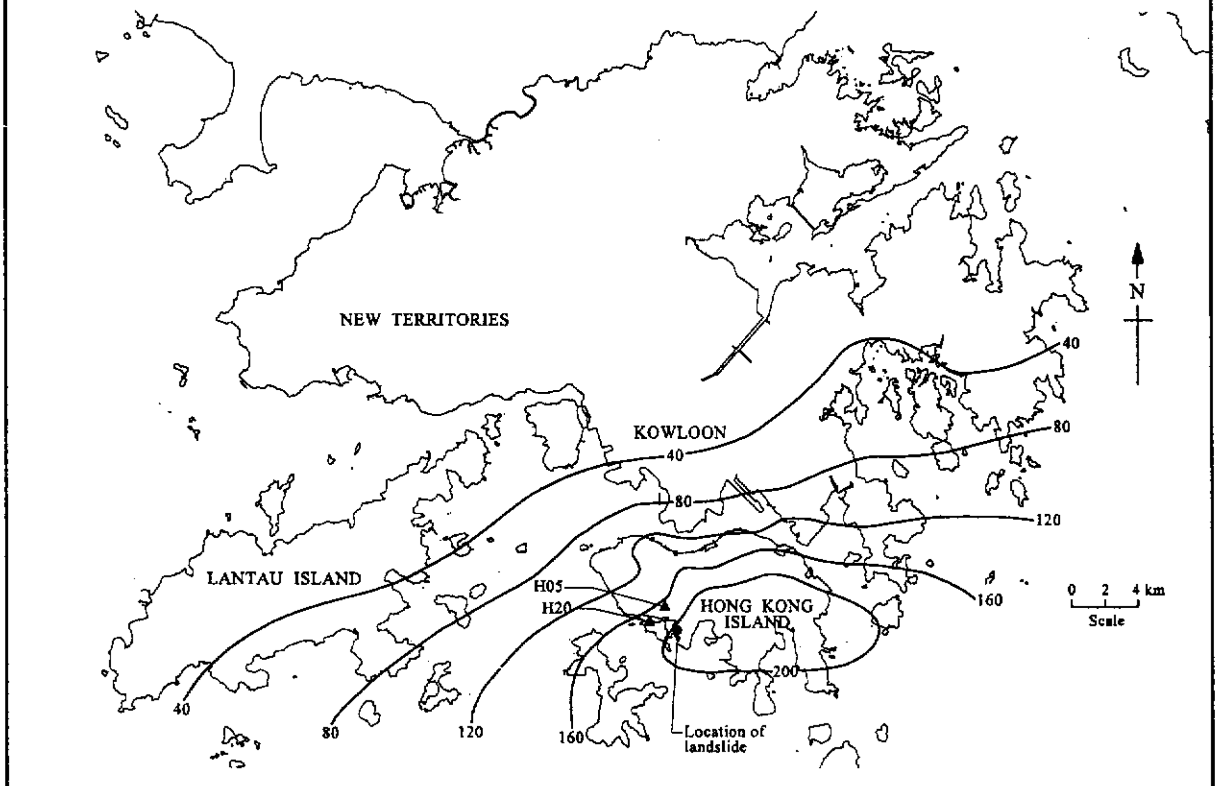
(1) Figure reproduced from map GASP/20/1/6, scale 1 : 20000, produced in the Geotechnical Area Studies Programme (Geotechnical Control Office, 1987a).

(2) The Physical Constraints Map should be used only as a guide to the general nature of terrain-related constraints for regional planning purposes. It is produced at a scale of 1:20 000 and should not be used to evaluate parcels of land smaller than 3 ha in size.

Figure 3 - Physical Constraint Map of the Landslide Area



(a) Rainfall Distribution from 04:00 Hours on 12 August 1995 to 04:00 Hours on 13 August 1995

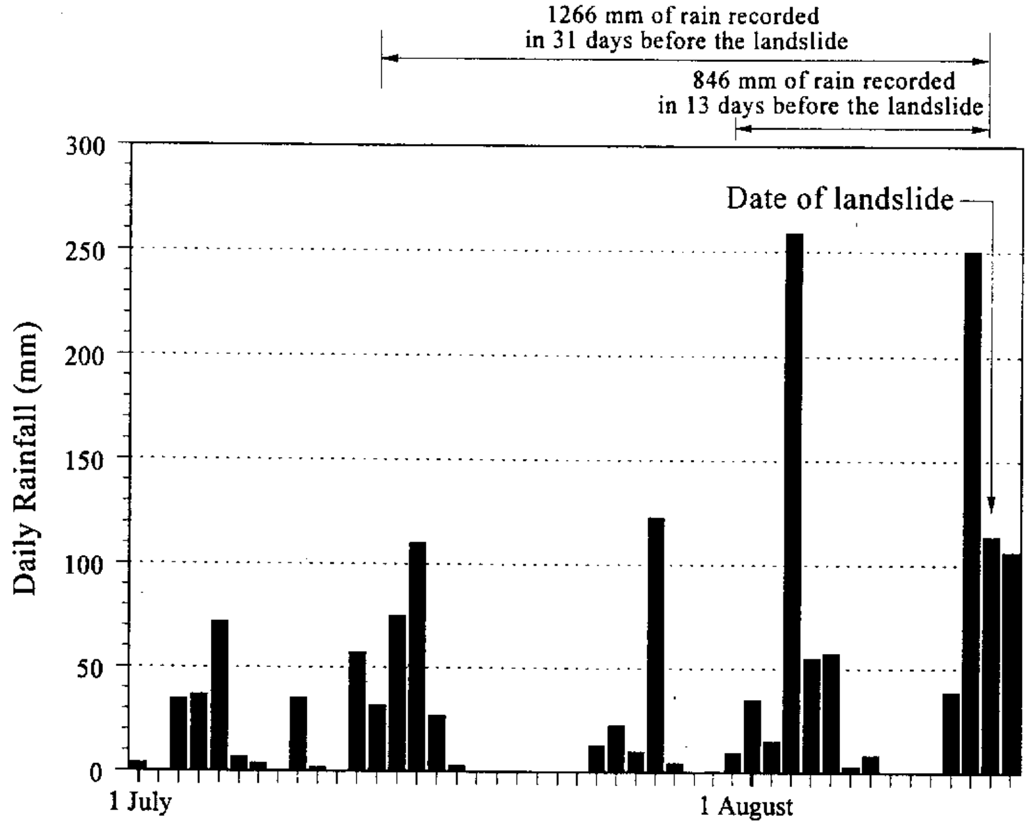


(b) Rainfall Distribution from 23:00 Hours on 12 August 1995 to 03:00 Hours on 13 August 1995

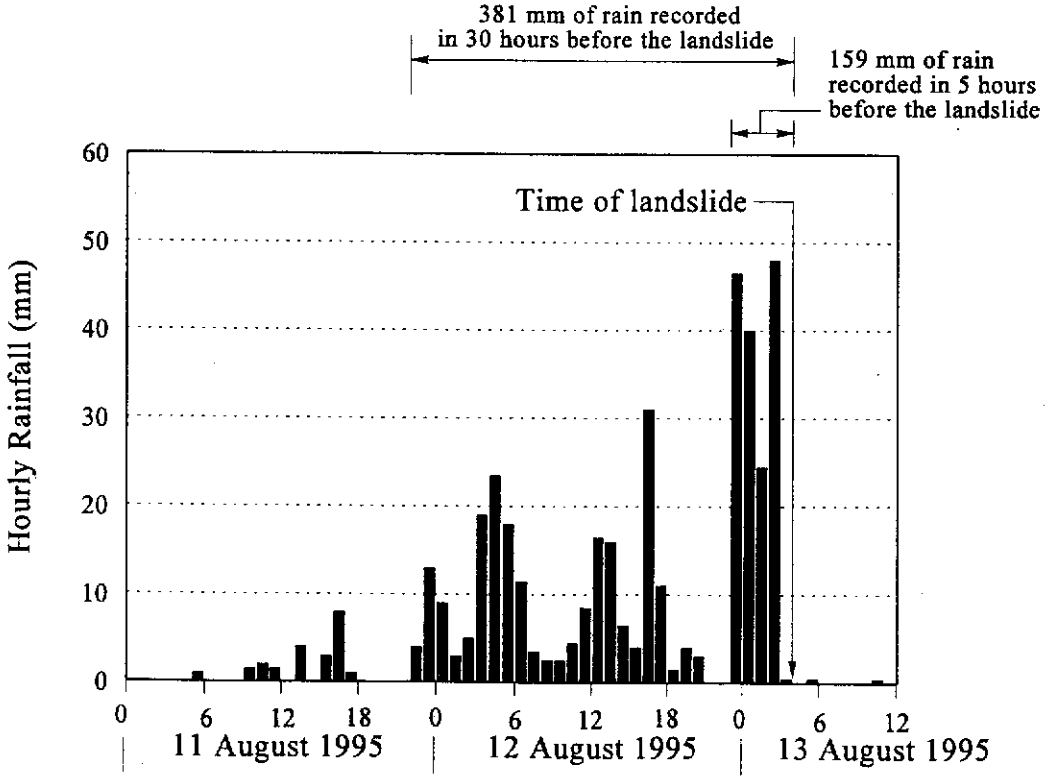
Legend :

–200–	Isohyet of rainfall in millimetres	▲	GEO Raingauge

Figure 4 - Rainfall Distribution Prior to the Landslide



(a) Daily Rainfall Intensity in July and August 1995



(b) Hourly Rainfall Intensity from 11 to 13 August 1995

Figure 5 - Rainfall Record of GEO Raingauge No.H05

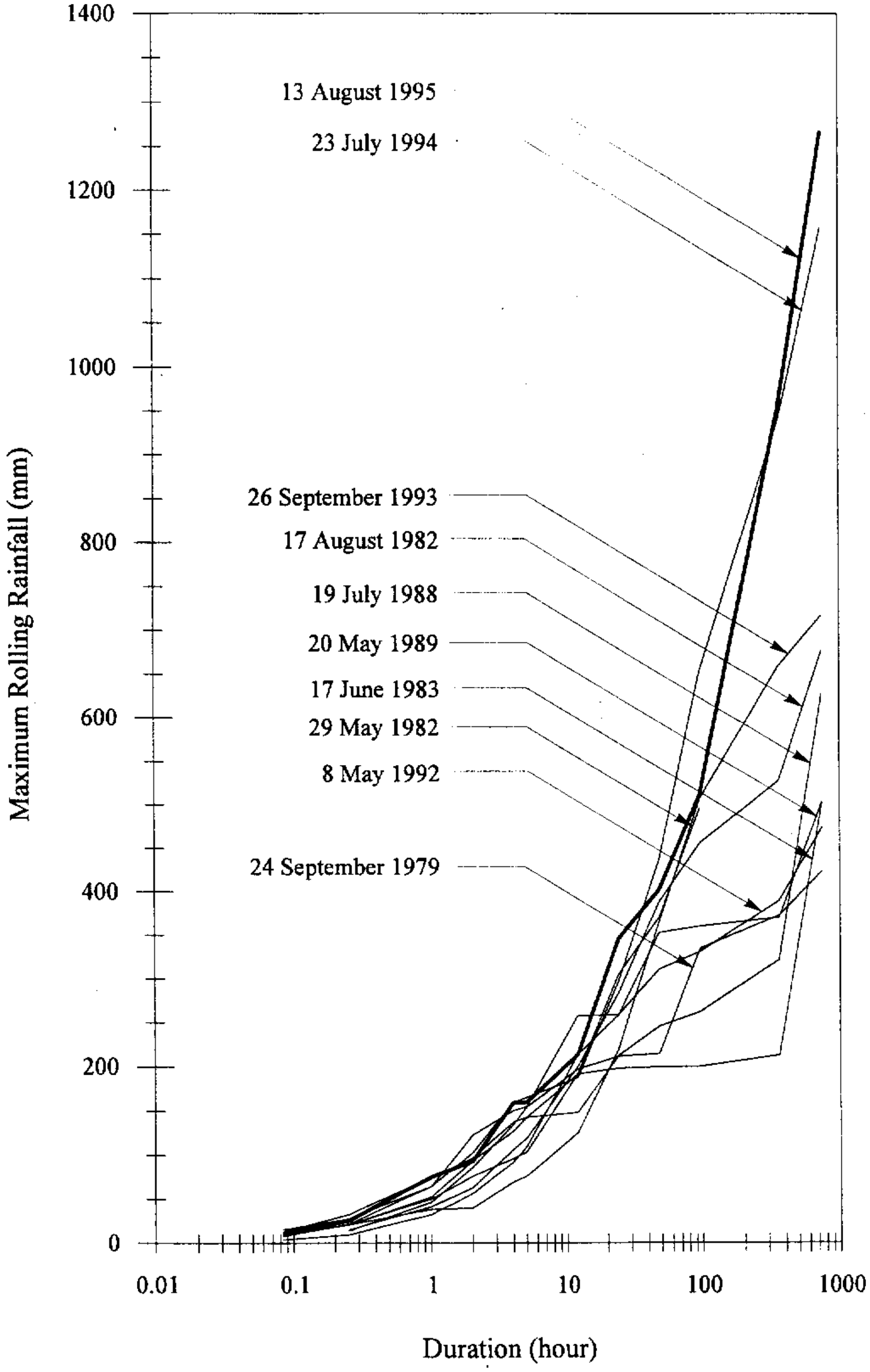
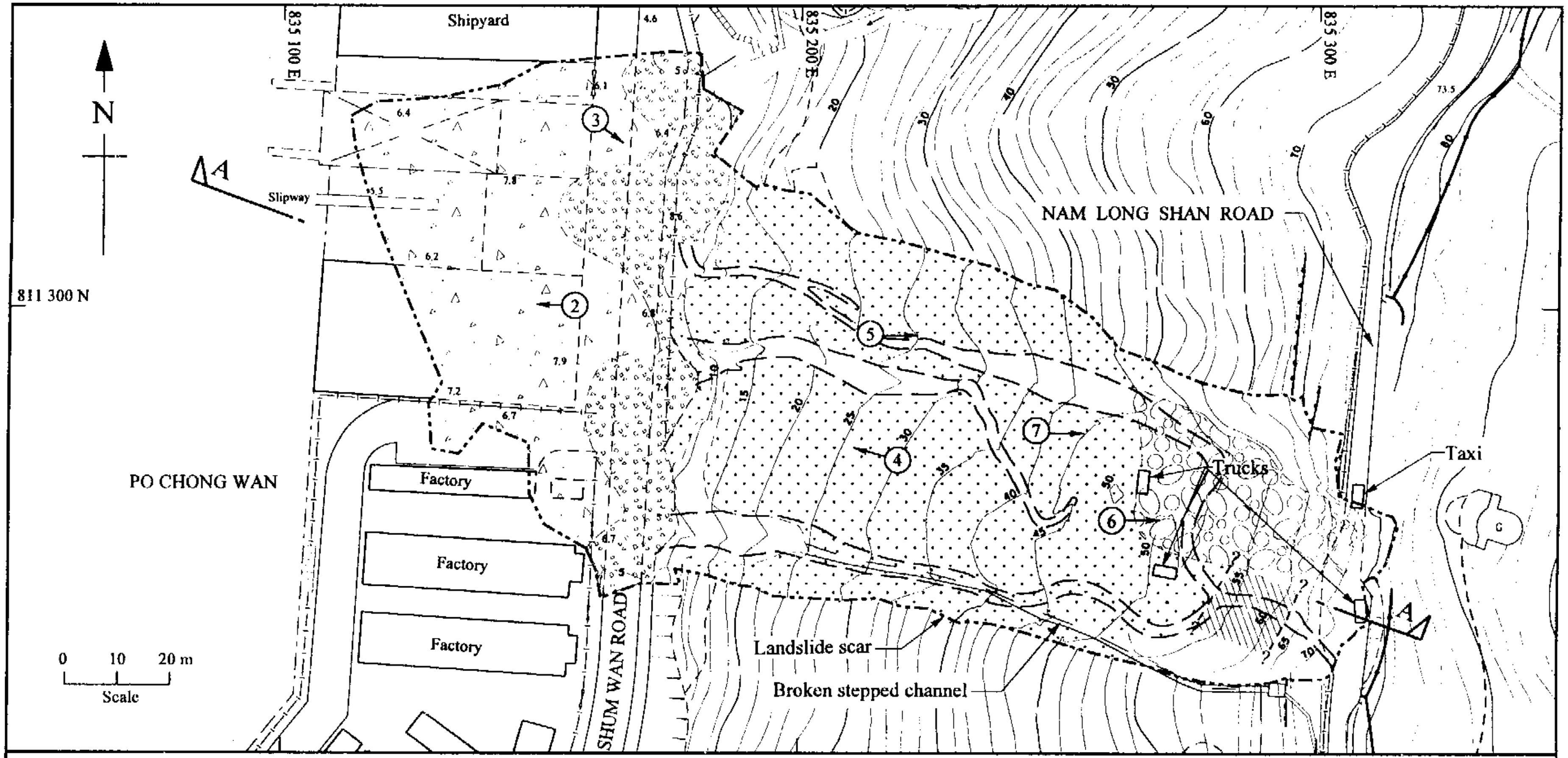
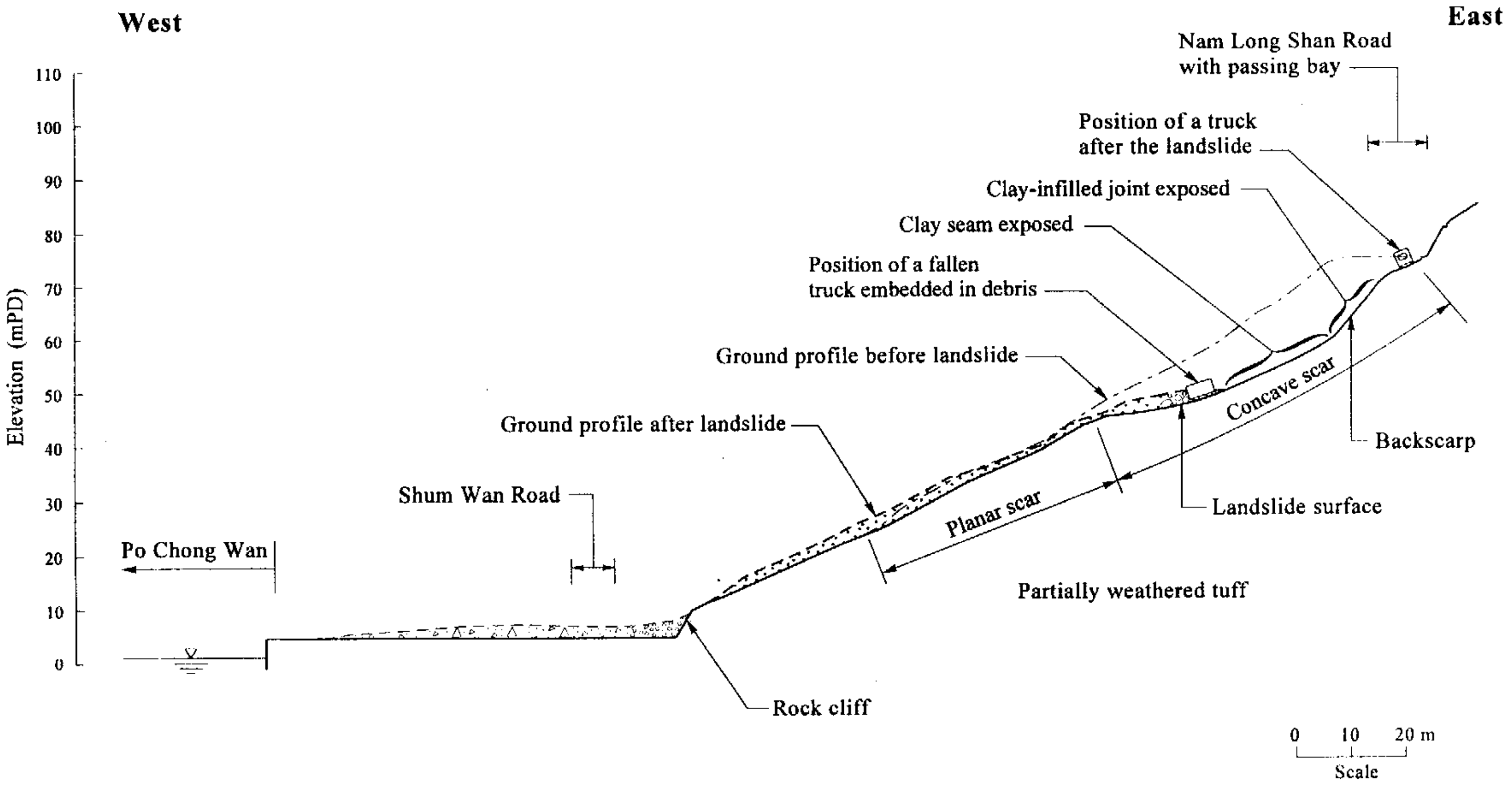


Figure 6 - Maximum Rolling Rainfalls at Raingauge No. H05 for Major Rainstorms



Notes :
(1) See Figure 8 for Section A-A.
(2) Information shown in this Figure is based on topographic survey, geological mapping and field observations carried out between 13 August and 23 November 1995.

Figure 7 - Plan of the Landslide



Notes : (1) See Figure 7 for location of section and legend of debris.

(2) Information shown in this Figure is based on topographic survey, geological mapping and field observations.

Figure 8 - Section A-A through the Landslide

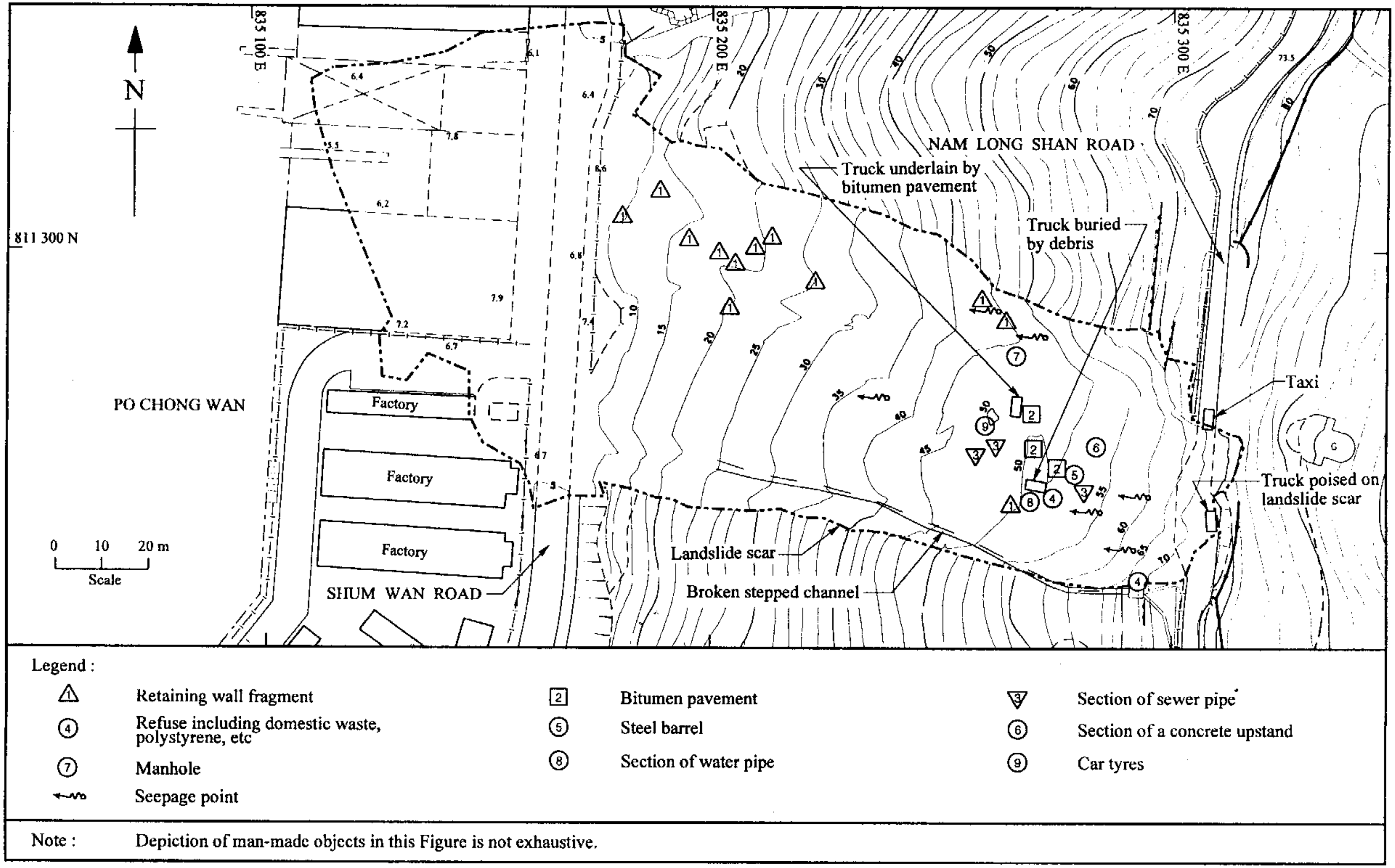


Figure 9 - Locations of Man-made Objects and Seepage Points

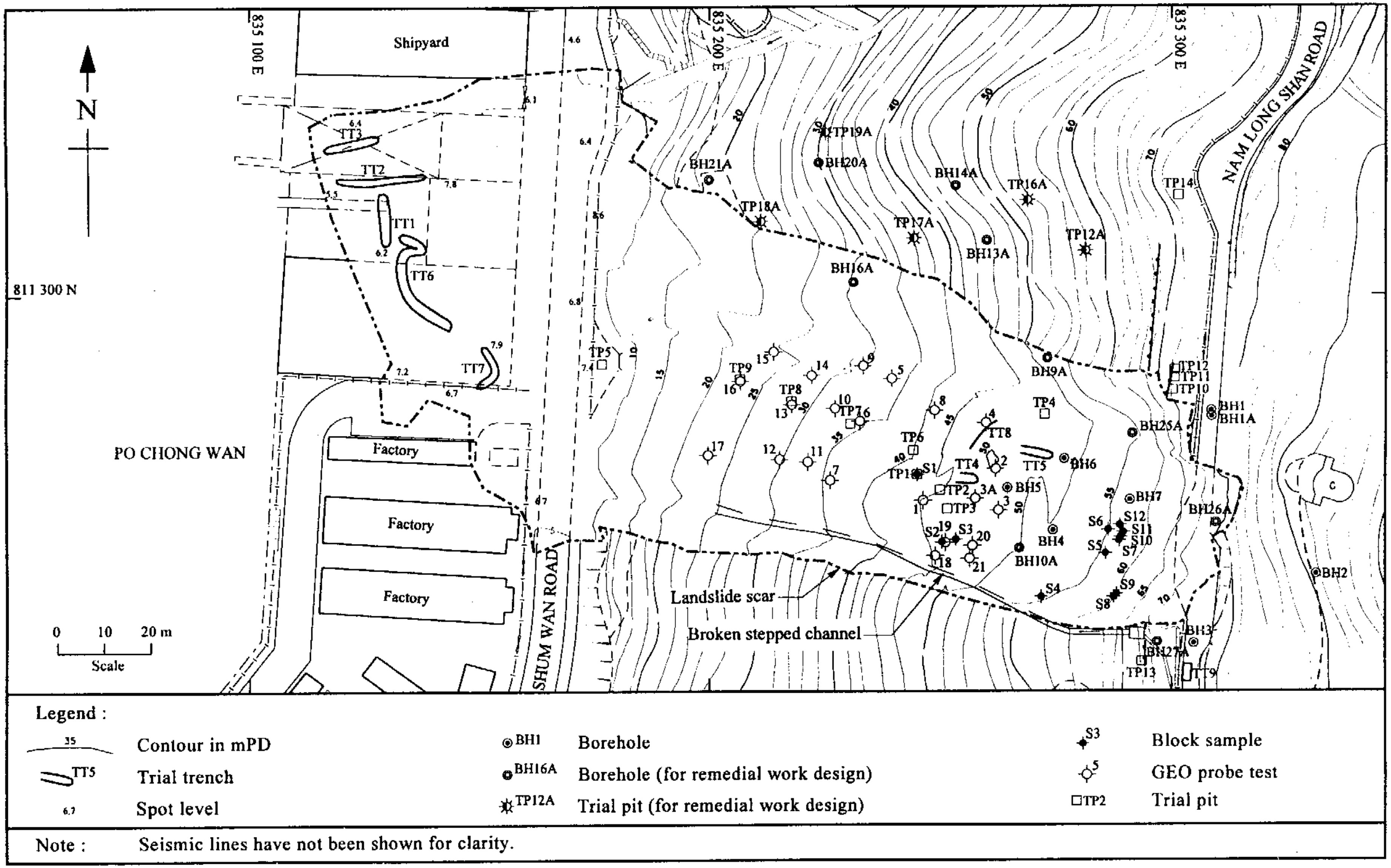
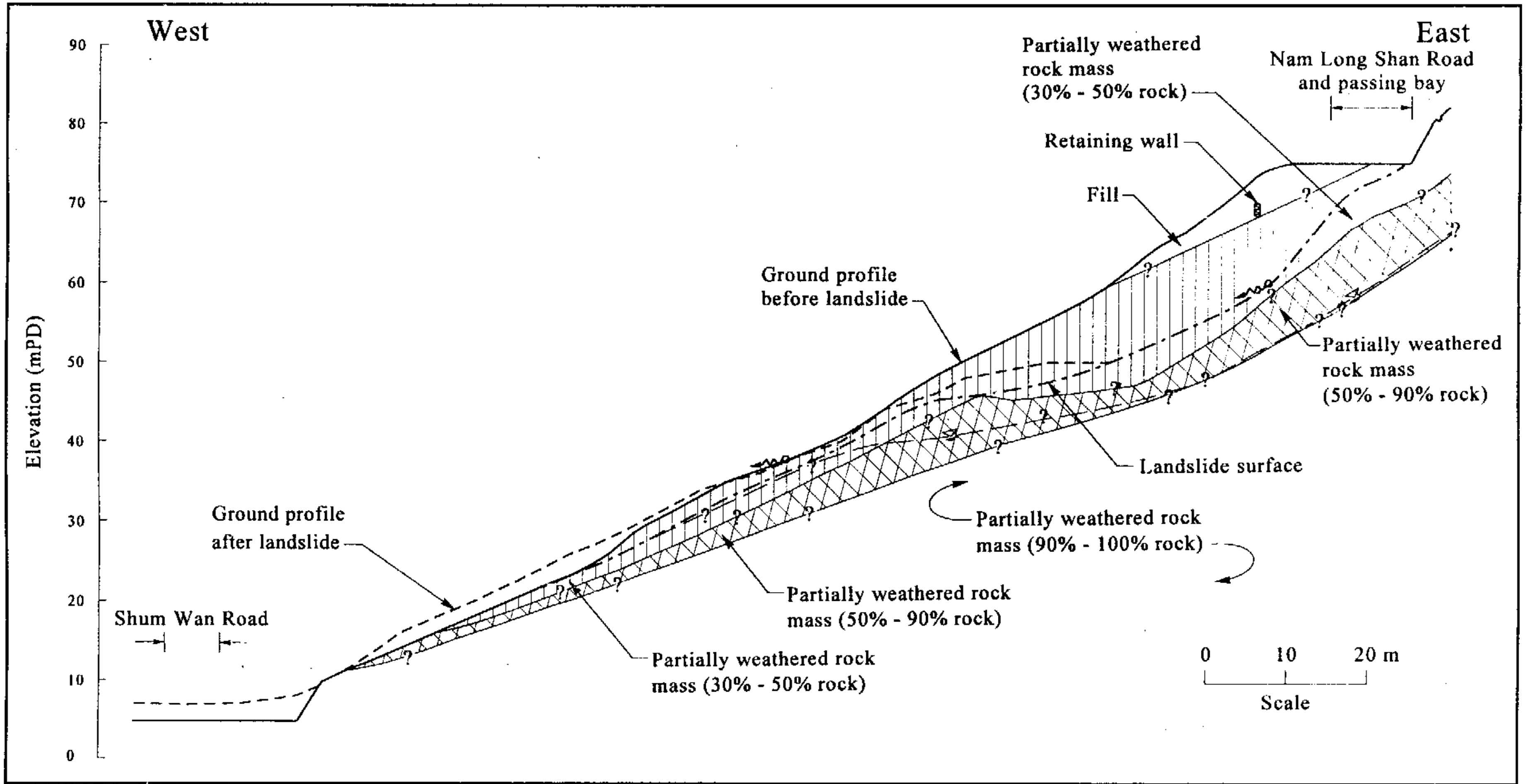


Figure 10 - Location Plan of Ground Investigation Work



Legend :

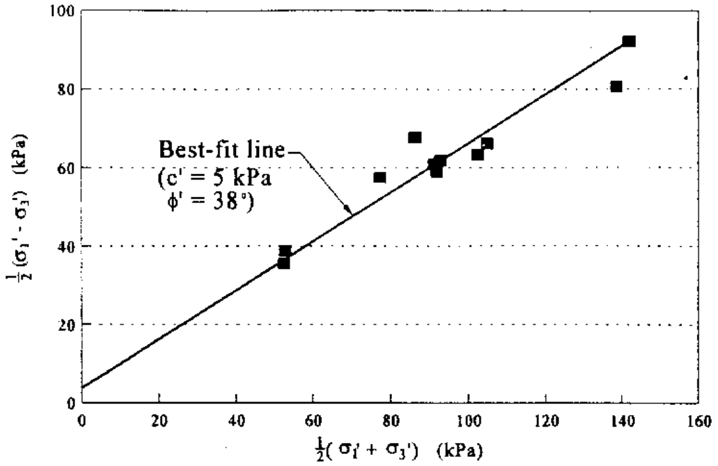
Seepage points observed one week after the landslide

Water level assessed from observations made on 28 October 1995

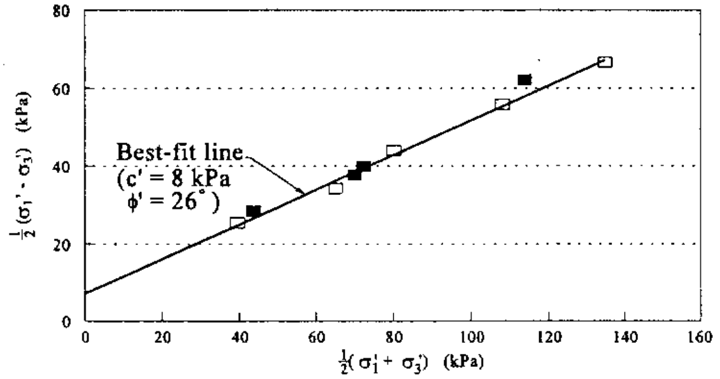
Notes :

(1) Location of this section corresponds to Section A - A in Figure 7.
(2) The extent of fill is estimated based on aerial photographs taken in 1963 and 1994.
(3) The thin layer of colluvium has not been shown for clarity.

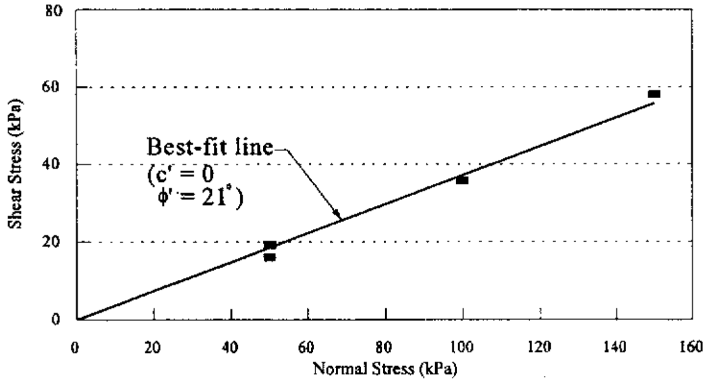
Figure 11 - Geological Section of the Site before the Landslide



(a) Results of Isotropically Consolidated Undrained Triaxial Compression Test with Porewater Pressure Measurement for Completely Decomposed Tuff



(b) Results of Isotropically Consolidated Undrained Triaxial Compression Test with Porewater Pressure Measurement for Yellowish Brown Clay in the Clay Seam



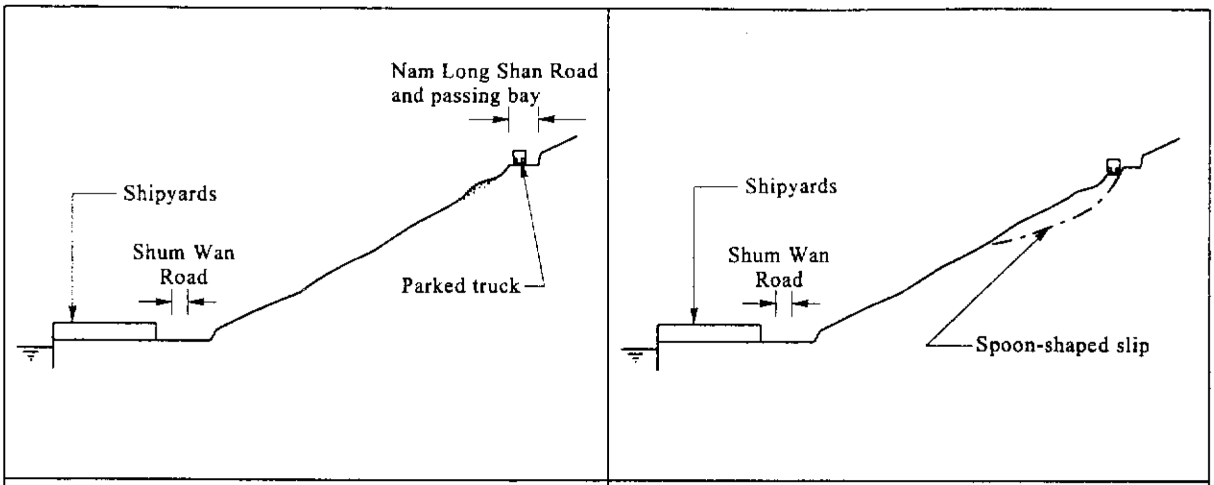
(c) Direct Shear Test Results for Slickensided Surface of Clay in the Clay Seam

Legend :

σ_1'	Major principal effective stress	■	'Undisturbed' block sample
σ_3'	Minor principal effective stress	□	Remoulded sample
c'	Apparent cohesion	φ'	Angle of shearing resistance

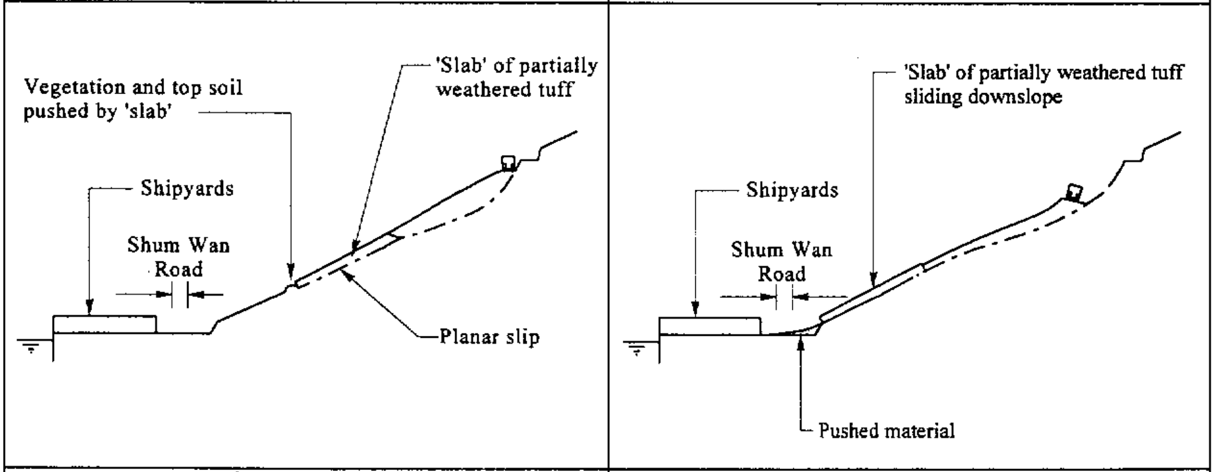
Note : The data points in Figures (a) & (b) are taken from test results at peak σ_1'/σ_3' ratio.
The data points in Figure (c) are taken from test results at the end of testing.

Figure 12 - Shear Strength of Materials



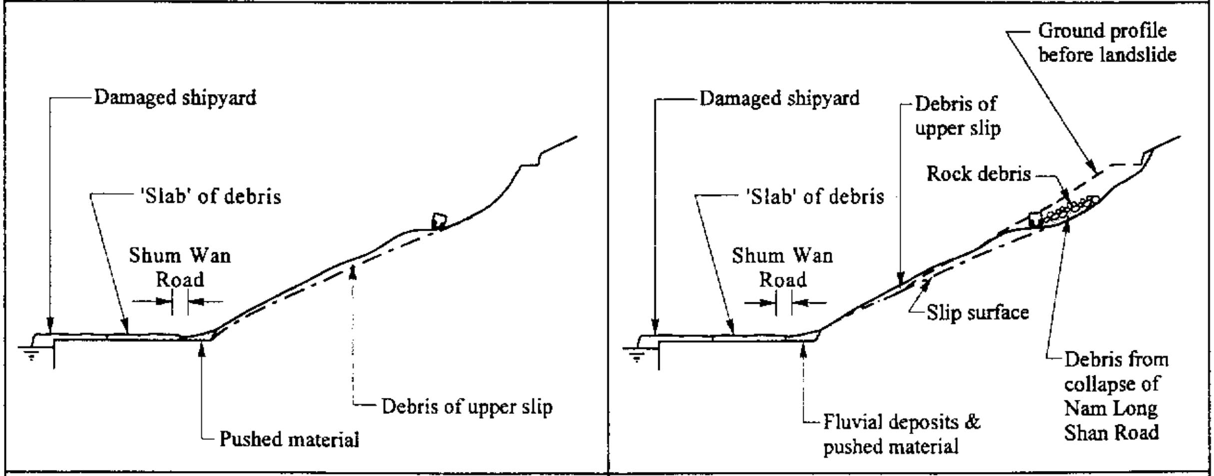
(a) Minor failure occurred at the fill embankment below the passing bay prior to the main landslide (between 11 p.m. and 3 a.m.).

(b) Spoon-shaped slip started at the upper part of the hillside (about 4 a.m.).



(c) Failed mass from upper slip initiated another slip at the lower part of the hillside (about 4 a.m.).

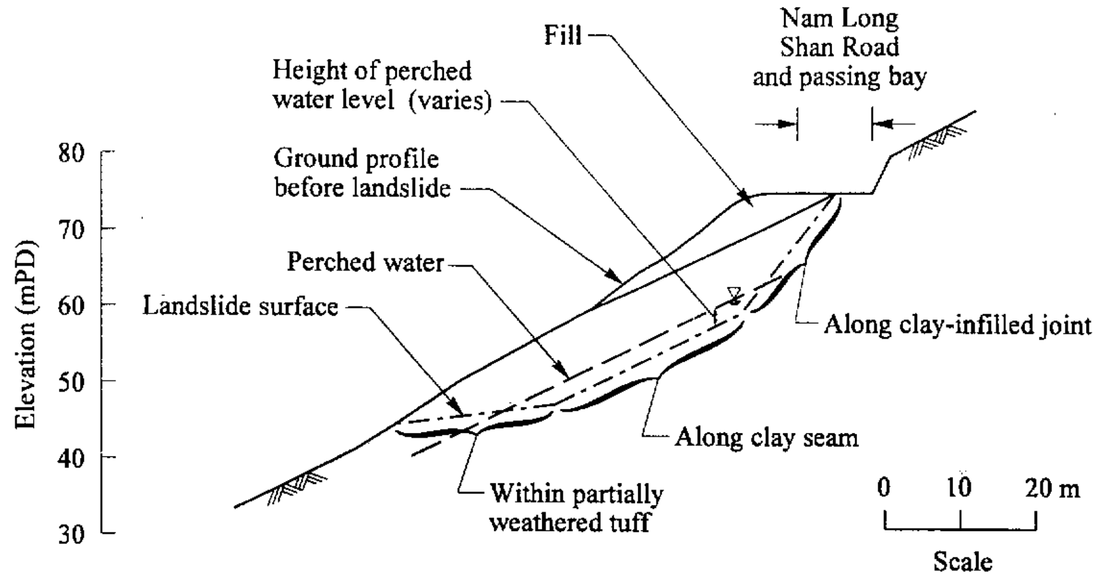
(d) Pushed material was deposited at toe of hillside (about 4 a.m.).



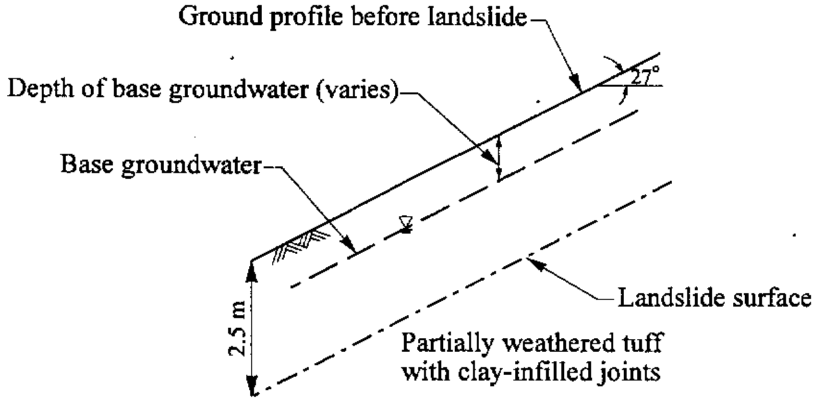
(e) 'Slab' of debris damaged shipyards and came to rest (about 4 a.m.).

(f) Subsequent slip brought down Nam Long Shan Road, followed by a later slip which released rock debris (about 4:30 a.m.).

Figure 13 - Schematic Representation of Inferred Sequence of Events



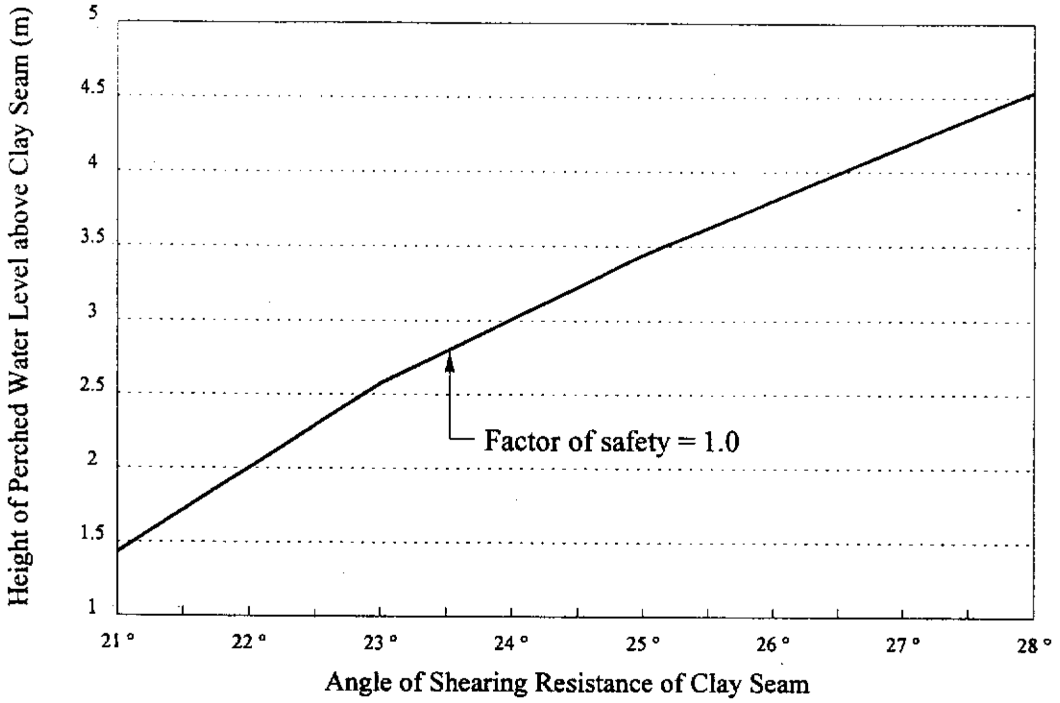
(a) Upper Spoon-shaped Slip



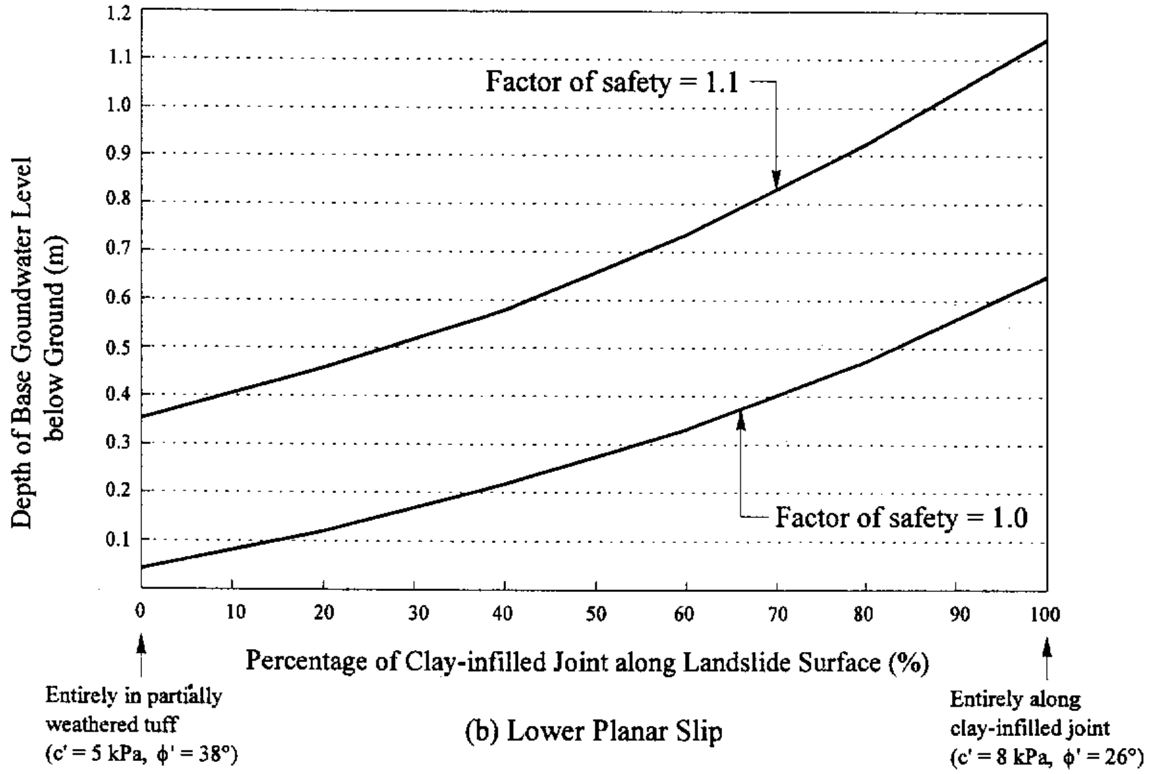
(b) Lower Planar Slip

Material		Apparent Cohesion c' (kPa)	Angle of Shearing Resistance ϕ'	Unit Weight (kN/m^3)
Partially weathered tuff		5	38°	19
Clay seam	Peak strength	8	26°	19
	with slickensiding	0	21°	19
Clay-infilled joint		8	26°	19

Figure 14 - Representative Cross-sections of the Landslide for Slope Stability Analyses



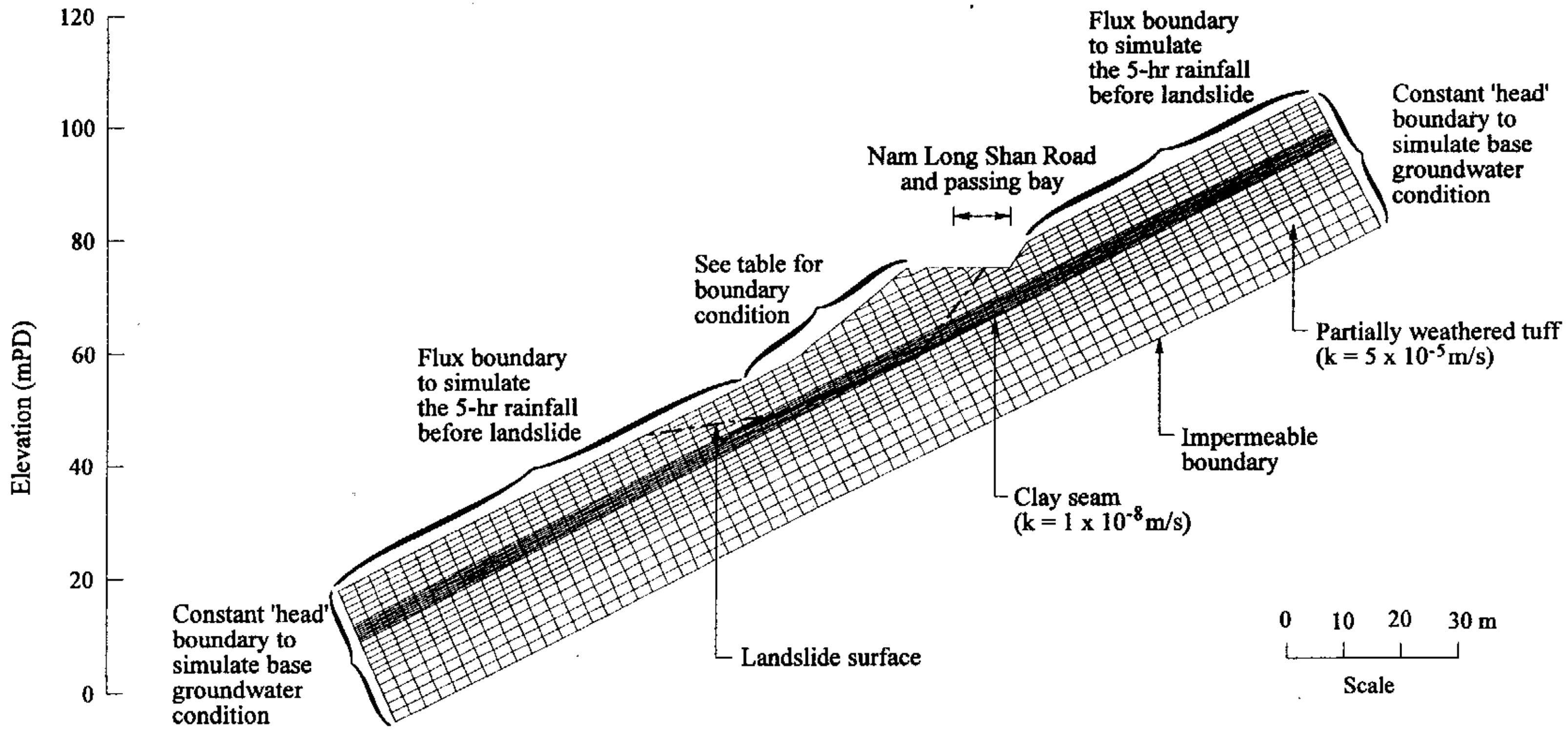
(a) Upper Spoon-shaped Slip



(b) Lower Planar Slip

Note :	For ease of comparison, c' = 0 is assumed for the analysis of the spoon-shaped slip. Taking peak strength of clay (c' = 8 kPa, ϕ' = 26°), the height of perched water level for factor of safety = 1.0 is 4.8 m.

Figure 15 - Results of Slope Stability Analyses for Hillside



Seepage Analyses	Boundary Condition
To simulate the 5-hr rainfall infiltration before landslide.	Flux boundary
To simulate overflow of water from Nam Long Shan Road.	Constant 'head' boundary

Legend :

k	Coefficient of permeability

Note : The initial condition for seepage analysis was obtained by assuming the ground surface to be a flux boundary that simulates the 13-day rainfall infiltration before the landslide (from 31 July 95 to 12 August 95).

Figure 16 - Analytical Model for Seepage Analyses

LIST OF PLATES

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Plate 1 - The Landslide on 13 August 1995

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Plate 2 - 'Slab' of Debris on the Reclaimed Land

Plate 3 - Deposits at the Toe of the Failed Hillside

Note : See Figure 7 for Locations of Photographs.

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Plate 4 - Debris with Fill Material and Refuse on Landslide Scar

Plate 5 - Retaining Wall Fragment on Lower Part of Landslide Scar

Note : See Figure 7 for Locations of Photographs.

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Plate 6 - Bituminous Pavement (1.5 m x 1 m) on Upper Part of Landslide Scar

Plate 7 - Rock Debris on Landslide Scar

Note : See Figure 7 for Locations of Photographs.