PERFORMANCE OF HORIZONTAL DRAINS IN HONG KONG

GEO REPORT No. 42

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PREFACE

In keeping with our policy of releasing information of general technical interest, we make available some of our internal reports in a series of publications termed the GEO Report series. The reports in this series, of which this is one, are selected from a wide range of reports produced by the staff of the Office and our consultants.

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

J.B. Massey
Acting Principal Government Geotechnical Engineer
November 1995

FOREWORD

This report is a record of a review of case histories of the use of horizontal drains in slope stabilisation in Hong Kong. It provides a brief account of the history of development and application of horizontal drains in Hong Kong. It presents basic data for 87 sites where horizontal drains were used and discusses in detail eight of the cases with better information. From these selected cases, observations are made on practical aspects of the design, construction, monitoring and assessment of performance of horizontal drains. These observations should be applied in the context of the quality of information available.

The review was started in 1987 by Dr I. Gray. Comments on a first draft report circulated within GEO in late 1988 resulted in substantial additional work being carried out to review background information and monitoring data for the selected cases. Dr J. Premchitt worked with Dr Gray on the project for a brief period in 1989. Dr R.P. Martin later took over the project, assisted by Mr K.L. Siu. Both did most of the work in their spare time especially since their transfer from the Special Projects Division in 1990 and 1991. This work included a search of GEO files and liaison with Housing Department in order to compile the basic data.

Mr K.W. Leung of Housing Department provided information on sites inside housing estates. Mr Ken K.S. Ho reviewed the fourth draft of the report. Their contributions are gratefully acknowledged.

(Y. C. Chan)
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1. INTRODUCTION

Horizontal drains are an expedient and generally low-cost means of improving the stability of slopes and retaining walls. They have been installed at many sites in Hong Kong over the last 15 to 20 years. Construction details and drain performance have been documented for a few of these sites, but in most cases little detailed information has been reported. To date there has been no attempt to carry out a general review of the performance of local horizontal drains.

In recognition of their growing importance, a review of horizontal drain installations was set up in 1987 as part of a project under the GEO's Research and Development theme on Slope Stability Drainage Measures. The main aims of the project were to evaluate drain performance data and to assess the implications for design, monitoring and maintenance. This report presents a summary of the case histories examined and the findings of the review of performance data.

Information from over 80 sites has been compiled from sources within the GEO and other government departments. For eight selected cases, all the available information on construction techniques, ground conditions and drain performance has been examined and evaluated. For the other cases, basic information such as the type, length and number of drains has been summarised and tabulated for reference.

During the course of the review, it became apparent that even for the eight selected cases, the quality and quantity of the data on drain performance varied greatly. Several could not be considered as complete case studies. However, by comparing different sites using some common features, it is possible to draw broad conclusions about the performance of drains installed in typical Hong Kong slopes.

Monitoring and maintenance issues are not considered in detail, except where relevant to the evaluation of drain performance for the case studies described in Section 3. A separate report on design considerations, monitoring and maintenance has already been issued as part of the project (Lam et al, 1989). A review of design theories for horizontal drains is given in the report by Gray (1986a).

A location map and basic information on all the drain sites are given in Appendix A.

2. BACKGROUND

2.1 Terminology

Since drains in slopes and retaining walls are invariably installed with a gradient falling towards the outlet, it would be more correct to call them "sub-horizontal" or "raking" drains. These terms are sometimes used in Hong Kong but "horizontal" is more popular and is retained in this report. Also, it should be noted that "drain" as used herein refers to both the hole formed in the ground and any liner or pipe inserted into the hole.

2.2 Purpose and Functions of Horizontal Drains

Drainage systems installed in slopes are of two basic types and serve different purposes :

(a) Designed drainage systems are installed to reduce groundwater pressures so that a specified factor of safety or margin of stability is achieved. Such drains may be used alone or in combination with other stabilisation measures (e.g. slope flattening, retention, reinforcement) to produce the desired improvement in stability.

(b) Prescriptive drainage systems are installed to provide some additional but unquantified improvement to slope stability by reducing groundwater pressures. Such drains are not critical items in achieving a specified factor of safety.

Most of the horizontal drains installed in slopes and retaining walls in Hong Kong are prescriptive. Only a few drainage systems have been designed to reduce groundwater pressures to specified levels: these are noted in the remarks column of Table A1 in Appendix A.

The basic functions and requirements of a horizontal drain are as follows :

(a) The size of the drain should be adequate to carry the maximum water flow without significant disturbance to the adjacent ground or development of excessive outflow pressures.

(b) The drain should permit entry of water into the hole and discharge at the exit without significant loss of flow by re-infiltration into the ground along the length of the drainhole.

(c) Any liner should be of adequate strength and rigidity such that it can be installed to the design length and orientation without breakage and is capable of supporting the borehole without collapse.

(d) The slotted or perforated length of any liner should be formed so as to prevent soil ingress, or it should be provided with an appropriate filter.

(e) In the long-term the drain should continue to operate satisfactorily without clogging and with the minimum of maintenance.

In the case of a designed drainage system, a more general requirement is that the system should be adequate to achieve the design groundwater drawdown.

All these requirements are idealised. There are many uncertainties with drain installation procedures. The scope for carrying out physical checks of the in-service condition along the full drain length is usually very limited. The degree of confidence that can be given to satisfactory long-term performance of horizontal drains is less than for many other slope stabilisation measures. In cases where satisfactory performance is vital to the stability of the slope being drained, the demands on long-term monitoring and maintenance are usually higher for horizontal drains as compared with other common slope stabilisation measures.

2.3 Types of Horizontal Drain Used in Hong Kong

The common types of drains used in Hong Kong are shown in Figure 1.

The first drain type used locally was a slotted PVC pipe with an impermeable invert and a plastic mesh or nylon 'fly screen' filter (Figure 1A). The holes were formed using wash boring with telescoped casing sizes. Once the hole was completed, the liner was installed within the casing and the casing was then withdrawn. The liner in this type of drain is usually a 75 mm diameter PVC pipe. The performated section either has 6 mm wide slots at about 25 mm centres, or 20 mm diameter holes at about 75 mm centres on top of the pipe. The pipe is wrapped in a fly screen, typically a 1 mm plastic square mesh.

A variant of the first type involved grouting of the drain invert (Figure 1B). The use of this type of drain has been described in detail by Tong & Maher (1975). In this design, three sets of slots are formed in the PVC pipe. The aim of the first set is to provide a permeable top half of the pipe to allow entry of groundwater. The slots are covered with a geotextile filter to prevent the ingress of soil. The second set of slots are located at or close to the invert in order to allow grout to flow out of the pipe into the annular void below. The third set, located just below the mid-height of the pipe, is to allow any excess grout from the annular void to flow back into the pipe and to be discharged through the outlet at the ground surface. The overall aim of this arrangement is to form an impermeable invert while at the same time preventing excess grout from backing up and setting in or around the upper permeable part of the drain. In the cases reported, the grouting was done in stages, starting near the outlet and progressing towards the deep end. After completion, the inside of the PVC pipe was flushed and brushed to remove any grout remaining within the pipe. Tong & Maher (1975) noted that the installation procedure could only be accomplished satisfactorily after extensive trials.

A development of the system described above is shown in Figure 1C. This involves simply using a long grout pipe, pumping the wet grout into the deep end of the drain, and letting the grout flow out around the annular void and back down the hole. The pipe used in this type of drain has an impervious invert. Slots in the pipe at mid-height are intended to permit excess grout to overflow into the hole and back to the outlet. Further details about this type of drain are given by Fugro (1986). Following a grouting trial by Fugro, one of these drains was exhumed and it was found that the installation technique was satisfactory.

Beginning in the early 1980s, the Design Division of the Geotechnical Engineering Office (GEO) developed several types of horizontal drain for use in the Landslip Preventive Measures (LPM) programme for slopes and retaining walls. These are shown in Figures 1D and 1E. Further details are given in Figure 21. The GEO Type 1 drain is simply a plastic perforated pipe with an impervious invert, typically 40 mm in diameter, inserted into a self-supporting (uncased) hole. Type 2 is similar to Type 1 but the pipe is wrapped with a geotextile filter. The Type 3 drain comprises two perforated pipes of different diameters (typically 40 mm and 65 mm) with impervious inverts. Only the inner pipe is sleeved with a geotextile filter. The larger pipe is first inserted into the hole, then the smaller pipe is placed within it.

Type 1 drains are typically used in reasonably sound rock, often to improve drainage from heavily jointed or fractured areas. Type 2 drains are appropriate for more weathered rocks where there is a risk of soil being washed into the drain. The Type 3 drains are used typically in soil or mixed rock/soil and are commonly 15-30 m long. Although more expensive, the main advantage of this type over Type 2 is that the inner pipe is usually much easier to remove and check for silting over the geotextile filter. Typical Type 2 and Type 3 drain liners are shown in Plates 1 and 2 respectively. Long pipes are usually formed by joining two or more segments using nylon line and couplers, as shown in Plate 3.

Figure 1F shows a drain including a stainless steel pipe which requires special techniques to install. This type has been used at one site in the Mid-levels area where drains of up to 90 m were required (see Section 3.1). The holes were drilled using an Odex down-the-hole hammer with full casing, telescoped to permit the required hole depth to be achieved. A 36 mm-diameter stainless steel pipe was then installed in the hole, after which the casing was withdrawn. The inner end of the pipe is provided with slots on one side to act as a well screen. Various grout pipes were then installed before the last section of casing was removed. The outer portion of the drain, which was expected to be above the water table, is not fitted with a screen and grout was placed between the pipe and the hole to prevent water flow in the annulus. Plate 4 shows an exhumed drain of this type.

3. CASE STUDIES

3.1 Site Selection

The eight cases reviewed in this Section were selected for the following reasons :

(a) The ground conditions and construction details are reasonably well documented in each case.

(b) Although variable in quantity and quality, sufficient monitoring data exist, and are readily accessible, to allow some evaluation of the performance of the drains at each site.

(c) Together the sites cover most of the common slope-forming materials in Hong Kong, i.e. bouldery colluvium, weathered fine- to medium-grained granite and weathered fine to coarse ash and lapilli tuff.

The cases are not arranged in any particular order. With the exception of the Hing Man Estate case (Section 3.8), all are examples of designed drainage systems.

3.2 Po Shan

3.2.1 General

The hillside behind Nos. 4-16 Po Shan Road in the Mid-levels area is the site of the longest horizontal drain system so far used in Hong Kong (Figure 2). The site covers registered slope/wall numbers 11SW-A/C20, CR175, CR176, CR178, CR179, R674, F72 and adjacent natural slopes.

The drainage system here has been more intensively studied and documented than at any of the other sites. It has been the subject of reports by Craig & Gray (1984), Gray (1986a), Pang (1987), Pang & Au (1988) and Suen (1992), and publications by Craig & Gray (1985) and Au (1990).

The natural slope is formed of bouldery colluvium overlying weathered fine ash tuff as shown in Figure 3. Prior to drain installation, the main groundwater table was generally high. The slopes behind Piccadilly Mansion and Po Shan Mansion were determined to have an inadequate margin of stability during the Mid-levels Study undertaken between 1979 and 1981 (GCO, 1982). This conclusion was confirmed by subsequent studies undertaken by the GEO. After examining various stabilisation measures including a tunnel drainage scheme, the installation of horizontal drains was recommended as the preferred solution to improve slope stability. Although the slopes in question had not experienced previous instability, they lie immediately to the west of the large 1972 Po Shan Road landslide scar (Government of Hong Kong, 1972), see Figure 2.

Plate 5 is a general view of the site. Cross-sections through slopes directly behind Po Shan Mansion and Piccadilly Mansion are shown in Figures 4 and 5.

3.2.2 Construction

Fifty-eight drains of length ranging from 40 m to 90 m were installed at three different levels in 1985 (Figure 2). Plates 6 and 7 show the outlets of drains installed in the natural slope and in the retaining wall behind Po Shan Mansion. All the drains were formed of stainless steel pipes slotted at the end to form a well screen (Figures 1F and 6). In most cases the annulus of the unscreened section of the drain was grouted using a two-stage grouting technique. In a few cases a tube-a-manchette was also installed to improve the lower seals around some pipes, particularly for sections of drains in bouldery colluvium where it was felt that the grout might be washed out easily. Figure 7 shows the grouting system adopted using the tube-a-manchette technique. The grouting methods employed and the problems encountered are discussed in some detail by Gray (1986a).

To assist in monitoring the performance of the drains, each pipe was provided with a valve at its open end to allow water flows to be measured after installation. Many of the drains in the lowest level immediately showed substantial flows, but it was also noted that significant seepage occurred elsewhere on the face of the retaining wall behind Po Shan Mansion (Figure 2). It was assumed that this was due to water being transferred along the annulus of the drains. To relieve this water pressure, a number of shorter drains, up to 30 m long and fully screened except for the first metre, were installed through the retaining walls and into the slopes behind Piccadilly Mansion and Po Shan Mansion (Figure 2). Some of these drains were found to discharge large amounts of water.

3.2.3 Performance

The performance of the Po Shan drains has been assessed mainly by comparing piezometric levels before and after drain installation. More than 50 piezometers were installed at this site, sixteen of which have been regularly monitored for up to ten years in order to determine long-term drawdown trends. Figure 8 shows the difference in piezometric levels for the main groundwater between July 1983 (prior to construction of the drains) and July 1986. In general, piezometric levels in both wet and dry seasons were lowered by more than 5 m across most of the site during this period, with a maximum of about 15 m. Suen (1992) confirmed that drawdowns of this magnitude have been maintained in the first seven years after installation, i.e. up to the end of 1992.

Measured flows from individual drains reveal a wide variation, both in flow rates and their response to rainfall. Detailed measurements during the 1985 and 1986 wet seasons showed that drains installed specifically to intercept perched water tables remained dry throughout, while those draining the main water table had a wide range of flows, as shown in Figure 9. About 70% of the total flow came from 10% of the drains. As a general rule, the drains that produced no flow were at a significantly higher elevation than nearby drains that were flowing. It is therefore reasonable to assume that the main water table had been generally drawn down below the non-flowing drains. The response of the flowing drains to rainfall was found to be very variable, as shown in Figure 10. The degree of response was further assessed by comparing the variation of drain flows with changes in groundwater head at the well screen, as shown in Figure 11 : the more responsive the drain, the greater the flow for a similar head rise.

The observed flow characteristics suggest that permeability over the site is highly variable, probably due to the presence of a number of preferential groundwater flowpaths. The latter could be due to faults, fracture or shear zones, relict joints, natural pipes, etc. All of these features can be well preserved when the tuff is decomposed to a soil.

With reference to Figure 3, after reviewing the first two years' monitoring results, Pang & Au (1988) considered that perched water on the hillside was not as widespread as previously predicted and was probably localized in small patches. In one area it was quite clear that drains installed to intercept the main watertable had drawn down the groundwater below the level of the "perched watertable drains" installed shortly afterwards. This indicated the connection between the two bodies of water in the area, as shown schematically in Figure 3.

Pang & Au (1988) reported on a number of tests on the completed drains and inspections of the insitu conditions. The tests included turning off the valves of selected drains and examining the pressure build-up in the ground nearby, and dye testing and water injection trials in drains through the retaining wall behind Po Shan Mansion. Insitu drain conditions were examined closely by the excavation of three drainage caissons in the area.

The drain turn-off tests showed that the rise in groundwater level after closure of the drains in the dry season was small. The dye testing and water injection results revealed some leakage through the annulus of the drains, but seepage from weepholes through the retaining wall was identified as coming largely from U-channels and surface infiltration immediately above the wall.

Several drains were uncovered and examined during excavation of the drainage caissons. The first was drain D208, which is about 60 m long. This had been drilled through bouldery fill behind the retaining wall and grouted using double-stage grout pipes. The exhumed drain is shown in Plate 8. The first-stage grout had not completely filled up all the voids and therefore did not provide a proper seal for the second-stage grouting. Water was found to be seeping slowly through the void below the pipe. The amount of seepage was found to increase after the drain was temporarily turned off. The second drain uncovered was D208B. This is a 20 m long, ungrouted drain screened over almost its full length. The supporting soil around the drain was found to have collapsed as shown in Plate 4. Water was found discharging into the excavation through the slots. This ceased when a root blockage lower down the drain was removed. The third drain examined was D203B, which was fully grouted using a tube-a-manchette, followed by two other grouts in each of their respective pipes as indicated in Figure 7. The drain was found to be fully sealed as shown in Plate 9 and no leakage of water was observed.

Rainfall records show that there were no storms of very high intensity at Po Shan in the first three years after construction, i.e. 1985-1988. However the system was tested quite severely in the heavy storms of 20-21 May 1989 and 8 May 1992, when peak intensities of around 350 mm in 24 hours were recorded over parts of Northwest Hong Kong Island. The review by Suen (1992) gave no grounds for concern over the performance of the system during the storm of 8 May 1992.

Overall, the conclusion from the first seven years of monitoring is that installation of the extensive drainage system at Po Shan has been effective and successful. In both wet and dry seasons, piezometric levels across the site have been lowered by more than 5 m in general, with a local maximum of about 15 m. The system has continued to perform satisfactorily up to mid 1993. Maximum water flows from the whole system of over 780 m^3/day (9 l/s) have been recorded, with a maximum individual drain flow of 35 m^3/day (0.4 l/s). However, individual drain flow rates are very uneven. A small number of drains yield a heavy discharge while the rest are either dry or have very small flows (Figure 2). The wide variation in flows probably reflects complex hydrogeological conditions across the site.

3.3 Grenville House

3.3.1 General

The site is located behind Grenville House, 1-3 Magazine Gap Road, in the eastern Mid-levels area as shown in Figure 12. It covers registered slope/wall numbers 11SW-B/C92, 11SW-D/C325 and R125.

This case is one of the best-documented early horizontal drain installations in Hong Kong. Choi (1974) described the theory and design principles used, while Tong & Maher (1975) discussed construction methods and the results of drain flow measurements in the first wet season after installation.

A typical section is given in Figure 13. Plate 10 shows a general view. The slope comprises mainly completely decomposed fine to coarse ash tuff at the crest, becoming highly decomposed with depth and grading into jointed rock near the slope toe. Groundwater is encountered mainly in the fractured bedrock. In detail the weathering profile is quite complex, as discussed by

Mak & Shelton (1985). The slope was formed in 1964 when the Grenville House site was first developed. The original slope angle varied from 50° to 90°. Following a landslip in 1972, the slope was regraded and resurfaced with a new chunam cover. Horizontal drains were provided to assist in improving the stability of the slope.

3.3.2 Construction

The drainage layout is shown in Figure 12. A total of 105 drains were installed in 1973 and early 1974. The liners are 57 mm-diameter slotted PVC pipes and are installed at a gradient of 1° to 2° to depths of 20 m to 35 m. The perforated upper part of the pipe is covered with a geotextile filter. The lower part of the annular void between the pipe and the drill hole was grouted to create an impermeable invert, as shown in Figure 1B. As discussed in Section 2.3, it was difficult to create a consistent grouted invert while at the same time not breaking the collar seal or blocking the permeable upper part of the drain. Extensive experimental trials were carried out before a workable procedure could be established. The outlet of a flowing drain at the slope base is shown in Plate 11.

3.3.3 Performance

Figure 14 shows the drain flow rates for the bottom row of drains on two occasions during May 1974, representing dry and wet days respectively (Tong & Maher, 1975). On the wet day (2nd May), the maximum single drain flow was about 14 m^3/day (0.16 l/s) and the total flow from the bottom row of drains was 54 m^3/day (0.62 l/s). The flow from different drains varied widely. Most of the total flow came from a small number of drains. Tong & Maher (1975) ascribed this to the heterogeneous nature of the ground, in particular variable jointing in the rock and relict joints in the weathered rock.

As a part of the present study, some flow measurements were made in August 1986, one day after a moderate rainstorm. The results are shown in Figure 14. The maximum flow was 19 m^3/day (0.22 l/s) and this came from the same drain which gave the maximum flow of 14 m^3/day twelve years earlier. The total flow from the bottom row in this case was 52 m^3/day (0.60 l/s), which was comparable to the previous total of 54 m^3/day measured twelve years earlier. As shown in Figure 15, the flows from different drains still varied widely, and about 97% of the total flow came from less than 10% of the drains. Since the times of measurement in relation to rainfall and the amount of rainfall were different in the two cases, it would not be appropriate to make a direct comparison. However, from the measured flow rates, both individually and totally, it is reasonable to conclude that there was no significant deterioration in drain performance during this 12-year period.

Tong & Maher (1975) also assessed the effectiveness of the drains in lowering the groundwater level. They mentioned that after drain installation, the level was generally low, in some places only several centimetres above the bedrock level. It was several metres lower than the estimated original level before the drain installation (up to 6 m as shown in Figure 6 of Tong & Maher).

Owing to the age of installation, it is highly likely that the Grenville House drains have been severely tested by intense storms on several occasions. Peak 24-hour rainfall intensities of between 320 and 380 mm were recorded over the Mid-levels region during the devastating storms of 25 August 1976, 28-29 May 1982, 16-17 June 1983 and 8 May 1992. Also, the total rainfall measured at the Royal Observatory in the 1982 wet season was the highest for more than 100 years.

Inspection of the slope in November 1992 revealed no signs of distress or deterioration around the drain outlets. It is clear that at least 15 of the drains produce perennial flows (Figure 12). Although the performance of the drains has not been comprehensively assessed from piezometric monitoring, the conclusion from the available evidence is that the drain system appears to be functioning satisfactorily and effectively after more than 18 years.

3.4 New Clear Water Bay Road

3.4.1 General

This drainage system was installed as part of the Stage III Development of Clear Water Bay Road in 1980 under PWD Contract 535/74. Information has been taken mainly from reports by the consultants for the contract (MAA, 1981 and 1983). The drains were installed in the unregistered cut slopes on either side of the New Clear Water Bay Road near the Shun Lee Overpass, as shown in Figure 16.

The natural ground consists of weathered fine- to medium-grained granite overlain by colluvium which fills an old valley. Typical sections through the slopes are shown in Figure 17. Prior to construction, the perched groundwater table in the colluvium, which was fed from the large catchment area behind, was rather high. To construct the New Clear Water Bay Road in the mid-1970s, the slopes on either side were cut to 45°, an angle considered at that time to be adequate for stability purposes in the absence of geotechnical analysis. Following the establishment of the Geotechnical Control Office, the stability of the slopes became a matter of concern. A consultant was appointed and geotechnical studies were carried out. As a result, horizontal drains were recommended to improve the stability of the slopes to an acceptable standard.

General views of the slopes are given in Plates 12 and 13.

3.4.2 Construction

A total of 88 drains, 61 and 27 on the northern and southern slopes respectively, were installed during the period from May to October, 1980. The drains are 33 m long at a gradient of 1 on 7 (8°), installed in several rows at a horizontal spacing of 7.5 m. Additional drains were installed in areas where large water flows were encountered during drilling and liner installation. The liners are slotted PVC pipes. The upper part is permeable and wrapped in a geotextile filter while the lower part was grouted, similar to that shown in Figure 1B. Experimental work had been carried out in the field to test the technique prior to the actual installation. About twenty piezometers were installed to monitor groundwater levels. Plate 14 shows seepage from a drain outlet in the central heavily-grassed section of the northern slope.

3.4.3 Performance

The western part of the northern cut slope is formed in an old valley infilled with colluvium. High piezometric levels and surface seepage were observed in this area prior to drain installation. After the drains were installed, monitoring records showed a piezometric level drop of about 3 m and high flows from a number of drains (piezometer M1, drains N4, N5 and N6, see Figure 16). In general, flow in the uppermost row of drains on the northern slope initially showed a more rapid response to rainfall than the lower rows, but decreased gradually over several months. This was probably due to a fall in the base groundwater level as more drains were installed, rather than clogging of the drains. The average persistent discharge of the flowing drains measured in the 1980 wet season was about 1 to 5 m^3/day (0.01 to 0.06 l/s) while others were either dry or showed slight seepage.

The two rows of drains in the southern slope were installed in a thin layer of fill and weathered granite. The initial groundwater level was lower than that in the northern slope. After installation of the drains, the groundwater level dropped by about 1 m in this area. Discharge from the flowing drains was generally less than 0.7 m^3/day (0.008 l/s) in the 1980 wet season.

Measurement of groundwater levels was resumed by MAA from July 1981 to June 1982. It was found that the levels continued to drop slowly. For example, the highest piezometric level in piezometer M1 was around 93 mPD in August and September 1981, which was about 1.5 m lower than that recorded 12 months before. Other piezometric readings showed a similar trend. No measurement of flow from the horizontal drains was made during this period. Drain flows were measured again by MAA in February 1983 but the data are incomplete.

Maintenance of the drainage system was carried out by the Highways Department in 1985-86, five to six years after installation. The work included flushing of all the drains and reinstatement of piezometers. Some improvements in drain flows were noted after silt deposited in the drains had been washed out. The flows measured by the GCO in August 1986 varied from about 0.7 to 6 m^3/day (0.08 to 0.7 l/s) for the drains which were flowing previously. The only exception was for drain N6, which was found to have a much higher discharge, up to 6.5 m^3/day (0.7 l/s), compared to less than 1 m^3/day (0.01 l/s) measured in August 1980. This increase may have been due to the blockage of drain N4 located in the lower part of the slope. Flow from drain N4 was up to 4 m^3/day (0.05 l/s) in August 1980, but decreased to zero in 1983.

As before, the flows from different drains in 1985/86 were found to vary significantly. About half showed some seepage while a few had significant flows. Piezometric levels in several remaining piezometers were found to be slightly lower than those measured previously. For example, the average piezometric level in M12 was 91.5 mPD in August 1986, compared to 93.5 mPD in August 1981 and 94 mPD in December 1980. The flow rates of drains adjacent to piezometer M12 were also found to be smaller than those recorded previously.

The drains at New Clearwater Bay Road were tested quite severely during the heavy rainstorms of 28-29 May 1982 and 16-17 June 1983. In each storm the maximum intensity in this area was around 300-320 mm in 24 hours. In addition, the 1982 wet season rainfall was the highest for over 100 years.

The fact that piezometric levels continued to be drawn down over a period of six years indicates that the drains have significantly improved the stability of these slopes. Inspection in November 1992 revealed no signs of slope distress or deterioration. Dry-season seepage was noted in a group of five drains in the central part of the northern slope (Figure 16).

3.5 Pun Shan Tsuen

3.5.1 General

Following Typhoon Ellen in September 1983, a large slow-moving landslide developed in registered slope number 6SE-D/C63 at chainage 550 on the Tuen Mun Highway, below the former village of Pun Shan Tsuen. The failure is discussed in the landslide study report by Choot (1984). The slope had failed previously in 1975 during construction of the Tuen Mun Highway, as discussed by Slinn et al (1976). Plate 15 shows a general view of the site.

The remedial works involved cutting back the slope to a flatter angle and installing a total of 55 drains during the period January to September, 1984 (Figures 19 and 20). The work was carried out under Contract 32/HO/83 by the Highways Office of the Engineering Development Department. Information on the drains has been obtained from records held by the GEO's Design Division.

The slope is composed of weathered coarse ash to lapilli tuff overlying and intruded by granodiorite (Figure 19). The depth to bedrock changes abruptly within the slope as a result of variable weathering, particularly in the tuff. Prior to the remedial works in 1984, the depth to moderately decomposed rock (Grade III) at the crest of the slope was about 16 m, increasing to 28 m half way down the slope, and reducing to zero at the base (Figure 20). This 'bowl' of relatively deeper weathered material is thought to have given rise to a concentration of groundwater flow into and through the central lower portion of the slope face.

A feature of the completely decomposed tuff at this site is its high erodibility. This is indicated by numerous natural pipes and erosion gullies that were prominent on the surface of the failure (Nash & Chang, 1987). Frequent subvertical relict joints in the tuff formed release and local shear planes during the failure and allowed ready infiltration of surface water. The high erodibility of the material appears to be related to its particle size. Laboratory tests showed the material to be gap-graded, lacking in medium to coarse silt.

3.5.2 Construction

The horizontal drains used were mostly GEO Type 3, varying from 14 m to 38 m long (see details in Figures 1E and 21). This was the first major use of this type of drain in Hong Kong. Most of the liners were placed in open holes formed by percussion drilling, without the need for casing. Initially there were concerns over the feasibility of installing flexible plastic liners in uncased holes to lengths of nearly 40 m, e.g. correct alignment of the unperforated pipe inverts, adequacy of the stitched joints, and whether the joints in the outer pipe might displace the filter fabric during insertion of the inner pipe. The contractor was required to demonstrate the adequacy of the installation procedure by a site trial before the main works commenced.

In the event, the only significant problem encountered was erosion around the drain outlets. The mortar plugs tended to be easily washed out due to erosion of the surrounding weak soil in newly-exposed areas affected by seepage or surface runoff. This problem was solved by placing small areas of well-compacted granular fill in the washout areas around the outlets and providing small concrete connecting channels between the outlet and surface U-channels on berms. A typical drain outlet is shown in Plate 16.

3.5.3 Performance

Data from twenty piezometers have been used, together with drain flow records, to assess drain performance. Piezometric data up to late 1985 were collected by the GEO and were summarised in a maintenance manual prepared for the Highways Office. Thereafter monitoring of piezometers and drain flows was continued by the Highways Office.

Ten piezometers installed during the ground investigation for the 1983 failure provided reliable data before and after drain installation. Measurements were generally taken infrequently (monthly or longer intervals) but the limited data show that there was a significant drop in most piezometric levels, of the order of 3 m to 5 m, which can be attributed to the drain installation. The design drawdown (Figure 20) was defined as the piezometric level above which the stability of the cut-back slope would be reduced to a factor of safety of less than 1.2. The data summarised in the maintenance manual show that after the drains were installed none of the piezometric levels rose above the design drawdown level.

Drain flows were monitored closely for the three-year period from 1986 to 1988. Of the four rows installed (Figure 19), piezometer readings prior to installation indicated that the uppermost two rows would be generally above the base groundwater level. This was confirmed to be the case as flows were recorded only from the lowest two rows of drains.

A summary of the data from selected drains in rows 3 and 4 is given in Figure 22. This shows that flows generally varied widely with rainfall and that flows from individual drains were also variable. The maximum flow from a single drain was about 14 m^3/day (0.16 l/s), measured in August 1986. The total flow from all drains on this occasion was approximately 36 m^3/day (0.42 l/s). A few strongly-flowing drains accounted for most of the total flow while the majority of the drains either showed slight seepage or were dry.

With regard to the severity of rainstorms, the drainage system at Pun Shan Tsuen was severely tested during the intense storm of 20-21 May 1989 when over 400 mm of rain fell in 24 hours in parts of Tsuen Wan.

Annual inspections and monitoring in the first nine years since installation suggest that there has been no significant deterioration in drain performance. Several drains in the lowest two rows have permanent flows, as shown in Figure 19. Clearly the drains at this site have been effective in achieving the design objective and are making a significant contribution to the long-term stability of the slope.

3.6 Choi Wan Estate

3.6.1 General

Horizontal drains were installed by the Housing Department in the Choi Wan Estate between October 1983 and January 1985. The purpose was to ensure that groundwater would not rise to a level sufficient to impair slope stability. Information about this case has been taken from the report by Fugro (1986).

The site consists of two registered slopes, 11NE-A/CR57 and 11NE-A/CR85, as shown in Figure 23. Slope CR57 is composed of a thin layer of fill overlying colluvium, which in turn overlies fine- to medium-grained weathered granite. At the western end there is a 5 m-high, 40 m-long concrete gravity retaining wall at the toe of the slope. The ground conditions and the configuration of slope CR85 are similar to slope CR57 except that a retaining wall 3 m to 5 m high runs along the entire length of the slope toe.

Typical sections through the slopes are shown in Figures 24 and 25. Plates 17 and 18 show general views of the upper (CR57) and lower (CR85) slopes respectively. Abundant signs of drain flow from outlets through the slope surfacing and toe walls are visible in both photographs.

3.6.2 Construction

A total of 140 drains were installed in the two cut slopes (Figure 21). To reduce water pressure behind slope CR57, sixteen 12 m-long drains were installed in two rows at 4 m to 6 m spacing respectively through the wall. A total of 124 drains were installed in slope CR85. These were in two to five rows of differing elevation with a 6 m spacing in each row. The two lowest rows were installed through the toe wall. The drains were mostly 19 m long, occasionally 16 m.

The details of the drains are shown in Figures 1C and 26. The liners are 75 mm diameter nylon porous pipes with an impervious invert. The upper permeable part of the pipe is covered with a geotextile filter. The lower part of the annular void was grouted. A long grout pipe was inserted through the full length of the drain and wet grout was pumped out at the inner end. The grout was allowed to flow downwards along the lower part of the annular void to the outlet in order to fill the full length of the void (see Section 2.3). The drains were installed at a gradient of about 3°.

3.6.3 Performance

High groundwater tables had been recorded previously in both slopes. Drain flows and piezometric levels were monitored for about one year after installation. No seepage was observed from existing weepholes in the retaining walls, indicating that the groundwater level behind both walls had been substantially lowered. The drain flows showed fluctuations in response to rainfall but the rates of flow varied greatly between different drains.

Drains in slope CR57 were found to flow only in response to heavy rain while those in slope CR85 generally had persistent flows and discharged at higher rates. Four drains in slope CR57 and sixteen in slope CR85 were found to be discharging, representing 25% and 15% of the total number in each slope respectively. The maximum flows recorded were 7.3 m^3/day (0.08 l/s) from drain A1.10 in slope CR85 (see Figure 27) and 3.5 m^3/day (0.04 l/s) from drain A2.10 in slope CR57.

Piezometric records were available before and after drain installation from two different sets of piezometers. The first set was monitored between December 1976 and January 1981 by Binnie & Partners (HK) (1981) and the second from January 1985 to January 1986 by Fugro (1986). The old set were destroyed during construction of the landslip preventive works. Twenty-four new piezometers were installed as a part of the works. The highest groundwater tables recorded before and after drain installation are shown in Figures 24 and 25. On the basis of these data, Fugro (1986) estimated that the highest piezometric levels one year after drain installation were 3.6 m and 1.5 m lower than those recorded in 1980, for slopes CR57 and CR85 respectively.

The Choi Wan Estate drains were tested fairly severely during the storms of 20-21 May 1989 and 8 May 1992. Each of these storms produced 24-hour maximum intensities of around 250 mm in this area.

In summary, this drain system appears to have performed satisfactorily in the first nine years since installation. The drains issue considerable volumes of water, particularly in the lower slope. A site inspection in November 1992 showed no obvious signs of deterioration of the slope or walls and at least 20 drains with dry-season flow or seepage (Figure 23). However, as with the previous cases reviewed, the flows from different drains vary greatly.

3.7 Tin Wan Hill Road

3.7.1 General

An extensive horizontal drain system was installed at Tin Wan Hill Road following several failures of registered cut slope 11SW-C/C13 between 1983 and 1986 (Figure 28). The history of slope instability is discussed by Johnson (1983) and Irfan (1986). A summary is given by Irfan et al (1987). The slope is composed of bouldery colluvium overlying weathered fine ash tuff with some eutaxite bands. Failures occurred both through the colluvium and the intensely-sheared highly to moderately decomposed tuff. These were the latest in a series of landslips that affected slope C13 and adjacent slopes since they were first formed for access road and housing estate development in the early 1960s.

A typical cross-section is given in Figure 29. Plate 19 is a general view of the slope.

3.7.2 Construction

Slope movements began in October 1983 and continued intermittently for several months. Ground investigation revealed that movement had occurred within variably decomposed and sheared tuff at depths of up to 12 m.

Initial remedial works consisted of temporary measures to protect a nearby school in the event of a major mobile failure. A large steel barrier was constructed at the slope toe and 20 GEO Type 2 drains were installed into the slope face prior to the 1984 wet season. The drains, up to 15 m long, were installed by percussion drilling and were regarded as sacrificial. Some large drain flows were observed during the 1984 wet season and slope movements generally decreased during this period.

The permanent remedial works consisted of a reinforced concrete cantilevered retaining wall at the slope toe, substantial slope excavation and installation of horizontal drains. Construction began in early 1985 under GEO Contract No. GC/84/02.

Renewed slope movements, including collapse of steep temporary cuts in colluvium, began early in the 1985 wet season during excavation for the retaining wall. This led to reconsideration of the LPM design. Other schemes involving drainage caissons and/or slope stabilising caissons were considered. In December 1985 it was decided to proceed with the original design on the grounds that it was relatively cheap and its performance would be easier to verify as compared with the other schemes.

A total of 68 permanent drains were installed between May and August 1986. The drains are all GEO Type 3 (Figure 1E) inclined at a gradient of about 1 in 20 (2.9°). Drains in the slope are either 15 m or 30 m long; those built through the toe retaining wall are 25 m long.

Both open-hole percussive drilling and rotary wash boring were used. The outer liner was installed in the drillhole first, then the inner liner wrapped with a geotextile filter was inserted. At some locations problems were encountered with the ingress of soil through the outer liner before the second liner was inserted. Because of the flexibility of the plastic pipes, it required some effort to place them in the correct orientation with the perforated part facing upward, particularly in the longer holes.

Close-up views of drain outlets through the retaining wall at the slope base and through the central part of the slope are given in Plates 20 and 21.

3.7.3 Performance

Because of concerns over the complicated nature of the failures, and some evidence for dry-season water levels being higher than those assumed in the design, arrangements were made to critically review the 1986 data and to carry out a detailed study of piezometric and drain flow responses to rainfall in the 1987 wet season. GEO survey staff were on standby to monitor piezometers and drain flows every two to three hours during heavy storms. Detailed monitoring was carried out in two storms : one in late May 1987 when 160 mm of rain fell in 36 hours, the other in late July when 264 mm was recorded in 72 hours.

The results of the study are reported by Whiteside (1987). Individual drain flows were found to vary over a large range but were generally consistent from storm to storm. This is shown in Figure 30 by the monitoring data from the two storms. On average six of the 68 drains contributed around two-thirds of the total flow while fifteen accounted for about 90%. Peak individual drain flows in the May storm were over 300 m^3/day (3.5 l/s) while the maximum combined flow from all the drains was about 1400 m^3/day (16.2 l/s) in the July storm (Figure 31).

The drains responded quickly to rainfall. Total flows in both storms increased significantly within the first hour of the storm starting and decreased close to background levels within an hour of rainfall ceasing.

An old set of piezometers which existed before installation of the drains was extensively damaged by the 1985 slope failures and the subsequent remedial works. A new set of more than twenty piezometers was installed after the 1985 wet season. Unlike the rapid response of the drains to rainfall, piezometric levels generally rose over a period of a day or more and fell over a period of about a week. The inference is that localised permeable drainage paths within the slope have been intercepted by the extensive drain network but not in general by the piezometers. In two areas of the slope closest to the most strongly-flowing drains the highest piezometric levels in 1987 were about 5 m lower than those recorded during the period when the drains were being installed in 1986. Elsewhere the maximum levels were at or just below the 1986 maxima.

Whiteside (1987) also examined the conditions of the drains insitu one year after installation. The inner liners were extracted from five drains to investigate whether they had become clogged. Silt was present to varying degrees, in some places up to 10 mm thick over the geotextile filter. However, based on the flow data this did not seem to have affected the drain performance. Several inner liners were partly exhumed during a site visit in November 1992. An example is shown in Plate 22. In all cases both the liner and the geotextile filter were in good condition.

From detailed analysis of the 1986 and 1987 data, Whiteside (1987) concluded that the drains were effective in that they reduced the flow of water from permeable drainage zones into surrounding less permeable ground by limiting both the magnitude of peak water pressures in these permeable zones and the time during which the peak pressures exist. He also concluded that the drains became relatively more effective as rainstorm intensity increased.

The GEO's Design Division reviewed piezometric levels for two further wet seasons (1988 and 1989), together with surface displacement and other performance monitoring data. No rises over 1986 levels were noted and in all cases the levels remained well below critical levels (approximately 1986 maxima plus 4 m). All the drains were flushed clean in January 1989. Monitoring was discontinued after the 1989 wet season.

The Tin Wan Hill Road drains are of similar age to those at Po Shan. The degree to which the system has been tested during severe storms up to June 1993 is likely to be similar to the Po Shan case. Maximum rainfall intensities of over 300 mm in 24 hours occurred in this area on 20-21 May 1989 and 8 May 1992. It is noted that the catchment area behind this site extends upslope towards Mount Kellett, which is very close to the area of maximum rainfall experienced in the storm of 8 May 1992.

A site visit in November 1992 revealed that three drains showed evidence of perennial flows (Figure 28). Up to mid-1993 the slope had remained in a stable condition and no significant piezometric rises had been detected. This suggests the drains are continuing to perform satisfactorily.

3.8 Hing Man Estate

3.8.1 General

The Housing Department installed 25 horizontal drains in an unregistered slope behind Tower C of the Hing Man Estate below Tai Tam Road, Hong Kong Island during April to June 1986. The slope had been found to have an inadequate margin of stability according to current standards.

Slope stability had been of concern at this site since formation works for the estate began in 1979. Several failures of other slopes within the estate in 1982 and 1983 led to a review of the existing preventive works design. As a result the Housing Department, on advice from consultants P&T Civil Engineers (HK) Ltd, decided to install horizontal drains to lower groundwater levels behind Tower C in a rockhead depression identified from additional ground investigation.

Figure 32 shows the location of the drains and surroundings. Plate 23 gives a general view of the slope. A typical section is shown in Figure 33. The drains were installed in varying grades of decomposed fine ash tuff. Adjacent to the drain locations on the northern side of Tai Tam Road, a cutting had revealed a number of natural pipes, some in highly to moderately decomposed rock (Gray, 1986b). This suggested that the natural groundwater in the slope was dominated by prominent preferred drainage paths. Pipes in both the decomposed rock and overlying volcanic colluvium had been observed earlier on several occasions elsewhere within the estate boundaries, e.g. in caisson wall excavations in 1979.

3.8.2 Construction

The drain holes were drilled using a down-the-hole hammer in an uncased hole. Drains similar to GEO Type 3 (Figure 1E) were used with lengths varying from 20 to 45 m, and at inclinations of 1 in 25 to 1 in 40 (1.4° to 2.2°).

In contrast to the other cases described previously, the drains at this site were constructed in groups fanning out at different orientations from a single location (Figure 32, Plate 24). Five groups of five drains each were installed. This had the obvious advantage of reducing the number of set-ups of the drill rig, which could be easily realigned between each hole in a group. Also, it was thought that the chances of intercepting preferred drainage paths in the slope would be increased if the drains were placed in different directions. The main disadvantage of this arrangement was the concentration of drain pipes near the outlets (Figure 33). This meant that water tended to accumulate in the ground near the outlet, making it difficult to seal the drain collars effectively. As a result, the soil in the area around the outlets became very wet and tended to slump.

3.8.3 Performance

Eleven of the 25 drains began to discharge water or were seeping on completion of the installation. Also, it was noted that piezometric levels in three of the existing eight piezometers in the area immediately dropped by about 1 m (Figure 32). The discharges from some drains were substantial. During a heavy storm on 4 July 1986 the three highest measured flows were 128, 57 and 5.8 m^3/day (1.48, 0.66 and 0.07 l/s). The locations of these drains are given in Figure 34. In view of the evidence for natural soil pipes in the area it is likely that the strongly-flowing drains intersected some of these preferential drainage paths while others did not.

On reviewing the 1986 wet season monitoring results, the Housing

Department found that groundwater responses to storms were considerably smaller than in previous years and piezometric levels were lower than those adopted in stability calculations. However, GEO checking engineers continued to have concerns over slope stability, and monitoring was continued for two more years. No significant rises in groundwater levels compared with 1986 were detected.

Regarding the severity of rainstorms, the age and location of the Hing Man Estate drains suggests that up to June 1993 this drainage system has been tested in a similar way to the drains at Po Shan and Tin Wan Hill Road. Maximum intensities of about 300 mm in 24 hours were experienced in this area during the heavy storms of 20-21 May 1989 and 8 May 1992.

Although drain performance has not been assessed in detail, the evidence indicates that the overall effect of this drainage system has been to reduce piezometric responses to heavy rainstorms. Monitoring data up to 1989 and inspections up to the end of 1992 suggest that the system has performed satisfactorily in the first six years since installation.

3.9 Tsz Wan Shan Estate

3.9.1 General

More than 600 drains were installed in the cut slopes behind the Tsz Wan Shan Estate in the early 1980s. The aim was to help improve slope stability to acceptable standards following a number of failures since the original site formation for the housing estate in the early 1960s. This case has been written up in several publications and consultants' reports, viz. SWKP (1979), SWKP (1981), Insley & McNicholl (1982), McNicholl et al (1985), and FHB Consultants (1990).

The site consists of six registered cut slopes, 11NE-A/C6, CR7, C8, C9, CR10 and C11, at the rear of the Tsz Oi and Tsz Ching Estates (Figure 35). The slopes are formed in moderately to completely decomposed medium-grained granite, overlain by bouldery colluvium up to 11 m thick. The slopes intersect a number of stream courses running down from the steep natural slopes of Lion Rock to the north. The colluvial deposits contain extensive perched water tables. Typical sections are given in Figures 36 and 37.

Plates 25, 26 and 27 show general views of slope numbers C6, CR7 and C8/C9 respectively. Signs of seepage from the drain outlets are visible in each photograph.

3.9.2 Construction

The slope works were designed by SWKP in 1978/79 and checked by Binnie & Partners. Construction began in late 1981 under the Housing Authority's Contract No. 123 and was completed in October 1983. The works consisted mainly of cutting back and installation of drains, but also included some toe retaining walls and ground anchors. In addition to horizontal drains, counterfort drains of 1 m wide and 3-5 m deep were installed at approximately 5 m centres along the toe of many of the slope batters. These consist of triangular wedges of filter material placed against the excavated soil, covered by no-fines concrete and chunam. A 2-3 m long porous pipe is incorporated at the base of the filter layer to discharge into surface channels on berms (Figure 36).

A total of about 640 horizontal drains with a combined length of about 7 km were installed in the six slopes (Figure 35). The majority were placed in slopes CR7, C8 and C9 to draw down perched groundwater tables in the colluvium. The drains are similar to the GEO Type 2 (Figure 1D), consisting of a 50 mm diameter perforated plastic pipe wrapped in a filter fabric inside a 75 mm diameter hole. The outer 2 m consists of an unperforated PVC pipe sealed with cement mortar in the annulus between the pipe and the hole. The typical arrangement of the horizontal and counterfort drains is illustrated in Figure 36.

Most of the drains are 12-15 m long and installed at horizontal spacings of between 1 m and 2.5 m. The gradients vary from 1 in 5 (11.3°) to 1 in 10 (5.7°). Up to eight rows of drains spanning a height range of up to 40 m were constructed in parts of slopes CR7 and CR9 (Figures 36 and 37). In slope C9 about 90 older drains dating from 1974 were already present in the base of the slope (Figure 37).

3.9.3 Performance

Drain performance has been reported by McNicholl et al (1985) and FHB Consultants (1990), the latter being based on a review of all the ground investigation and monitoring records dating back to 1973.

There were five phases of ground investigation between 1974 and 1990, each including drillholes and installation of piezometers. FHB Consultants (1990) listed about 150 separate holes containing either one or two piezometers. Perched water levels in the colluvium were reliably recorded in about 65 holes and the main water levels in the decomposed granite in about 130 holes. Monitoring of most of the piezometers appears to have been terminated in 1985, i.e. within two to three years of completion of drain installation. General references to drain flows are made in the FHB Consultants' report but no flow data are given.

McNicholl et al (1985) noted that in the two-year period after completion of the works "considerable amounts" of seepage occurred from both the horizontal and counterfort drains. They claimed that the drainage scheme was operating satisfactorily and that the extensive use of horizontal drains was an economical method of improving slope stability on this large site.

Despite the large amount of piezometric data available, FHB Consultants (1990) found that only limited measurements could be used to directly assess the drain performance. Their assessment was based on piezometric records from 18 boreholes covering the period late 1973 to November 1984.

For slope 11NE-A/C6, comparisons of piezometric levels in four drillholes (one drilled before and three after drain installation) revealed no significant effect of the drains on the perched water levels in the colluvium. However, for the main water table in the decomposed granite, a similar comparison of the piezometric data (which was not reported by FHB Consultants) suggests that the drains have contributed to an average reduction in piezometric levels of between 3 m and 12 m.

For slope 11NE-A/C8, a perched piezometric head in the colluvium of up to 8 m was consistently recorded in the period up to mid-1981, whereas no perched water was detected in an adjacent borehole during the first three years after drain installation.

In slope 11NE-A/C9, data from four boreholes suggest that the drains have had a 'damping' effect. Annual fluctuations of piezometric levels in the main water table in the decomposed granite were reduced from typically 8-13 m before 1981 to 4-9 m in the two years following drain installation. Also, data from two piezometers placed in the same drillhole after drain installation showed a trend of declining response in perched water head to major rainstorms in the period 1982-84, as compared with consistent response of the main water table. This suggests that the uppermost rows of drains had an increasing drawdown effect over time.

Many of the drains constructed at Tsz Wan Shan are likely to have experienced quite severe groundwater conditions during the heavy rainstorms of 28-29 May 1982, 15-16 August 1982 and 20-21 May 1989. Maximum intensities of about 350 mm in 24 hours affected this area in the May storms of 1982 and 1989.

FHB Consultants reported that there was insufficient data to allow a definite conclusion to be drawn about overall drain performance. There is, however, considerable inferential evidence to suggest that many of the drains are performing effectively. Site inspection in November 1992 revealed that while dry-season flows were confined to only a few drains in slopes C6, C8 and C9 (Figure 35), a large number of the other drains showed signs of flow scour on the chunam surfaces below the outlets (Plate 28). Clearly many of these drains are active during each wet season, while others experience intermittent flows only during or after exceptional rainstorms. In general the areas with perennial seepage and signs of flow scour below the drain outlets coincide with the areas of seepage originally mapped by SWKP (1979) prior to the improvement works in 1981-1983.

Up to mid-1993 the slopes had remained in a stable condition since the improvement works in the early 1980s. Limited piezometric data and abundant indirect evidence from surface observations support McNicholl et al's (1985) views that the drains are performing effectively and continue to have a beneficial effect on slope stability.

3.10 Other Cases

3.10.1 General

A list of the known local horizontal drain sites as at June 1993 is given in Appendix A. This includes the eight sites described in Sections 3.2 to 3.9. The list has been compiled from a review of GEO files and as-built LPM drawings, records held in the Geotechnical Information Unit of the Civil Engineering Library, and information provided by the Housing Department.

The list covers 87 sites. The information given for each site includes the number, type and typical length of drains and the type of ground material. Nearly all of the additional cases have drains which are shorter than 30 m. Most are in the range of 5 m to 20 m. These are 'short' drains in comparison with the 90 m-long drains used at Po Shan. The number of drains at each site varies from two to about 450 but is generally less than 50. Most of these drains were installed as prescriptive measures, rather than as part of a designed drainage system (see Section 2.2).

Site observations and file records reveal that at most of these sites only a few drains have measurable flows. The majority show only slight seepage or remain completely dry. The reasons for this are probably the same as those found in the eight case studies reviewed in Section 3 : either the drains were installed conservatively at high elevations in relation to main water tables, or groundwater levels were reduced by the lower rows of drains causing drains above to cease flowing.

Several large drainage systems apart from the eight cases reviewed in Section 3 are included in Appendix A. Of particular note are those constructed by the Housing Department as part of extensive site formation works for housing estate development at Chai Wan, Siu Sai Wan, Shau Kei Wan East and West, Choi Fai and Choi Ha. The Department has a term contract for monitoring and maintenance of drainage systems at HKHA sites. It would be valuable if performance reviews could be undertaken and reported for these sites also.

3.10.2 Cases of Suspected Inferior Drain Performance

During the search of background information to compile Appendix A, special attention was paid to any evidence for substandard drain performance. Comments on suspected inadequacies of installed drains were discovered in the files concerning four sites.

Three of these sites are in close proximity at Shiu Fai Terrace, off Stubbs Road on Hong Kong Island (Cases I28, I29, and I30 in Appendix A). All are in cut slopes in weathered fine- to medium-grained granite. Regarding slope 11SW-D/CR394, a stability assessment report produced by the GEO's Design Division in May 1988 concluded, from inspection of seepage and piezometric data, that it was unclear if the horizontal drains were effective. For the adjacent slope 11SW-D/CR395, a similar assessment produced the conclusion that the drains were not considered effective. Thirdly, for slope 11SW-D/CR396 it was concluded from a comparison of pre- and post-drain installation piezometric data that the drains did not significantly alter groundwater levels.

The drains at each of these sites were among the first to be installed in large cut slopes in Hong Kong. All are thought to be similar to the detail shown in Figure 1A. From an examination of the files and stability assessment reports, it is considered that, while there are reasonable grounds for doubting the effectiveness of the drains, there are insufficient data to categorically conclude that they have not performed adequately.

The fourth case concerns drains installed in a large cut slope in weathered coarse ash tuff at the Water Supplies Department's Pak Kong Treatment Works site near O Long Village in Sai Kung (Case ME17 in Appendix A). Three sets of drains were installed, the first two during two stages of site formation works in 1987 and 1990 and the third as part of remedial works in 1991 to a failure of the cut slope. Up to 1991 the consultants to WSD who designed and supervised construction of the works were generally confident about the performance of the drains, claiming that they were effective in controlling groundwater levels. However, following a further major failure of the slope in May 1992, their view appeared to have changed. The GEO's Mainland East Division concluded in February 1993 that the drains appear to have been unsatisfactory, noting that this may be due to their limited length (maximum 20 m).

A study of the background reports and file information on the Pak Kong site reveals that there is conflicting information regarding overall performance of these drains. Some of the evidence is clearly sufficient to cast doubt on their general effectiveness but, as with the Shiu Fai Terrace cases, it seems reasonable to regard this as a case of suspected rather than proven inadequate performance.

It is also worth noting that some reservations on drain performance were expressed within the GEO during construction of the drains at Po Shan (Section 3.2) and Tin Wan Hill Road (Section 3.7), and by the Highways Department shortly after construction of the drains at Pun Shan Tsuen (Section 3.5). In all three cases however, the evidence for satisfactory performance since completion of the drains suggests that these doubts were unfounded.

4. DISCUSSION

4.1 Construction Aspects

4.1.1 Pipe Material

As mentioned in Section 2.2, one of the basic requirements of a horizontal drain is that if a liner is included it needs to be sufficiently strong and rigid. The commonly-used plastic pipes (PVC or polyethylene) are usually strong enough to support boreholes without collapsing or suffering excessive deformation.

Stainless steel or other rigid pipes are not necessary for most normal applications of short drains. However, if plastic pipes are too long, their inherent flexibility makes them difficult to install without causing breakage and/or spiralling. As a result, the impermeable invert may not end up as the true invert, thus allowing the drain to lose water back into the surrounding ground.

The limitations of plastic pipes needs more investigation, but it seems that 30 m to 35 m is a maximum practical length. Rigid pipe material, such as the stainless steel used at the Po Shan site, is preferable for longer drains. However, stainless steel is expensive and galvanised iron has been suggested occasionally as an alternative. Possible long-term corrosion of galvanised iron pipes used as horizontal drains warrants further investigation.

Drains installed in jointed rock in Hong Kong in general do not need a filter. If liners are installed usually they serve only to prevent rock fragments from falling into the drain hole and to prevent water loss back into the rock mass close to the drain outlet. Boreholes without pipes or liners should be adequate in many cases as drains in rock.

4.1.2 Grouting

Grouting all or part of the annulus of a horizontal drain is often a topic of concern. Field trials are often carried out. The drains used in local trials have usually been relatively short, less than 10 m in most cases. While such trials are generally reported as successful, difficulties are known to have been experienced on several occasions during the installation of longer working drains.

Grout slots can easily become blocked as a result of soil ingress. Also, where groundwater flows are large, the grout may be washed away before it sets. It is very difficult to carry out complete field checks of grout seal along drain inverts.

The need for a grouted invert in the first place is very much open to question. With regard to the drains exhumed at Po Shan, it appeared that the soil tended to collapse fairly uniformly around ungrouted drains and there was no evidence of major losses of flow into the surrounding ground. Grouting is not required for the three types of GEO plastic drain (Figures 1D and 1E), all of which have unperforated inverts. These drains appear to have performed satisfactorily in all the cases reviewed.

4.1.3 Clogging

Clogging is a problem generally associated with mineral formation in the drain screen, root growth close to the drain outlet, or an incorrectly-designed filter.

Apparently no serious clogging problems have occurred in the cases reviewed. Water tests at Po Shan showed no evidence of significant mineral precipitation from solution. Root growth has been encountered in some drains. The most practical way to deal with this is to put an unperforated drain pipe in the outer section near the slope surface to a depth of a few metres. Where drainage through a perforated pipe is required closer to the surface, the drain will need maintenance to remove any root penetration. GEO Type 3 drains, or similar drains with removable inner pipes, are suitable in these conditions.

Filter clogging is a problem associated with the use of a very fine screen. The 1 mm-diameter slots used in the stainless steel drains at Po Shan have proven to be satisfactory in the soil formed of weathered fine ash tuff at that location. Slots of this size should also be satisfactory in other weathered volcanic soils with similar gradings and in the generally coarser-grained weathered granite soils in Hong Kong.

4.1.4 Erosion Around Outlets

Erosion around drain outlets during or immediately after installation is a common problem, especially at an early stage in construction. In areas of high groundwater and surface seepage, the first few drain holes often attract heavy flows. For drains installed in soil, this can quickly lead to rapid erosion, natural pipe formation and soil washouts on the slope face. On the other hand, once a few more drains are installed nearby it is commonly found that flows are quickly redistributed more evenly and erosion ceases.

When soil erosion occurs it is common practice for site staff to prevent further drain flows by whatever means possible, e.g. filling the borehole or drain pipe with cement grout, compacted soil, aggregate, or a combination of the same. This usually requires considerable time and effort. Although understandable, the use of such methods is undesirable as the effects of blocking heavy flows at one location may result in sudden increases in groundwater pressures elsewhere on the site, perhaps leading to more serious consequences.

When site access is not difficult, erosion problems can often be avoided by phasing the drain construction, beginning in the upper parts of the site (where water pressures and drain flows will usually be relatively low) and working successively downwards.

Where the ground investigation information suggests that drain flows are not likely to be strongly correlated with elevation, an alternative approach is to construct the early drains in areas of predicted low flows, since this may reduce the likelihood for high concentrations to develop along preferred flow paths.

An important lesson drawn from the case studies is the need to adopt the 'observational' approach during site investigation and construction in order to minimise potential erosion problems.

4.2 Drain Performance

4.2.1 General

The quality and quantity of data on drain performance vary widely for the cases reviewed. The drains installed at Po Shan have been well documented and it is possible to make a fairly complete review of performance over many years. All 58 drains at this site and more than 15 piezometers have been monitored regularly since installation in 1985.

None of the other cases reviewed have records of similar quality. Often the monitoring was carried out regularly only during the first year or so after installation, but was then allowed to lapse, or the frequency was greatly reduced. Nevertheless, the data from the other seven cases reviewed in Section 3 provide some support for the general conclusions derived from the Po Shan case.

4.2.2 Drain Discharge

The most notable common feature of drain performance is the very variable discharge from different drains at the same site, even when comparing adjacent drains. This is the case for all the sites even though the drain types, nature of the soil and rock materials, and groundwater conditions vary greatly between sites.

The main reason for such variable drain flows is the heterogeneous nature of the weathered rock and soils encountered in Hong Kong. Colluvial soils are by their nature highly variable. In weathered rocks, local variations in degree of decomposition of the rock material, discontinuities in the rock mass, and relict structures in saprolitic soil, may all have a significant influence on near-surface groundwater flow and form preferential flowpaths. Drains that intercept such paths will have high flows. Natural soil pipes have also been observed in many slopes in Hong Kong and are likely to contribute to highly variable flows.

Interference between drains is another factor that contributes to variable discharge, as can be seen from the effects of newly-installed drains on existing drains. It has been observed that drains installed later at lower elevations on a site can cause the higher drains to dry up.

A second notable feature is that drain discharges are usually consistent over time. Drains that discharge large amounts of water as soon as they are installed generally continue to do so for many years. Initially dry drains continue to be dry, albeit with some exceptions where short periods of flow occur during or immediately after heavy rain. This feature is typical of all the sites examined, despite the variation in drain installation techniques and ground conditions.

The range of discharges from flowing drains at each site increases significantly during periods of heavy rain. The maximum measured discharge from a single drain is 280 m^3/day (3.2 l/s) at Tin Wan Hill Road, but this is exceptional. Maximum discharges from single drains at the other sites tend to be in the range of 5 to 35 m^3/day (0.06 to 0.41 l/s).

4.2.3 Groundwater Lowering

Drains have generally been effective in causing significant lowering of groundwater levels at the eight sites reviewed in detail.

For the well-documented case at Po Shan, piezometric levels have been lowered by about 5 m across most of the site, with a maximum of 15 m. Piezometers at this site have been monitored consistently for many years both before and after drain installation.

The other sites are characterised by fewer piezometers and shorter periods of monitoring. Also, the quality of the piezometric data is generally inferior to that of the drain flow data. Therefore, determination of groundwater lowering is not as clear-cut as for the case at Po Shan. In spite of these inadequacies, the data indicate significant reductions of base groundwater levels of typically 3 m to 5 m for these other sites, especially in areas close to high-flowing drains. Had there been more closely-spaced piezometers that were monitored frequently both before and after installation (as at Po Shan), it is probable that larger drawdowns would have been detected in these cases.

Even though the piezometric data are not adequate to fully determine groundwater lowering over the whole slope at many sites, the consistent drain flows observed provide good evidence for concluding that slope stability has been generally improved by drain installation. Clearly the drains have helped to quickly remove groundwater which would otherwise have accumulated in the slope or have seeped out much more slowly.

4.3 Implications for Design and Monitoring

The review has shown that successful drain performance is mainly dependent on the placing of drains at the appropriate location and depth. For relatively short drains (<30 m), the drain type and installation technique do not appear to be major factors affecting drain performance, provided that reasonable care is taken during installation. Serious deterioration of drain performance due to clogging or other factors has not been detected. The data reviewed covers monitoring periods of up to 18 years since installation (up to June 1993). This augurs well for continuing satisfactory performance in the longer term. Regular maintenance of drains helps to ensure that they continue to perform well.

Since successful performance is determined largely at the time of installation, routine monitoring of complete drain systems at fixed frequencies over many years may not be necessary, except for special drain systems or for research purposes. Generally it is more appropriate for an efficient monitoring programme to be based on periodic data reviews, with monitoring frequencies adjusted accordingly. When a sufficient degree of confidence in drain performance has built up over a reasonably long period, the frequencies of monitoring of piezometers and drain discharges can be reduced. On large sites this approach could result in variable monitoring frequencies at different locations within the site.

When assessing the length and frequency of monitoring for designed drainage systems, consideration should be given, if data are available, to the severity of rainfall experienced at the site since the drains were constructed and hence the degree to which the drainage system has been 'tested' with respect to design rainstorm and groundwater conditions. Ideally this will involve assessment of storm return periods and the extent to which both storm-related and seasonal rises in groundwater have approached critical levels during the period of monitoring. Collection of definitive data for such assessments is often difficult and a good deal of judgement is usually necessary.

Careful selection of drain location and depth may help to increase the number of flowing drains at a site. In the cases reviewed, drains installed to lower perched water tables, or to intercept infiltrating groundwater above base water tables, have usually remained dry. The lowest rows of drains installed at any site are generally the most effective. If the location of likely preferential groundwater flow-paths is known (e.g. closely-spaced relict joints, major fracture, fault or shear zones, or zones of relatively more intense weathering), then it clearly makes sense for drains to be positioned to intercept them.

A small number of drains installed at appropriate locations in accordance with a well-conceived conceptual groundwater model may be more effective than a larger number of drains installed at uniform spacing over the slope. The 'observational approach' to design, whereby drain locations are determined during construction on the basis of piezometric data, signs of seepage and flows from existing drains just installed, may also help to increase the number of flowing drains in the final system. It follows that the number and layout of drains should be specified in contract documents in such a way as to permit easy modification during construction.

5. SUMMARY AND CONCLUSIONS

Horizontal drains have been installed to improve the stability of slopes or retaining walls at more than 80 sites in Hong Kong. Basic information on the drains at these sites has been compiled. For eight selected cases all the available information on ground conditions, construction techniques and drain performance has been evaluated up to June 1993. The length of the monitoring period in these selected cases varies between 5 and 18 years.

The main conclusions of this review are :

(a) Horizontal drains are an effective means of reducing groundwater pressures in typical Hong Kong slopes formed in colluvium, weathered granites and weathered volcanic rocks. In the eight cases reviewed in detail, the drains have generally lowered the main groundwater levels by 3 m to 5 m across part or all of the site, with the greatest drawdown being locally 15 m at Po Shan.

(b) No cases of inadequate drain performance or significant deterioration in performance with time have been proven, although four cases of suspected inferior performance have been noted (see Section 3.10.2). Individual drain discharges, although seasonally variable in many cases, have been generally consistent throughout the periods of monitoring. Together with the evidence from some exhumed inner drain liners, this suggests that clogging is not a significant problem over periods of 5 to 15 years or more. The prospects for continuing effective performance of existing drains in the longer term appear to be good.

(c) Drains installed to lower main water tables that have been accurately identified through careful ground investigation and piezometric monitoring are the most successful. Those located to drain perched water tables, or to intercept surface infiltration, have been observed to be less effective in some cases.

(d) Owing to heterogeneous ground conditions, the flow from different drains at a site usually varies widely. Typically only a small number of drains account for most of the total flow while the majority issue little or no water. Appropriate initial siting of the drains in accordance with a well-conceived conceptual groundwater model may help to increase the number of flowing drains and hence increase the efficiency of the drainage system. The use of the 'observational approach' in modifying initial drain locations during construction is also beneficial.

(e) Regular monitoring of piezometric responses to rainfall immediately prior to and after drain installation, and of drain flow rates after installation, is essential to properly assess the performance of any horizontal drain system. Once the effectiveness of a system is confirmed, normally it should be feasible to reduce the scope and frequency of monitoring. Regular long-term maintenance will help to ensure that drains continue to be effective.

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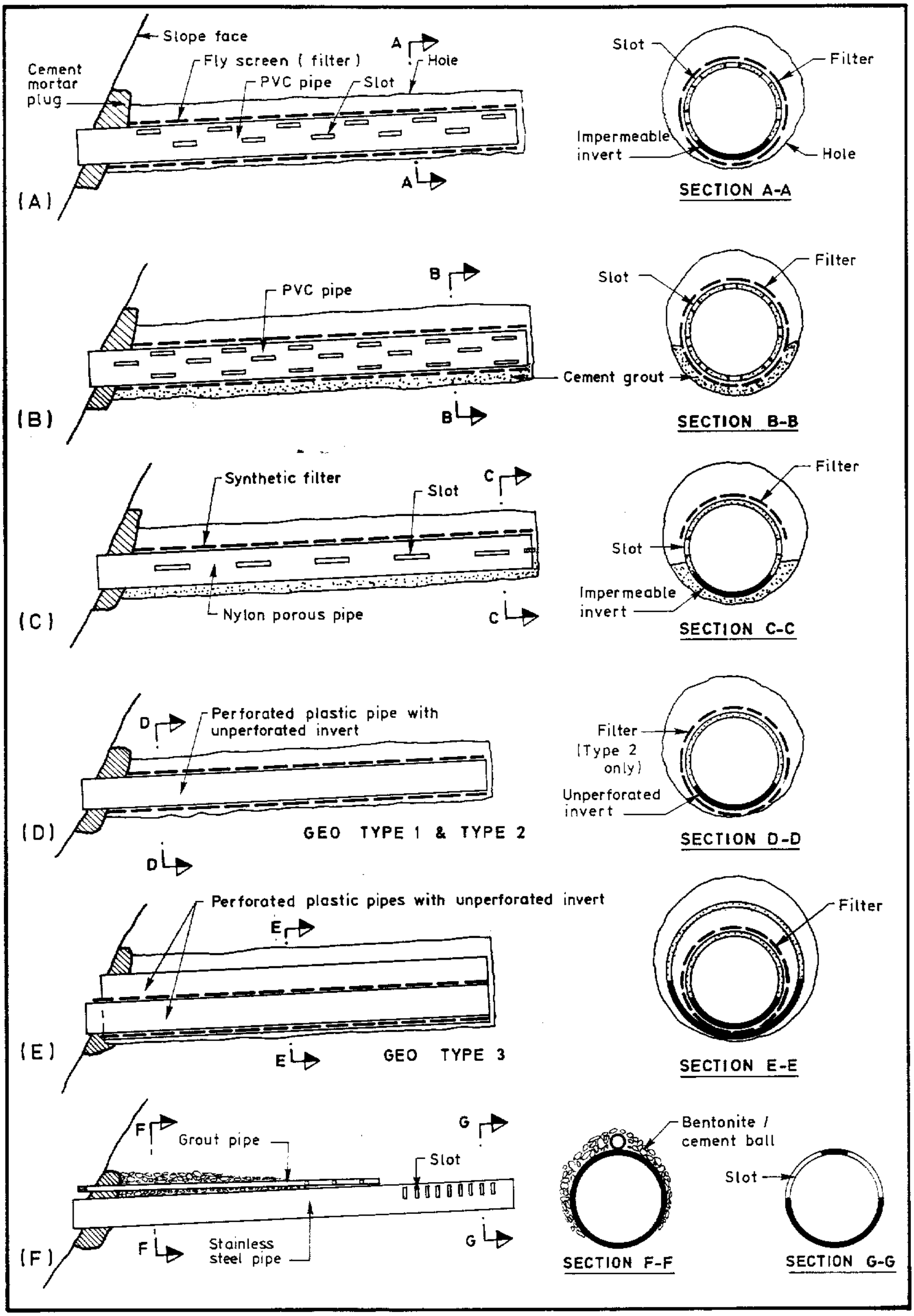
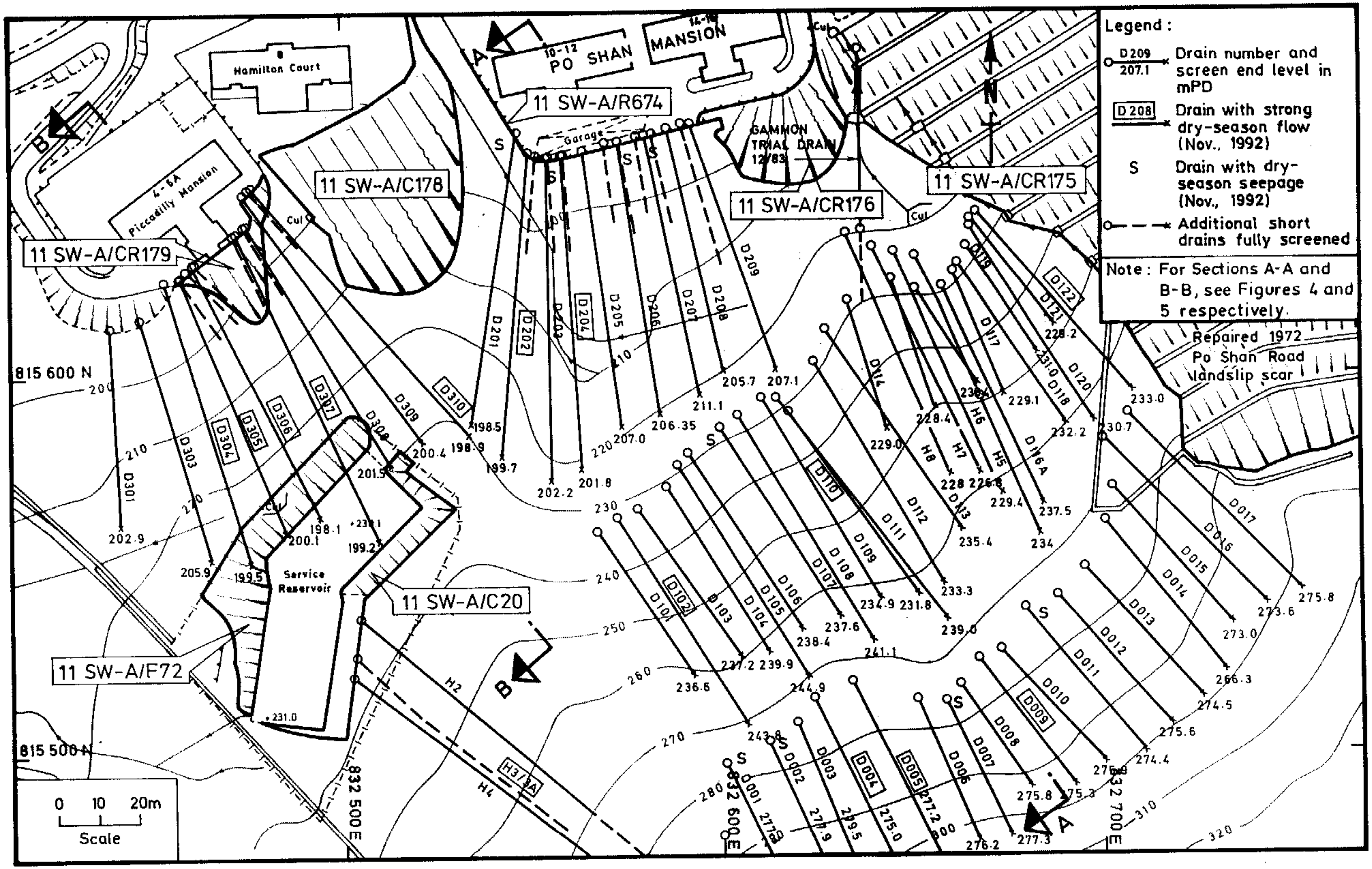


Figure 1 - Common Types of Horizontal Drain Used in Hong Kong



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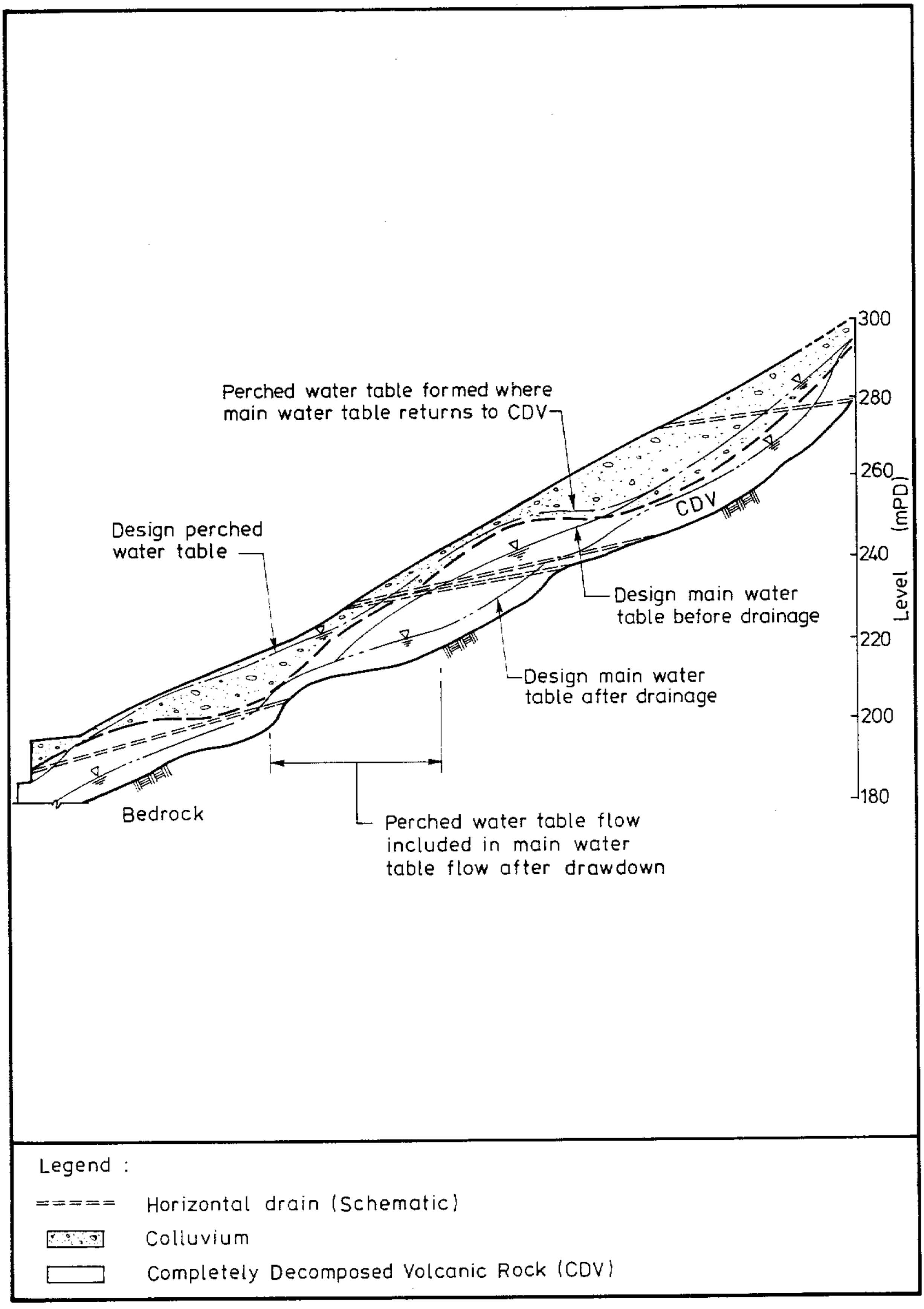

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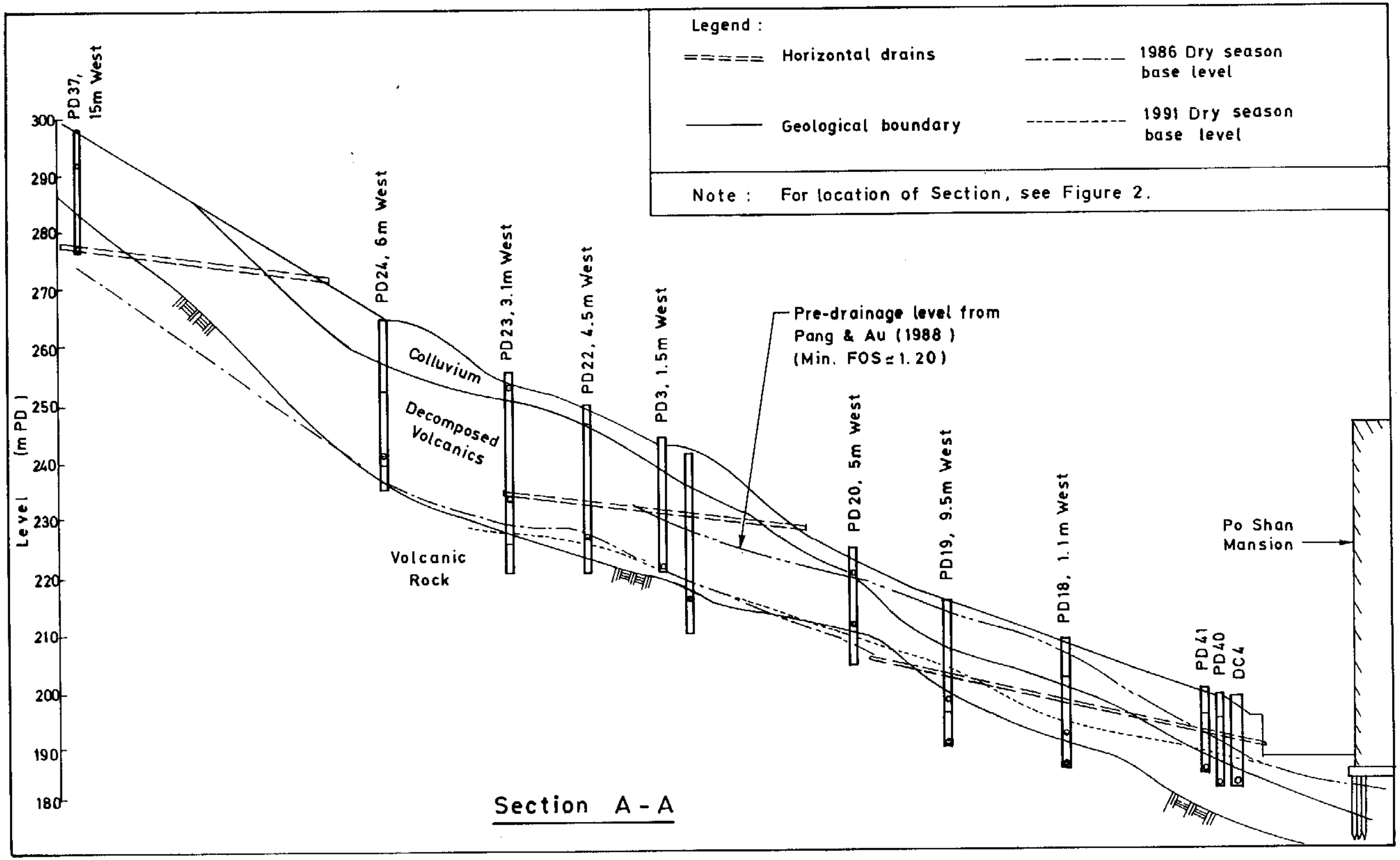


Figure 4 - Ground Conditions and Positions of Horizontal Drains Behind Po Shan Mansion (after Pang & Au, 1988 & Suen, 1992)

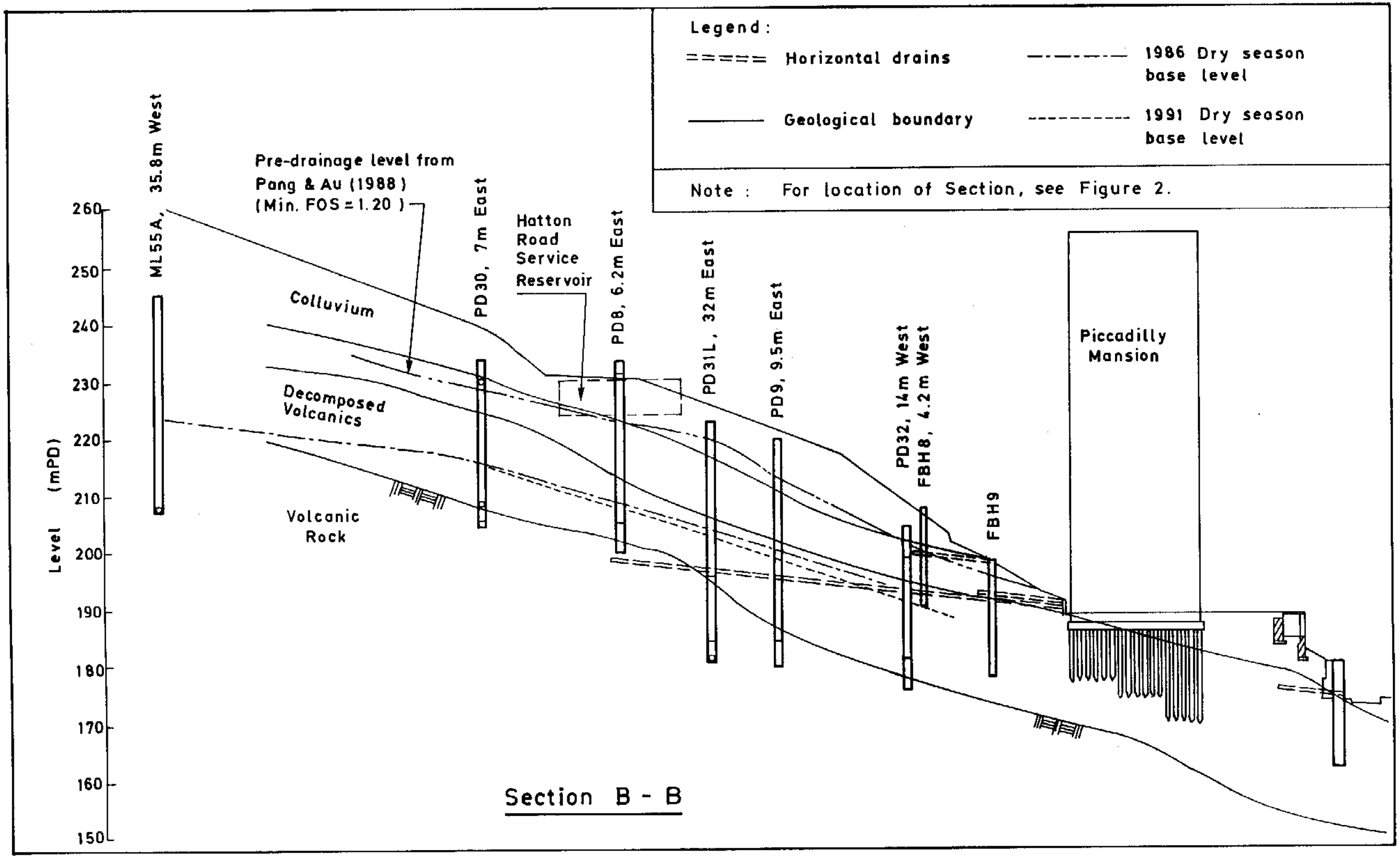


Figure 5 - Ground Conditions and Positions of Horizontal Drains Behind Piccadilly Mansion (after Pang & Au, 1988 & Suen, 1992)

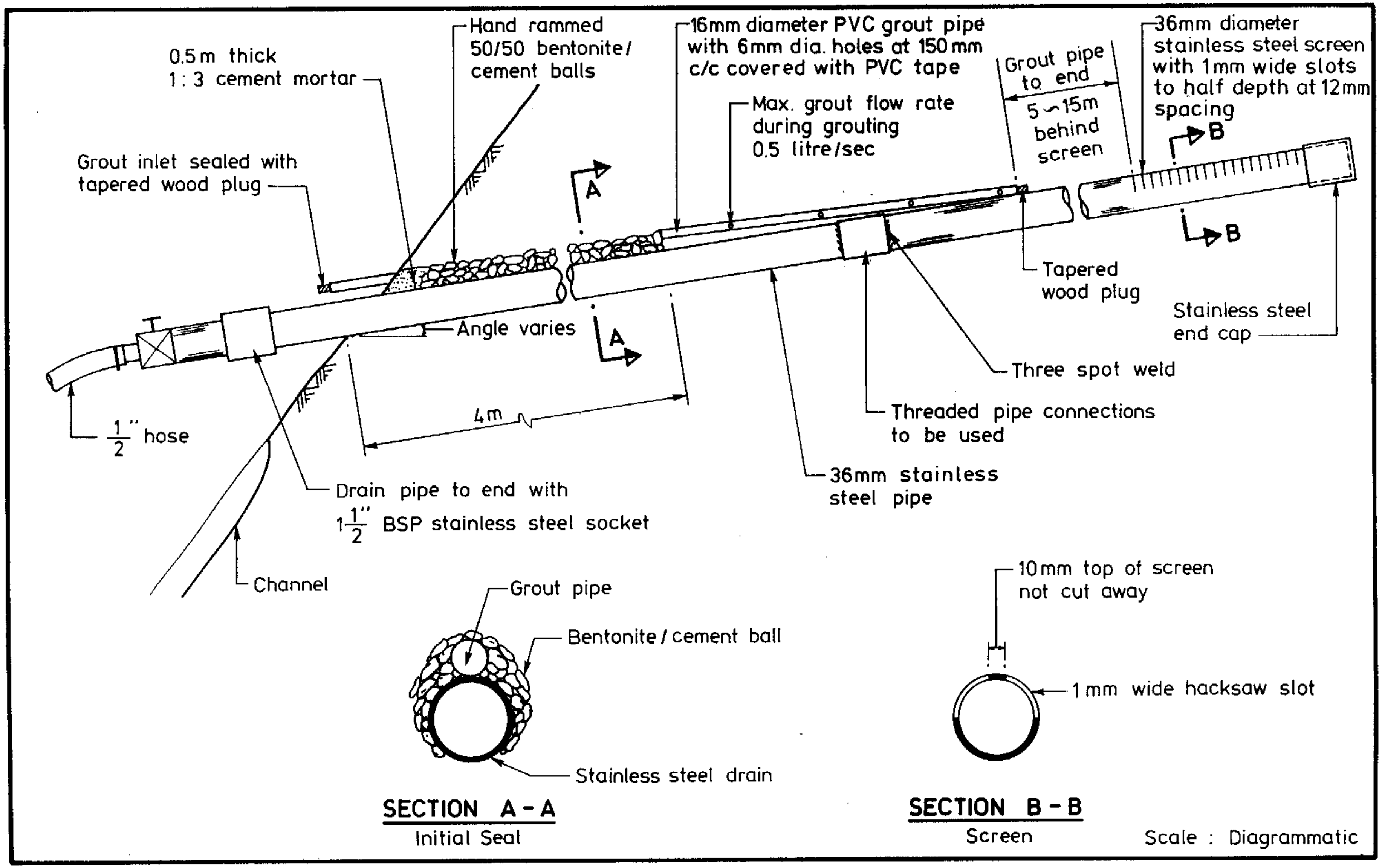
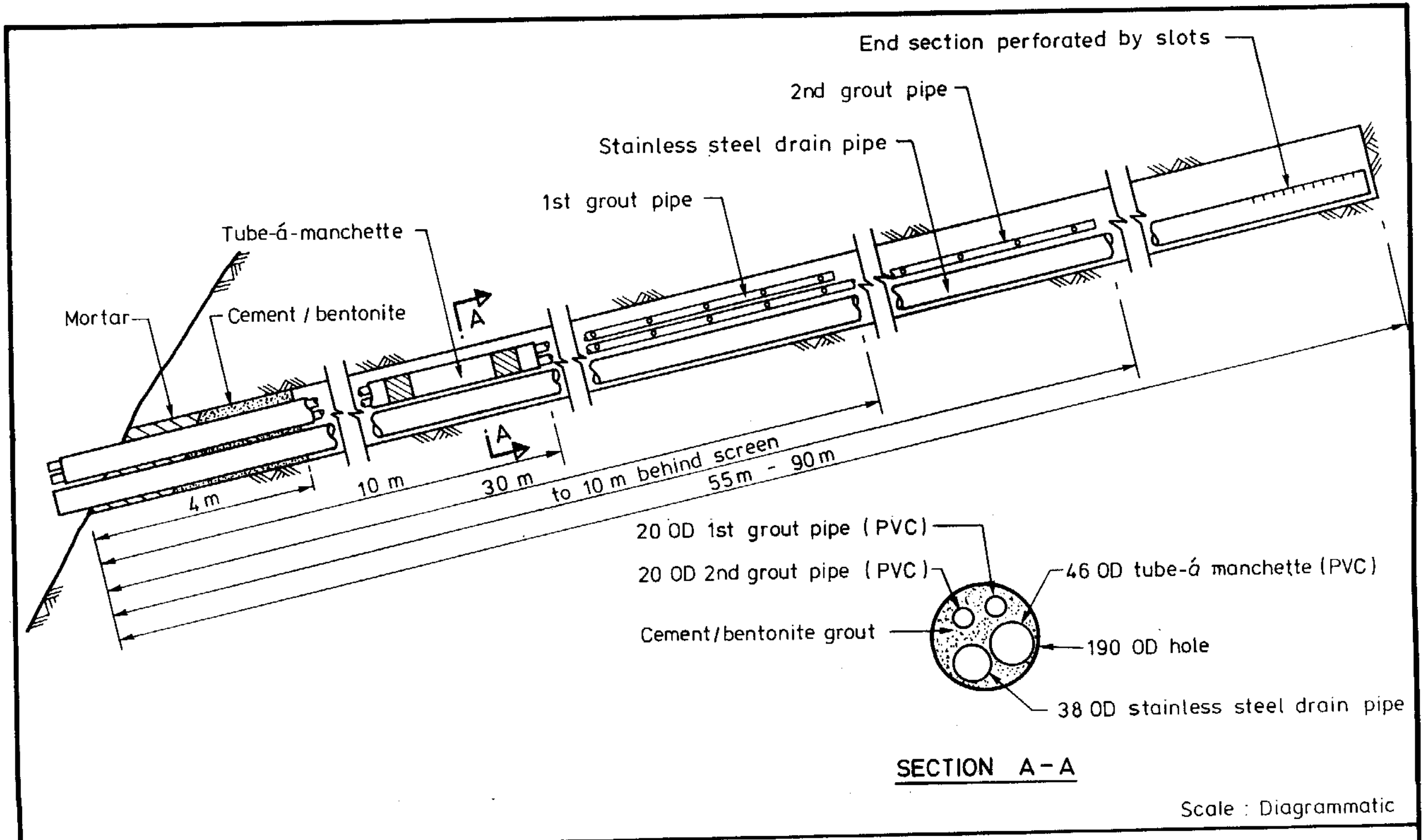


Figure 6 - Details of Horizontal Drains at Po Shan



Note : All dimensions are in millimetres unless stated otherwise.

Figure 7 - Grouting System for Drains Installed in the Retaining Wall Behind Po Shan Mansion

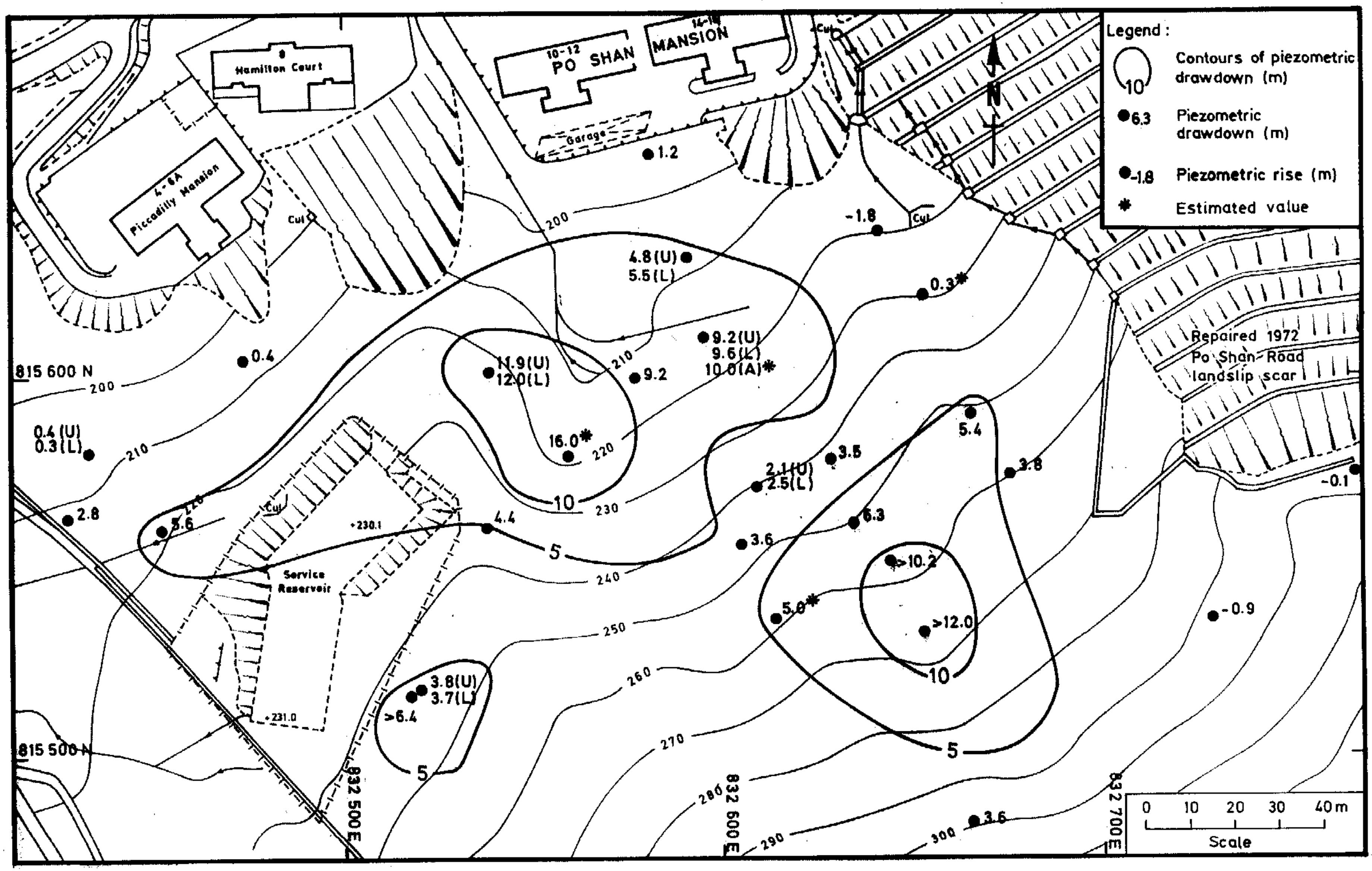


Figure 8 - Difference in Piezometric Levels at Po Shan between July 1983 and July 1986

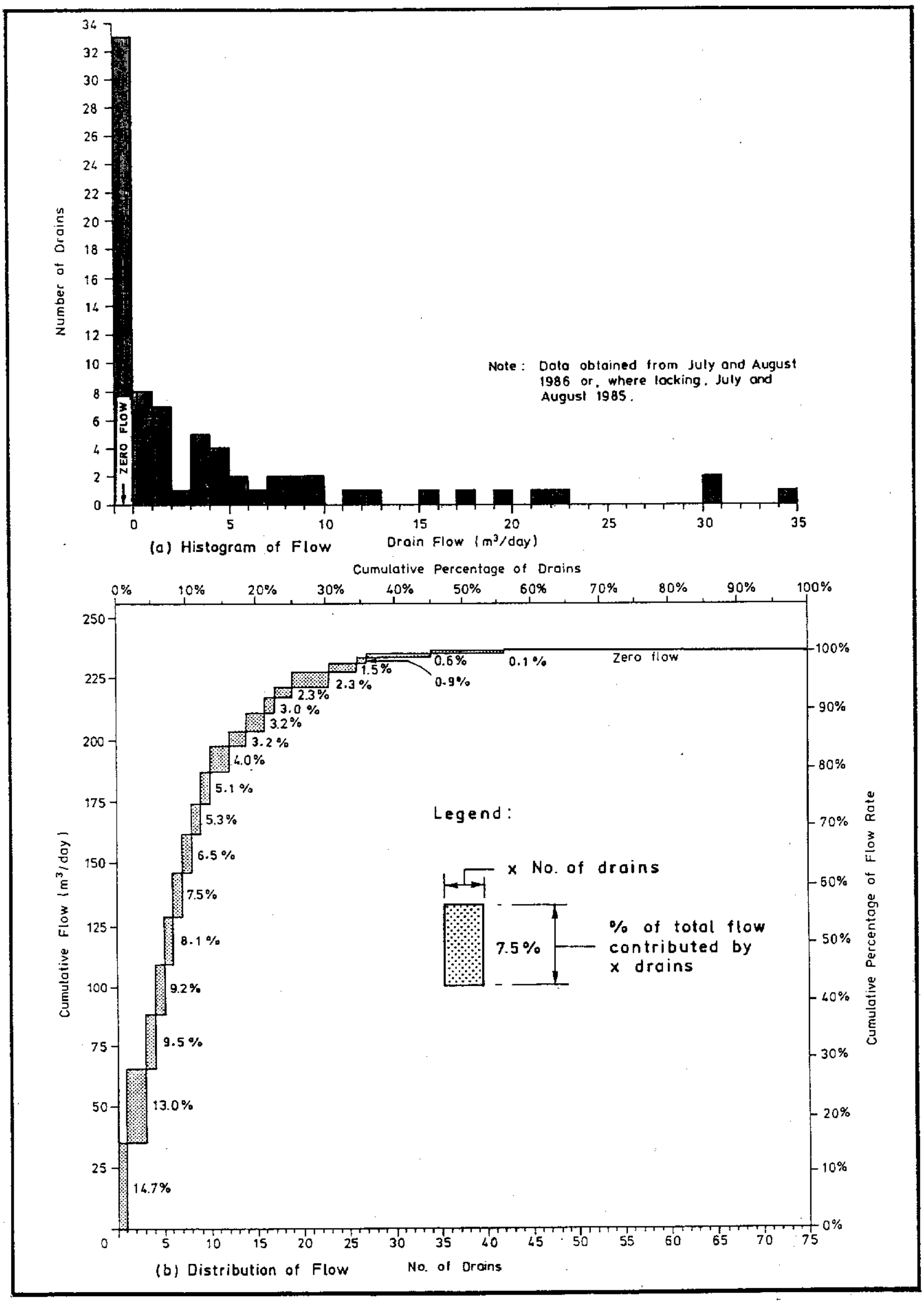
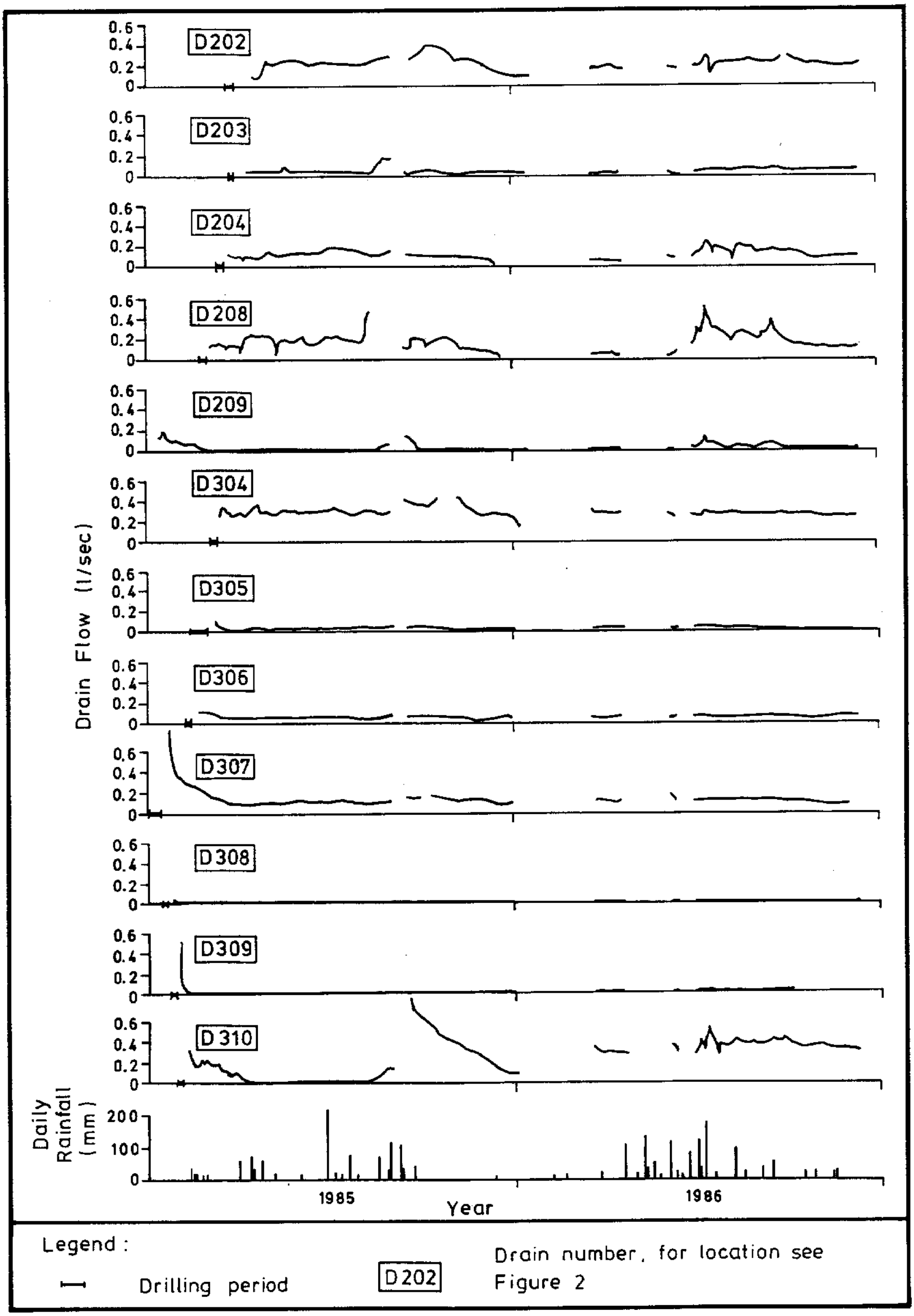


Figure 9 - Histogram and Distribution of Total Drain Flows at Po Shan in the 1985-86 Wet Seasons



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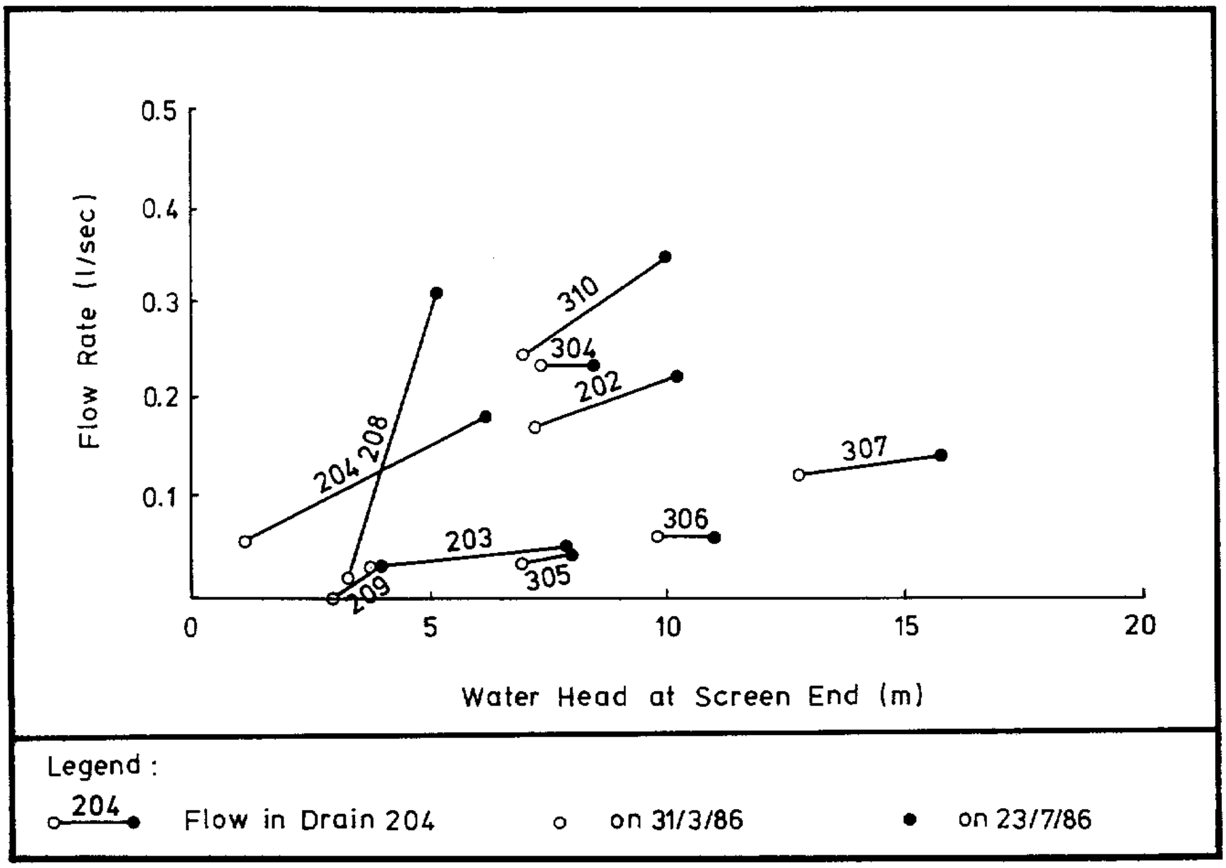

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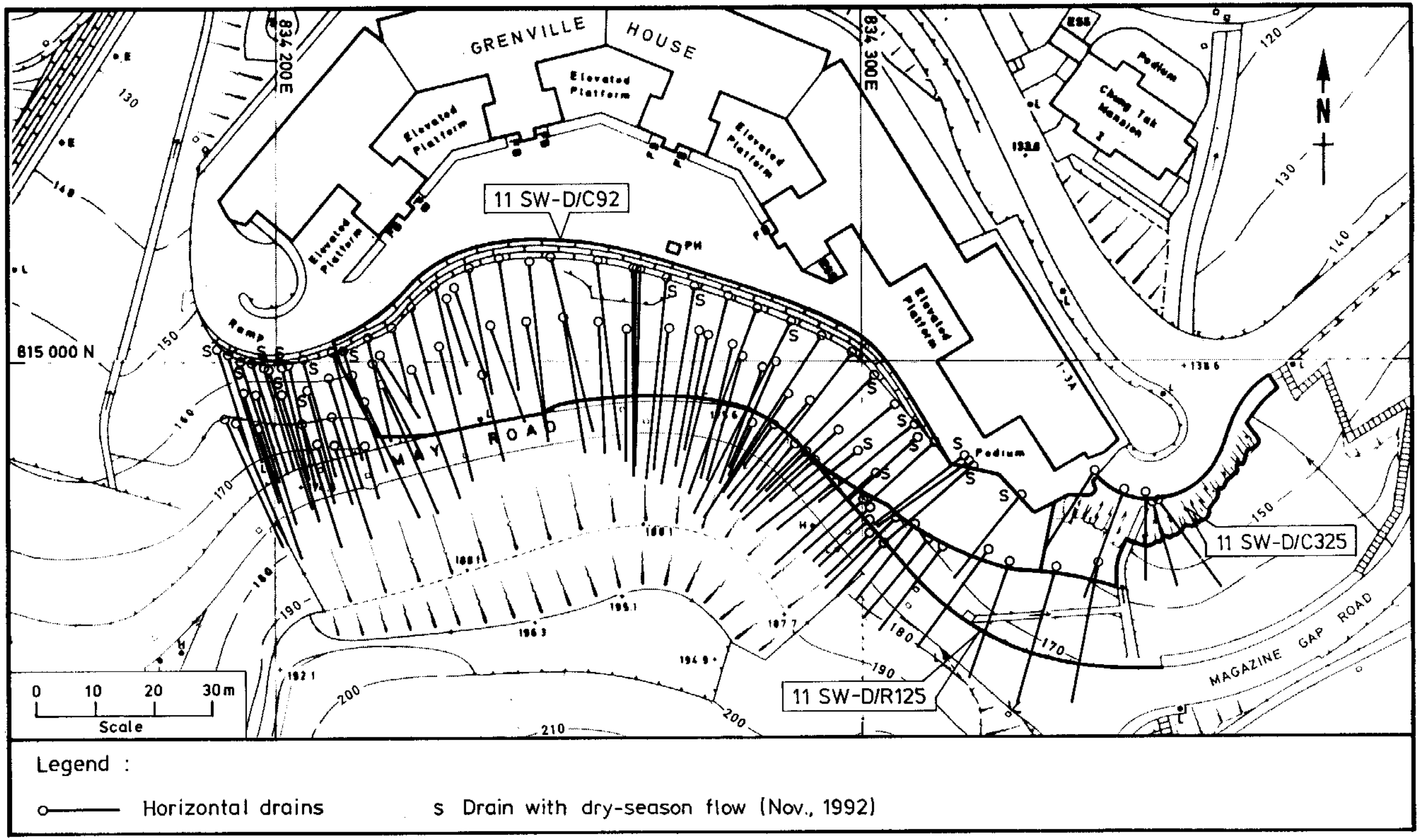

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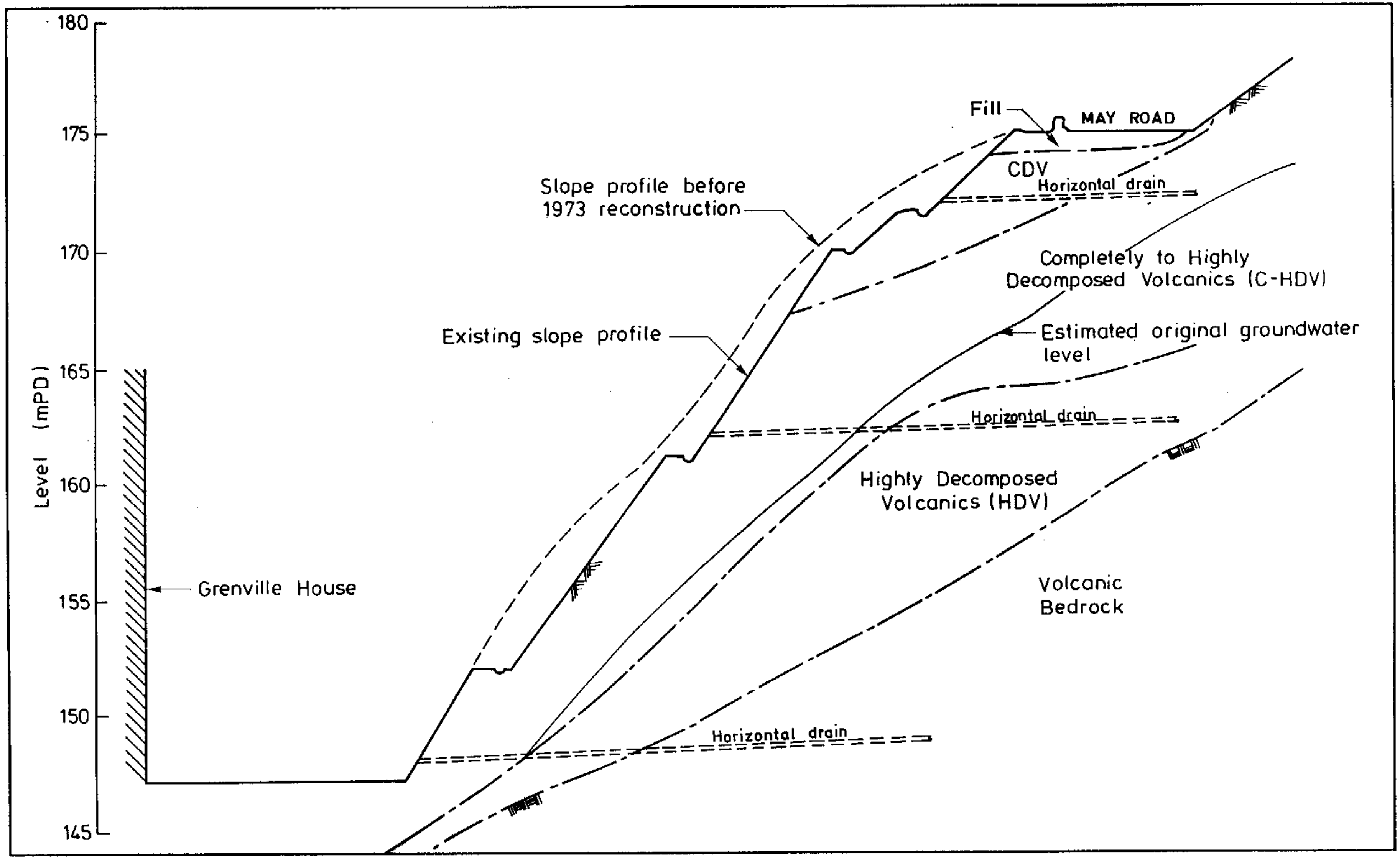

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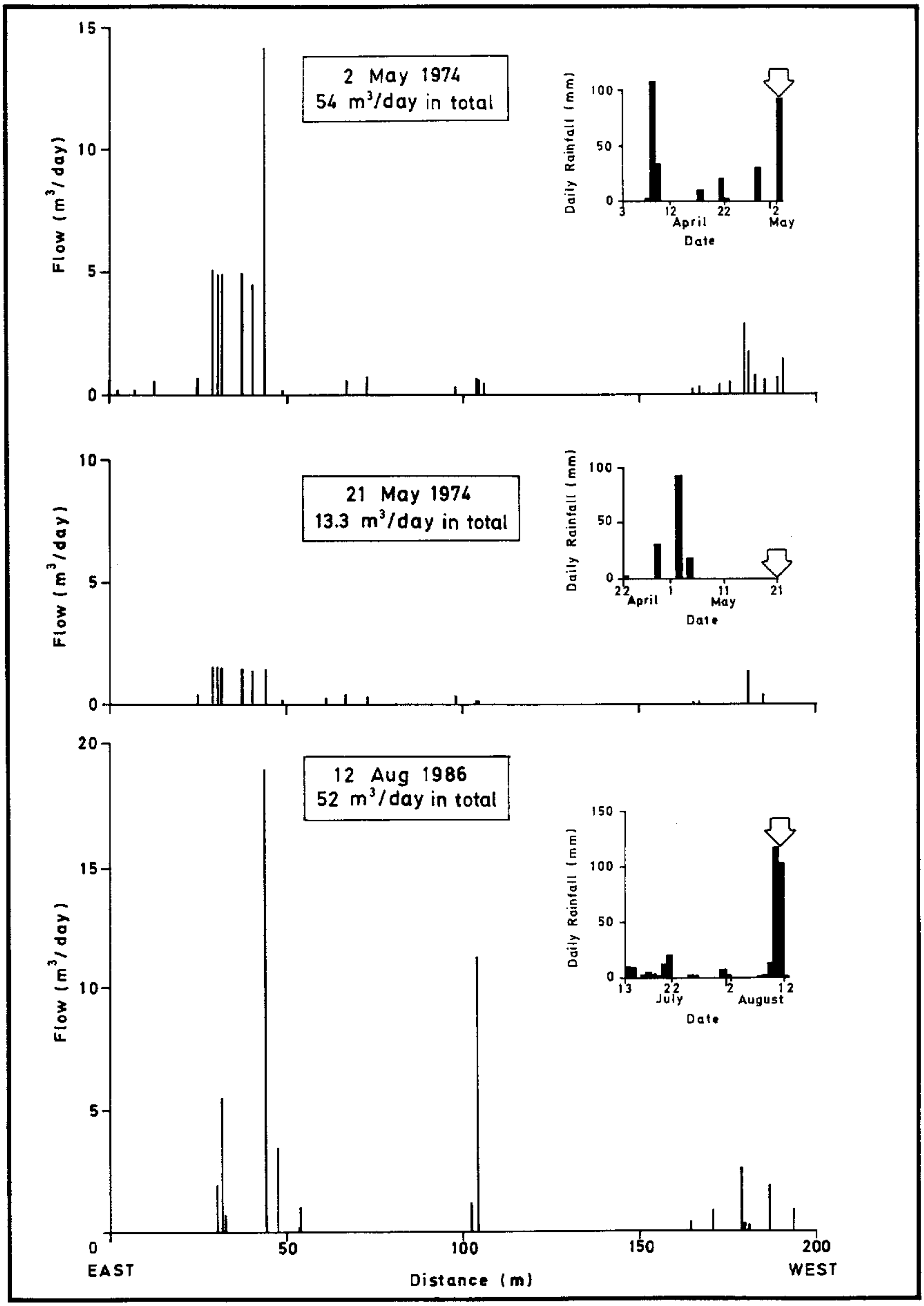

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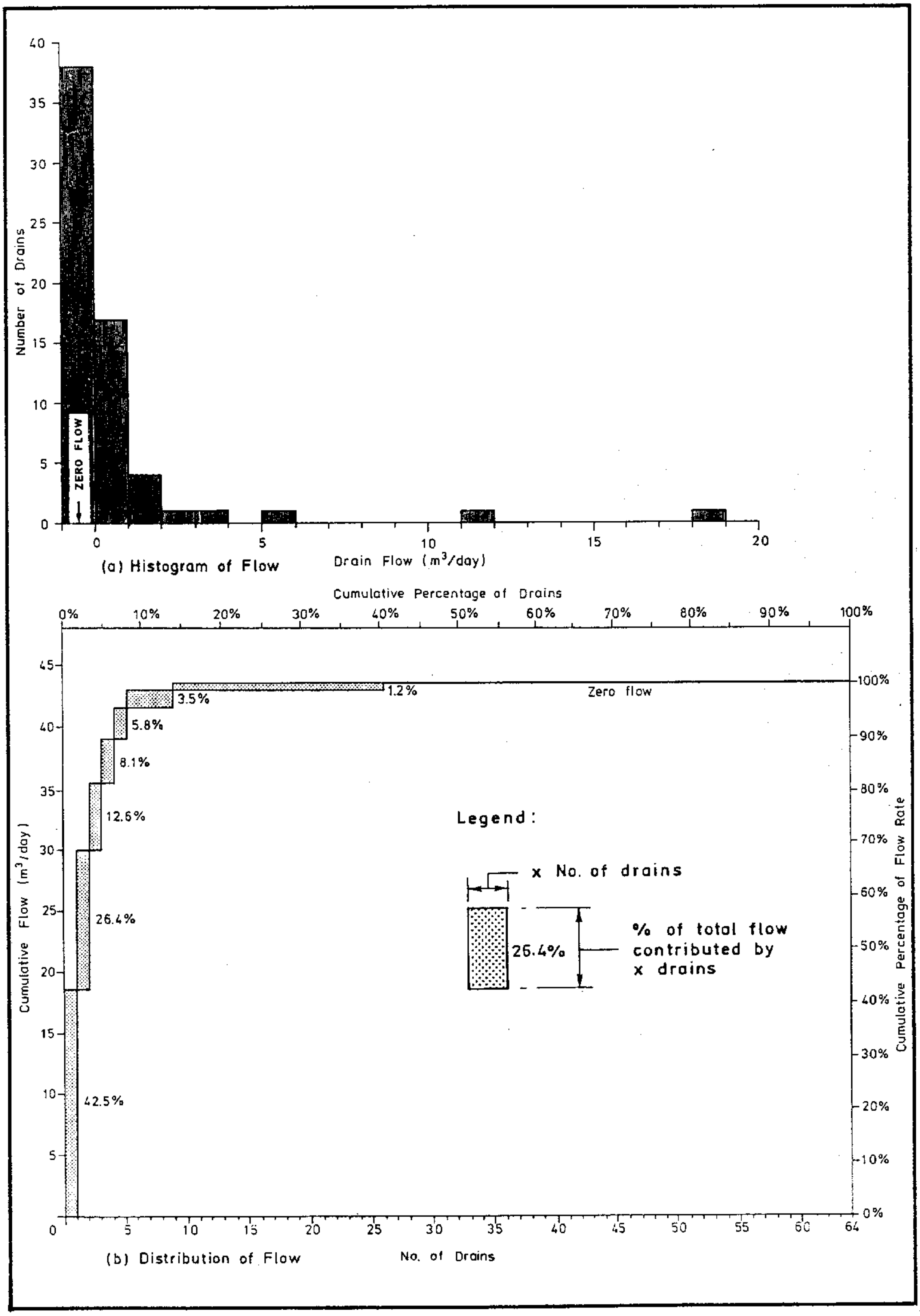

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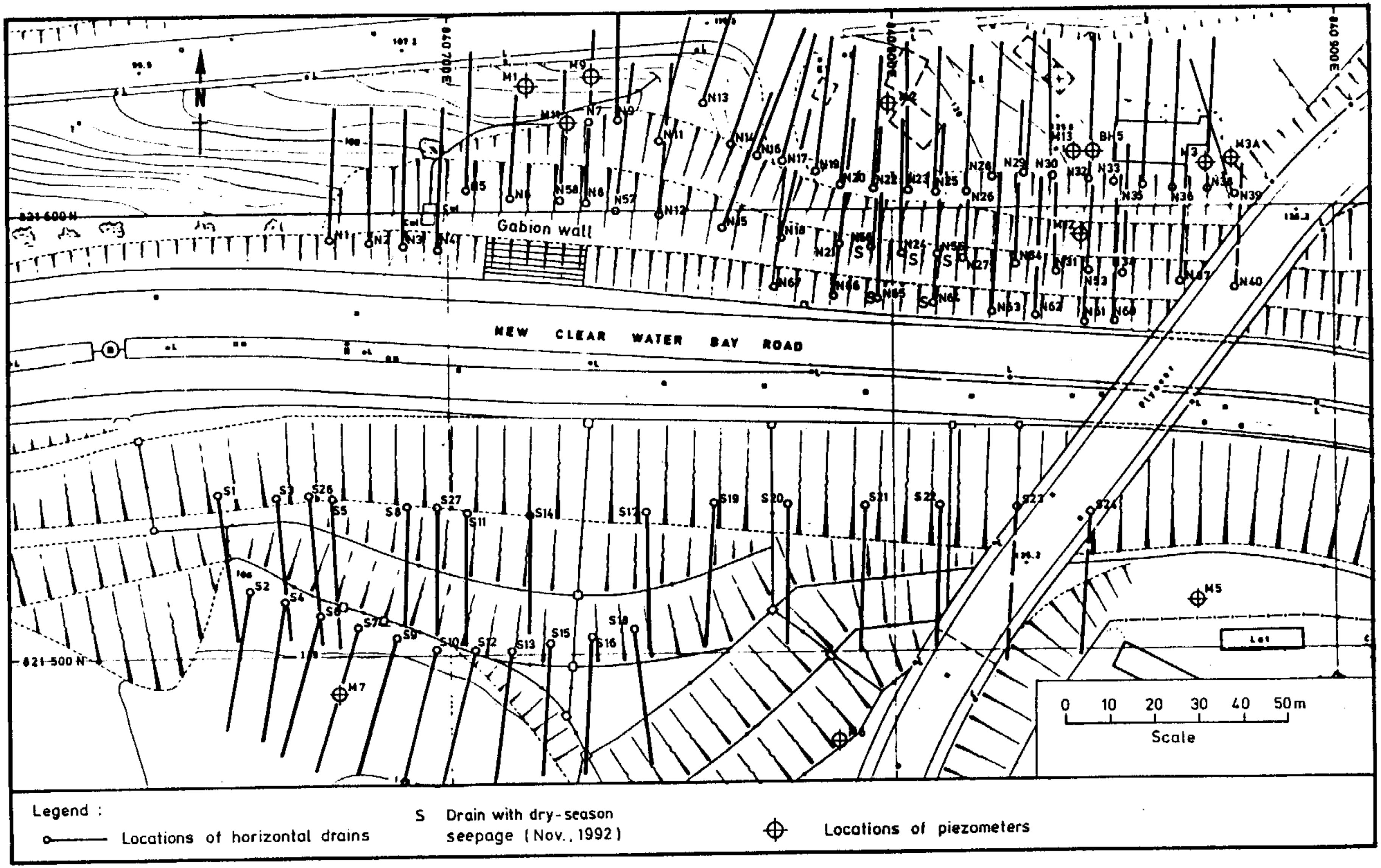

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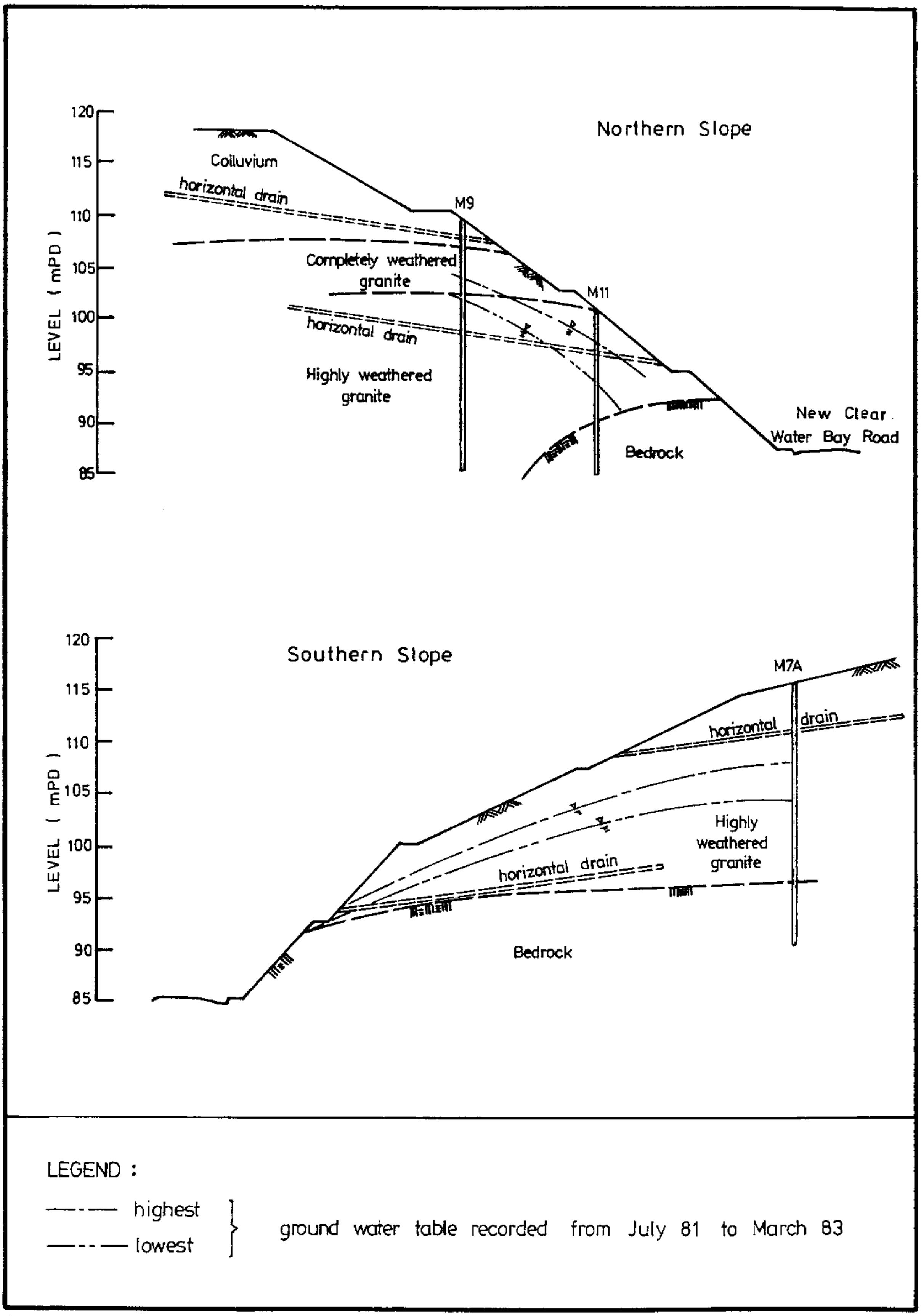

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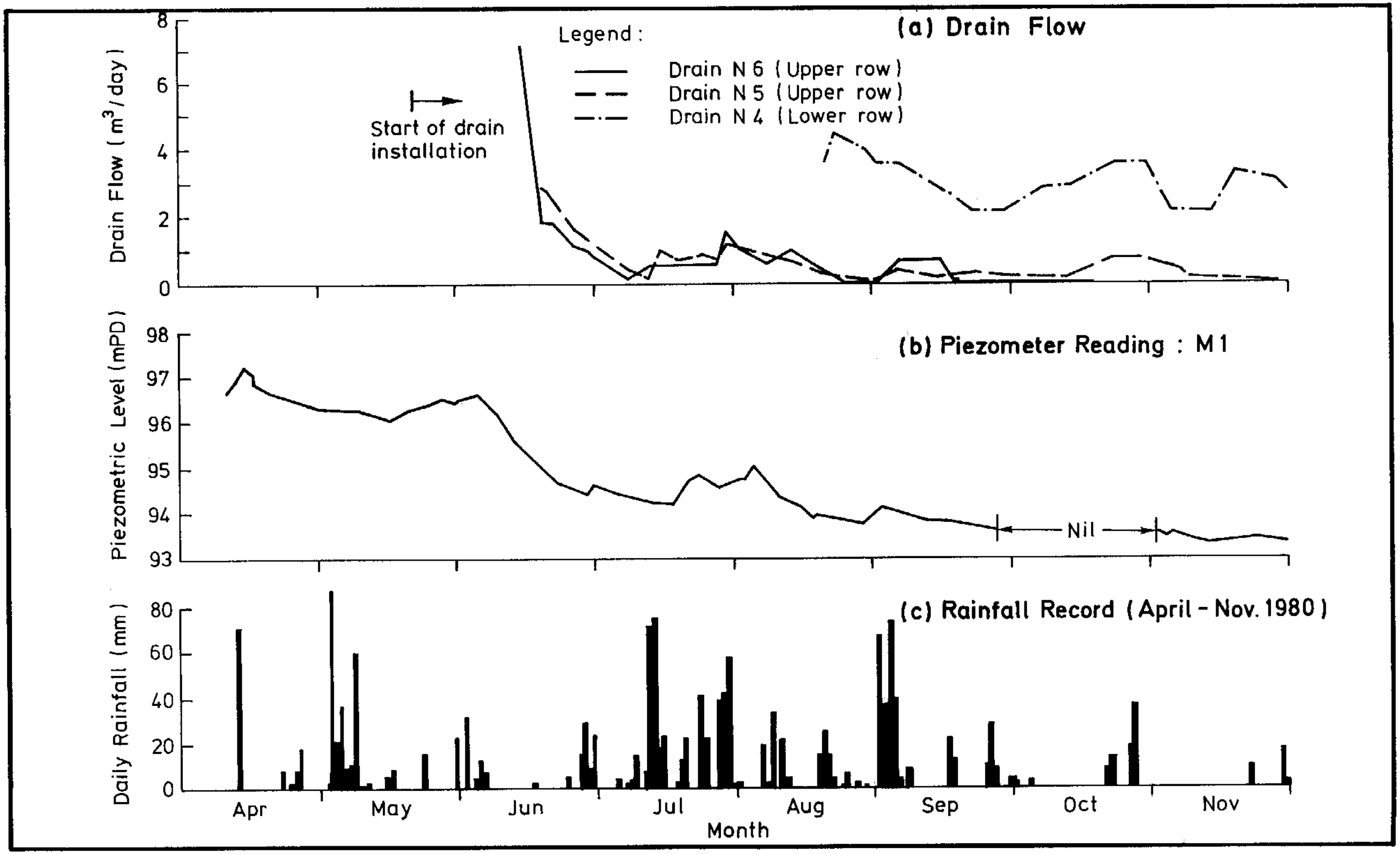

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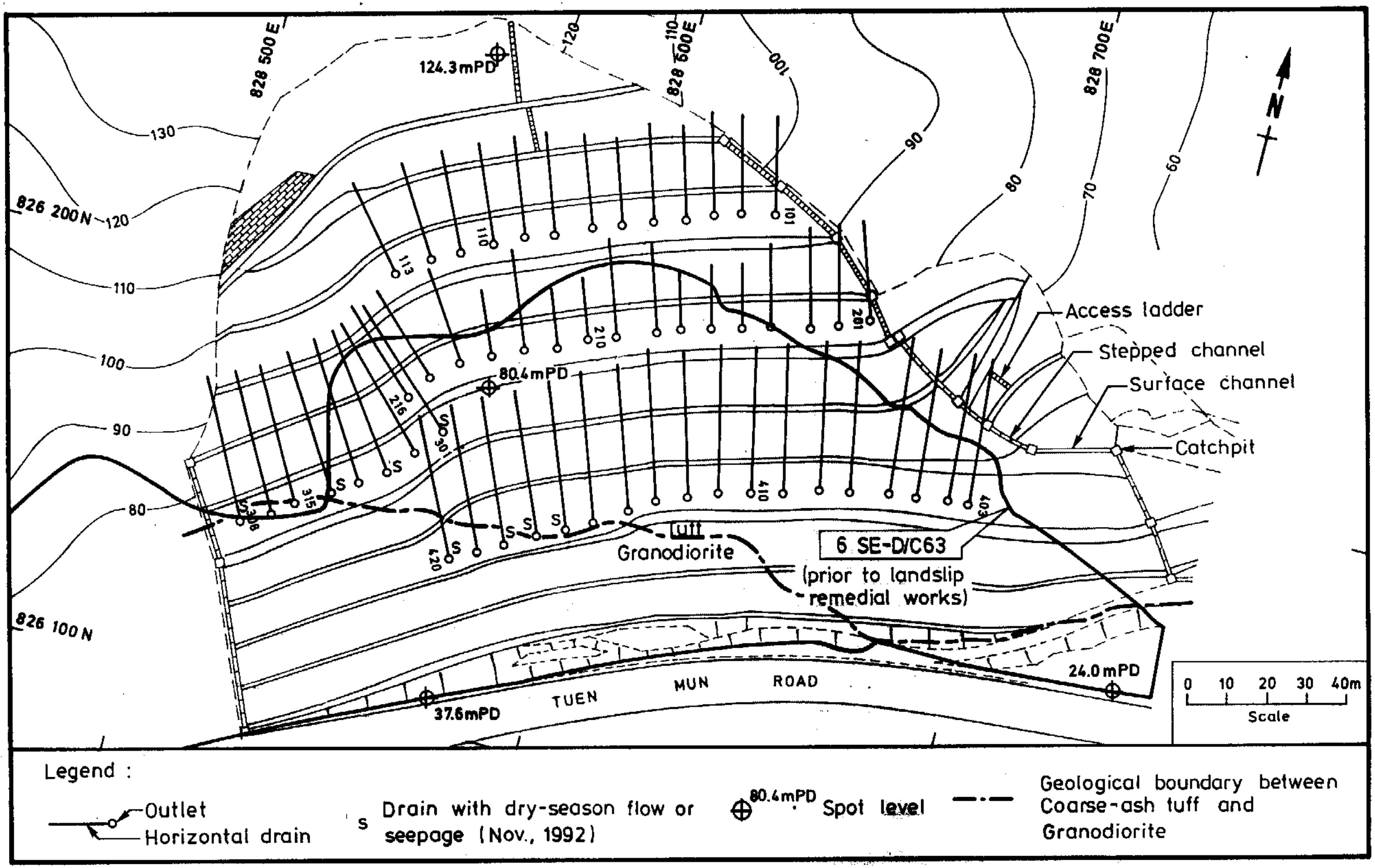

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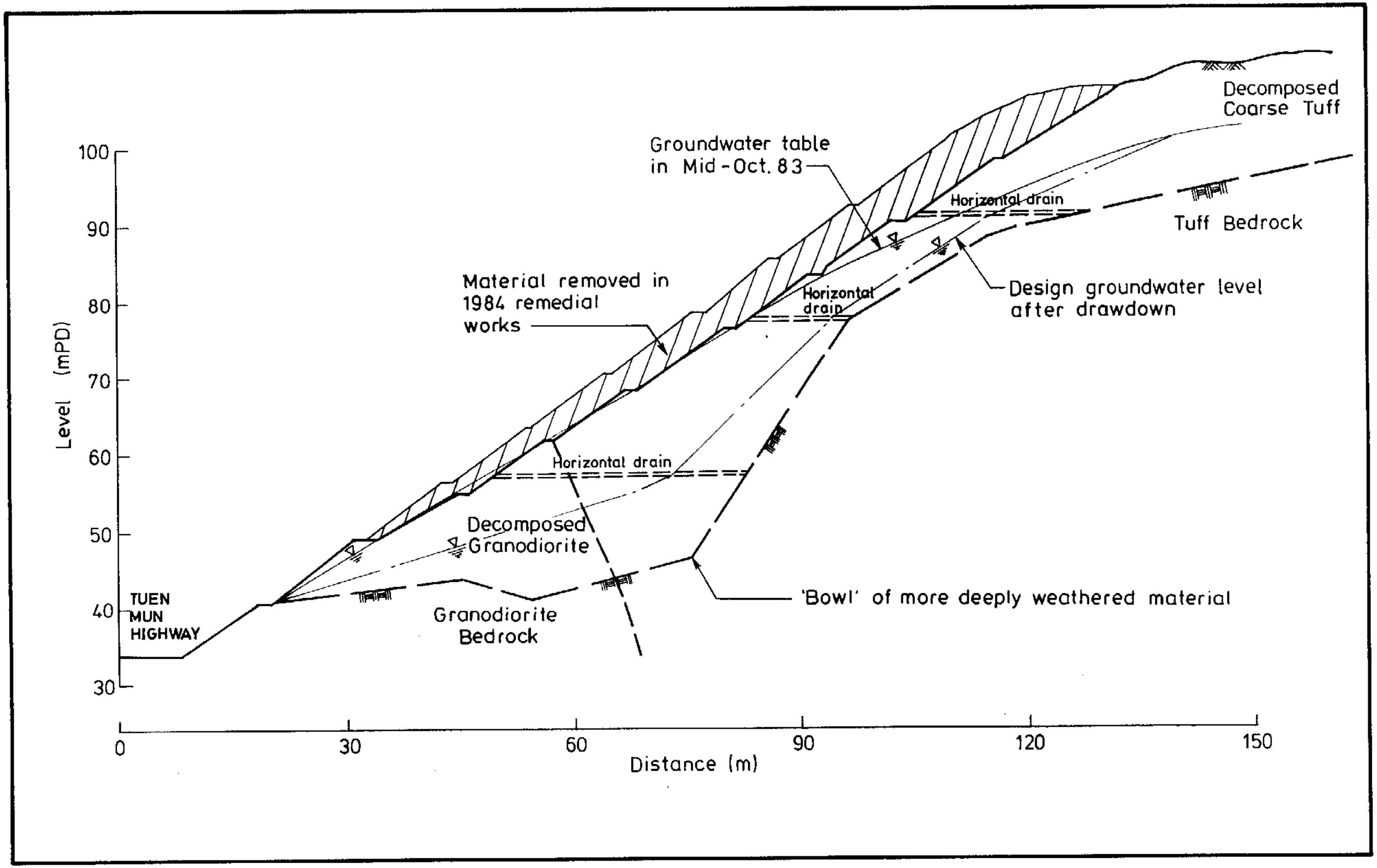

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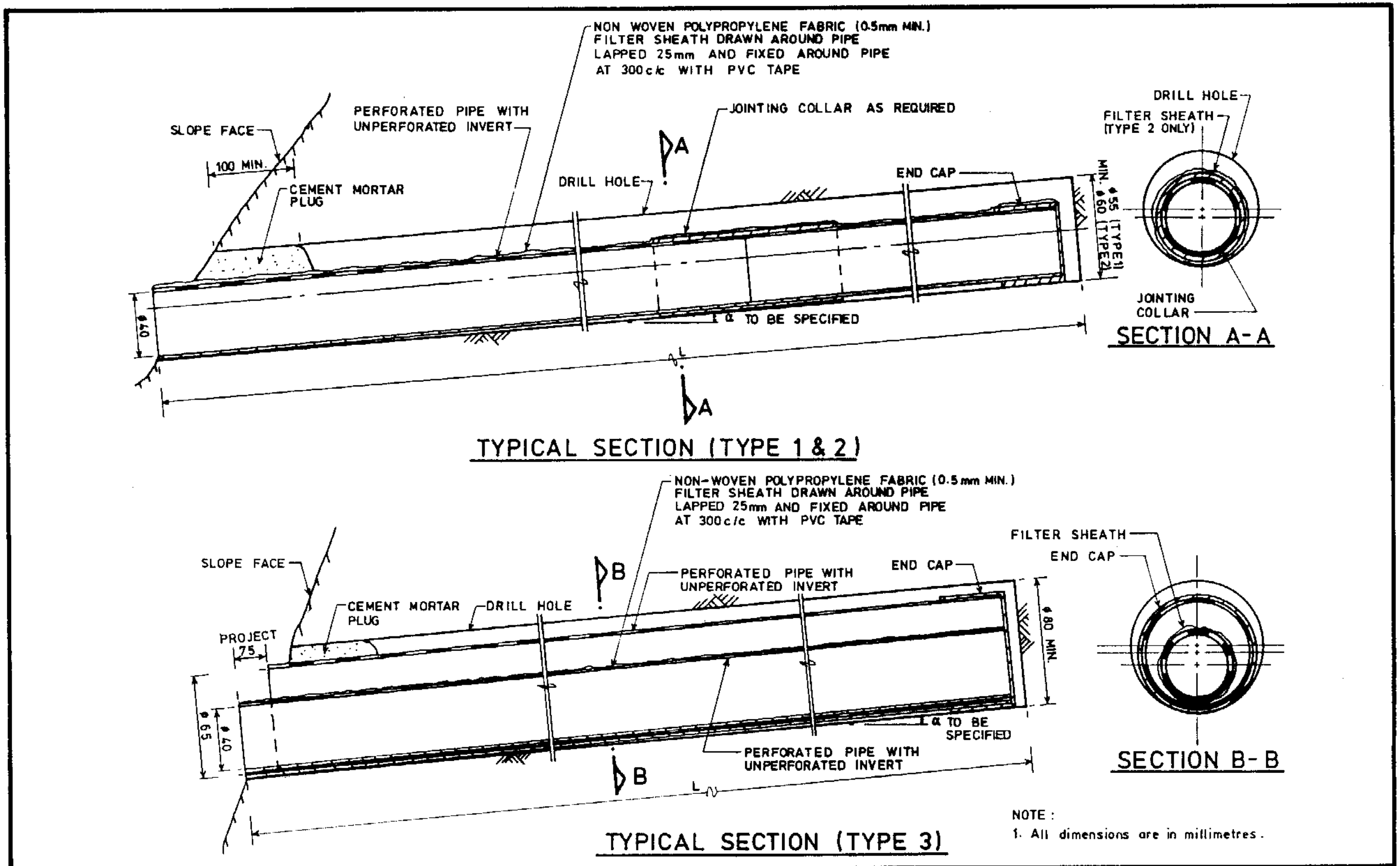

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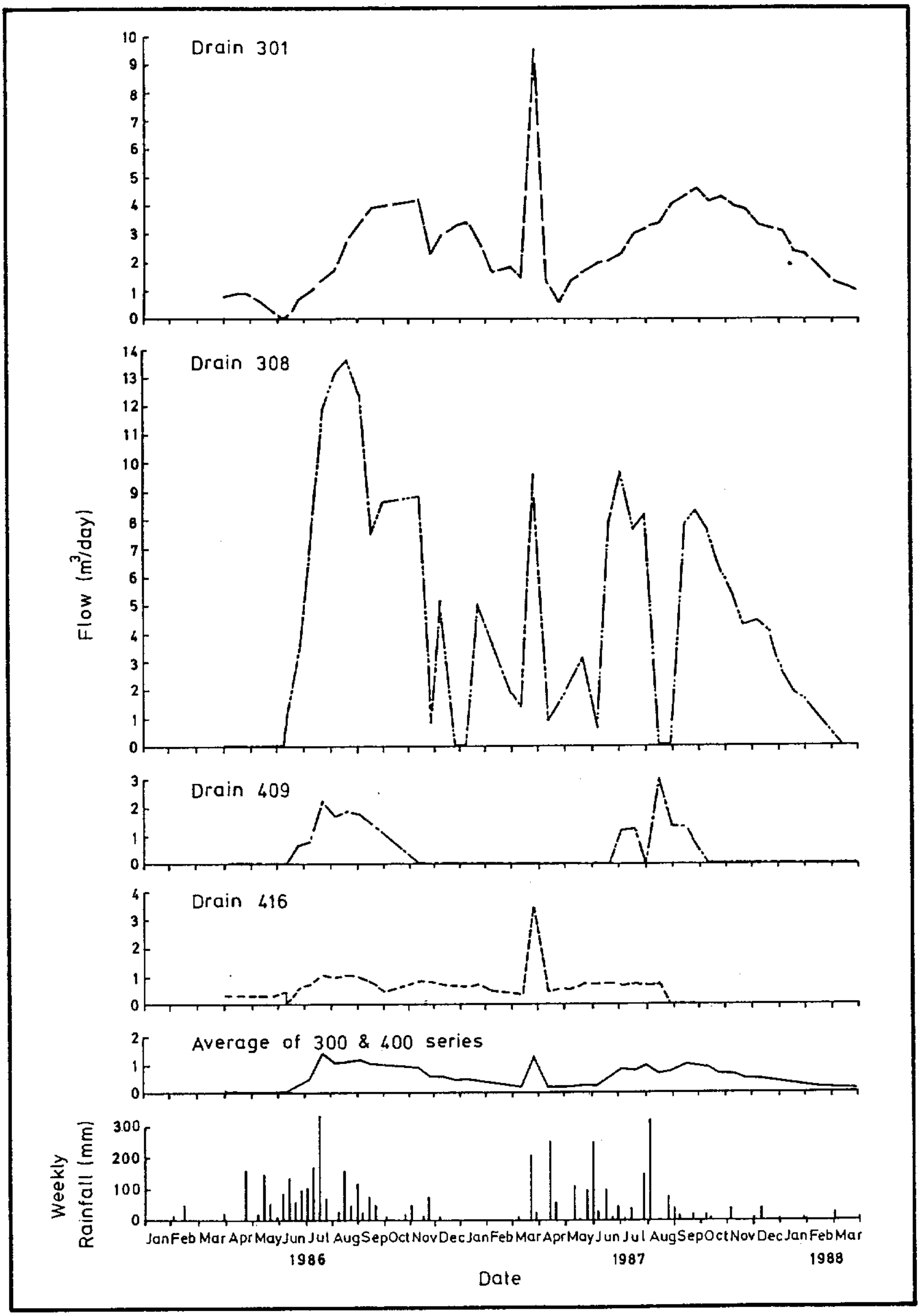

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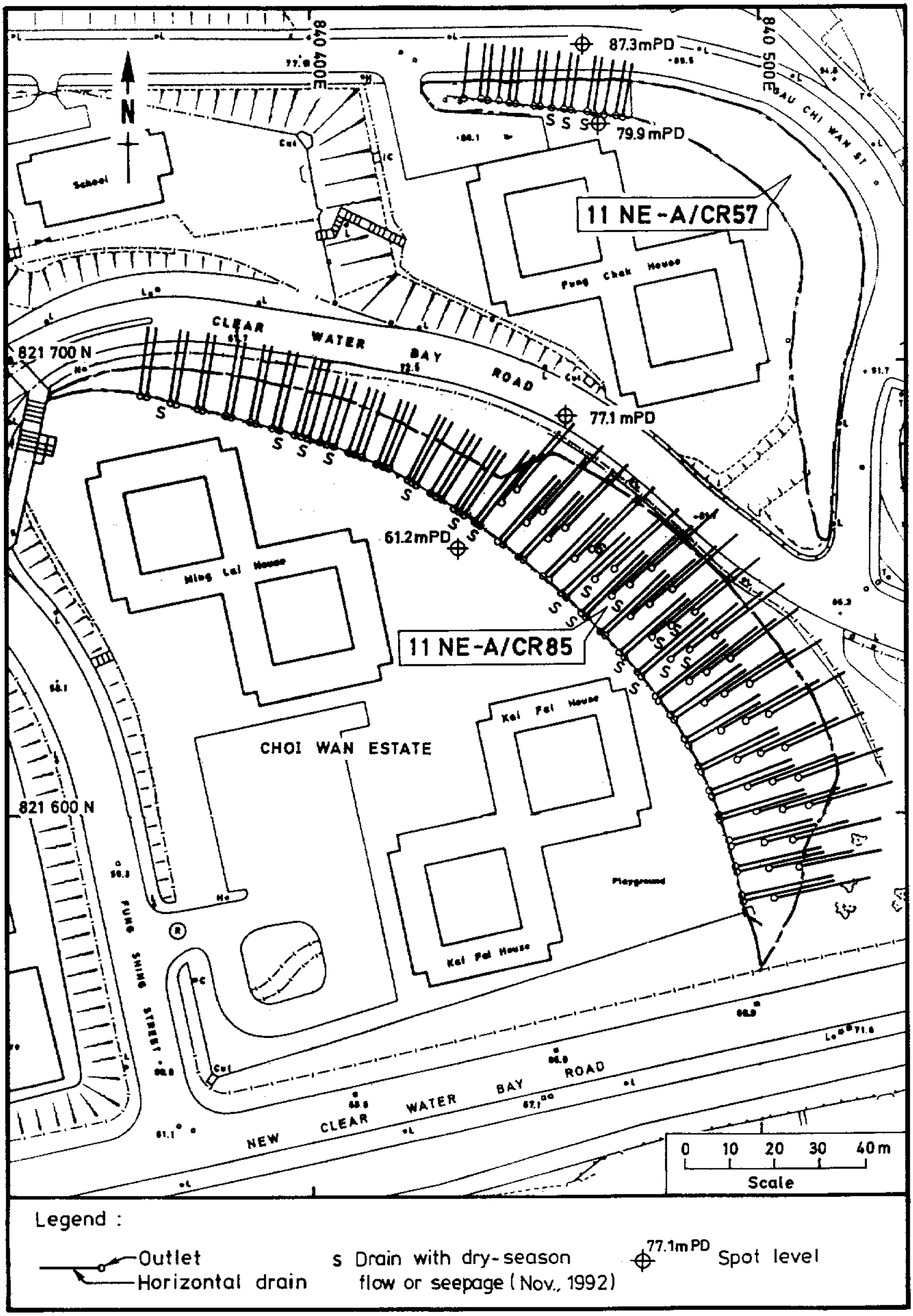

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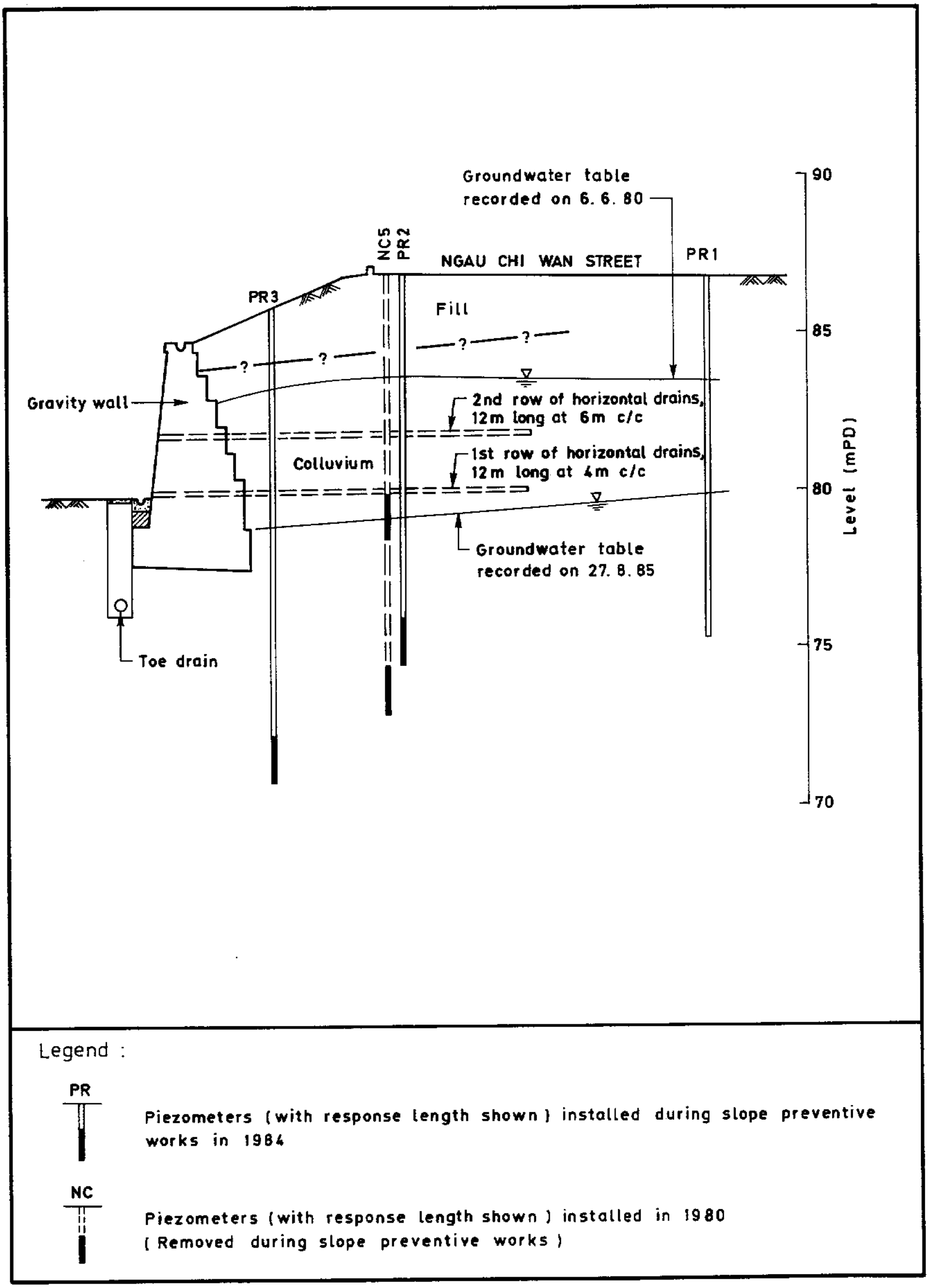

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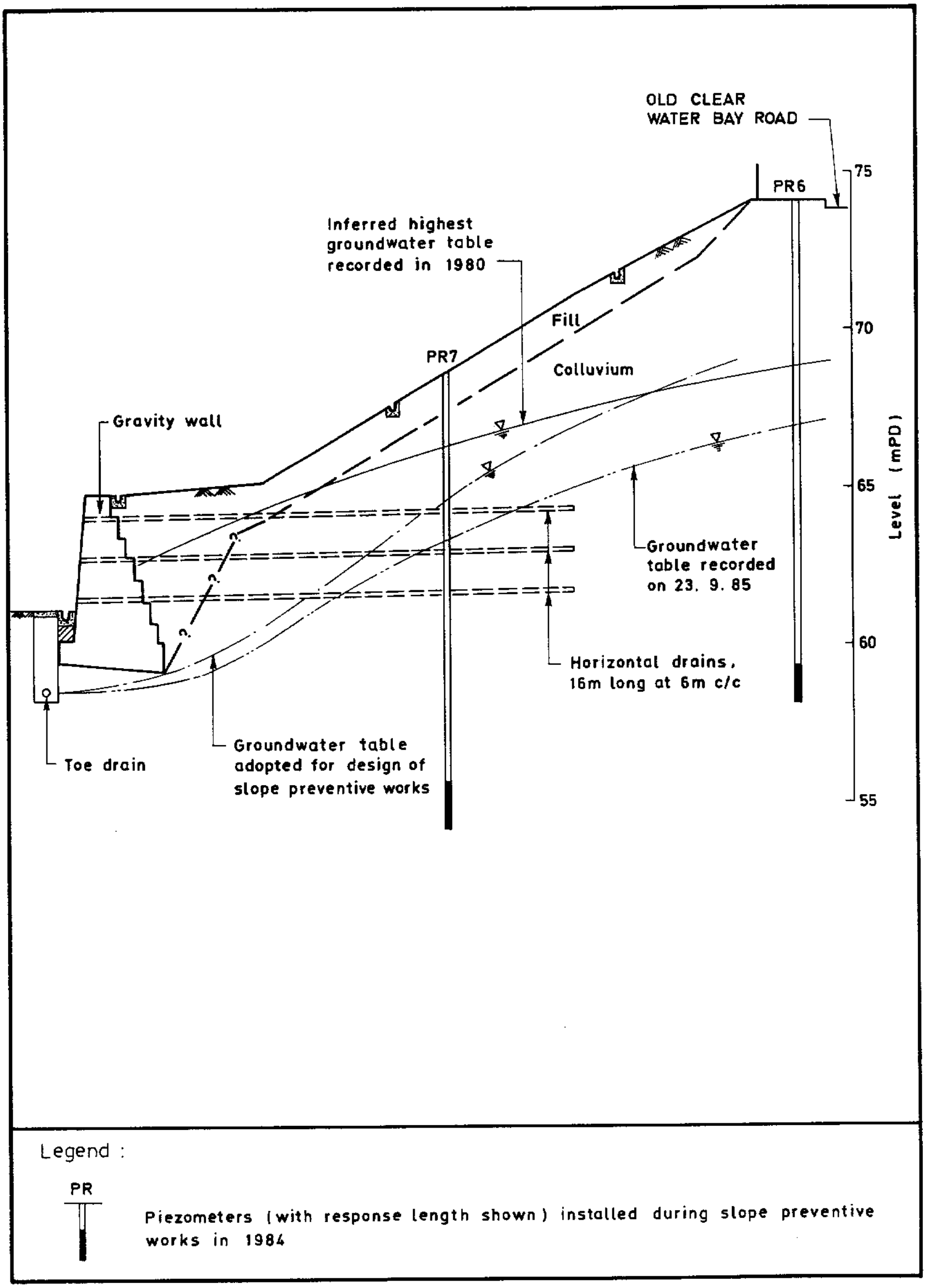

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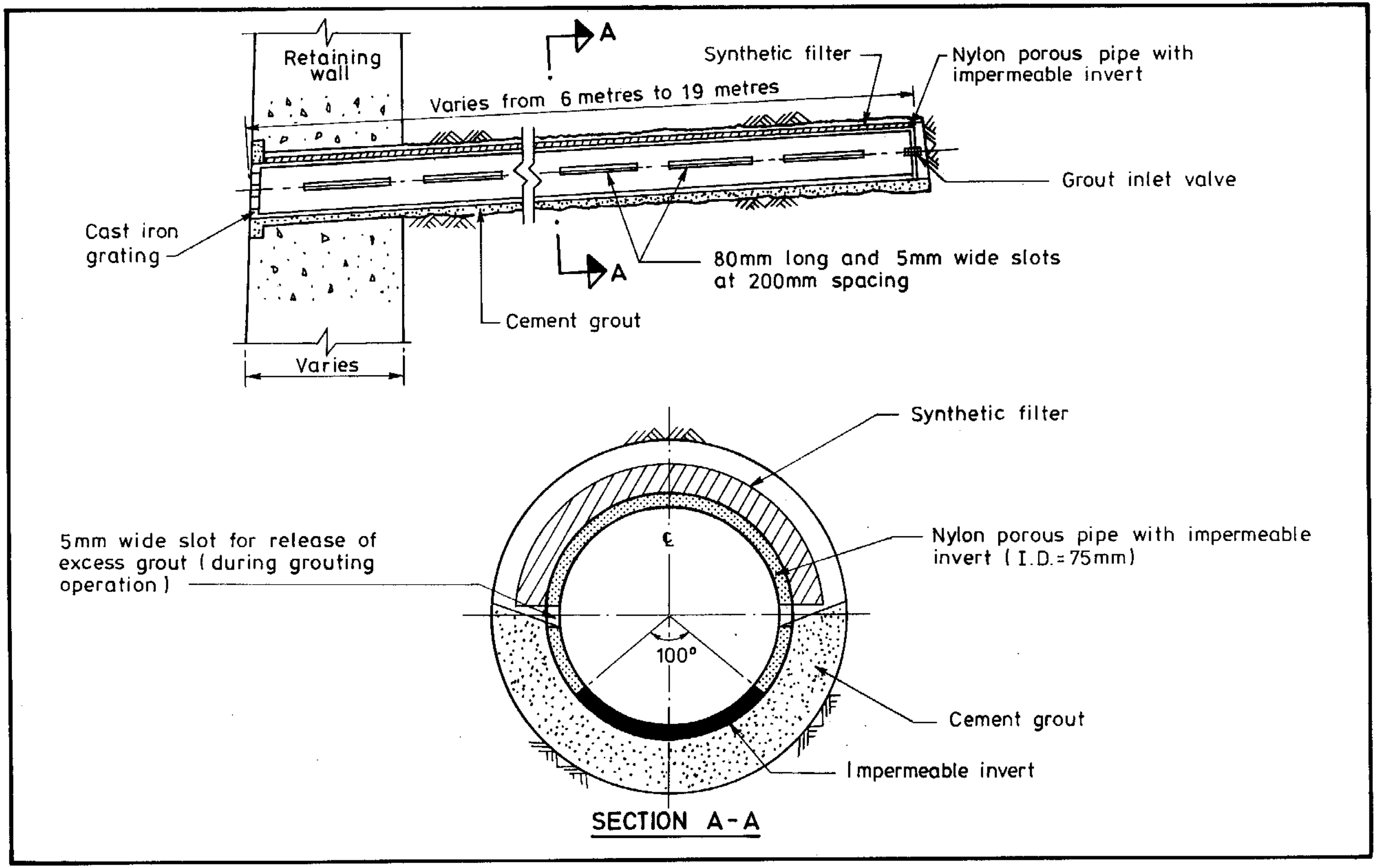

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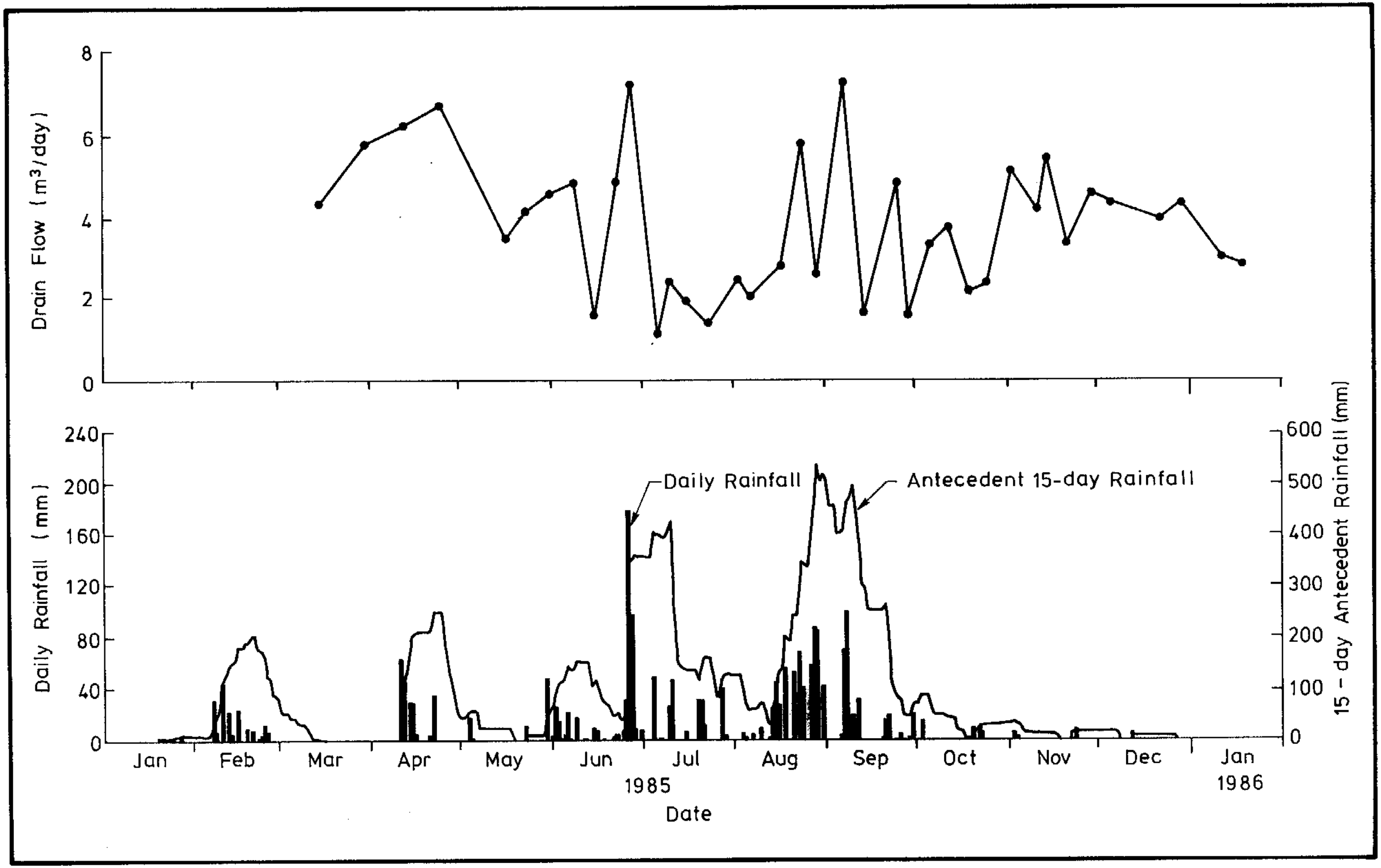

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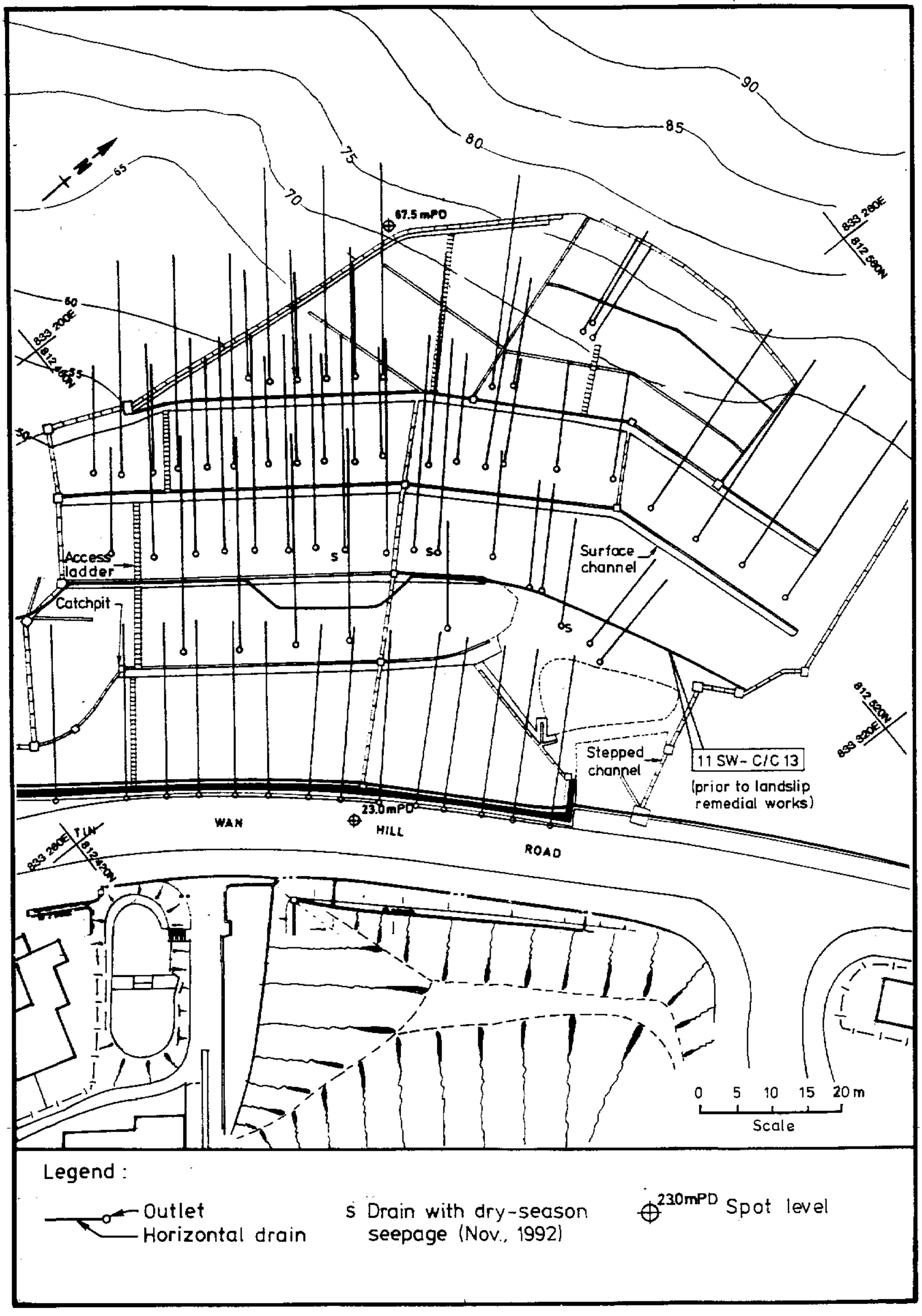

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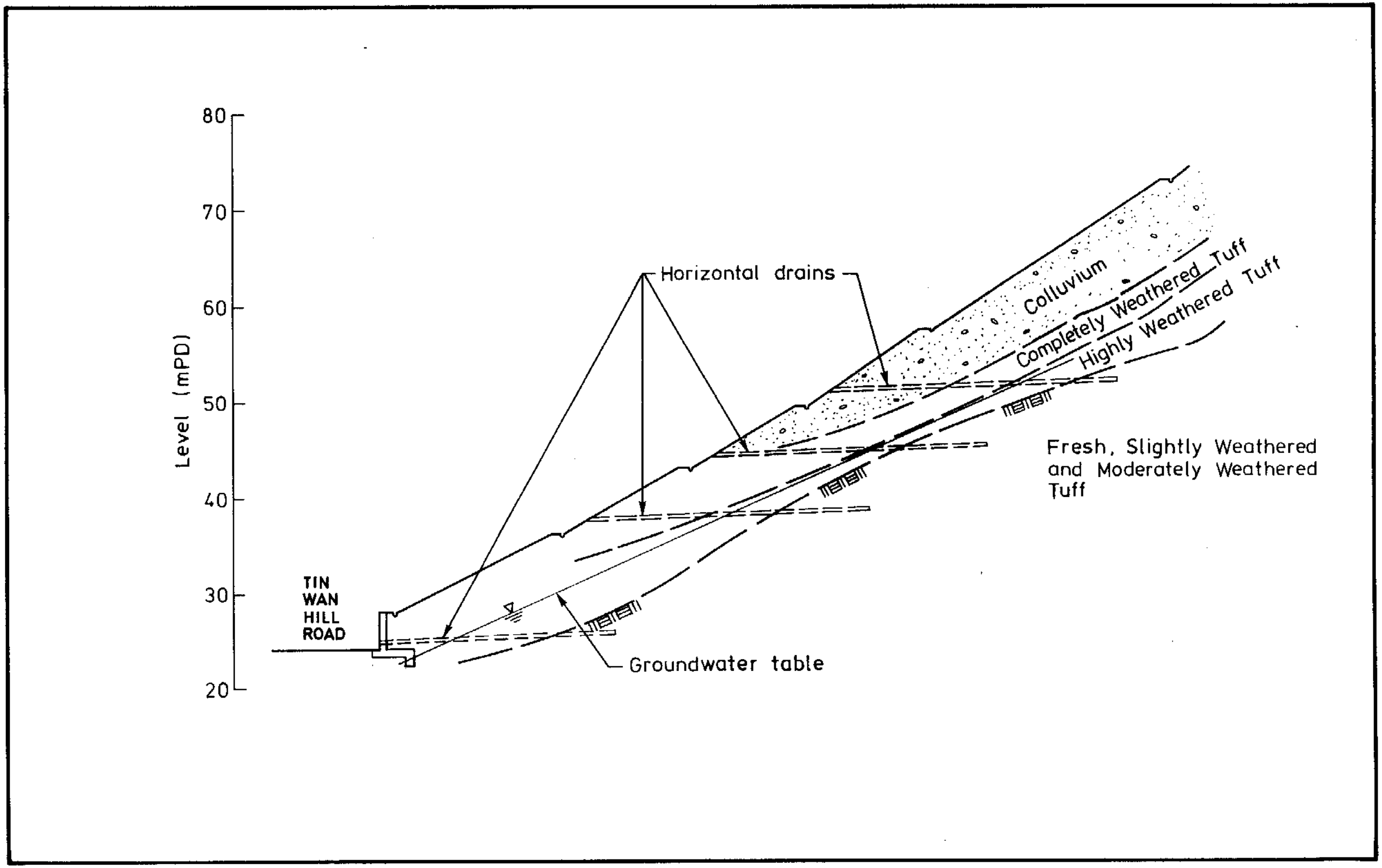


Figure 29 - Typical Section Showing Ground Conditions and Positions of Horizontal Drains at Tin Wan Hill Road

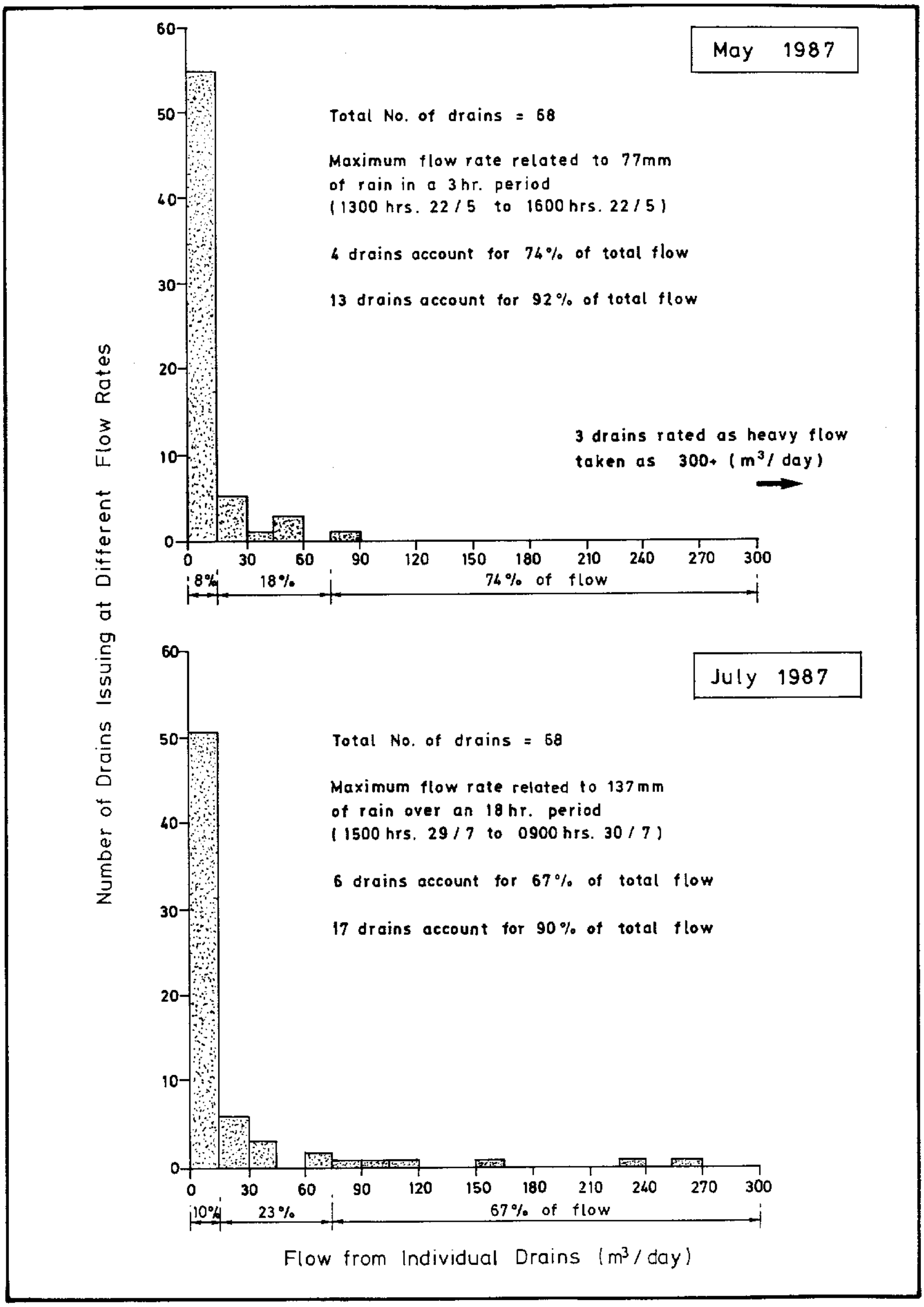


Figure 30 - Histograms of Drain Flows at Tin Wan Hill Road in the May and July 1987 Multiple Storms (after Whiteside, 1987)

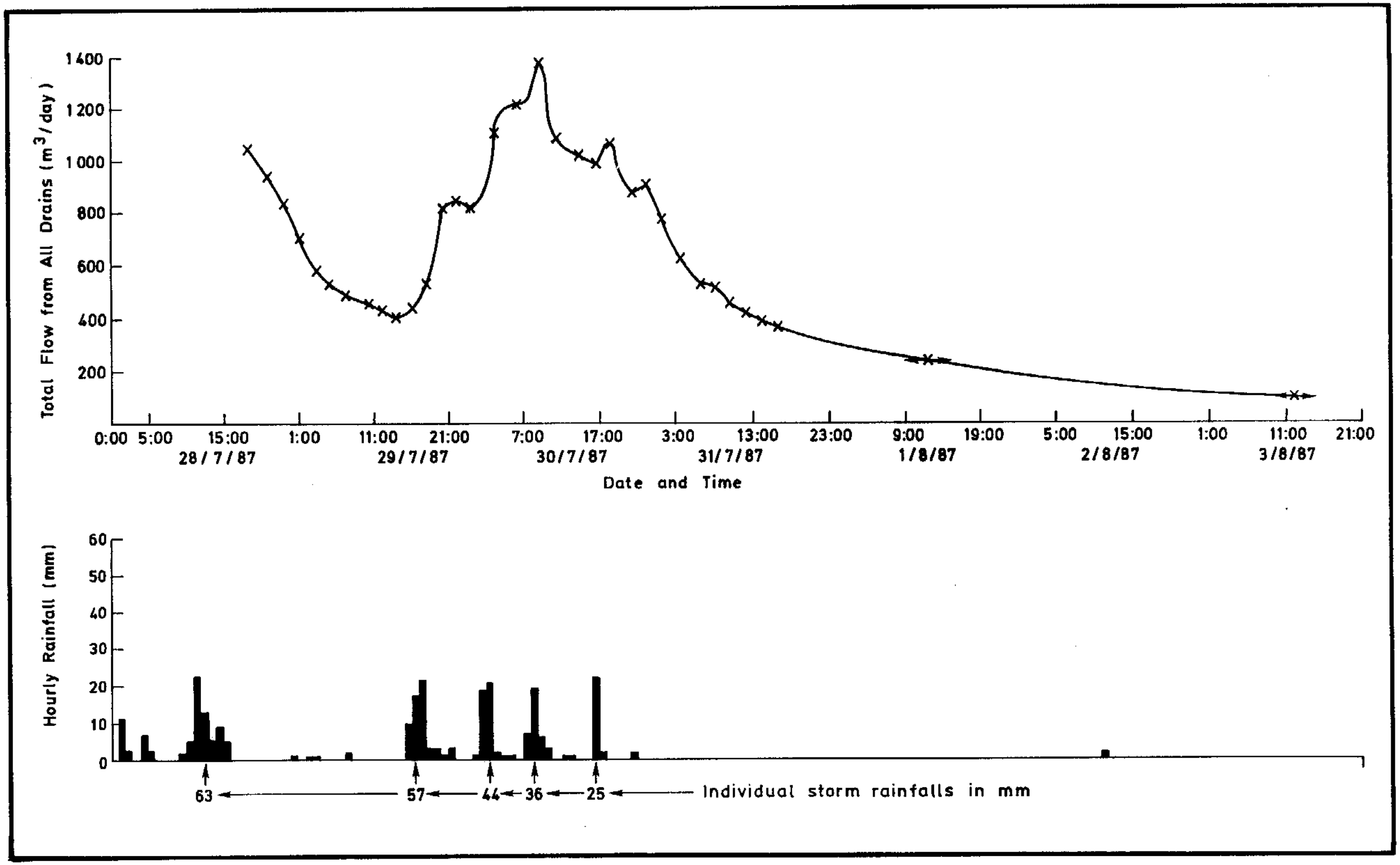


Figure 31 - Rainfall and Total Flow from All Drains at Tin Wan Hill Road in the July 1987 Multiple Storm (after Whiteside, 1987)

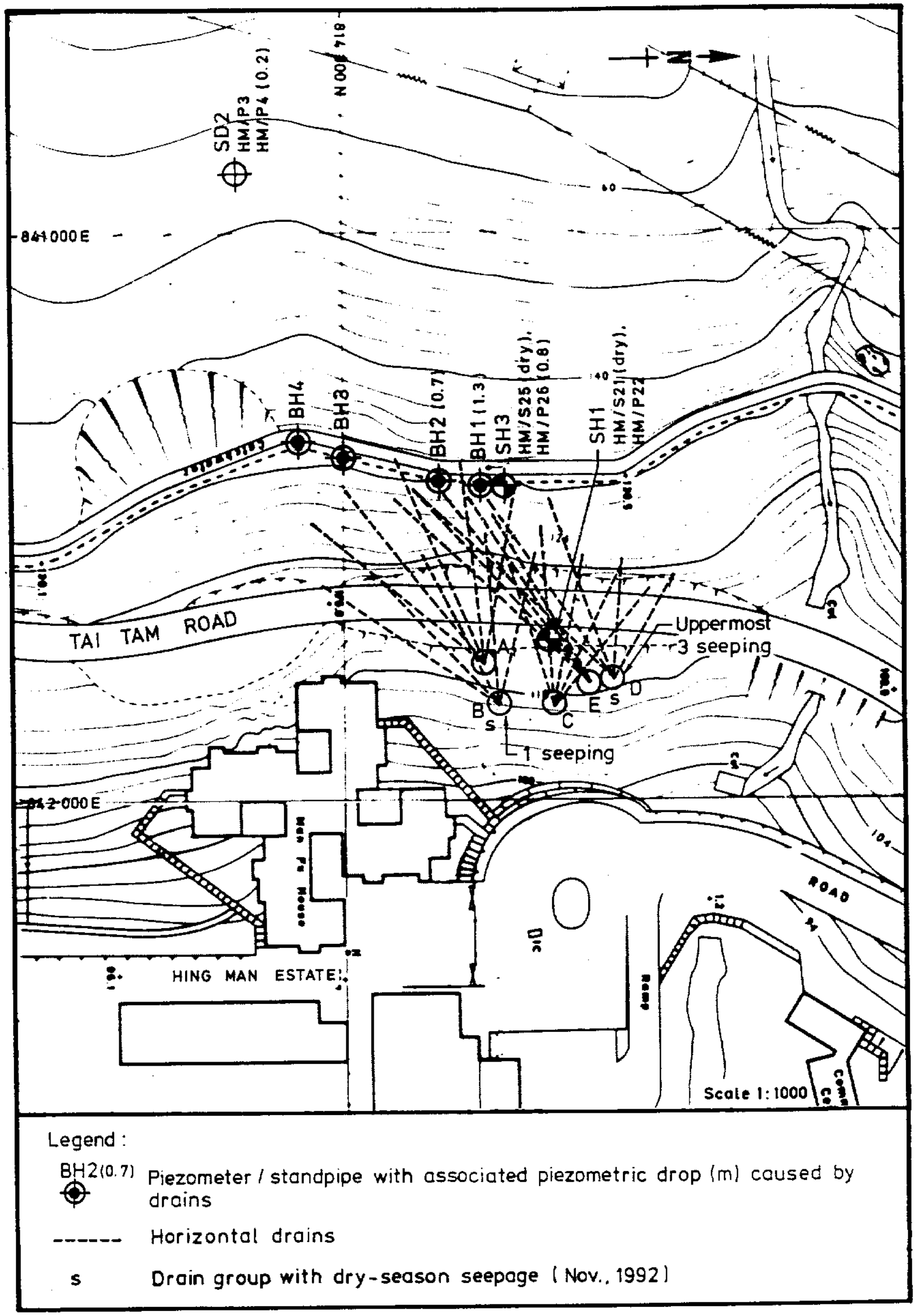


Figure 32 - Layout of Horizontal Drains at Hing Man Estate

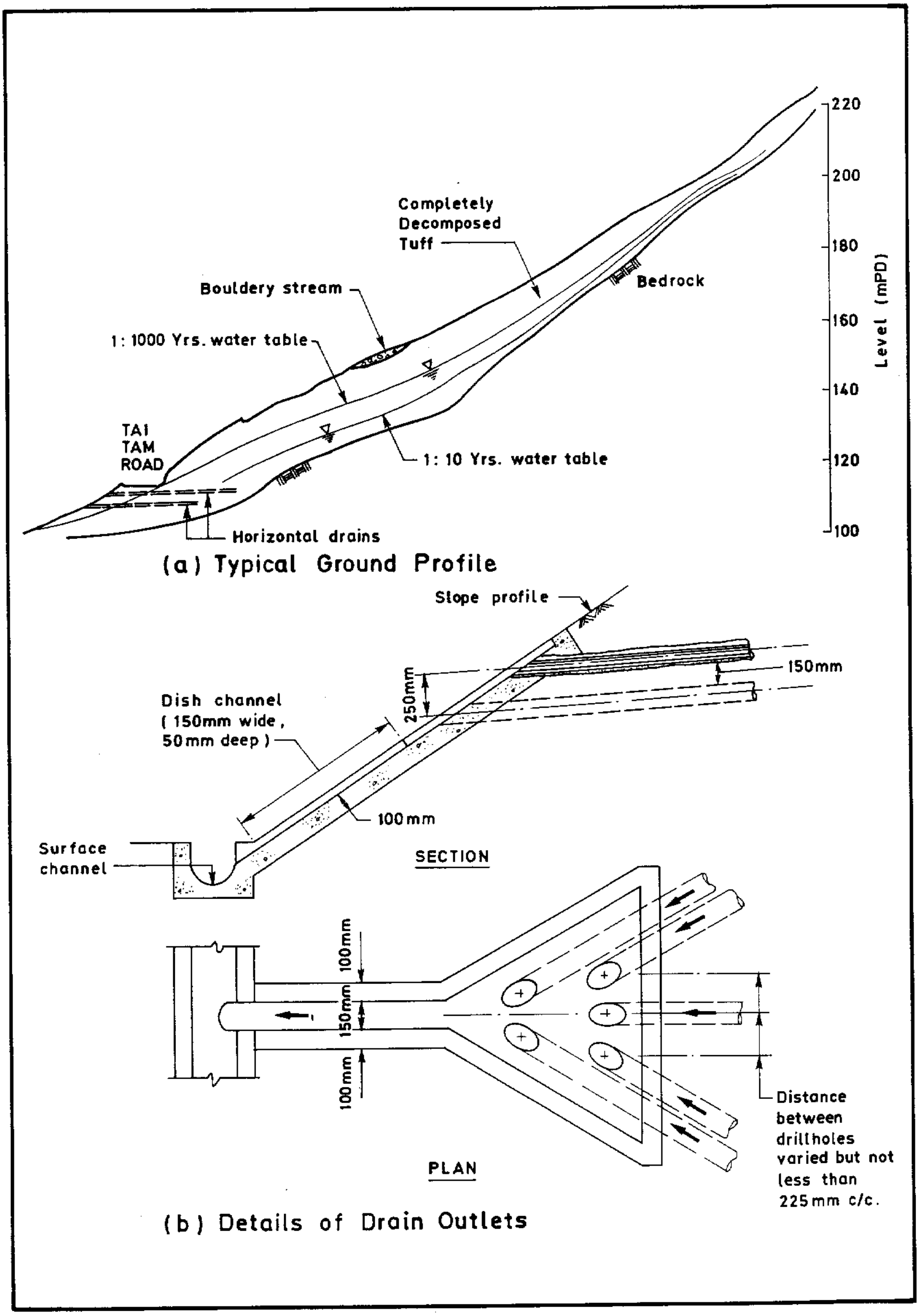


Figure 33 - Typical Section and Details of Drain Outlets at Hing Man Estate

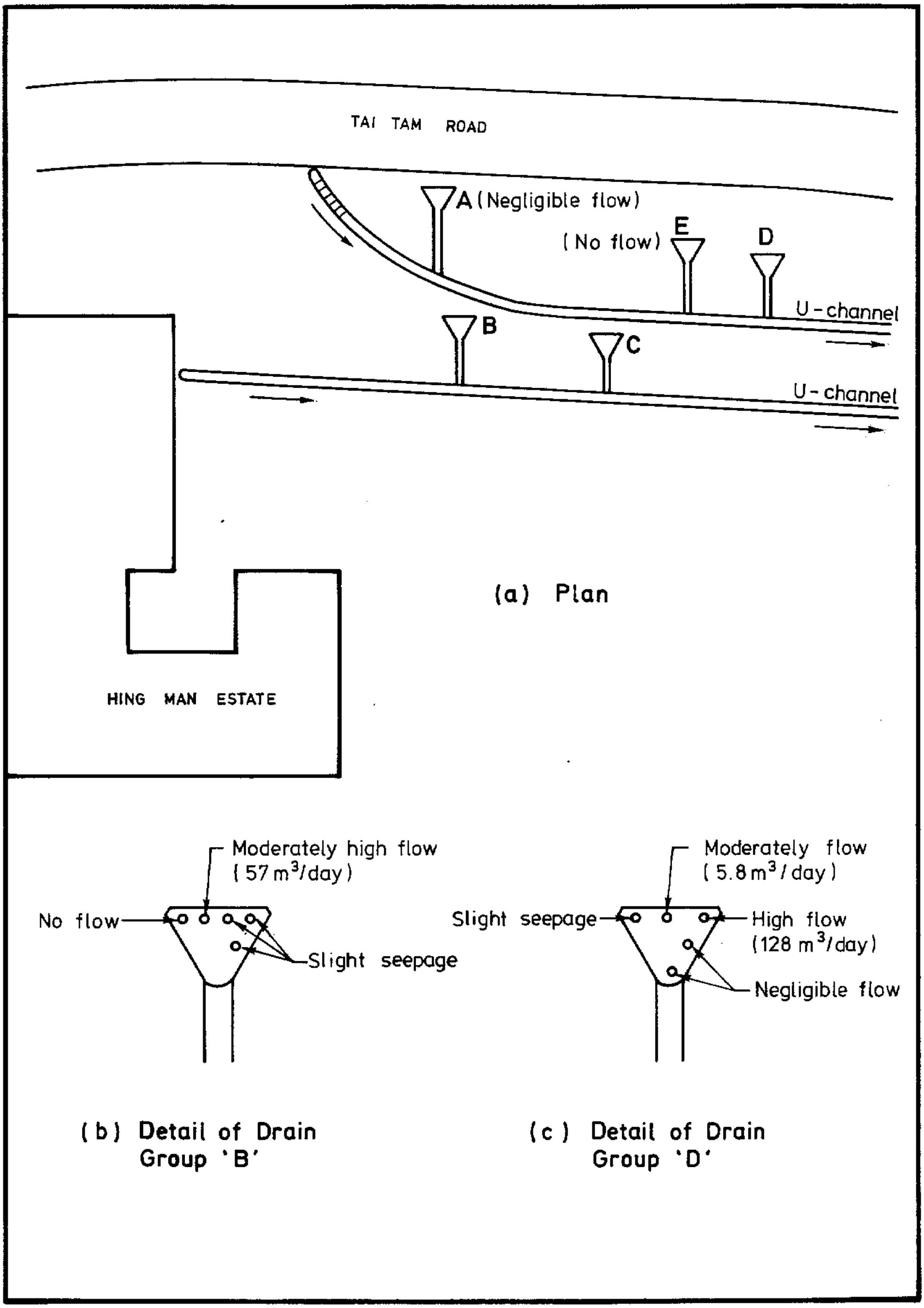


Figure 34 - Sketch of Horizontal Drains at Hing Man Estate Showing Flows on 4 July 1986

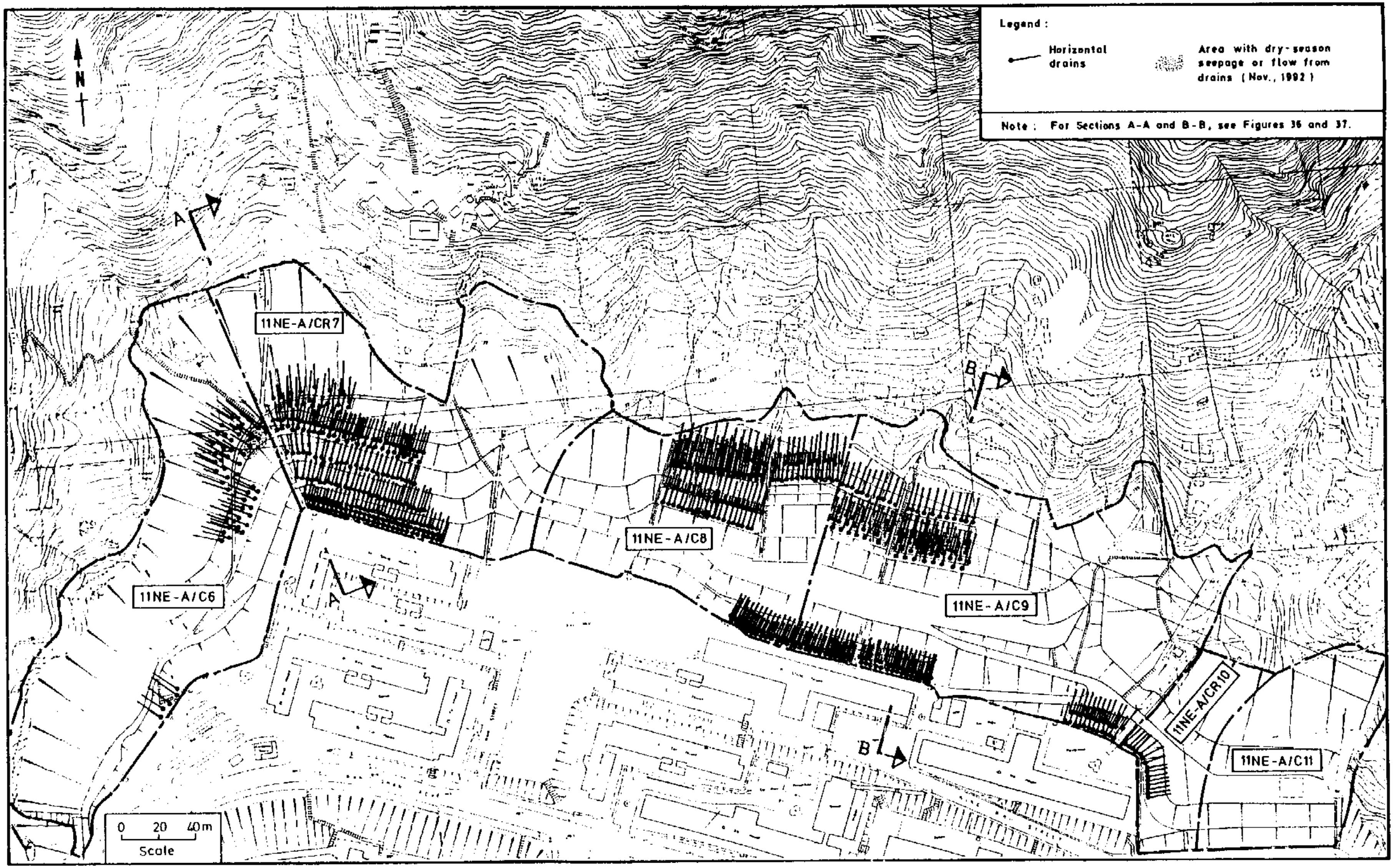


Figure 35 - Layout of Horizontal Drains at Tsz Wan Shan Estate

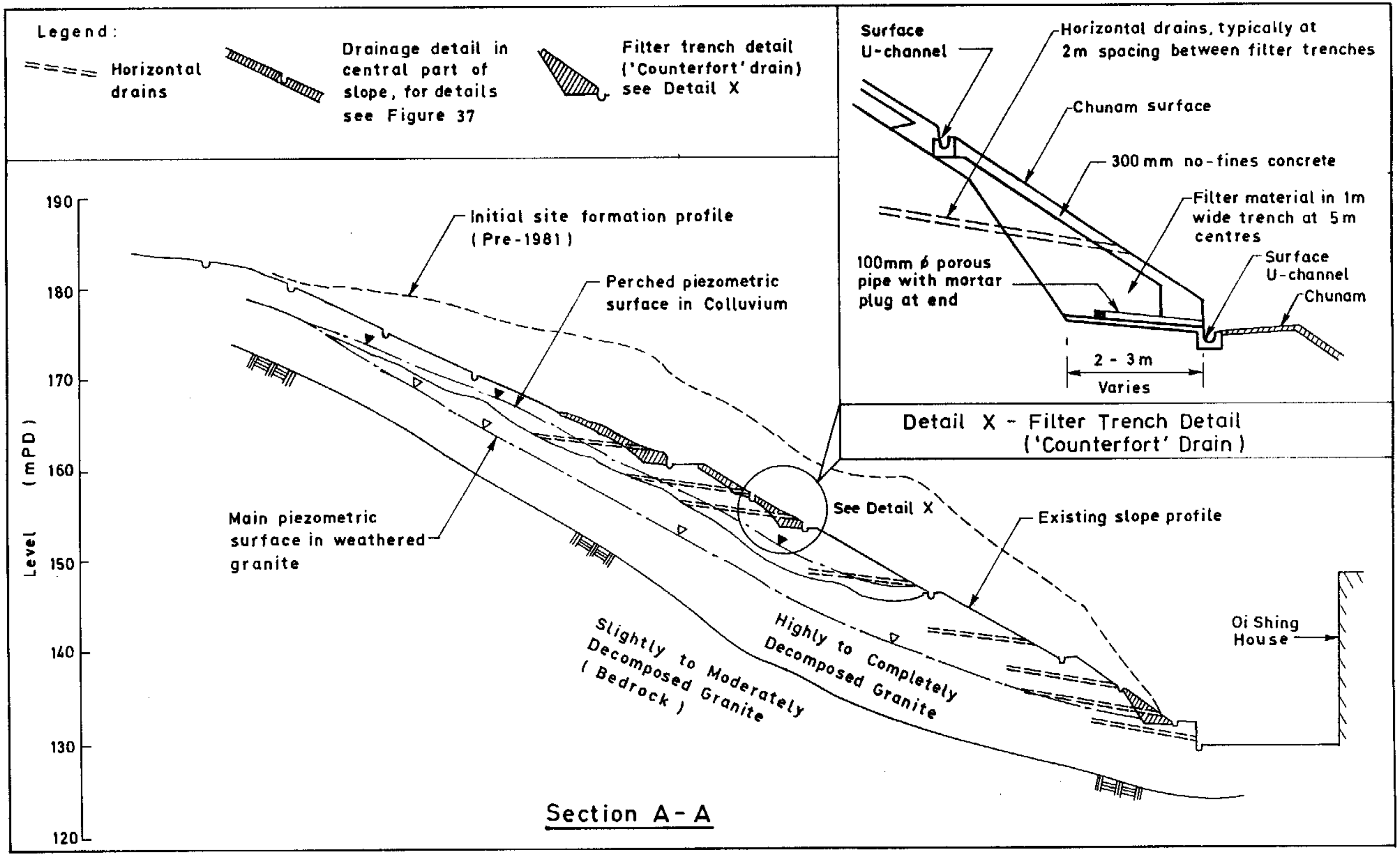
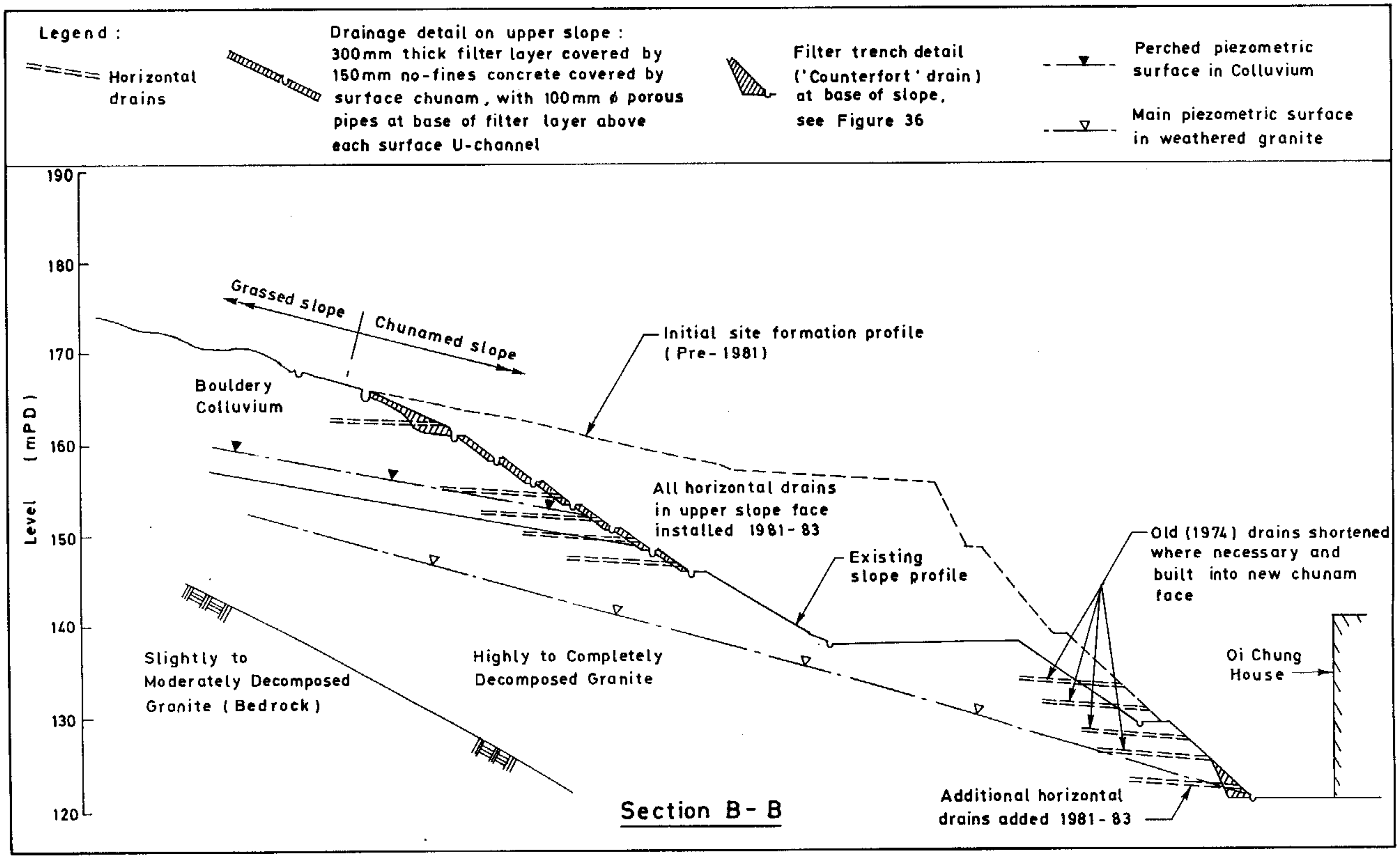


Figure 36 - Ground Conditions and Positions of Horizontal Drains at Slope 11NE-A/CR7, Tsz Wan Shan Estate (after SWKP, 1979 & FHB Consultants, 1990)



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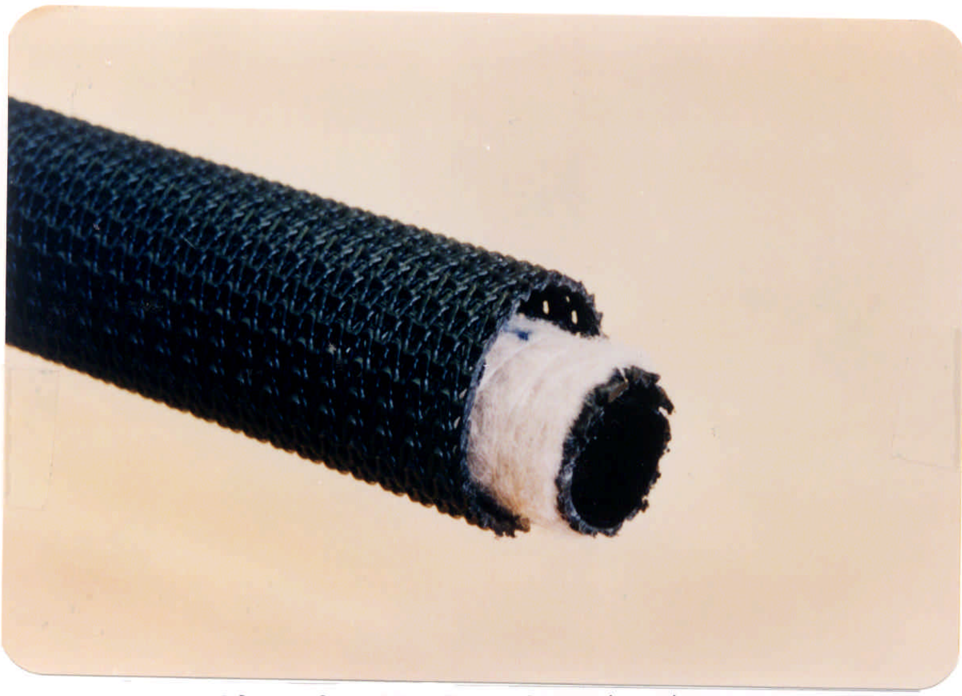
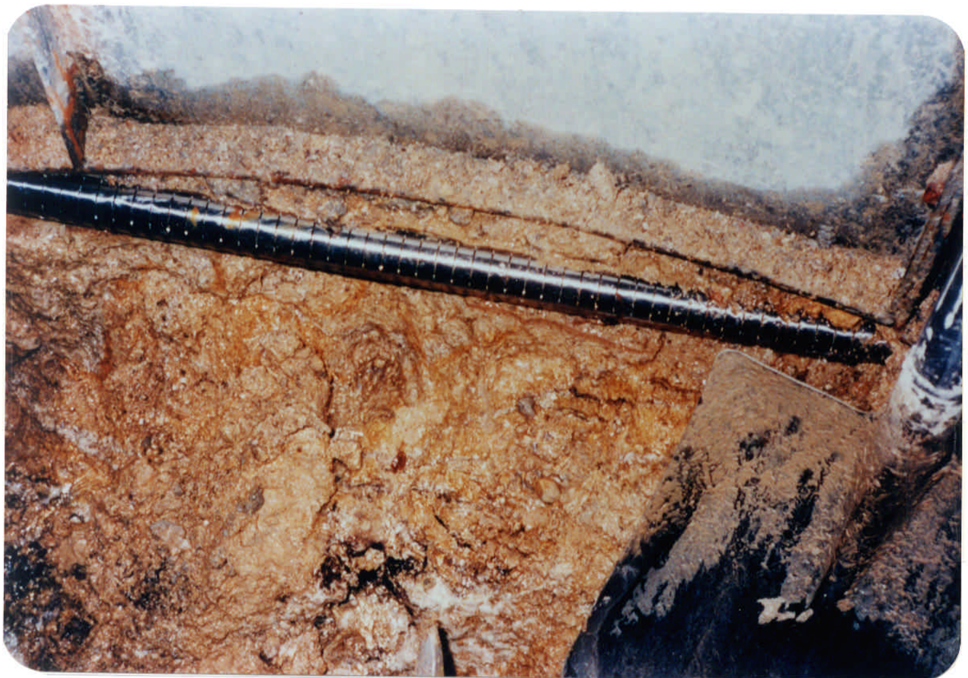


Plate 2 - GEO Type 3 Drain Liner

EG 93/37/3

Plate 3 - Joint in GEO Type 3 Drain Liner Tied by Nylon Line

SP 8811523



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PSl 33

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SITES WITH HORIZONTAL DRAINS IN HONG KONG

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Sai Wan Estate, off Ka Wai Man Road, Kennedy Town	11SW-A/FR50	I01	Similar to GEO Type 2	8	10m	S	?	GCI 3/2/164
Belcher's Street opposite Sai Cheung Street, Kennedy Town	11SW-A/C154	I02	GEO Type 3	5	5m	R	1986	GCD 2/A1/11SW-A/C154 LPM Contract 5/GCO/83
Natural Slope Behind Piccadilly Mansion & Po Shan Mansion, Po Shan Road, Mid-levels	11SW-A/C20, CR175, CR176, CR178, CR179, R672, F72	I03	As Figure 1E	58	15-90m	S&R	1985	GCI 2/A2/2 & other Island Division files GCD 2/A1/537 GCSP 2/D4/9(6) LPM Contract GC/84/01 Craig & Gray (1985) (Designed drains)
The Mid-levels Police Station, High Street	11SW-A/R429	I04	GEO Type 2	6	1m	S	1986?	GCD 2/A1/11SW-A/R429 LPM Contract GC/85/06
50-58, Po Hing Fong, Mid-levels	11SW-A/R53 & R56	I05	GEO Type 3	8	11m	S	1985	GCD 2/A1/11SW-A/R53, R56 LPM Contract 14/GCO/83
60-72, Po Hing Fong, Mid-levels	11SW-A/R64	I06	GEO Type 3	6	6.5m	S	1985	GCD 2/A1/11SW-A/R64 LPM Contract 14/GCO/83
Junction of Ladder St & Upper Lascar Row, Central	11SW-A/R26	I07	GEO Type 3	13	2-3m	S	1987	GCD 2/A1/11SW-A/R26 LPM Contract GC/85/06
Junction of Tank Lane and Square Street	11SW-A/R38	I08	GEO Type 3	12	2m	S	1987?	GCD 2/A1/11SW-A/R38 LPM Contract GC/85/06

Table A1 - Summary of Sites with Horizontal Drains (Sheet 2 of 13)

Site Location	Registered Slope/Wall Number	GEO District & Code Number (see Figure A1)	Drain Type (see Figure 1)	Number of Drains	Length of Drains	Ground Type (S = Soil R = Rock)	Date of Completion	GEO File Number/ Contract Number/ Remarks
2, Bridges Street, Mid-levels	11SW-A/R92	I09	GEO Type 2	8	5m	S	1991	GCD 2/A1/11SW-A/R92 LPM Contract GC/88/05
60, Bridges Street, Mid-levels	11SW-A/R76, R79, R80	I10	GEO Type 2	12	4m (R76) 10m (R79 & R80)	S	1991	GCD 2/A1/11SW-A/R80 LPM Contract GC/88/05
1-12, Wing Lee Street, Mid-levels	11SW-A/R91	I11	GEO Type 3	13	5m	S	1985	GCD 2/A1/11SW-A/R91 LPM Contract 14/GCO/83
Opposite 78 Peel Street, Mid-levels	11SW-A/R188	I12	GEO Type 3	11	5m	S	1985	GCD 2/A1/11SW-A/R188 LPM Contract 14/GCO/83
Fairmont Gardens, 39A, Conduit Road	11SW-A/CR16	I13	Similar to Figure 1B?	12?	12-19m?	S&R	Pre-1975	GCD 2/A1/11SW-A/CR16 GCI 3/1/502 Tong & Maher (1975) (Designed drains)
105, Robinson Road, Mid-levels	11SW-A/C61, R384, R385	I14	Intermediate between GEO Types 1 & 2	c.100	2-10m	S	1990-91	GCD 2/A1/11SW-A/C61 LPM Contract GC/88/05 Roll of Tensarmat netting placed inside liner, no filter fabric on outside
Caine Lane, adjacent to 147-151 Caine Road, Mid-levels	11SW-A/FR74	I15	GEO Type 2	19	6m	S	1988	GCD 2/A1/11SW-A/FR74 LPM Contract GC/86/04
144, Caine Road, Mid-levels	11SW-A/R106	I16	?	8	?	S	1993	GCD 2/A1/11SW-A/R106 LPM Contract GC/89/13

Table A1 - Summary of Sites with Horizontal Drains (Sheet 3 of 13)

Site Location	Registered Slope/Wall Number	GEO District & Code Number (see Figure A1)	Drain Type (see Figure 1)	Number of Drains	Length of Drains	Ground Type (S = Soil R = Rock)	Date of Completion	GEO File Number/ Contract Number/ Remarks
Grenville House, 1-3, Magazine Gap Road, Mid-levels	11SW-B/C92 11SW-D/C325, R125	I17	As Figure 1B	105	20-35m	S&R	1973-74	GCI 1/2/3209/62 GCSP 2/D4/9(2) Tong & Maher (1975) (Designed drains)
Beaconsfield House, behind Victoria District Court, Queen's Road Central	11SW-B/R81 & R179	I18	GEO Type 2	13	4m & 5m	S	1988	GCD 2/A1/11SW-B/R179 LPM Contract GC/86/03
Bowen Drive, off Kennedy Road, adjacent to Electric House	11SW-B/FR59	I19	GEO Type 3	11	4m & 9m	S	1985	GCD 2/A1/11SW-B/FR59 LPM Contract 4/GCO/83
Peak Road near junction with Magazine Gap Road	11SW-D/FR135	I20	GEO Type 3	4	17m	S	1987	GCD 2/A1/11SW-D/FR135 LPM Contract GC/85/06
Watford Road, off Peak Road, Behind Quarters Blocks A-F	11SW-D/FR21	I21	GEO Type 3	29	5-13m	S	1985	GCD 2/A1/11SW-D/FR21 LPM Contract 4/GCO/83
Mount Kellett Road	11SW-C/CR260	I22	GEO Type 2	12	6m	S	1992	GCD 2/A1/11SW-C/CR260 LPM Contract GC/90/06
Tin Wan Hill Road	11SW-C/C13	I23	GEO Type 3	68 (54 on slope, 14 through toe wall)	15-30m (15m & 30m through slope, 25m through wall)	S&R	1986	GCD 2/A1/11SW-C/C13 GCSP 2/D4/9(7) LPM Contract GC/84/02 (Designed drains)

Table A1 - Summary of Sites with Horizontal Drains (Sheet 4 of 13)

Site Location	Registered Slope/Wall Number	GEO District & Code Number (see Figure A1)	Drain Type (see Figure 1)	Number of Drains	Length of Drains	Ground Type (S = Soil R = Rock)	Date of Completion	GEO File Number/ Contract Number/ Remarks
11-12, Tang Fung Street, Aberdeen	11SW-C/C34	I24	GEO Type 3	3	10m	S&R	1988	GCD 2/A1/11SW-C/C34 LPM Contract GC/85/06
Ap Lei Chau North Reclamation Phase 1, below Ap Lei Chau Estate	15NW-A/C7	I25	GEO Type 1?	13	10m	R	1991-92	GCD 2/A1/15NW-A/C7 LPM Contract GC/89/13
24-46, Aberdeen Main Street	11SW-D/C81	I26	GEO Type 3	6	10m?	S&R	1988	GCD 2/A1/11SW-D/C81 LPM Contract GC/84/04
Junction of Ap Lei Chau Main Street & Hung Shing St APIL 114	Unregistered	I27	? 75mm ø pipe included	c.20	9-10m ?	S&R	1985	GCI 3/4/2032 81 GCSP 2/D4/9(1)
10, Shiu Fai Terrace, off Stubbs Road	11SW-D/CR396	I28	? 50mm ø	17	12-18m	S&R	1977	GCD 2/A1/11SW-D/CR396 Drains installed via BOO Notice D 91/HK/76. Unsatisfactory performance suspected
11-12, Shiu Fai Terrace, off Stubbs Road	11SW-D/CR395	I29	Similar to Figure 1A 75mm ø	c.85	12m	S&R	1973	GCD 2/A1/11SW-D/CR395 Drain installed by developer as remedial works to landslip on 16.6.72 during site formation. Unsatisfactory performance suspected

Table A1 - Summary of Sites with Horizontal Drains (Sheet 5 of 13)

Site Location	Registered Slope/Wall Number	GEO District & Code Number (see Figure A1)	Drain Type (see Figure 1)	Number of Drains	Length of Drains	Ground Type (S = Soil R = Rock)	Date of Completion	GEO File Number/ Contract Number/ Remarks
14-15, Shiu Fai Terrace, off Stubbs Road	11SW-D/CR394	I30	Similar to Figure 1A? 75mm ø	c.20	30m	S&R	1974	GCD 2/A1/11SW-D/CR394 Drains installed by developer as part of site formation works. Unsatisfactory performance suspected
Behind Gold & Silver Exchange School, Link Road, Leighton Hill, Causeway Bay	11SW-B/FR42	I31	GEO Type 3	10	8m & 11m	S	1986	GCD 2/A1/11SW-B/FR42 LPM Contract GC/84/04
10-12, Fung Fai Terrace	11SW-D/C13	I32	As Figure 1A	9	30m	S&R	1982-83	GCI 3/4 DH/59/78 HK GCSP 2/D4/9(1)
Tai Hang Service Reservoir, off Tai Hang Road	11SW-D/C378	I33	GEO Type 2	10	11m	S	1992	GCD 2/A1/11SW-D/C378 LPM Contract GC/90/06
Opposite 93-99, King's Road	11SE-A/C158	I34	GEO Type 1	11	3m	R	1988	GCD 2/A1/11SE-A/C158 LPM Contract GC/86/03
Opposite 104-106, Tin Hau Temple Road, North Point	11SE-A/FR48	I35	GEO Type 3	14	16m	S	1986	GCD 2/A1/11SE-A/FR48 LPM Contract GC/84/05
60-74, Kai Yuen Street, North Point	11SE-A/C98	I36	GEO Type 2?	10	5m	R	1992	GCD 2/A1/11SE-A/C98 LPM Contract GC/89/13

Table A1 - Summary of Sites with Horizontal Drains (Sheet 6 of 13)

Site Location	Registered Slope/Wall Number	GEO District & Code Number (see Figure A1)	Drain Type (see Figure 1)	Number of Drains	Length of Drains	Ground Type (S = Soil R = Rock)	Date of Completion	GEO File Number/ Contract Number/ Remarks
North Point Government Primary School, King's Road, North Point	11SE-A/CR83	I37	GEO Type 3	37	20m	R	1987	GCD 2/A1/11SE-A/CR83 LPM Contract GC/85/05
26-46, Shing On Street, Sai Wan Ho	11SE-A/C242	I38	GEO Type 1	3	3m	R	1990	GCD 2/A1/11SE-A/C242 LPM Contract GC/88/05
Shau Kei Wan West Development	Unregistered	I39	Similar to: GEO Type 1 GEO Type 2 GEO Type 3	 180 51 396	))10-20m)	S&R	1990	GCI 3/2/167 HKHA Contract 43/88
Shau Kei Wan East Development	Unregistered	I40	Similar to: GEO Type 1 GEO Type 3	 287 457	)5-20m)	S&R	1988	GCI 3/2/166 HKHA Contract 141/86
A Kung Ngam Road, Opposite Blocks 1-11, Ming Wah Dai Ha, Shau Kei Wan	11SE-B/C85 & C86	I41	GEO Type 1	22	5m	R	1986	GCD 2/A1/11SE-B/C85 LPM Contract GC/84/02
Below Tai Tam Road, Hing Man Estate, Chai Wan	Unregistered	I42	Similar to GEO Type 3	25	20-45m	S&R	1986	GCI 3/2/13 GCSP 2/D4/9(10)
Chai Wan Estate, San Ha Street, Chai Wan	11SE-D/C18	I43	Similar to GEO Type 3	61	10m	S	1985	GCI 3/2/31 HKHA Contract 51/84
Fung Wah Estate, off Wan Tsui Road, Chai Wan	Unregistered	I44	Similar to GEO Type 3	5	2-40m	S&R	1987	GCI 5/5/BC 845/HGS/63 HKHA Contract 197/85

Table A1 - Summary of Sites with Horizontal Drains (Sheet 7 of 13)

Site Location	Registered Slope/Wall Number	GEO District & Code Number (see Figure A1)	Drain Type (see Figure 1)	Number of Drains	Length of Drains	Ground Type (S = Soil R = Rock)	Date of Completion	GEO File Number/ Contract Number/ Remarks
Siu Sai Wan Estate	Unregistered	I45	Similar to GEO Type 3	175	12-15m	S&R	1985	GCI 3/2/105 HKHA Contract 124/84
Opposite Cheshire Home, Chung Hom Kok Road	15NE-C/C82	I46	GEO Type 3	29	7-13.5m	S&R	1989-90	GCD 2/A1/15NE-C/C82 LPM Contract GC/86/03

Table A1 - Summary of Sites with Horizontal Drains (Sheet 8 of 13)

Site Location	Registered Slope/Wall Number	GEO District & Code Number (see Figure A1)	Drain Type (see Figure 1)	Number of Drains	Length of Drains	Ground Type (S = Soil R = Rock)	Date of Completion	GEO File Number/ Contract Number/ Remarks
Kowloon City Police Station, 202 Argyle Street	11NW-D/FR148	ME01	GEO Type 1	7	5m	S	1988-89	GCD 2/A1/11NW-D/FR148 LPM Contract GC/87/11
Lion Rock High-level Service Reservoir, above Tunnel Portal at Kowloon Entrance	11NW-B/C135	ME02	GEO Type 2	11	5m & 7m	S	1991-92	GCD 2/A1/11NW-B/C135 LPM Contract GC/89/13
Fung Wong Service Reservoir, Shatin Pass Road, near Tsz Wan Shan	11NE-A/C21	ME03	GEO Type 1 GEO Type 2	8 38	)) 7m	S&R	1990	GCD 2/A1/11NE-A/C21 LPM Contract GC/88/06
Junction of Wong Tai Sin Road & Sha Tin Pass Road	11NE-A/F89	ME04	As Figure 1A	6?	c.10m	S	1981	GCMd 2/B2/20 PWD Contract 528/78
Tsz Wan Shan Estate, off Tsz Wan Shan Road	11NE-A/C6, CR7, C8, C9, CR10, C11	ME05	Similar to GEO Type 2	734	12-15m	S	1982	GCMd 3/2/28 HKHA Contract 123/81 (Designed drains in slope C8)
Tsz Wan Shan Estate, off Tsz Wan Shan Road	11NE-A/C12	ME06	Similar to GEO Type 2	40	12-20m	S	1987	GCD 2/A1/11NE-A/C12 HKHA Contract 105/86
Choi Wan Estate, off New Clear Water Bay Road	11NE-A/CR57 & CR85	ME07	As Figure 1C	140	12-19m	S	1983-85	GCMd 3/2/68 GCSP 2/D4/9(9) HKHA Contract 133/83 (Designed drains)

Table A1 - Summary of Sites with Horizontal Drains (Sheet 9 of 13)

Site Location	Registered Slope/Wall Number	GEO District & Code Number (see Figure A1)	Drain Type (see Figure 1)	Number of Drains	Length of Drains	Ground Type (S = Soil R = Rock)	Date of Completion	GEO File Number/ Contract Number/ Remarks
Choi Wan Estate, off New Clear Water Bay Road	11NE-A/C80	ME08	Similar to GEO Type 3	27	20m	S	1982	GCMd 3/2/10 HKHA Contract 23/81
New Clearwater Bay Road, near Shun Lee Overpass	Unregistered	ME09	As Figure 1B	88	33m	S	1980	GCSP 2/D4/9(5) GCMd 2/C2/1 PWD Contract 535/74 (Designed drains)
New Clearwater Bay Road	11NE-A/C63	ME10	GEO Type 2	13	9m	S	1992	GCD 2/A1/11NE-A/C63 LPM Contract GC/90/06 Middle portion of slope is fill
Choi Ha Estate, off Choi Ha Road, Ngau Tau Kok	Unregistered	ME11	Similar to GEO Type 3	268	10m	S&R	1986	GCMd 3/2/179 GCSP 2/D4/9(11) HKHA Contract 40/85
Jordan Valley Estate, Ngau Tau Kok	11NE-C/C12	ME12	Similar to GEO Type 2	34	10m	S&R	1987	GCMd 3/2/187 GCMd 2/E1/11NE-C/C12 HKHA Contract 105/86
Choi Fai Estate, off Ngau Chi Wan Street	Unregistered	ME13	Similar to GEO Type 3	528	20m	S	1990	GCMd 3/2/201 HKHA Contract 116/88
On Tin Street, Opposite Blocks 19 & 20, Lam Tin Estate	11NE-D/C78 & C79	ME14	GEO Type 2	38	17m	R	1985	GCD 2/A2/113-5(J) LPM Contract 13/GOO/83

Table A1 - Summary of Sites with Horizontal Drains (Sheet 10 of 13)

Site Location	Registered Slope/Wall Number	GEO District & Code Number (see Figure A1)	Drain Type (see Figure 1)	Number of Drains	Length of Drains	Ground Type (S = Soil R = Rock)	Date of Completion	GEO File Number/ Contract Number/ Remarks
West of Block 17, Yau Tong Estate, Cha Kwo Ling Road	11SE-B/C36	ME15	GEO Type 1 GEO Type 2	3 7	)3-5m)	R	1989	GCD 2/A1/11SE-B/C36 LPM Contract GC/86/04
Ko Chiu Road Estate, off Ko Chiu Road	11SE-B/C12 & C13	ME16	Similar to GEO Type 3	21	15m	S	1982	GCMd 3/2/215 HKHA Contract 23/81 (Designed drains)
Near Sam Yuk Middle School, Clearwater Bay Road	12NW-C/C14	ME17	GEO Type 3	22	5m	S	1988-89	GCD 2/A1/12NW-C/C14 LPM Contract GC/86/04
Near Leung Fai Tin, Clearwater Bay Road	12NW-C/CR8	ME18	GEO Type 2	7	5m?	S&R	1988	GCD 2/A1/12NW-C/CR8 LPM Contract GC/86/04
Pak Kong Water Treatment Works, near O Long Village, Sai Kung	Unregistered?	ME19	75 mm ø with single plastic liner?	c.45	15-20m	S	1987-1991 (3 separate sets of drains)	GCMd 2/B7/86 GCMd 2/E2/92-3(E) Unsatisfactory performance suspected
Tat Yip Lane, Sha Tin	Unregistered	ME20	Similar to GEO Type 2	c.6	15m	R	1984	GCMd 2/B3/16 GCSP 2/D4/9(3)
Lok Lam Road, Area 43, Sha Tin	Unregistered	ME21	Similar to GEO Type 2	10	10m	S&R	Pre-1982	GCMd 2/B3/14 GCSP 2/D4/9(3)
Sui Wo Road, Area 42, Sha Tin	Unregistered	ME22	Similar to GEO Type 2	16	15m	S&R	1984	GCMd 2/B3/16 GCSP 2/D4/9(3)

Table A1 - Summary of Sites with Horizontal Drains (Sheet 11 of 13)

Site Location	Registered Slope/Wall Number	GEO District & Code Number (see Figure A1)	Drain Type (see Figure 1)	Number of Drains	Length of Drains	Ground Type (S = Soil R = Rock)	Date of Completion	GEO File Number/ Contract Number/ Remarks
Opposite Ming Yin College, Woh Chai Street, Shek Kip Mei	11NW-B/C39	MW01	GEO Type 2	10	4m	R	1989	GCD 2/A1/NW-B/C39 LPM Contract GC/87/11
Lion Rock Tunnel Road, above Tunnel Portal at Sha Tin Entrance	7SW-D/C48 & C97	MW02	GEO Type 1?	13	5-10m	R	1991	GCD 2/A1/7SW-D/C48 LPM Contract GC/88/06
CLP 400 KV Substation, Heung Fan Liu, Sha Tin	Unregistered?	MW03	Similar to GEO Type 2	c.20	10-25m	S&R	1988	GCMd 3/5/9007/87 (Designed drains)
Dow Chemical (HK) Ltd Tsing Yi Plant, TYTL 59, Tsing Yi	Unregistered?	MW04	?	20	10-30m	S&R	1983 & 1986 (last 4)	GCMd 3/5/9019/81 Remedial works to slope failure August 1982 (Designed drains)
PEPCO Slope 1, North of PEPCO Power Station, Tsing Yi	10NE-B/C46	MW05	Similar to GEO Type 3?	c.115	5-35m	S&R	1975, 1977, 1985-86 (majority in last period)	GCMd 2/B4/35 NIDD Contract 1/TW/83 (Designed drains, in combination with c.100 drainage caissons)
Tsing Yi Road, Southwest Tsing Yi	5 Unregistered slopes along 900 m length of road	MW06	Similar to GEO Type 2?	165	5-20m	S&R	1978-80	GCMd 2/B4/13 PWD Contract 524/77 (Some are designed drains, not all)
Front of Block 5, Kwai Shing West Estate, Kwai Shing Circuit	7SW-C/C38	MW07	GEO Type 2	6	3m	R	1988	GCD 2/A1/7SW-C/C38 LPM Contract GC/85/07

Table A1 - Summary of Sites with Horizontal Drains (Sheet 12 of 13)

Site Location	Registered Slope/Wall Number	GEO District & Code Number (see Figure A1)	Drain Type (see Figure 1)	Number of Drains	Length of Drains	Ground Type (S = Soil R = Rock)	Date of Completion	GEO File Number/ Contract Number/ Remarks
Chung Kwai Chung Tsuen, Fu Uk Road, Tsuen Wan	7SW-C/C259	MW08	GEO Type 2	25	?	R	1986	GCD 2/A1/7SW-C/C259 LPM Contract GC/84/02
Behind Nos 29-58, Ham Tin Tsuen, off Kwok Shui Road, Tsuen Wan	7SW-C/C263	MW09	GEO Type 2?	35	5m & 10m	S&R	1986-87	GCD 2/A1/7SW-C/C263 LPM Contract GC/84/03
Behind Nos 59-81, Ham Tin Tsuen, off Kwok Shui Road, Tsuen Wan	7SW-C/C265	MW10	GEO Type 2?	30	5m & 10m	S&R	1986-87	GCD 2/A1/7SW-C/C265 LPM Contract GC/84/03
Behind Nos 16-21, Ho Pui Tsuen, off Kwok Shui Road, Tsuen Wan	7SW-C/C290	MW11	GEO Type 3	12	8m	S	1988	GCD 2/A1/7SW-C/C290 LPM Contract GC/85/07
Yeung Uk Tsuen, Ting Fung Street, off Kwok Shui Road, Tsuen Wan	7SW-C/C268	MW12	GEO Type 2?	22	5m	S&R	1986-87	GCD 2/A1/7SW-C/C268 LPM Contract GC/84/03
Behind 105-110, Yeung Uk Tsuen, off Kwok Shui Road, Tsuen Wan	7SW-C/C271	MW13	GEO Type 1?	5	3-4m	R	1990	GCD 2/A1/7SW-C/C270 GCD 2/A1/7SW-C/C271 LPM Contract GC/87/11
Lei Muk Shue Estate	7SW-C/C131	MW14	GEO Type 2	29	10m	S	1985	GCMd 3/2/142 HKHA Contract 51/84
Lo Wai Public School, Lo Wai Road, Tsuen Wan	7SW-C/C300	MW15	GEO Type 3	13	10m	S&R	1988-89	GCD 2/A1/7SW-C/C300 LPM Contract GC/86/04 (Designed drains)

Table A1 - Summary of Sites with Horizontal Drains (Sheet 13 of 13)

Site Location	Registered Slope/Wall Number	GEO District & Code Number (see Figure A1)	Drain Type (see Figure 1)	Number of Drains	Length of Drains	Ground Type (S = Soil R = Rock)	Date of Completion	GEO File Number/ Contract Number/ Remarks
Lo Wai Road & Hilltop Road, Area 39, Tsuen Wan North Development, Tsuen Wan	4 Unregistered slopes (Slopes C2, C4, C7 & C8 in Area 39)	MW16	Similar to GEO Type 3	43	10m	S	1981-82	GCMd 2/B4/52 PWD Contract 622/79 (Designed drains except for slope C2)
Pun Shan Tsuen, off Tuen Mun Highway near Tsuen Wan	6SE-D/C63	MW17	GEO Type 3	55	14-38m	S&R	1984	GCD 2/A1/6SE-D/C63 GCSP 2/D4/9(8) HD Contract 32/HO/83 (Designed drains)
DD 114, Lot 1799, University of Hong Kong Field Research Station, Lam Kam Road, near Shek Kong	Unregistered	MW18	?	10?	?	S	1984	GCMd 3/5/9335/80
Tuen Mun Service Reservoir, near Fu Tei Chung Tsuen	6SW-A/C10	MW19	GEO Type 1	26	3m	R	1990	GCD 2/A1/6SW-A/C10 LPM Contract GC/87/11