EVALUATION OF APPLICATION OF DRILLING PROCESS MONITORING (DPM) TECHNIQUE FOR SOIL NAILING WORKS

GEO REPORT No. 189

J.S. Lam & C.K. Siu

GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING AND DEVELOPMENT DEPARTMENT

THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

EVALUATION OF APPLICATION OF DRILLING PROCESS MONITORING (DPM) TECHNIQUE FOR SOIL NAILING WORKS

GEO REPORT No. 189

J.S. Lam & C.K. Siu

This report was originally produced in July 2004
as GEO Technical Note No. TN 3/2004

First published, August 2006

Prepared by:

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

Table of Contents
Table of Contents
Table of Contents

PREFACE

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. The GEO Reports can be downloaded from the website of the Civil Engineering and Development Department (http://www.cedd.gov.hk) on the Internet. Printed copies are also available for some GEO Reports. For printed copies, a charge is made to cover the cost of printing.

The Geotechnical Engineering Office also produces documents specifically for publication. These include guidance documents and results of comprehensive reviews. These publications and the printed GEO Reports may be obtained from the Government's Information Services Department. Information on how to purchase these documents is given on the last page of this report.

R.K.S. Chan
Head, Geotechnical Engineering Office
August 2006

FOREWORD

The Drill Process Monitoring (DPM) technique was developed by the Department of Civil Engineering, University of Hong Kong for real-time, continuous monitoring of soil nail drilling operation and site characterization based on the measured drill penetration rates. A trial use of the technique was carried out at a slope upgrading works site under the Landslip Preventive Measures (LPM) programme to evaluate the feasibility of adopting the technique. This Report describes the mechanism of drill-hole formation, discusses the various factors affecting drill penetration rates and reports the results of the site trial.

This study was undertaken by Mr J.S. Lam under the supervision of Mr C.K. Siu. The trial was carried out in collaboration with the Department of Civil Engineering, University of Hong Kong and the Works Division who respectively provided the DPM equipment and made the necessary arrangements for conducting the trial in a LPM site. Technical Officers of the Special Projects Division, Messrs C.K. Lee, S.Y. Tse and C.P. Wong were responsible for analyzing and plotting of the test data. All their contributions are gratefully acknowledged.

W.K. Pun
Chief Geotechnical Engineer/Standards and Testing

Table of Contents
Table of Contents
Table of Contents
Table of Contents

ABSTRACT

The University of Hong Kong has developed a technique, viz. Drilling Process Monitoring (DPM), to monitor the drilling process for soil nailing works and have used it to characterize the ground conditions at a number of slopes. In collaboration with the HKU, a trial use of the DPM technique was carried out at a site under the LPM programme.

The objective of the study is to find out the possible roles of the DPM technique in improving the design and construction process of soil nailing works. DPM data from a total of 111 drill holes formed using a rotary percussive down-the-hole drilling machine were collected and studied.

The study found that data analysis and interpretation using manual sorting/filtering was rather labor intensive. Apart from ground condition, penetration rate, being the most important parameter for characterisation of ground condition, also depends on other factors including state and construction of drilling equipment, operator skill, groundwater regime and nail length. Penetration rate from the DPM system/technique at its present state has good potential for crude qualitative assessment of the ground intercepts, especially for inferring rock.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

CONTENTS

Table of Contents
Table of Contents
Table of Contents

Page No.

Table of Contents
Table of Contents
Table of Contents

1. INTRODUCTION

In Hong Kong, soil nailing is a commonly used technique for enhancing the stability of slopes. The Civil Engineering Department of the University of Hong Kong (HKU) has developed a technique to monitor the drilling process for soil nailing works. The technique, called Drilling Process Monitoring (DPM), involves continuous monitoring and recording of a series of parameters representing the full drilling process in real time sequence, including position of the drill chuck/bit, supply air pressures for percussion action, upward and downward thrust on the drill bit and rotation of the drill-string using a pneumatic rotary percussive down-the-hole (DTH) drilling machine. Results of research conducted by the HKU at a number of sites in Hong Kong reveal that data collected from the DPM technique could be used to characterize ground conditions at the slopes.

In collaboration with the HKU, a field trial was conducted by GEO to find out the possible roles of the DPM technique in improving the design and construction process of soil nailing works. This report presents the results of the study.

2. PRINCIPLES OF ROTARY PERCUSSIVE DRILLING

2.1 General

An understanding of the principles of rotary percussive drilling including methods of hole formation is essential to the evaluation of the application of DPM technique for improving soil nail design and construction. Relevant literature on this subject was reviewed. A contractor specialized in soil nail construction was also interviewed to further understand the mechanism of hole formation and drilling practice in Hong Kong. This Section documents the findings of this exercise. The focus is on air-driven down-the-hole (DTH) hammer because it is the main drilling tool for installation of soil nails in Hong Kong.

2.2 Methods of Hole Formation

2.2.1 Basic Methods of Hole Formation

Forming holes in the ground requires detaching materials from the cut face and removing the detached materials. The three basic methods of detaching materials from the ground are percussive crushing, rotary crushing and rotary shearing (Chugh, 1985). In all three methods, the rock is broken up by applying high pressure from a button or an insert of cemented carbide. Figure 1 shows the general principles.

In percussive crushing, a number of hard conical buttons or inserts at the drill bit knocks against the cut face. The impact crushes the part of the ground at the tip of the buttons where stresses concentrate. This impact is generated by a reciprocal hammering mechanism that could be placed outside the hole or inside the hole immediately behind the cutter bit. A reciprocal mechanism inside the hole is called a down-the-hole (DTH) hammer.

In rotary crushing, the drill bit is equipped with rollers on which conical buttons or inserts are placed. The rollers rotate with the action of the bit, so that the buttons bear on the cut face in turn to crush the ground.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

In rotary shearing, hard inserts at the drill bit scrape the face as the bit is rotated and pressed against the ground. The inserts are commonly diamond or cemented carbide. This is the common method for drilling for the purpose of sampling.

The detached ground, in form of chips, is removed from the hole either by air, water or other forms of drilling fluid. Chips that collect at the face would act as a cushion that relieves the pressure of the buttons or inserts on the ground. This would reduce the effectiveness of the cutting action.

2.2.2 Down-the-hole (DTH) Hammer

A DTH hammer can be driven hydraulically or by compressed air. The latter is much more common for soil nail installation in Hong Kong. The exhaust air from the hammer also flushes the hole of chips.

When compressed air is applied, the hammer builds up a pressure which, on being released, drives the piston inside the hammer forward. The piston strikes on the shank adaptor and releases the kinetic energy to the drill bit. When a button on the drill bit knocks against the ground, the stress concentration at the tip of the button crushes and displaces the ground around it. A dent is formed. If the button strikes the dent again, the stress concentration would be small and further crushing would be minor. To ensure effective cutting, the cutter head is rotated between strikes. The rotation also helps cutting by breaking the ridges between dents. For effective hammering, the bit has to be thrust tight against the face (Chugh, 1985). For smooth and effective drilling, the thrust needs to be adjusted to suit the percussion pressure. Generally, a high percussion pressure requires a high feed and vice versa (Frequent Drillers Club, 2002).

To start drilling, air pressure is first applied to the hammer. The drill bit is rotated and pressed against the ground gently until percussion action starts in the hammer. The thrust is increased to allow the tool to run smoothly. Chugh (1992) mentioned a minimum thrust of 10 bars. Rotation speed of the bit is also important for optimum penetration. Chugh (1985) suggested a head rotation of 40 to 60 rpm for button bits of 50 to 90 mm. The rotational speed could be lower for larger bits to reduce peripheral speed.

2.2.3 Penetration Rate of Percussive Drilling

2.2.3.1 Theory

The penetration rate (R) of a percussion bit depends on the number of strikes of the hammer per unit time (N) and the energy of each strike (Chugh, 1985). The strike energy is approximated by the product of the net air pressure on the piston (P), the area of the piston (A) and the piston stroke (S). Overall, the penetration rate can be expressed as

$$R = k_1 NPAS$$

The product AS is the volume of the cylinder in which the piston travels to do work. At the end of each cycle, the air in the cylinder is exhausted. If there are N strikes per unit time, the air-flow rate would be proportional to NAS. The penetration rate could then be

Table of Contents
Table of Contents
Table of Contents
Table of Contents

re-expressed as:

$$R = k_2 2PQ$$

where Q is the flow rate of compressed air through the hammer

Assuming that the hammer is working properly, k_1 and k_2 depend on the condition of the drill bit, the construction of the hammer, and the ability of the driller to optimize the percussion, thrust and rotation of the hammer for the particular ground (Kwok, 2004).

The net pressure on the piston (P) is the difference between the air supply pressure and the back pressure at the cut face of the hole. To maintain an annular flow of air and efficient cleaning of the debris, a certain amount of pressure at the bottom of the hole is needed (Chugh, 1992). This pressure is called the back pressure. It is this pressure that the hammer must exhaust into. Chugh (1985) suggested a minimum air-flow rate of 15-30 m/sec for effective removal of chips in the case of a vertical hole. The velocity needed would reduce with the inclination of the hole from the horizontal.

2.2.3.2 Discussion

At least some hammers rely on the rebound of the drill bit to activate the upward stroke of the piston. There will not be percussive action and hence hammering action if the rebound is too low to activate the upward stroke, as in the case of drilling in soft ground.

Without hammering action, the drill bit will rely on rotary shearing for cutting the ground. Penetration rate will depend on the thrust pressure and the rotary speed of the bit. The type and condition of the drill bit can also affect the penetration rate in this case. A percussion drill bit is not particularly effective for rotary shearing.

Exhaust air from the DTH hammer flushes the hole through the annulus between the hammer-drill rod string and the wall of the hole. A tight annulus would require high back pressure to drive the air through it. High back pressure reduces hammer efficiency. Drillers sometimes surge the rotating drill string to and fro in the hole to enlarge it.

If the hole is too large, e.g., due to overcutting or wall collapse, the flow velocity at the annulus may be too low for removing the cuttings and chips. A casing could be inserted to reduce the annulus to a manageable size.

Long hole would lead to high back pressure, especially when the length exceed 30 m. (Chugh, 1977). Enlarging the hole would lower the pressure but then the flow velocity may not be sufficient to flush the hole of cuttings and chips. Using higher input air pressure is the only remedy.

Chips that collect at the face of a hole, apart from cushioning the drill bit against the face, may block the air outlet of the DTH hammer and stop the hammering action. This problem is particularly serious if the chips are fine-grained and there is water in the hole because the chips could then turn into mud. Chips that collect at the face can be cleaned by occasionally raising the tool 150 to 200 mm for about 1 minute. The uninhibited flow of air

Table of Contents
Table of Contents
Table of Contents
Table of Contents

through the hammer will maximise flow velocity in the hole and help flush out the chips. A hammer with the air outlet blocked by mud will have to be taken out and cleaned.

Water in a hole could be blown out by compressed air through the hammer at the start of drilling. Fast ingress of water into the hole will add to the flush load and may result in high back pressure which is detrimental to the efficiency of the hammer.

Over-drilling and hole collapse are more likely in saturated soil because the ground is less strong. The same is true for loose ground.

When drilling upward, e.g. for installing horizontal drains, fragment of materials that detach from the face could fall down the bore. These could be caught wedged in the annulus and cause high friction between the drill string and the wall of the hole. The practice was to slow down rotation and surge the drill string to and fro in the hole until the fragment is worn down to sufficiently smaller fragments (Kwok, 2004).

2.3 Factors Affecting Penetration Rate

Penetration rate depends on a number of factors including ground conditions, state and construction of drilling equipment, operator skill, groundwater regime and nail length. The dependence of penetration rate on ground conditions is complicated, which includes the factor on whether the ground is firm enough to excite the percussion action of the down-the-hole hammer. The dependence of penetration rate on the various factors is further discussed in Section 5.

3. FIELD TRIAL

3.1 General

A field trial of the DPM equipment was conducted at the slope 11NW-D/C92 located at Chung Yee Street, Ho Man Tin in the autumn/fall of 2003. At the time of the trial, the slope was being upgraded under the Landslip Preventive Measures (LPM) programme. Figure 2 shows the location of the slope on plan.

The feature is a cut slope of about 120 m long and 21 m high. Plate 1 shows the general appearance of the site. A total of 110 soil nails, out of the 418 prescribed for the site, were monitored using the DPM equipment during the period 4.9.2003 to 8.10.2003. The drillholes monitored all have a diameter of 115 mm and an inclination of 15° to the horizontal. Length of the soil nail varies from 6 m to 11 m. The monitored holes were drilled using the same drilling machine. Layout of the soil nails is presented in Figure 3.

3.2 Ground and Groundwater Conditions

According to the Stage 3 Study Report (S3R No. 267/2002) for the slope, no specific ground investigation had been carried out on the slope (Pau, 2002). However, there is limited information on ground investigations carried out by others in the vicinity of the slope. This includes: (i) one vertical borehole and two trial pits behind the slope crest from a GI

Table of Contents
Table of Contents
Table of Contents
Table of Contents

carried out for the development of the open space behind the slope crest, (ii) one borehole near the toe of the slope from a GI for the Ho Man Tin Recreation Leisure Centre across the street, and (iii) one drillhole and two trial pits near the crest of the slope at its western end from a GI carried out at an adjacent slope (11NW-D/C94). Location of these boreholes and trial pits are shown in Figure 2.

In general, the GI information reveals that there is at least 15 m of completely decomposed granite (CDG) at the slope crest and sound bedrock is at least 15 m below the slope toe. Fill was encountered at the site but was limited to the vicinity of a masonry wall located at the crest of the western end of the slope.

A piezometer installed in one of the drillhole (approximately 20 m behind the slope crest at the western end of the slope) and monitored for a period of two months in end of 1999 indicated groundwater level at 52.17 mPD, about 5 m below the slope toe.

An interpreted geological model of the slope presented in the Stage 3 Study Report is shown in Figures 4 and 5 for reference.

3.3. Drilling Machine and DPM Equipment

3.3.1 Rotary Percussive Down-the-hole (DTH) Drilling Machine

Air-driven rotary percussive drilling machines were used for the installation of the soil nails at the site. Plate 2 shows one of the drilling machines. Main components of the drilling machine comprise a drilling unit mounted on a crawler carrier frame, a manual control panel and an air compressor. The drilling unit includes a swivel drill chuck equipped with an air-driven motor for rotation, an air-driven motor for thrust, a loop chain and steel frame for sliding the drill chuck/drill string, and a drill string with a DTH hammer and a drill bit at the end. Compressed air from the compressor is fed into the manual control panel where it is separated into five channels. The drilling operator uses the control panel to regulate the supply air pressures to the drilling unit for the execution of various activities of the drilling unit such as percussion action, downward and upward thrust (push forward and pull-back of the drill chuck/bit), clockwise and anti-clockwise rotation.

3.3.2 DPM Equipment

The DPM equipment is a portable system, comprising seven (7) sensors and a data processing and logging unit, powered by a 12V battery. One of the sensors is installed on the swivel drill chuck of the machine for measuring the rotation speed of the drill stem/bit. Another one records the forward and backward movement of the drill string by making use of the loop chain on the drilling machine. The remaining five (5) sensors are pressure sensors which measure the supply air pressures for (i) the percussion action of the DTH hammer, (ii) mobilizing a motor to apply upward and downward thrust on the drill stem/bit and (iii) mobilizing a separate motor for clockwise and anti-clockwise rotation of the drill. These sensors are installed on the manual control panel which receives the main air supplies from the compressor and regulates the air supplies for the various movement of the drilling machine as controlled by the operator.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Electrical signals in the form of voltage output are fed into the data processing and logging unit which samples and records the data in 0.5 or 1.0 second intervals. The data processing and logging unit has the capacity for storing data generated from 1 day of DPM operation, after which the data would need to be downloaded. A schematic diagram of the DPM system installed on a drilling machine is presented in Figure 6. Plates 3 to 6 show the keys components of the DPM equipment.

3.4 Operation of DPM Equipment

Installation of the DPM equipment onto the drilling machine was found to be relatively straight forward. First, the sensors were mounted onto the drill chuck, the loop chain and the manual control panel. This was followed by linking the sensors to the data processing and logging unit with electrical cables. The installation procedure was completed in less than an hour. While the sensors were left on the drilling equipment for the duration of the monitoring period, the data processing and logging unit was disconnected from the rest of the DPM equipment and brought back to the office at the end of each day for data download and charging of the battery.

Mounting of the sensors onto the drilling machine was conducted by staff of the HKU. The day-to-day operation of the DPM equipment, complete with hooking and unhooking of the data processing and logging unit from the sensors and drilling equipment, was mainly carried out by GEO staff with technical support from the HKU as required.

3.5 Data Collection

In general, data collection was successful. Malfunction of the DPM equipment occurred occasionally (mostly to do with electrical connections), but the situations were readily rectified by the HKU staff (generally within a day). Some data was lost as a result of the malfunction.

4. DATA ANALYSIS AND INTERPRETATION

4.1 Typical DPM Data

Raw data downloaded from the data processing and logging unit comprise electrical signals in the form of voltage output from the seven (7) sensors. These are then converted into units of pressure and distances using conversions provided by HKU. A typical plot of the full DPM data is presented in Figure 7. The plot shows in real time over the duration of monitoring the position of the drill chuck/bit, the applied compressed air pressures associated with the various movements of drilling machine.

To enhance interpretation of the data, full DPM results are simplified to show the drill chuck position, the supply air pressure for percussion, the net air pressure for thrust instead of upward and downward thrust, and the RPM. Supply air pressures for the rotational movement of the drill are not shown as the plot of RPM provides essentially the same information for the interpretation. Figure 8 shows an example of the simplified plots of the DPM data. The simplified plots of DPM data for the rest of the drillholes are included in Appendix A which is contained in the CD attached to this report.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

4.2 Interpretation of DPM Data

4.2.1 Identification of Various Drilling Activities

The key to the interpretation of DPM data relies largely on identification the various drilling activities inferred by the data such as penetration of the drill bit (actual advancement of the drill in soil/rock), push forward and pull-back of the drill chuck/string (without actual drilling), tightening and un-tightening of the drill rod/stem, flushing (quick back and forth movement of the drill stem) and pause during drilling.

The chart showing the position of the drill chuck during drilling is the most important one for the interpretation of drilling activities. However, the interpretation has to be made in conjunction with the remaining charts with information on percussion, thrust and rotation movement of the drill. An example of interpretation showing the various drilling activities inferred by the DPM data is presented in Figure 9. At Line 1 shown in the figure, the drill bit is penetrating into the ground, i.e. true drilling through solid material. This is accompanied by percussive action of the hammer with an air pressure about 13 bars, a net positive supply air pressure for forward thrust and a forward or clockwise rotation. At Line 2, the drill chuck position shows that the bit has reached the furthest point for the run, indicating that this is the end of the run. This is consistent with a reduction of supply air pressure for percussion and a negative net air pressure for pull-back of the drill string.

4.2.2 Derivation of Penetration Rate

Data analysis and interpretation focused mainly on derivation of penetration rate as it is the most important parameter for characterization of the ground. Penetration rate is expressed as penetration of the drill bit (i.e. actual advancement of the bit through soil/rock) versus time. The data/chart on the movement of the drill chuck (hence the movement of the drill bit except when the drill chuck is detached from the drill string for adding rods) in real time sequence provided most of the information in constructing the penetration depth versus time plot. However, as the desired drill depth was achieved by adding sections of 1 m long drill rods one at a time, the chart also contains data associated with drilling activities that needed to be carried out for the addition of rods such as pull-back and push forward of the drill chuck for tightening and un-tightening of rods and resting of the drilling machine (i.e. when drilling was temporarily halted). Flushing of the hole, which was carried out to clear the hole of debris from time to time, was recorded as quick pull-back and push forward of the drill stem.

After identifying and sorting the various drilling activities, the penetration versus time plot was constructed by joining sections of the data which are associated with penetration only, i.e. actual drilling. Apart from filtering out activities such as flushing, the exercise also required the identification of the start and end points of each drill run (i.e. each section of drill rod). As demonstrated by the example shown in Figure 9, the points representing the end of drilling of each drill rod could normally be identified without much difficulty. However, accurate identification of the start point was found to be not so easy. This is because after a rod is added to the drill string, the bit has to travel a certain distance before it is pressed against the bottom of the hole for further advancement. This distance is unknown and it is different each time a rod is added. The identification of the start point for each drill rod is further complicated by the movement of the working platform at the start of penetration.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Backward movement of the platform (i.e. away from the slope), and hence the drill machine, as a result of providing reaction forces for the drilling would be recorded as a positive movement of the drill chuck or bit into the slope. For the purpose of deriving the penetration rate, the start point of each drill run was located by measuring backward from the end point of each run (which could be identified) the distance between the start point and the end point of each drill run which is taken as 1 m (i.e. the length of the drill rod). In reality, the actual drill depth of each run is not exactly the same as it is not possible for the drilling operator to stop the drill chuck at exactly the same point at the end of each drill run. Hence, the drill depth of each rod is likely to be slightly more or less than 1 m.

A typical plot of penetration depth of the drill bit versus time based on the data analysis and interpretation is shown in Figure 10. The plots for the remaining drillholes are included in Appendix B which is contained in the CD attached to this report.

4.3 Characterization of Ground Condition

Based on the Stage 3 Study Report, materials in the slope (within the reach of the soil nails) comprise basically CDG. Whilst this is consistent with the site observation, corestones were also observed at the slope surface, which were in more abundance at the western part of the site. That is, there are two basic materials in the slope, CDG and corestones, i.e. soil and rock in a more general sense. Therefore, in looking at the drill record, it is reasonable to expect that the penetration rate would reduce distinctively when the drill penetrated from the CDG (i.e. soil) into the corestones (i.e. rock). This is indeed reflected by the DPM data where the penetration rate derived for some of the drillholes show abrupt changes along the ground profile. In fact, the abrupt change in penetration rates is observed to be more frequent in drillholes at the western part of the slope where more corestones were exposed at the slope surface.

The ground conditions inferred by the DPM data along a series of cross sections across the site are presented in Figures 11 to 17.

The characterization of the ground using the derived penetration rate is basically qualitative, i.e. to distinguish a soil from a rock. The characterization relied much on the distinct difference in penetration rate between the two materials.

5. DISCUSSION

5.1 Data Analysis and Interpretation

The main challenge in data analysis and interpretation was to understand the drilling process, i.e. differentiate the various drilling activities, inferred by the drill record. Field observations and a good understanding of the drilling procedure on site were found to be important for making correct interpretation of the data. Moreover, knowledge on the principles of the air-driven rotary percussive DTH drill and the mechanism of hole formation was also essential for the task.

Interpretation of the DPM data was found to be labour intensive and time consuming. This is mainly because a tremendous amount of data was sorted/filtered manually for

Table of Contents
Table of Contents
Table of Contents
Table of Contents

identification of the various drilling activities. Detailed examination of raw data was also conducted in some cases to confirm results of interpretation. Also, as a first time user, a learning curve is required for the interpretation process. Yue et al (2004) recently developed a sorting algorithm for processing the data using a computer based on a number of sorting (filtering) criteria to differentiate the various drilling activities. Under the scope of the current study, GEO has not reviewed this algorithm.

5.2 Factors Affecting Penetration Rate

Results of the field trial and DPM data interpretation have demonstrated that penetration rate is generally dependent on ground condition. However, literature and information on drilling practice and experience in Hong Kong suggest that there are other factors which can affect penetration rate. These include drilling equipment, operator skill, groundwater condition and nail length.

As discussed in Section 2, penetration rate by percussive drilling is a function of frequency of the strikes (blows) and the energy per strike of the piston inside the hammer. The energy of each strike is derived from the net air pressure acting on the top of the piston, which is the difference between the air supply pressure and the back pressure at the cut face of the hole. Whilst the supply air pressure for the percussion is monitored, information on the back pressure and hence the net air pressure acting on the piston is unknown. Data on the frequency of strikes, which could vary during drilling, are also not available. In the absence of this information, it is difficult to account for the effect on penetration rates due to these factors.

Also worth mentioning is that all pressure sensors are installed on the air pressure control panel instead of on the down-the-hole hammer. There will be loss of pressure and energy dissipation due to frictional resistance along the drill rod. Therefore, the measured supply air pressure cannot be equated to the net pressure acting on top of the piston.

Condition of the bit can reduce penetration rate significantly. As a button continues to crush the ground, a flat area is formed at its base due to wear and tear. As the size of the flat area increases, the penetration rate drops. In some cases, the penetration rate could be reduced by over 30%, depending on the size of the “wear flat” (Frequent Drillers Club, 2002).

Groundwater, if encountered in large quantities during drilling, could increase the back pressure in the hole and reduce hammer efficiency (Chugh, 1977, 1985). In other words, the penetration rate for drillholes in similar ground conditions can vary due to having different groundwater conditions.

The supply pressure for the percussion is irrelevant at all if there is no percussion action, e.g. when drilling in soft ground.

Skill of the drilling operator, that is, his ability to optimize the percussion, thrust and rotation of the hammer for the particular ground, can make a significant difference in penetration rate. Whilst all operators may have the same basic skills, an experienced operator or an operator who is familiar with a certain model/made of machine may be able to harmonize the various air pressures to optimize penetration rate.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

5.3 Characterisation of Ground Condition

The current DPM system attempts to characterize ground conditions from the penetration rates with focus on the energy delivered to the down-the-hole hammer only. Given the dependence of penetration rates also on other factors as discussed above, ground conditions inferred by the present state of the DPM process could only be qualitative and crude. Whilst more data from additional field trials may allow further assessment of dependence of penetration rate on these factors, it is doubtful whether such information would ever be sufficient for this purpose.

As for the subject slope, the dependence of penetration rate on factors related to state and construction of the drilling equipment and operator skill has been significantly reduced. This is because (i) the same machine and operator was used for all the drillholes monitored and (ii) no major seepage was encountered during drilling of the holes. Therefore, the ground conditions inferred by the DPM, as presented in Section 4, are considered to be reasonably valid.

5.4 Potential Areas of Application of DPM in Soil Nailing Works

The present state of the DPM system, being mainly capable of inferring a qualitative and crude assessment of the ground condition, could potentially be used by designers to verify the location of the bedrock, and, where practicable, revise soil nail design during construction for cost saving.

The technique could also be used to record the length of the drilled hole, the time of drilling and, to a certain extent, provide information on the skill of the driller. The issue relating to movement of the scaffolding working platform may need to be addressed to improve accuracy in filtering the DPM data for derivation of penetration rate.

6. CONCLUSIONS

The on-site use of DPM equipment for monitoring drilling process was found to be reasonably straight-forward.

Data analysis and interpretation using manual sorting/filtering was found to be labor intensive and time consuming. Presumably, this process can be carried out more efficiently using automatic filtering of the full DPM data. Yue et al (2004) has developed an algorithm for automatic differentiation of the various drilling activities in the drilling process.

Penetration rate depends on a number of factors including ground conditions, state and construction of drilling equipment, operator skill, groundwater regime and nail length. The dependence on ground condition is complicated, including the suitability of whether the ground is firm enough to excite percussion action of the down-the-hole hammer.

Quantitative characterisation of ground conditions from the penetration rates requires knowledge of two groups of factors. The first group relates to the energy delivered by the down-the-hole hammer and includes parameters such as pressure supply to the hammer, back

Table of Contents
Table of Contents
Table of Contents
Table of Contents

pressure at the exit port of the hammer and the frequency of percussion. The second group relates to the efficiency of the hammer in cutting and removing the ground. It includes the state and construction of the drilling machine, and the skill of the driller at optimising the drilling process. The present DPM attempts to characterise the first group by the air pressure to down-the-hole hammer. This is insufficient. It is doubtful whether there is a practical way of characterising the second group at all. For the time being, penetration rates from the DPM system could at best be used for crude qualitative assessment of the ground intercepts, especially for inferring rock.

7. FURTHER WORK

Data analysis and interpretation using manual sorting/filtering are labor intensive and time consuming. Consideration may be given for the development of a user-friendly computer program for automatic interpretation of the DPM data.

Further field trial may be conducted to investigate if factors such as state and construction of drilling equipment and skill of driller at optimising the drilling process can be effectively characterised for their impact on penetration rate.

8. REFERENCES

Chugh, C. P. (1977). Drilling Technology Handbook. Oxford & IBH Publishing Co., India, 460 p.

Chugh, C. P. (1985). Manual of Drilling Technology. A A Balkema. Rotterdam, 567 p.

Chugh, C. P. (1992). High Technology in Drilling and Exploration. A A Balkema. Rotterdam, 781 p.

Frequent Drillers Club (2002). Article on Drilling Theory: Principles of Percussive Drilling. Internet website: www.drillersclub.com

Kwok, H. (2004). Personal communication on percussion drilling practice in Hong Kong.

Pau, L.L.Y. (2002). Slopes 11NW-D/C92 & C94, Chung Yee Street & Chung Hau Street, Homantin. Stage 3 Study Report No. S3R 267/2002, Geotechnical Engineering Office, Hong Kong, 40 p.

Sugawara, J, Yue, Z.Q., Tham, L.G & Lee, C.F. (2003). Weathered Rock Characterization Using Drilling Parameters. Canadian Geotechnical Journal. Vol. 40, pp 661-668.

Yue, Z.Q., Lee, C.F., Law, K.T. & Tham, L.G. (2004). Automatic Monitoring of Rotary-persussive Drilling for Ground Characterization - Illustrated by a Case Example in Hong Kong. International Journal of Rock Mechanics and Mining Sciences. Vol 41, pp 573-612.

Table of Contents
Table of Contents
Table of Contents
Table of Contents

LIST OF FIGURES

Table of Contents
Table of Contents
Table of Contents

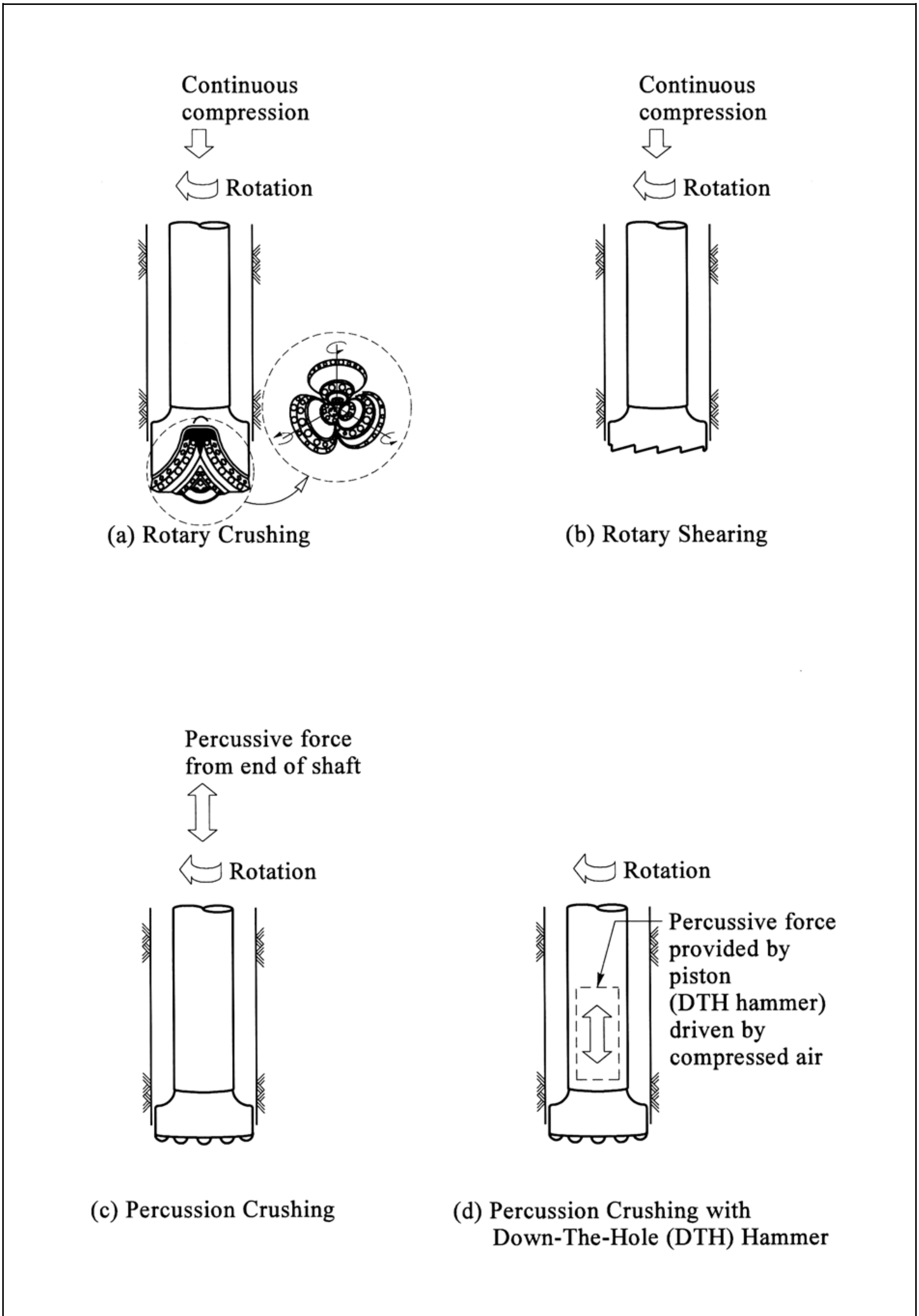


Figure 1 - Basic Methods of Drilling

Table of Contents
Table of Contents
Table of Contents
Table of Contents

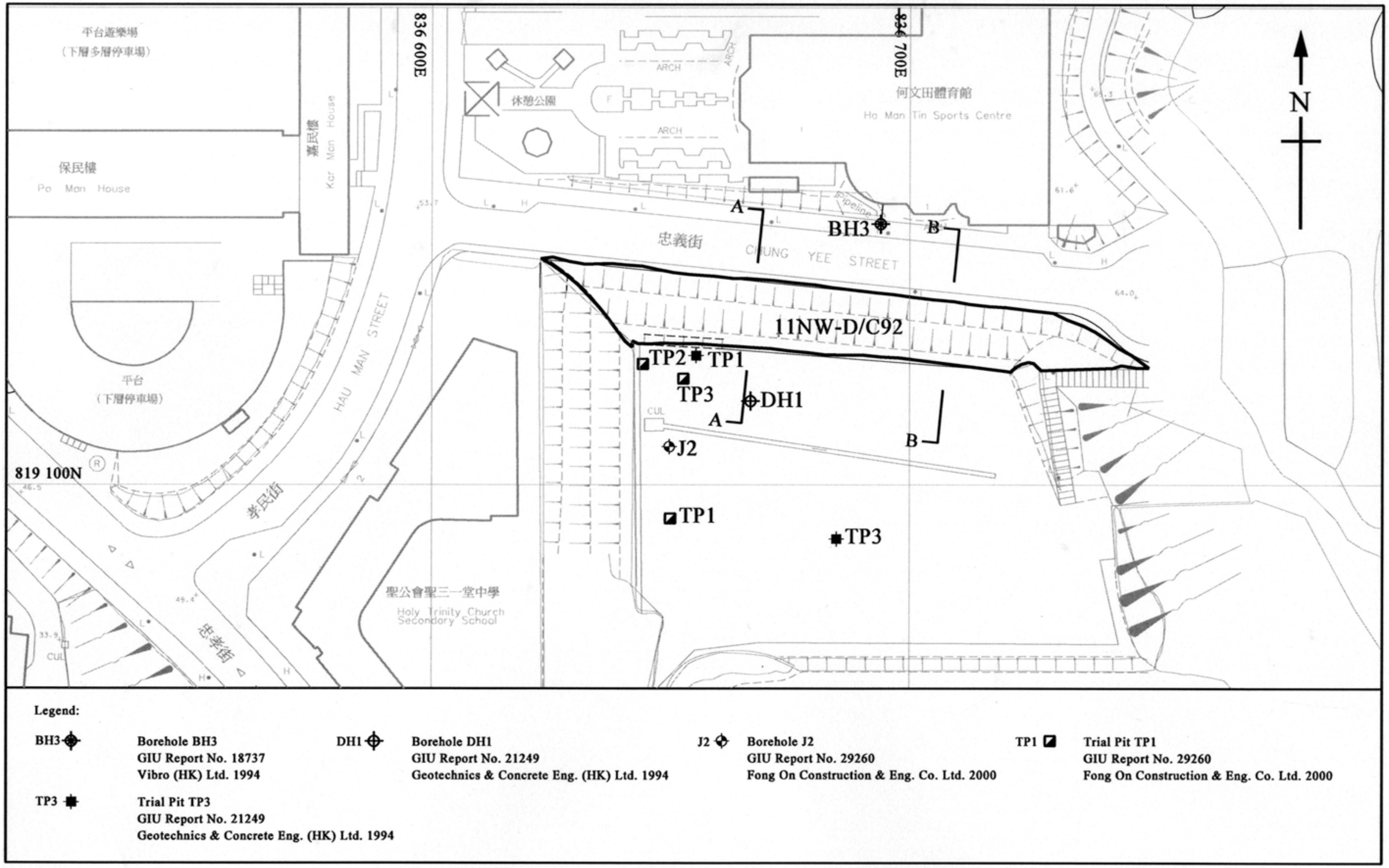


Figure 2 - Location and Investigation Plan

Table of Contents Table of Contents Table of Contents Table of Contents

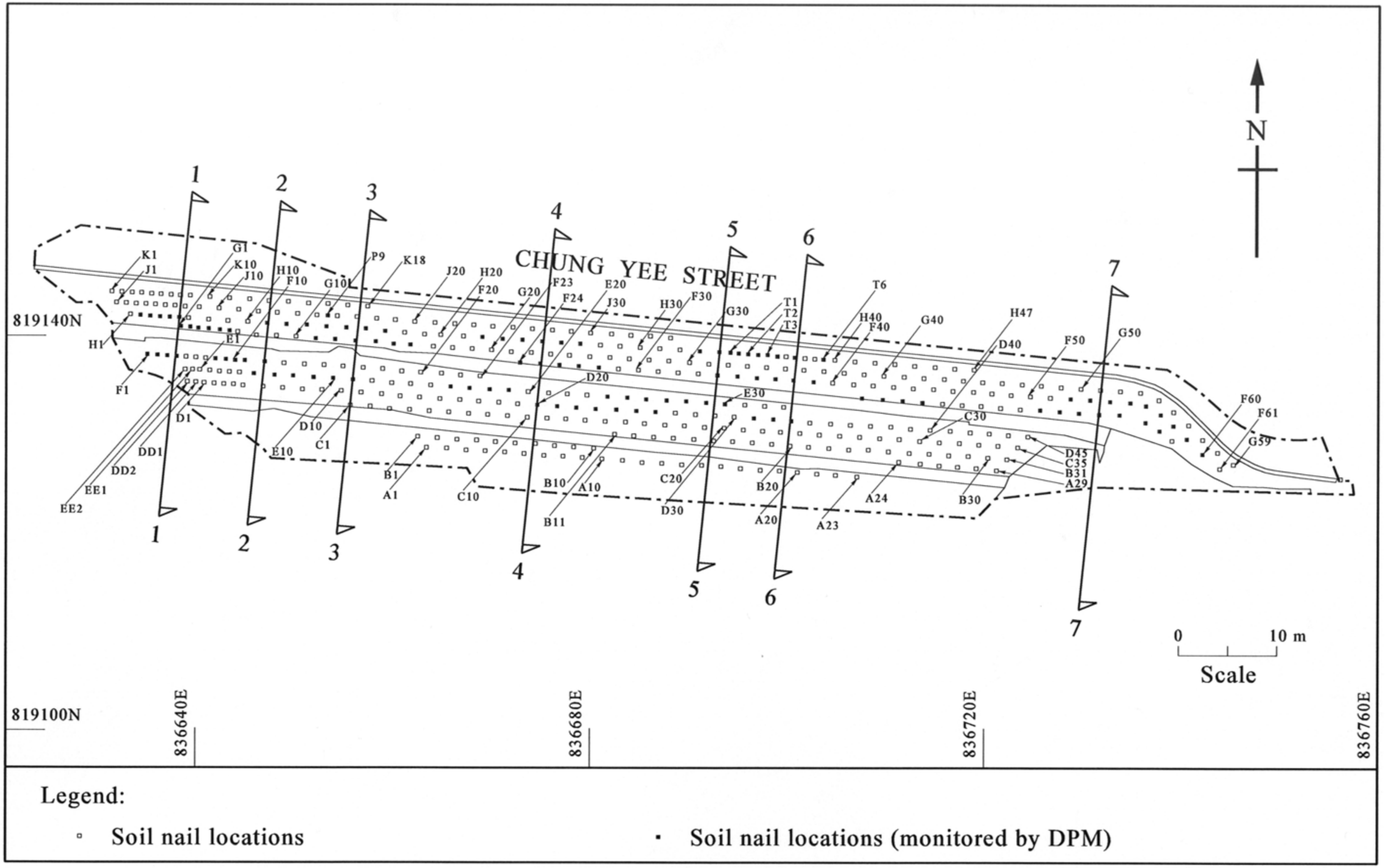
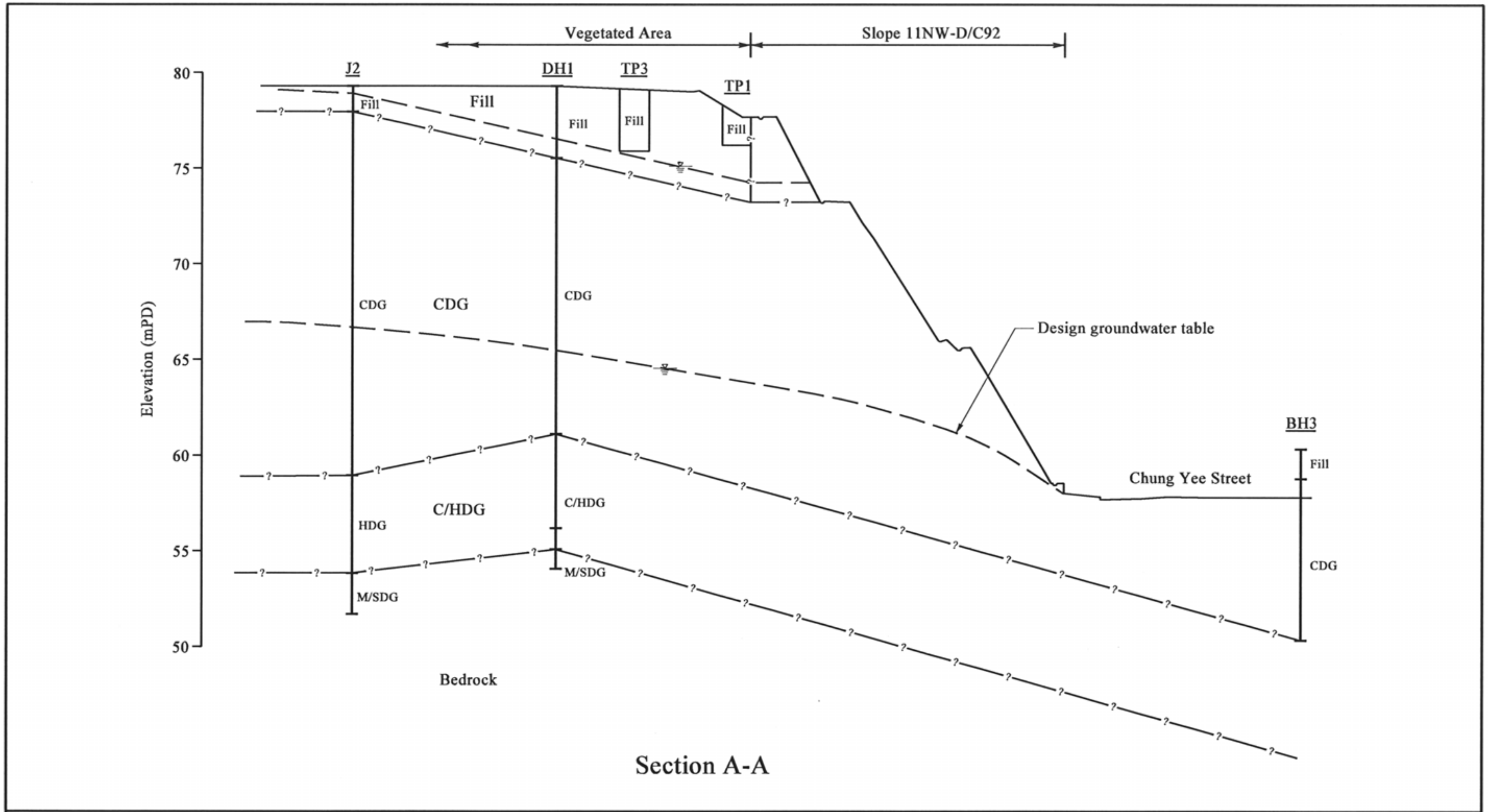


Figure 3 - Layout of Soil Nails

Table of Contents
Table of Contents
Table of Contents
Table of Contents

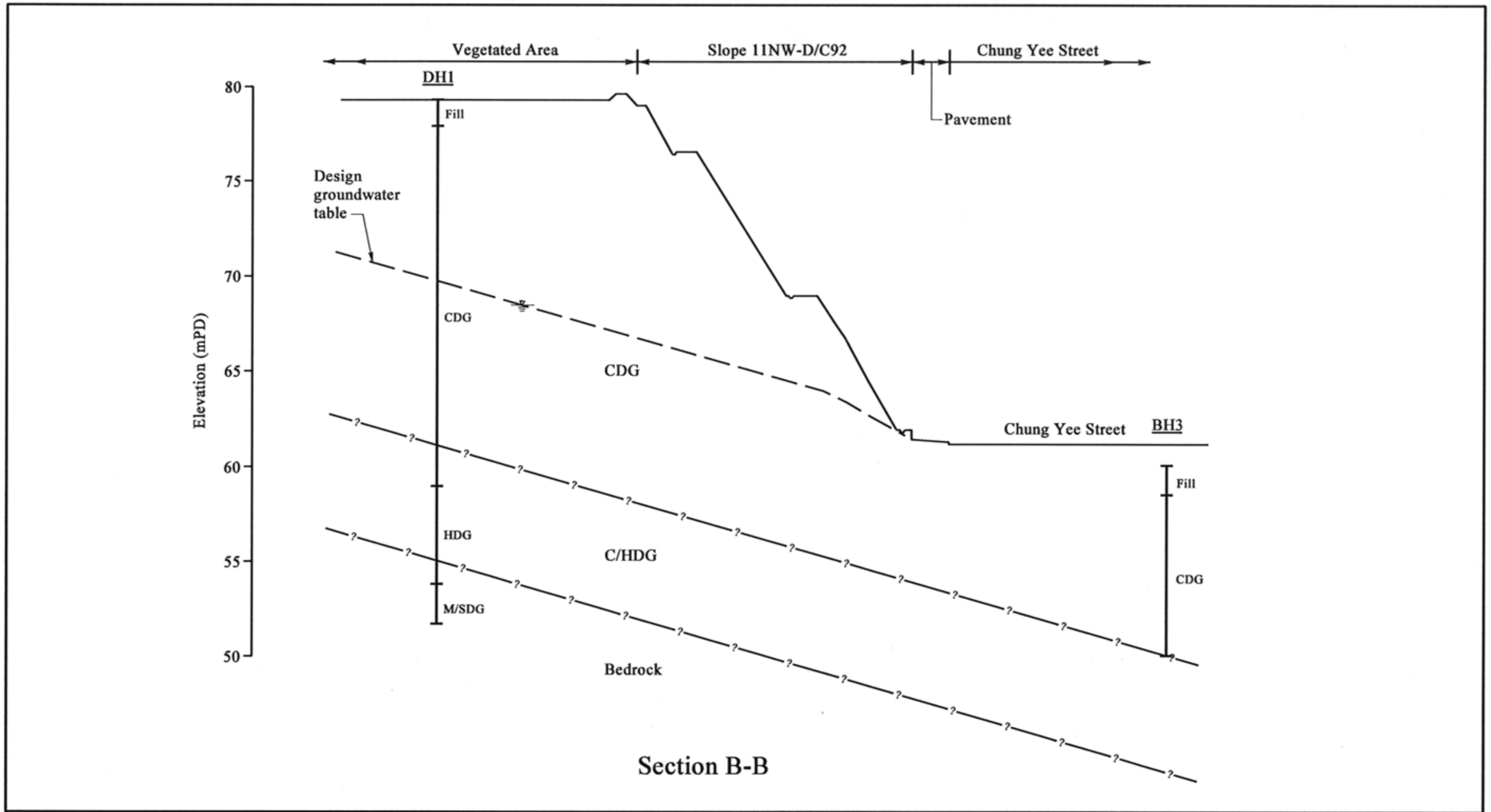


Legend:

CDG	Completely decomposed granite	MDG	Moderately decomposed granite	DH1	Borehole DH1	J2	Borehole J2
HDG	Highly decomposed granite	SDG	Slightly decomposed granite	BH3	Borehole BH3	TP1	Trial Pit TP1

Figure 4 - Interpreted Geological Profile of Slope 11NW-D/C92 at Section A-A

Table of Contents
Table of Contents
Table of Contents
Table of Contents



Legend:

CDG	Completely decomposed granite	MDG	Moderately decomposed granite	DH1	Borehole DH1
HDG	Highly decomposed granite	SDG	Slightly decomposed granite	BH3	Borehole BH3

Figure 5 - Interpreted Geological Profile of Slope 11NW-D/C92 at Section B-B

Table of Contents
Table of Contents
Table of Contents
Table of Contents

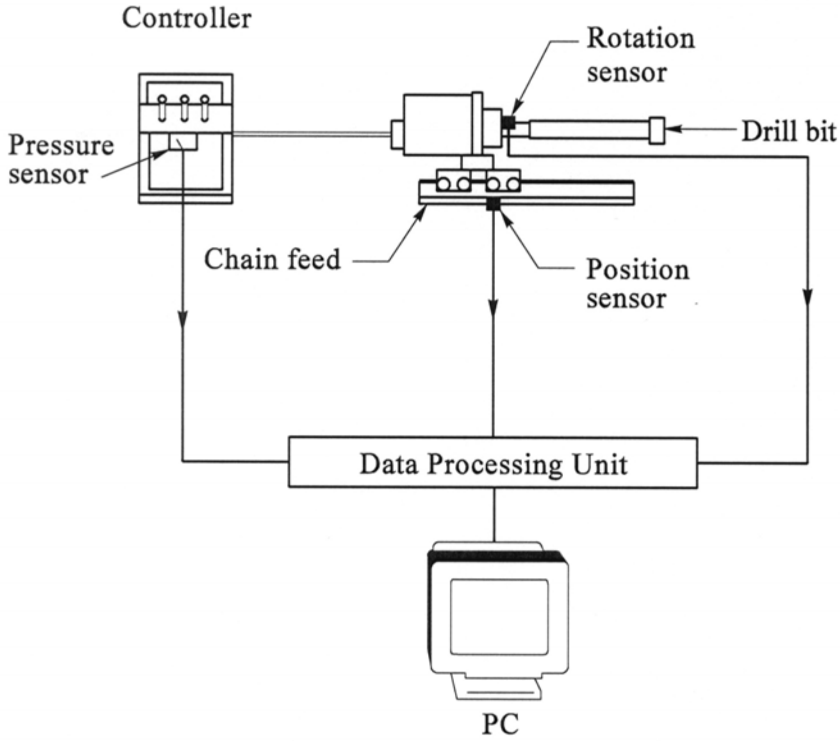


Figure 6 - Schematic Diagram of DPM (adopted from Sugawara et al, 2003)

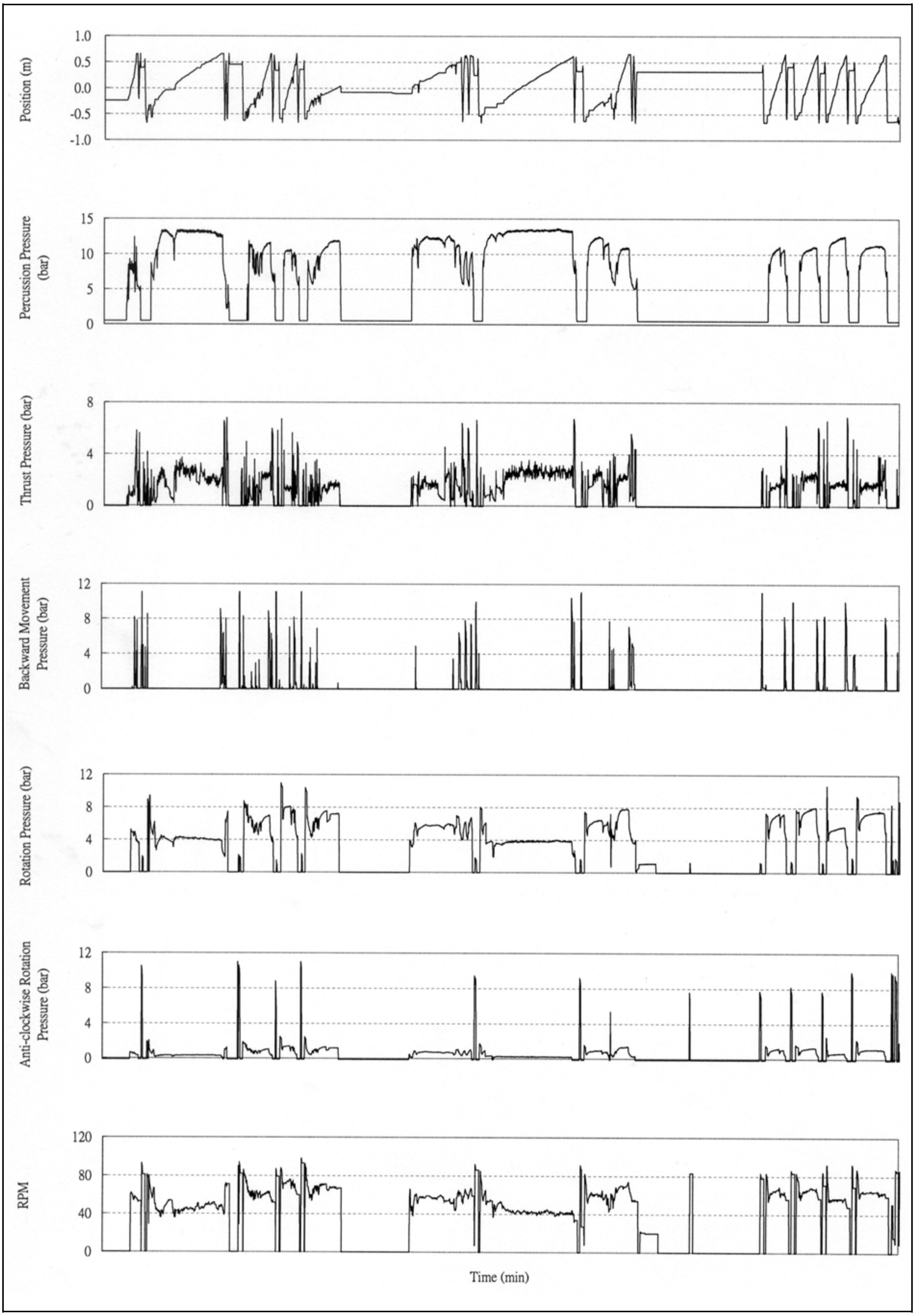


Figure 7 - Origanal DPM Data for Drillhole G12

Table of Contents
Table of Contents
Table of Contents
Table of Contents

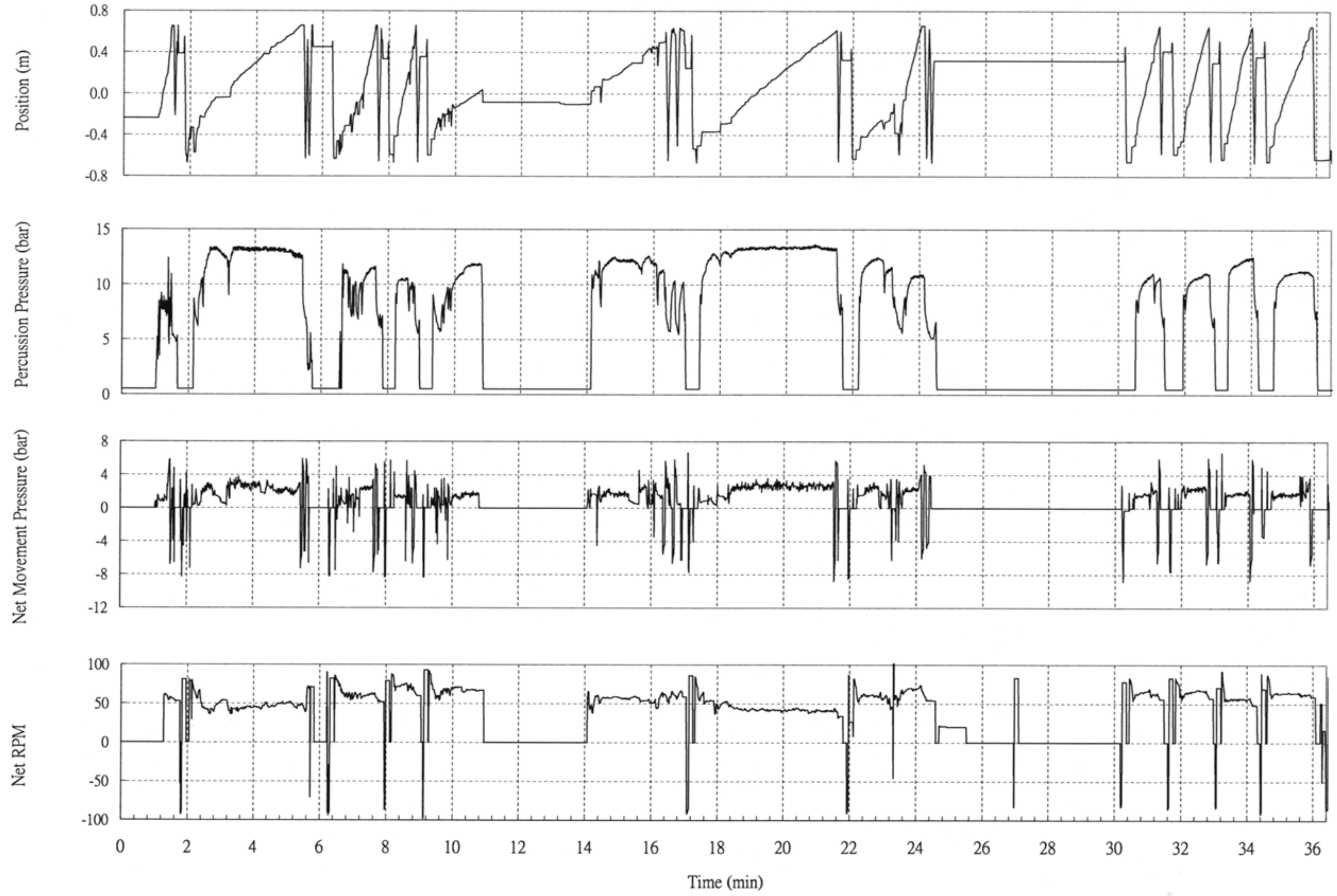


Figure 8 - Simplified DPM Data for Drillhole G12

Table of Contents
Table of Contents
Table of Contents
Table of Contents

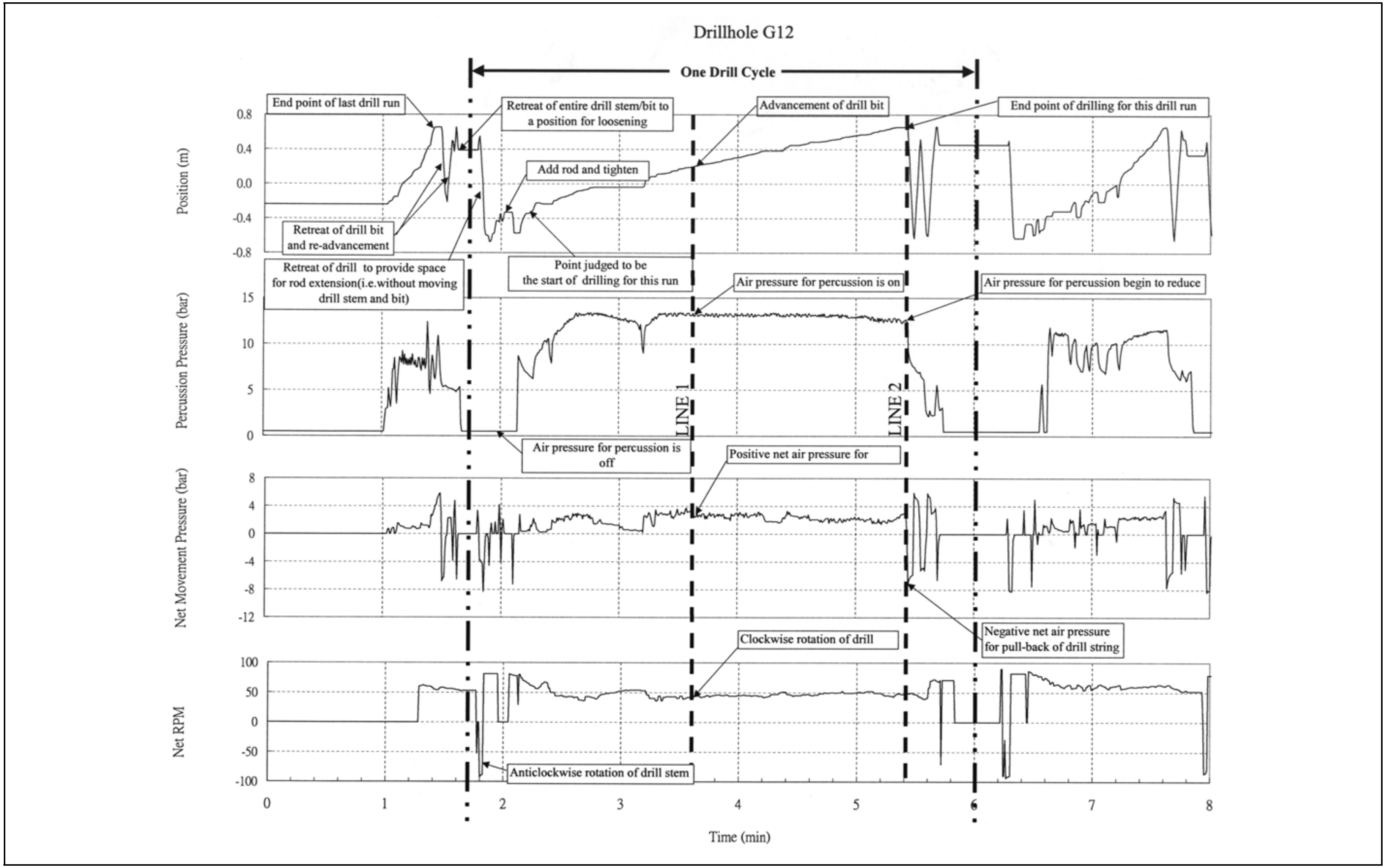


Figure 9 - Various Drilling Activities Inferred by DPM Data

Table of Contents
Table of Contents
Table of Contents
Table of Contents

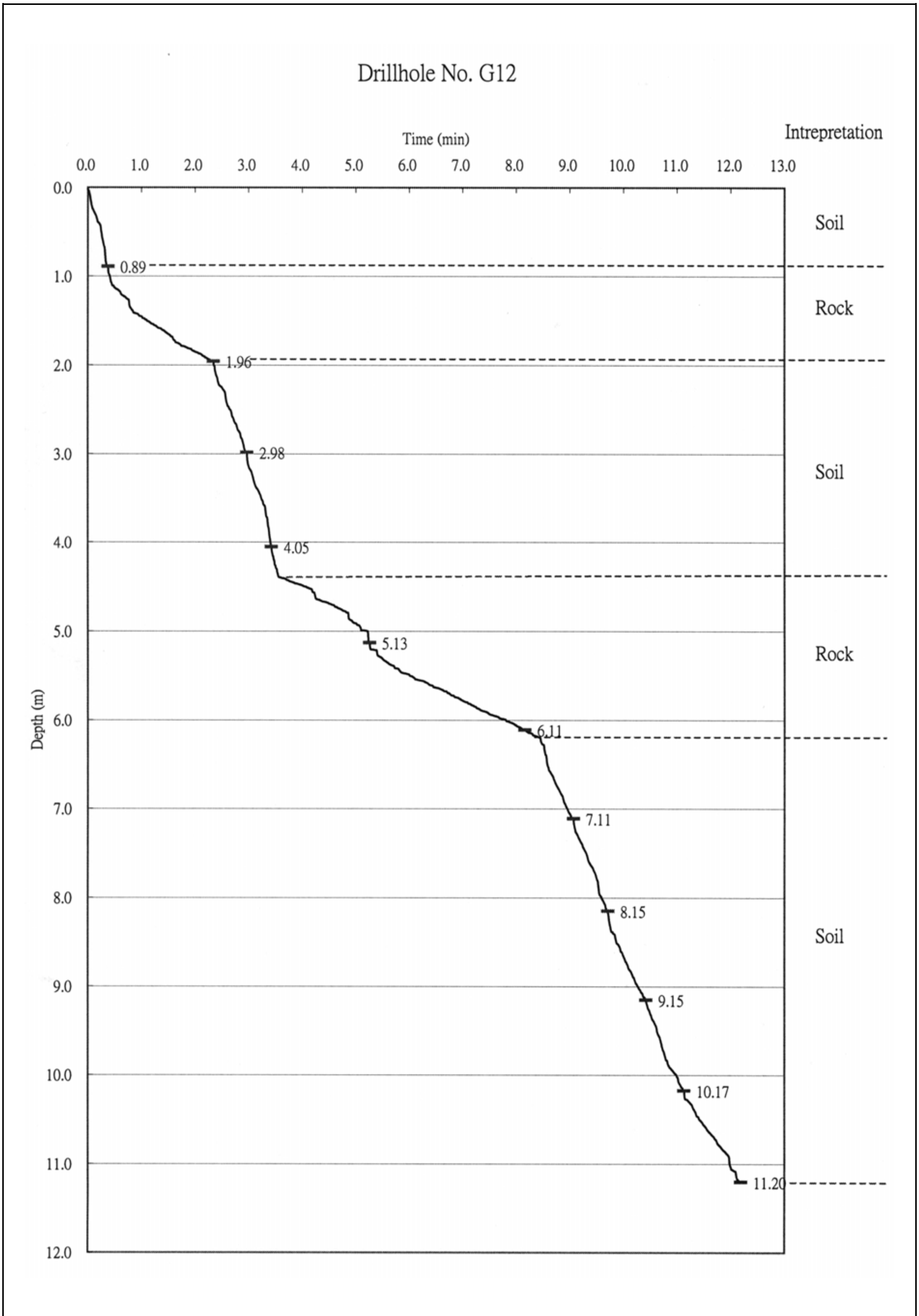


Figure 10 - Variation of Penetration Depth with Time

Table of Contents
Table of Contents
Table of Contents
Table of Contents

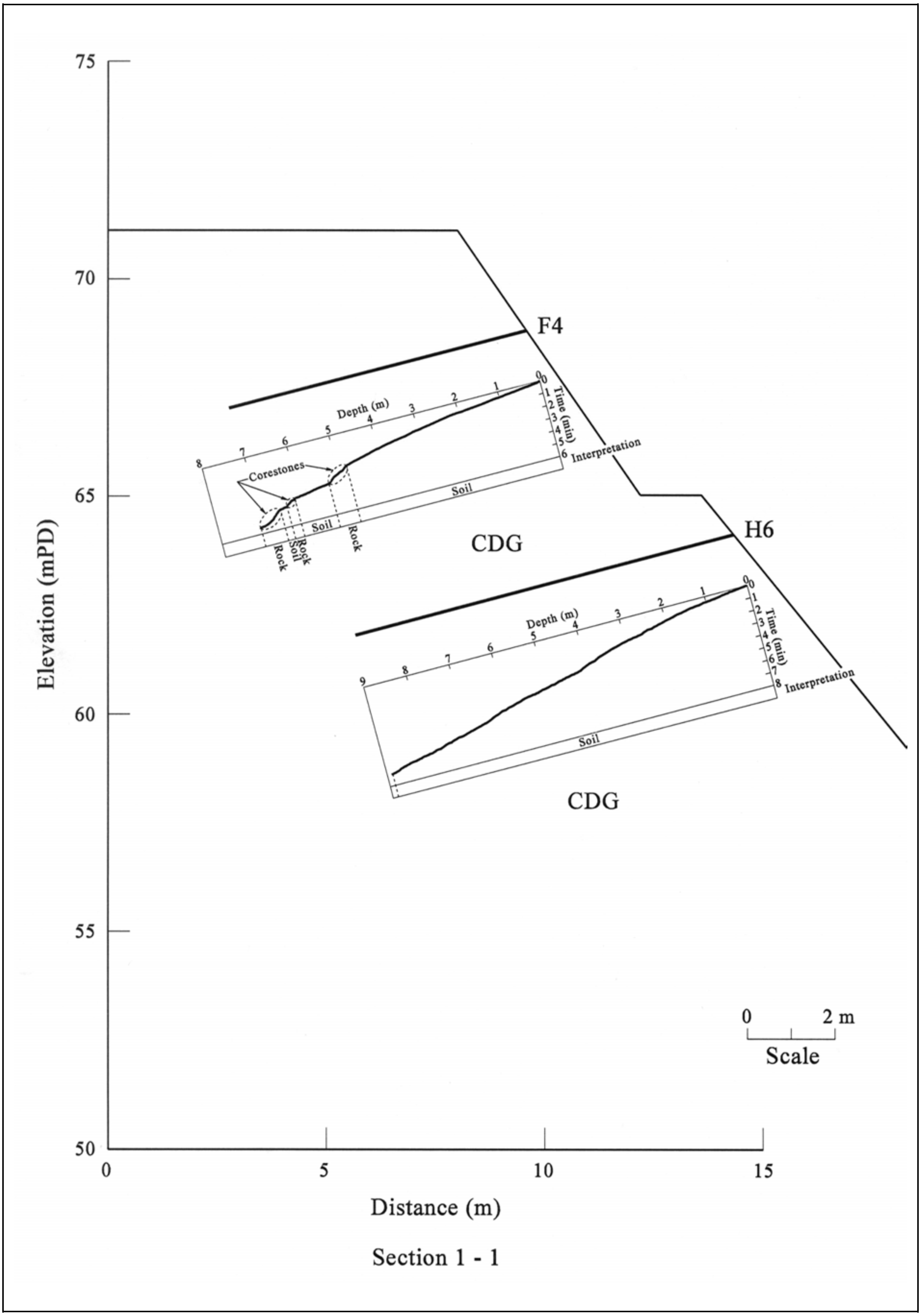


Figure 11 - Ground Condition Inferred by DPM Data

Table of Contents
Table of Contents
Table of Contents
Table of Contents

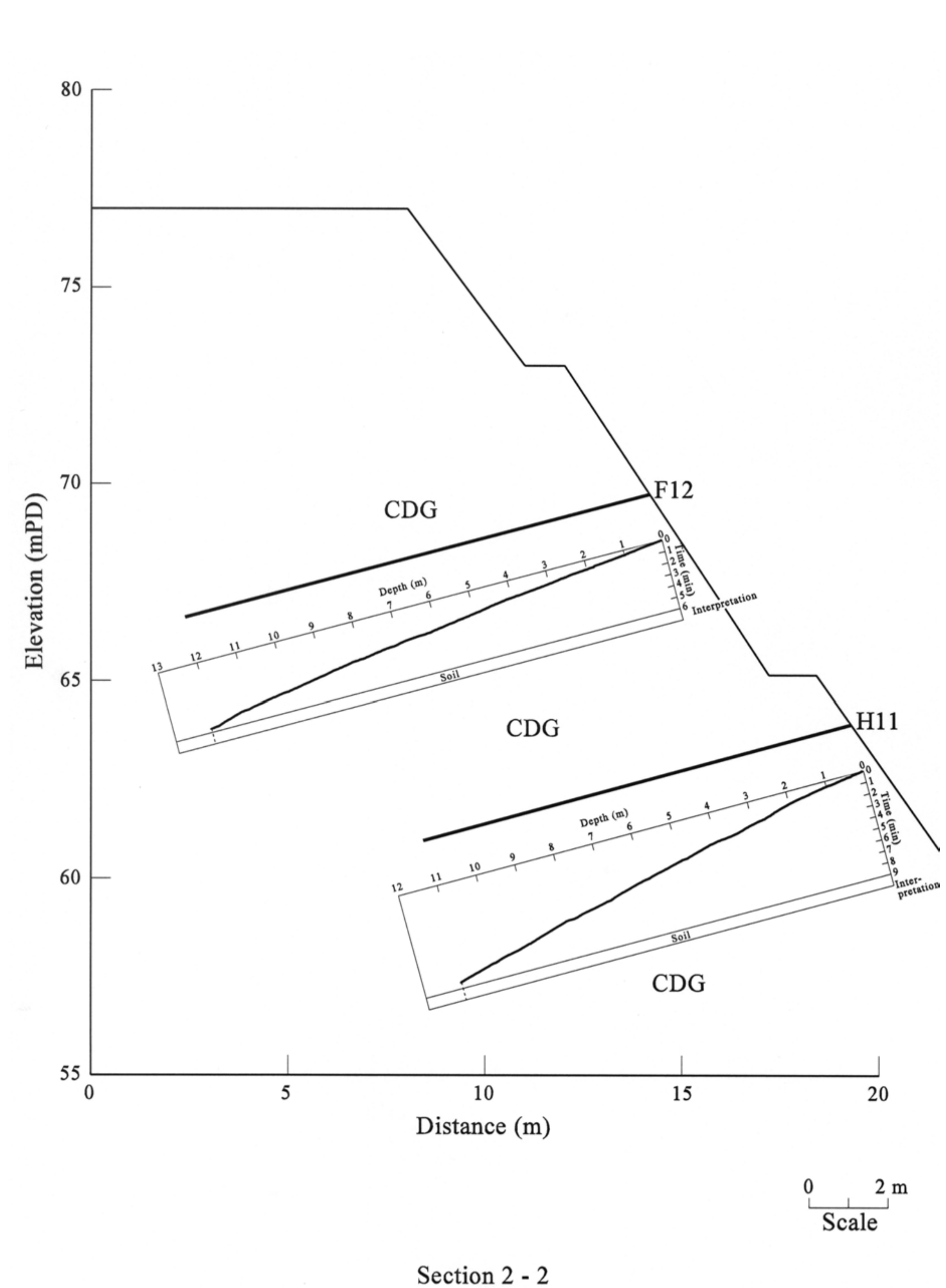


Figure 12 - Ground Condition Inferred by DPM Data

Table of Contents
Table of Contents
Table of Contents
Table of Contents

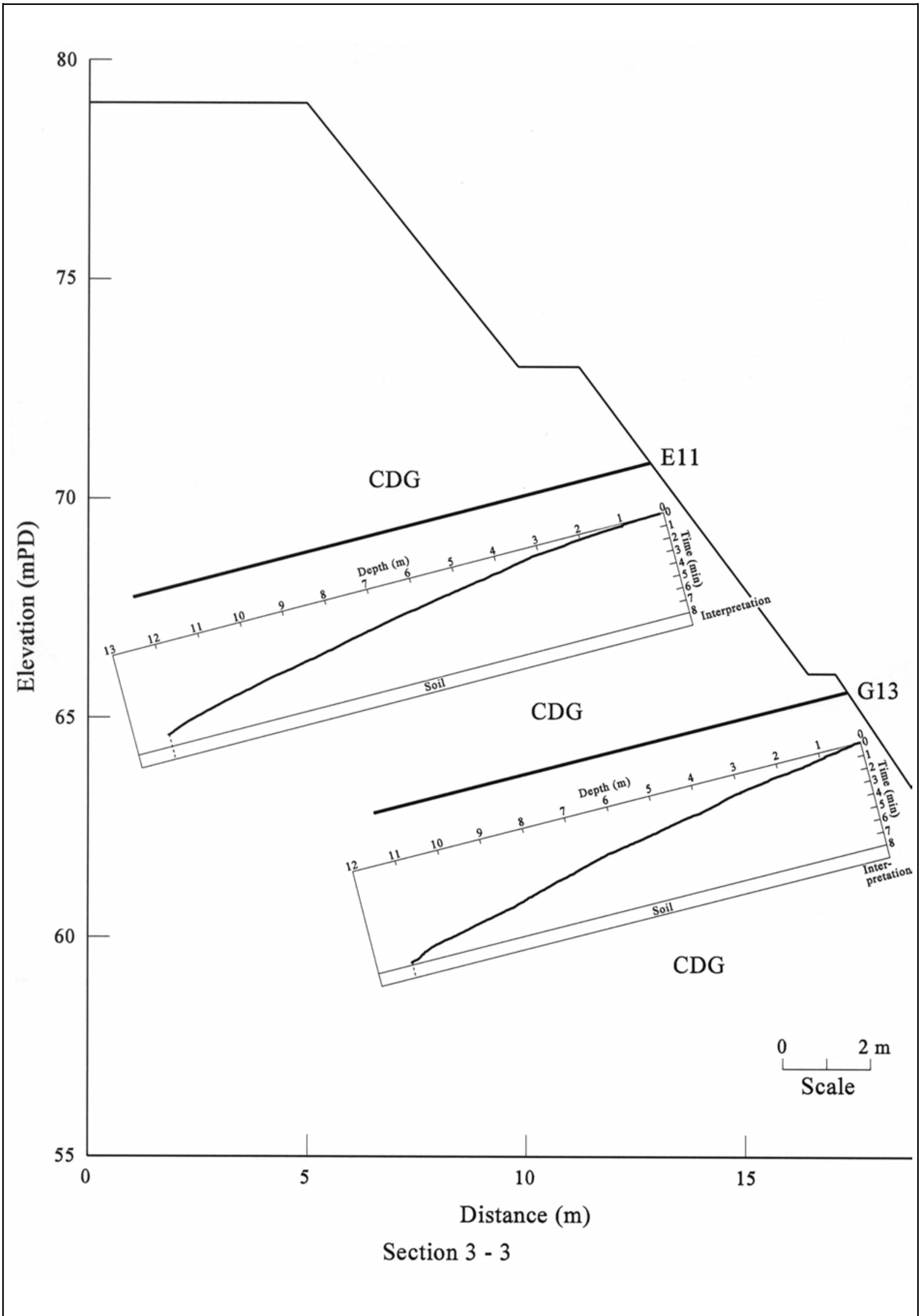


Figure 13 - Ground Condition Inferred by DPM Data

Table of Contents Table of Contents Table of Contents Table of Contents

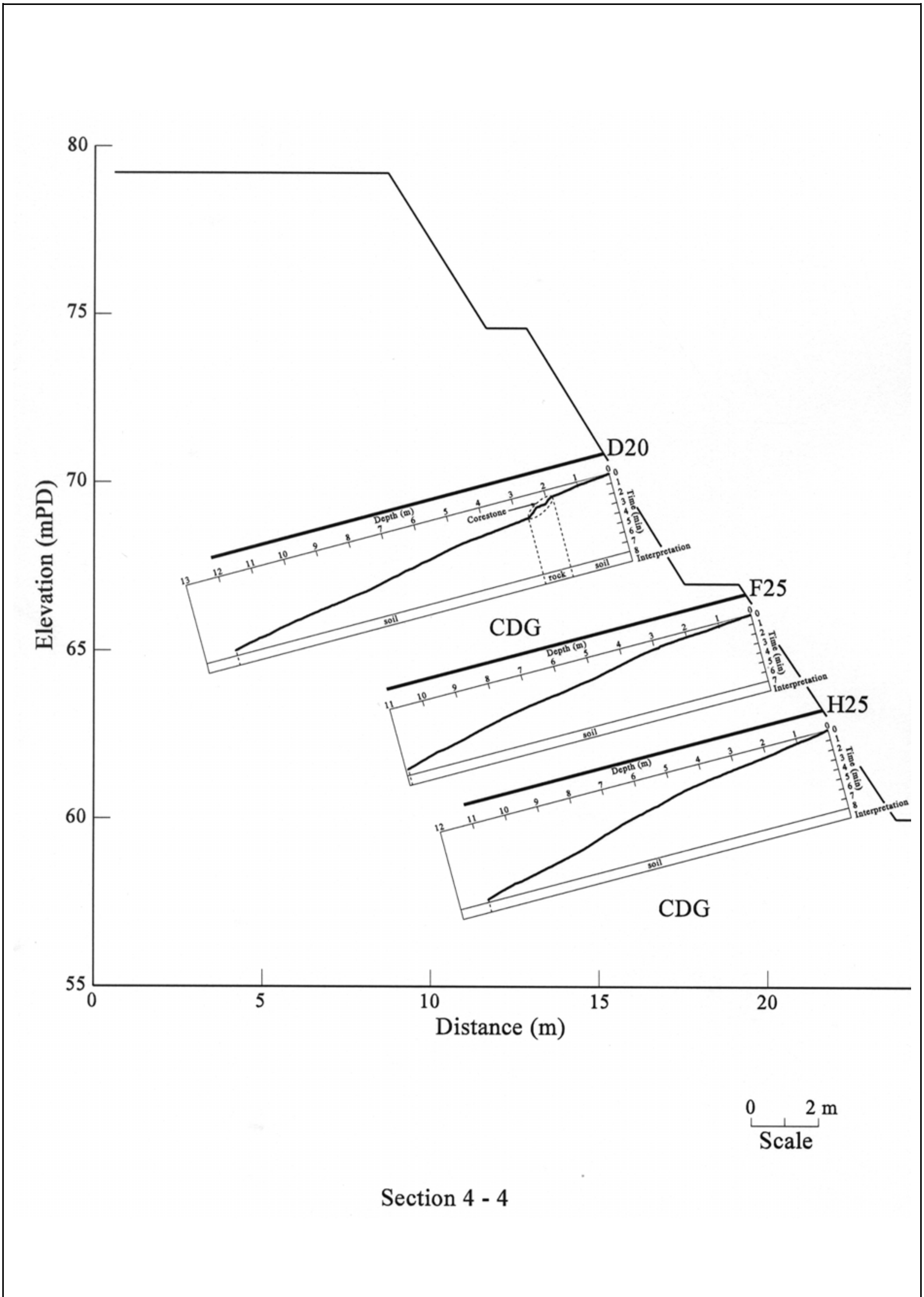


Figure 14 - Ground Condition Inferred by DPM Data

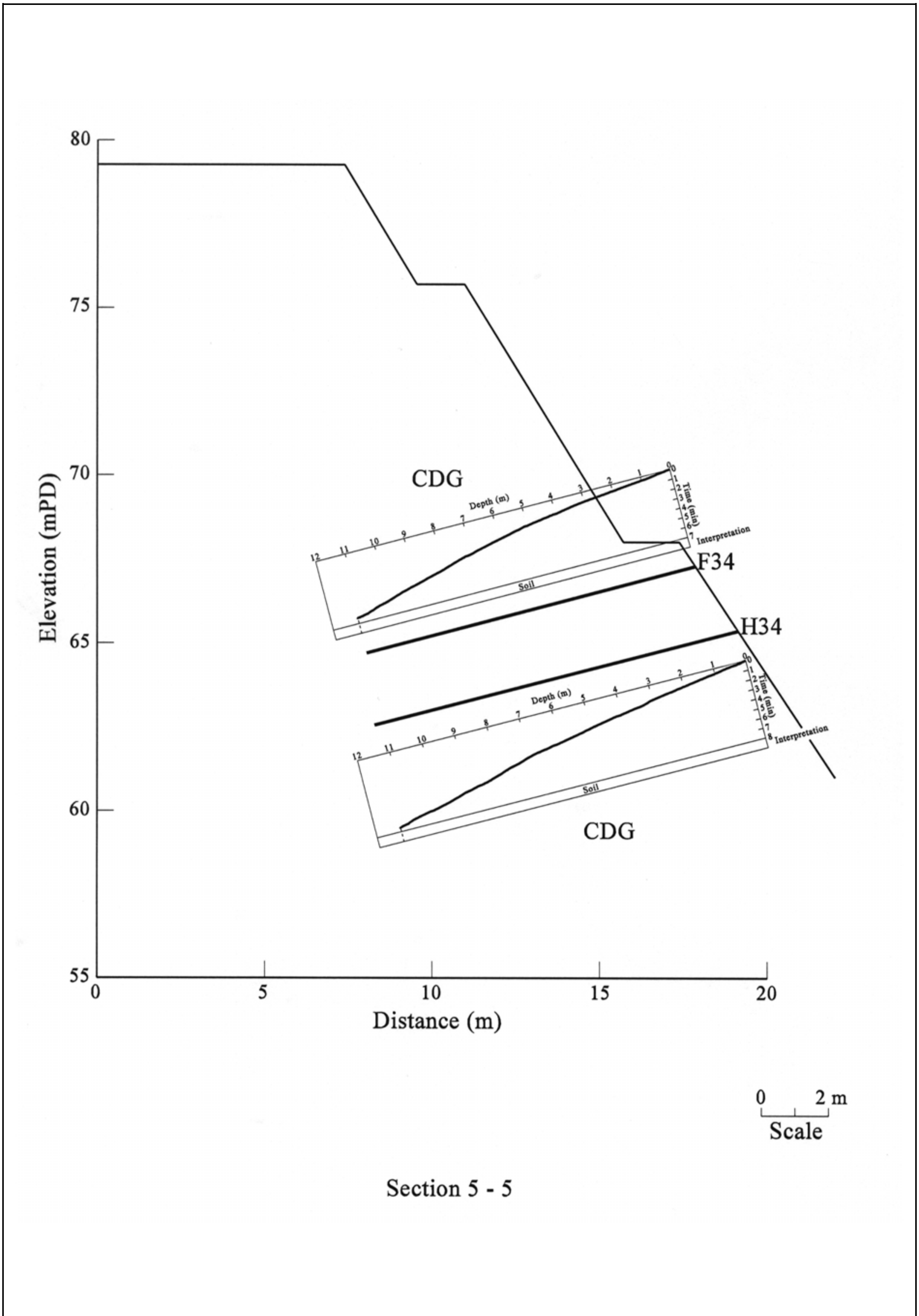


Figure 15 - Ground Condition Inferred by DPM Data

Table of Contents
Table of Contents
Table of Contents
Table of Contents

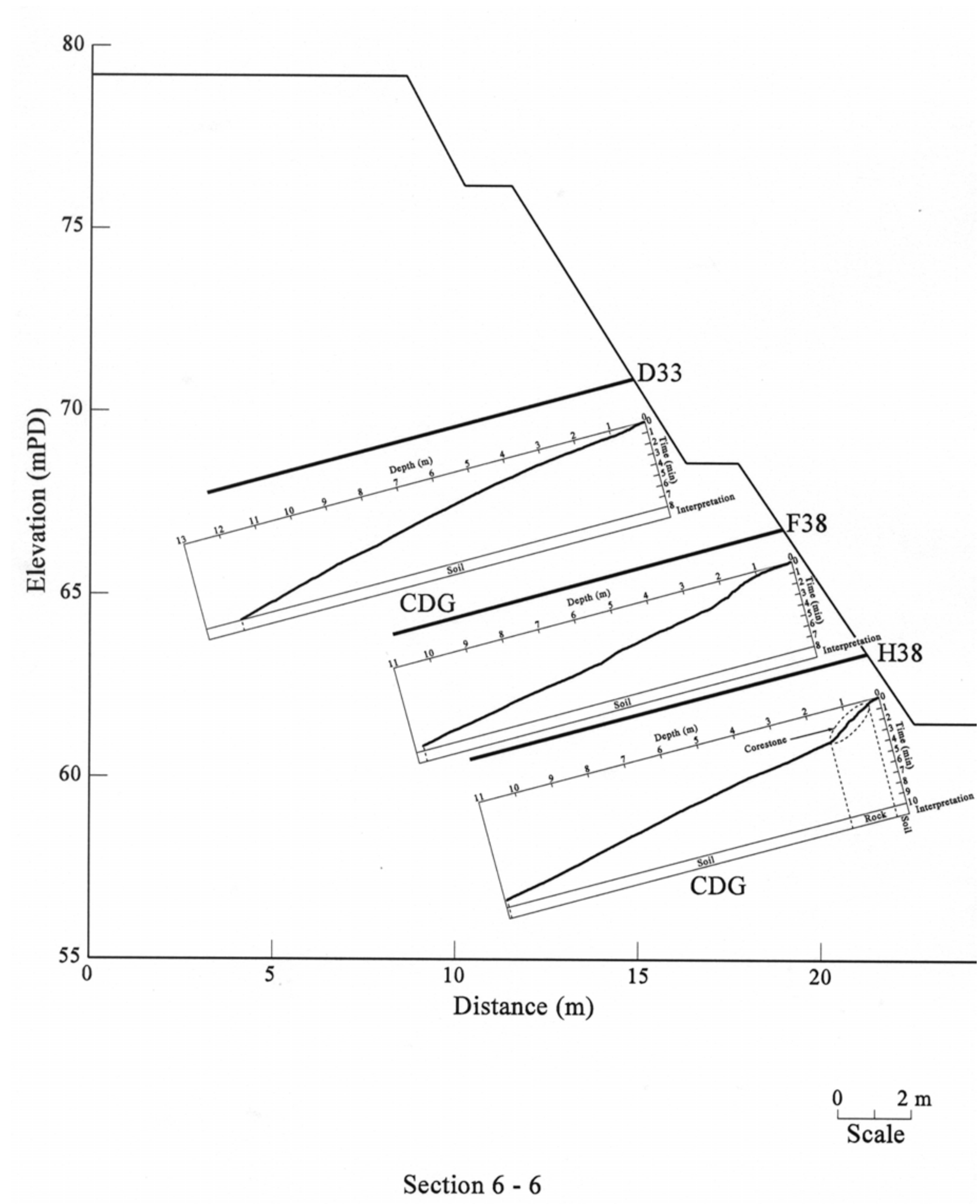


Figure 16 - Ground Condition Inferred by DPM Data

Table of Contents
Table of Contents
Table of Contents
Table of Contents

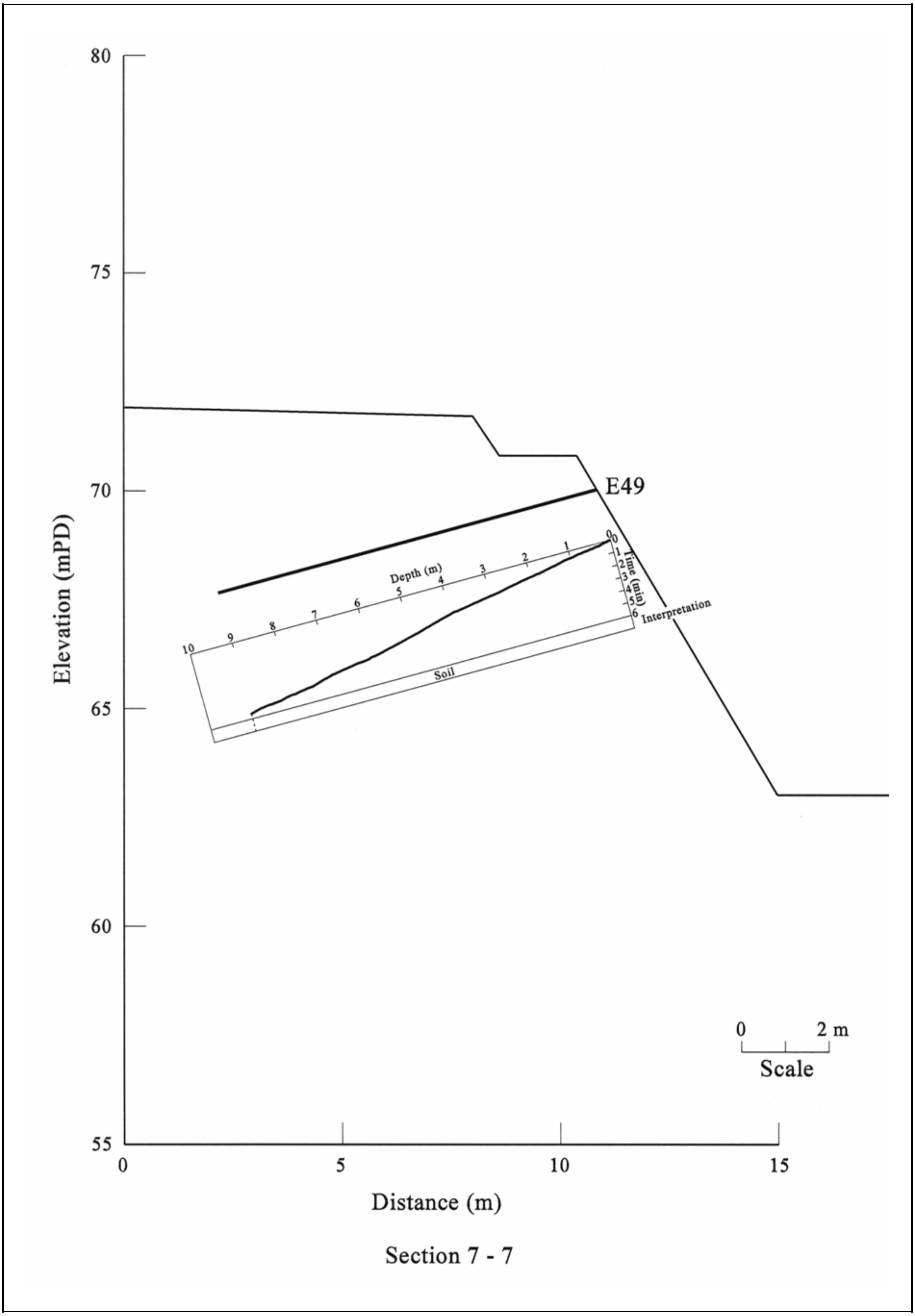


Figure 17 - Ground Condition Inferred by DPM Data

Table of Contents
Table of Contents
Table of Contents
Table of Contents

LIST OF PLATES

Plate 1 - General Site Appearance

Plate 2 - Air-driven Rotary Percussive Down-the-hole Drilling Machine Used at the Site

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Plate 3 - Data Processing and Logging Unit

Plate 4 - Sensor for the Measurement of Rotation Speed

Table of Contents
Table of Contents
Table of Contents
Table of Contents

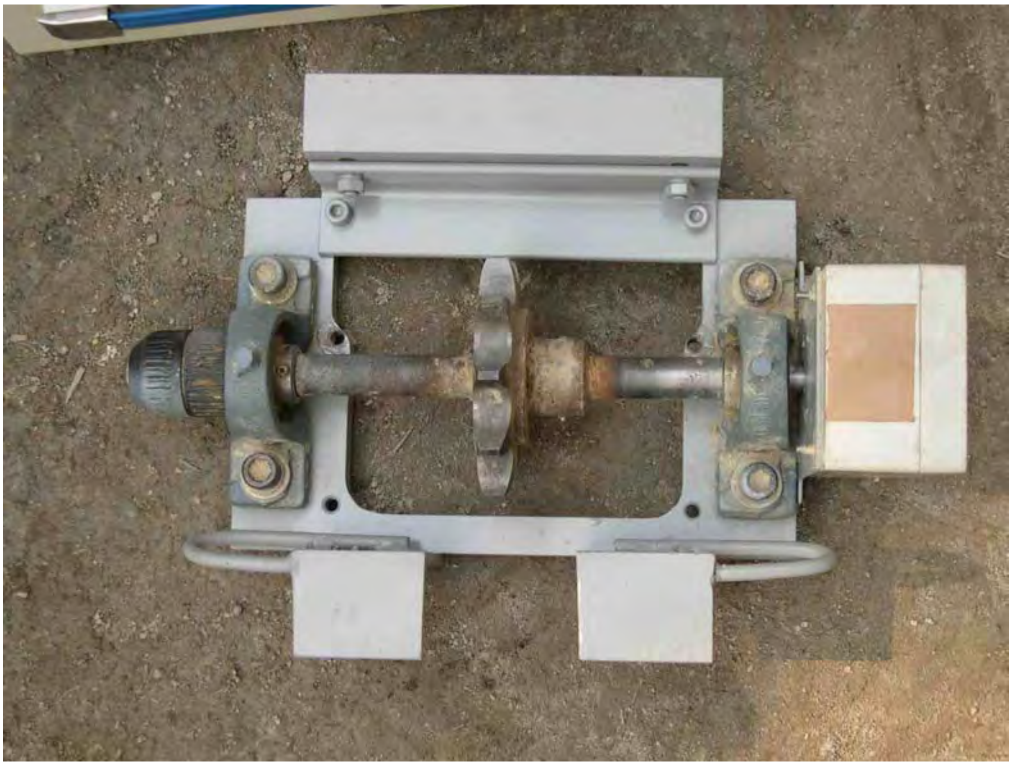


Plate 5 - Sensor for the Measurement of Drill Chuck Position
(installed onto the loop chain of the drilling machine)

Plate 6 - Sensors Installed onto the Manual Control Panel

Table of Contents
Table of Contents
Table of Contents
Table of Contents

Table of Contents

Table of Contents

APPENDIX A

SIMPLIFIED PLOTS OF DPM DATA
(Contained in CD attachment)

Table of Contents

Table of Contents

Table of Contents

Table of Contents

APPENDIX B

PLOTS OF PENETRATION RATE VERSUS TIME
(Contained in CD attachment)

Table of Contents

Table of Contents

GEO PUBLICATIONS AND ORDERING INFORMATION
土力工程處刊物及訂購資料

A selected list of major GEO publications is given in the next page. An up-to-date full list of GEO publications can be found at the CEDD Website http://www.cedd.gov.hk on the Internet under "Publications". Abstracts for the documents can also be found at the same website. Technical Guidance Notes are published on the CEDD Website from time to time to provide updates to GEO publications prior to their next revision.

部份土力工程處的主要刊物目錄刊載於下頁。而詳盡及最新的土力工程處刊物目錄，則登載於土木工程拓展署的互聯網網頁 http://www.cedd.gov.hk 的"刊物"版面之內。刊物的摘要及更新刊物內容的工程技術指引，亦可在這個網址找到。

Copies of GEO publications (except maps and other publications which are free of charge) can be purchased either by:

writing to
Publications Sales Section,
Information Services Department,
Room 402, 4th Floor, Murray Building,
Garden Road, Central, Hong Kong.
Fax: (852) 2598 7482

or

- Calling the Publications Sales Section of Information Services Department (ISD) at (852) 2537 1910
- Visiting the online Government Bookstore at http://bookstore.esdlife.com
- Downloading the order form from the ISD website at http://www.isd.gov.hk and submit the order online or by fax to (852) 2523 7195
- Placing order with ISD by e-mail at puborder@isd.gov.hk

讀者可採用以下方法購買土力工程處刊物(地質圖及免費刊物除外):

書面訂購
香港中環花園道
美利大廈4樓402室
政府新聞處
刊物銷售組
傳真: (852) 2598 7482

或

- 致電政府新聞處刊物銷售小組訂購 (電話：(852) 2537 1910)
- 進入網上「政府書店」選購，網址爲 http://bookstore.esdlife.com
- 透過政府新聞處的網站 (http://www.isd.gov.hk) 於網上遞交訂購表格，或將表格傳真至刊物銷售小組 (傳真：(852) 2523 7195)
- 以電郵方式訂購 (電郵地址：puborder@isd.gov.hk)

1:100 000, 1:20 000 and 1:5 000 maps can be purchased from:

Map Publications Centre/HK,
Survey & Mapping Office, Lands Department,
23th Floor, North Point Government Offices,
333 Java Road, North Point, Hong Kong.
Tel: 2231 3187
Fax: (852) 2116 0774

讀者可於下列地點購買1:100 000，1:20 000及1:5 000地質圖：

香港北角渣華道333號
北角政府合署23樓
地政總署測繪處
電話: 2231 3187
傳真: (852) 2116 0774

Requests for copies of Geological Survey Sheet Reports, publications and maps which are free of charge should be sent to:

For Geological Survey Sheet Reports and maps which are free of charge:
Chief Geotechnical Engineer/Planning,
(Attn: Hong Kong Geological Survey Section)
Geotechnical Engineering Office,
Civil Engineering and Development Department,
Civil Engineering and Development Building,
101 Princess Margaret Road,
Homantin, Kowloon, Hong Kong.
Tel: (852) 2762 5380
Fax: (852) 2714 0247
E-mail: jsewell@cedd.gov.hk

For other publications which are free of charge:
Chief Geotechnical Engineer/Standards and Testing,
Geotechnical Engineering Office,
Civil Engineering and Development Department,
Civil Engineering and Development Building,
101 Princess Margaret Road,
Homantin, Kowloon, Hong Kong.
Tel: (852) 2762 5345
Fax: (852) 2714 0275
E-mail: ykhui@cedd.gov.hk

如欲索取地質調查報告、其他免費刊物及地質圖，請致函：

地質調查報告及地質圖:
香港九龍何文田公主道101號
土木工程拓展署大樓
土木工程拓展署
土力工程處
規劃部總土力工程師
(請交:香港地質調查組)
電話: (852) 2762 5380
傳真: (852) 2714 0247
電子郵件: jsewell@cedd.gov.hk

其他免費刊物:
香港九龍何文田公主道101號
土木工程拓展署大樓
土木工程拓展署
土力工程處
標準及測試部總土力工程師
電話: (852) 2762 5345
傳真: (852) 2714 0275
電子郵件: ykhui@cedd.gov.hk

Table of Contents
Table of Contents
Table of Contents
Table of Contents

MAJOR GEOTECHNICAL ENGINEERING OFFICE PUBLICATIONS
土力工程處之主要刊物

GEOTECHNICAL MANUALS

Geotechnical Manual for Slopes, 2nd Edition (1984), 300 p. (English Version), (Reprinted, 2000).

斜坡岩土工程手冊(1998)，308頁(1984年英文版的中文譯本)。

Highway Slope Manual (2000), 114 p.

GEOGUIDES

Geoguide 1	Guide to Retaining Wall Design, 2nd Edition (1993), 258 p. (Reprinted, 2000).
Geoguide 2	Guide to Site Investigation (1987), 359 p. (Reprinted, 2000).
Geoguide 3	Guide to Rock and Soil Descriptions (1988), 186 p. (Reprinted, 2000).
Geoguide 4	Guide to Cavern Engineering (1992), 148 p. (Reprinted, 1998).
Geoguide 5	Guide to Slope Maintenance, 3rd Edition (2003), 132 p. (English Version).
岩土指南第五冊	斜坡維修指南，第三版(2003)，120頁(中文版)。
Geoguide 6	Guide to Reinforced Fill Structure and Slope Design (2002), 236 p.

GEOSPECS

Geospec 1	Model Specification for Prestressed Ground Anchors, 2nd Edition (1989), 164 p. (Reprinted, 1997).
Geospec 3	Model Specification for Soil Testing (2001), 340 p.

GEO PUBLICATIONS

GCO Publication No. 1/90	Review of Design Methods for Excavations (1990), 187 p. (Reprinted, 2002).
GEO Publication No. 1/93	Review of Granular and Geotextile Filters (1993), 141 p.
GEO Publication No. 1/2000	Technical Guidelines on Landscape Treatment and Bio-engineering for Man-made Slopes and Retaining Walls (2000), 146 p.
GEO Publication No. 1/2006	Foundation Design and Construction (2006), 376 p.

GEOLOGICAL PUBLICATIONS

The Quaternary Geology of Hong Kong, by J.A. Fyfe, R. Shaw, S.D.G. Campbell, K.W. Lai & P.A. Kirk (2000), 210 p. plus 6 maps.

The Pre-Quaternary Geology of Hong Kong, by R.J. Sewell, S.D.G. Campbell, C.J.N. Fletcher, K.W. Lai & P.A. Kirk (2000), 181 p. plus 4 maps.

TECHNICAL GUIDANCE NOTES

TGN 1	Technical Guidance Documents