A REVIEW OF DOWNHOLE GEOPHYSICAL METHODS FOR GROUND INVESTIGATION

GEO REPORT No. 99

K.C. Lau

GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING DEPARTMENT

THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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Prepared by:

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

PREFACE

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R.K.S. Chan
Head, Geotechnical Engineering Office
March 2000

FOREWORD

This report reviews the capability and applicability of downhole geophysical and optical methods for ground investigation in Hong Kong. It is an extension of Phases 1 and 2 of the Site Characterisation Study (SCS) which considered non-invasive geophysical methods.

As a result of this review, a preliminary list of downhole geophysical methods has been established for further evaluation, with a view to conducting field trials.

The study was undertaken by Dr. K.C. Lau of the Planning Division. Dr. L.S. Chan and Ms. Q.F. Chen of the University of Hong Kong and Dr. Charles W.W. Ng of the Hong Kong University of Science and Technology provided valuable advice and suggestions. The assistance of Mr. K.C. Chan and Mr. P.C. Cheng in helping to prepare the illustrations is acknowledged, as is the advice given by Mr. Nick Koor, Dr. C.A.M. Franks, Mr. W.W.L. Shum, Mr. P.C.T. Cheung, and Mr. H.H. Choy.

(R.P. Martin)
Chief Geotechnical Engineer/Planning

ABSTRACT

One question raised in the December 1996 SSTRB meeting (Slope Safety Technical Review Board, 1997) that relates to the Phase 2 of the Assessment of Geological Features Related to Recent Landslides in Volcanic Rocks of Hong Kong study was "What methods of site investigation are available and should be adopted to establish the continuity and thickness of kaolin seams?" In response to this question, a research study on downhole geophysical methods for ground investigation in Hong Kong was initiated.

The objective of the study is to evaluate the capabilities and applicability of downhole geophysical and optical methods to 1) characterise discontinuities, in particular clay-infilled sheeting joints, within weathered rock in Hong Kong, and 2) determine small strain stiffness properties of weathered rock masses.

In this report, a review of downhole geophysical methods was conducted. Based on the existing data on the conditions of discontinuities, in particular clay-infilled sheeting joints, within a weathered rock mass in Hong Kong preliminary downhole geophysical methods were selected for the field trials to be conducted in the next phase of the study.

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1. INTRODUCTION

Following on from the Fei Tsui Road landslide of 13 August 1995 (GEO, 1996a & 1996b), a phased pilot study, the *Assessment of Geological Features Related to Recent Landslides in Volcanic Rocks of Hong Kong* was initiated. One of the objectives of that study was to identify locations in slopes where the geological features are similar to those that influenced the Fei Tsui Road and Shum Wan Road landslides. Phase 2 of the study relating to the Chai Wan and Aberdeen areas is now complete (Campbell & Koor, 1996; Franks et al., 1997). One question raised in the December 1996 SSTRB meeting (Slope Safety Technical Review Board, 1997) that relates to the Phase 2 studies was "What methods of site investigation are available and should be adopted to establish the continuity and thickness of kaolin seams?" In response to this question, a research study on downhole geophysical methods for ground investigation in Hong Kong was initiated.

The objective of this present study is to evaluate the capabilities and applicability of downhole geophysical and optical methods to:

1. characterise discontinuities, in particular clay-infilled sheeting joints, within weathered rock in Hong Kong, and

2. determine small strain stiffness properties of weathered rock masses.

The study is an extension of the *Site Characterisation Study* (Koor, 1997), which up to now has considered the use of non-invasive geophysical techniques applied to man-made slopes and retaining walls.

This report reviews the use of downhole geophysical methods to characterise discontinuities and assess the stiffness of saprolite soils in Hong Kong. Section two of the report reviews existing data on the conditions of discontinuities, in particular clay-infilled sheeting joints, within a weathered rock mass. A summary of the international literature on the subject is contained in Section three. Section four of the report provides a factual account of the current practice of the use of downhole geophysical methods in Hong Kong. Preliminary downhole geophysical methods selection for the field trials is made in Section five.

2. CHARACTERISATION OF CLAY-INFILLED DISCONTINUITIES

2.1 The Clay Rich Zones

The results of the Phase 2 study of the *Assessment of Geological Features Related to Recent Landslides in Volcanic Rocks of Hong Kong* showed that kaolin is commonly found within the PW0/30 rock mass weathering zone (of predominantly Grades IV and V materials). It is also concentrated at, and parallel to the often abrupt and planar weathering front (PW0/30 and PW90/100 interface) in fine-grained volcanic rocks. The thickness of the kaolin zones typically varies from a few millimeters to hundreds of millimeters. Since drillholes are normally cased within the PW0/30 zone, and keyed into the PW90/100, the zones of interest will typically be within the cased length of the drillhole.

Kaolin concentrations along weathered sheeting joints within the prominently unweathered rock mass were also identified in two study areas (Campbell & Koor, 1996 & Franks et al., 1997). These zones are within the open length of the drilled hole and could affect the stability of natural or cut slopes if adversely oriented.

2.2 Conditions at Fei Tsui Road Landslide Site

At this site a laterally-extensive layer of kaolinite-rich altered tuff dipping approximately to the north at about 10° to 25° was noted (GEO, 1996a). At the eastern edge of the landslide, the kaolinite-rich altered tuff layer is about 0.5 m thick and is overlain by moderately to slightly decomposed tuff. The layer is highly kaolinised and completely decomposed, with abundant kaolinite veins. The thickness of the veins ranges from 2 mm to 20 mm.

The average fines (i.e. clay and silt) content of altered tuff excluding kaolinite veins was found to be 71%, and that of kaolinite veins in the altered tuff to be 92%. The plasticity index of the fines of altered tuff and kaolinite veins ranged from 9 to 18, and the liquid limit ranged from 29 to 50.

For altered tuff samples with kaolinite veins aligned to the direction of shearing in direct shear tests, the average friction angle was 29°, with zero cohesion. The lower bound friction angle value was 22°, which corresponds to the situation for shearing through soil of high clay content.

2.3 Conditions at Shum Wan Road Landslide Site

Over the area of the concave scar, the completely to highly decomposed tuff was up to about 20 m thick prior to the landslide (GEO, 1996b). Joints within the partially weathered tuff were commonly coated with manganese oxide and infilled with white clay up to about 15 mm thick. An extensive clay seam formed part of the base of the concave scar. It comprised a soft yellowish brown clay layer, typically 100 mm thick (but locally up to 300 mm) with highly decomposed tuff fragments, underlain in places by a thin soft white clay with manganese coating.

The results of X-ray diffraction tests show that both clays contain kaolinite and probably halloysite (Merriman and Kemp, 1995). The white clay and the yellowish brown clay are mineralogically similar.

The average fines content of the yellowish brown clay near the ground surface was found to be 90%, the plasticity index ranged from 60 to 75, and the liquid limit ranged from 99 to 123.

From isotropically consolidated undrained triaxial compression tests on the yellowish brown clay, the friction angle was 26°, with an apparent cohesion intercept of 8 kPa. The direct shear test results for slickensided clay surface gave a friction angle of 21°, with zero cohesion.

2.4 Current Ground Investigation Methods Used in Hong Kong

Routine ground investigation methods used in Hong Kong include boring/drilling and soil sampling, probing and penetration testing, shallow trial pits and slope surface stripping, and occasionally deep trial pits and caissons (Geoguide 2).

The limitations of each of these methods to characterise discontinuities, in particular clay-infilled sheeting joints, within weathered rock are:

Method	Weakness
Boring/drilling and soil sampling	Continuous high quality sampling is very expensive and may not always be successful. Visual inspection of high quality continuous samples is required to confirm presence of clay filled discontinuities. Cannot determine the orientation of the discontinuities.
Probing and penetration testing	No samples available for visual inspection. Not applicable to the present study due to the variable penetrability of weathered rock.
Shallow trial pits and slope surface stripping	Only apply when clay seams are close to ground surface. Slope surface stripping can be expensive unless the protection surface is being removed for repair.
Deep trial pits and caisson	Very expensive, time consuming, and dangerous.
Borehole impression packer tests to map discontinuities.	Time consuming and often imprecise.

This table shows that each ground investigation method has its limitations to characterise discontinuities, in particular clay-infilled joints, within weathered rock. The needs for better methods for the characterisation of discontinuities are clear. Although downhole geophysical methods have made tremendous advancement during the last decade in the fields of civil engineering and groundwater, they are seldom used for site characterisation in Hong Kong.

In Hong Kong the engineering properties of soils and rocks are usually determined by conventional laboratory testing on samples obtained from the field. The small strain stiffness properties are seldom determined. These properties are very important in the prediction of ground movements especially in deep excavations (Malone et al., 1997). Owing to factors such as sample disturbance and recent stress history effects, these properties are extremely difficult to determine accurately by conventional laboratory tests (Atkinson et al., 1990 & Tatsuoka & Kohata, 1995). In this study the capabilities and applicability of downhole geophysical methods to determine small strain stiffness properties of weathered rock masses are also evaluated.

3. <u>REVIEW OF DOWNHOLE GEOPHYSICAL METHODS</u>

3.1 <u>Introduction</u>

Downhole geophysical logging is a technique used to determine the physical properties and distribution of soil and rock surrounding a borehole annulus. These measurements may record naturally occurring physical phenomena, or they may use an artificial physical source, such as electrical, nuclear and acoustic, to perturb the medium and measure the response to the perturbation. From these measurements, physical properties such as density, porosity, thickness, orientation, and lithological identification of soil and rock surrounding the borehole annulus may be determined. These non-disruptive in situ physical measurements of the soil, rock and fluids are collectively known as geophysical logging (Patrick, 1990).

Borehole geophysical measurements may be made in a single borehole or simultaneously in multiple boreholes. When the source of the probe is located in the borehole and the receiver is located on the ground surface, this configuration is called a hole-to-surface configuration. In the surface-to-hole configuration, the source of the probe is located on the ground surface and the receiver is located in the borehole. When the source and the receiver are located in different boreholes, the configuration is called a hole-to-hole or crosshole arrangement.

The choice of appropriate geophysical methods requires an understanding of the geologic environment and the borehole conditions. Very seldom can a geological property be identified from a single geophysical log (BS7022, 1988). It usually involves a combination of methods to identify each property of interest.

The additional benefits of using downhole geophysical methods in conjunction with routine ground investigation methods are:

1) downhole geophysical measurements sample a larger volume than core samples,

2) downhole geophysical measurements are continuous throughout the length of the drillhole, while sample analyses are usually discrete,

3) downhole geochemical, hydrogeologic, and geophysical measurements provide a complete record of a drillhole, and

4) downhole geophysical measurements maximise the return of the investment in a drillhole.

It is important to note that geophysical methods are intended to supplement direct methods; they are not a substitute for direct methods of site assessment such as drilling and trenching. However, by careful planning and use of geophysical methods, the number of borings required for adequate definition of subsurface conditions sometimes can be greatly reduced (Geological Society Engineering Group Working Party, 1988).

During the past decade the use of microprocessor-controlled field recording systems has increased the usefulness of downhole geophysical methods. Digital field systems increase the usefulness of geophysical measurements in many ways: 1) the engineer can easily access and manipulate digital geophysical logs, 2) digital geophysical logs can be stored and accessed conveniently, 3) geophysical logs from different contractors can be adjusted to a common base by applying simple correction factors to the digital data, 4) quantitative calculations from geophysical logs can be recomputed to take advantage of the latest processing techniques, and 5) advanced digital filtering techniques can be easily applied to the digital data.

Initially geophysical methods were developed mainly for the petroleum and mining industries. Nevertheless there has been a steady growth in the application of various geophysical methods to civil engineering and groundwater studies. Depending on the perturbation sources and the properties measured, borehole geophysical methods can be categorised into five main classes. They are the electrical, electromagnetic, nuclear, acoustic, seismic wave and optical methods. A summary of case histories on the application of downhole geophysical methods obtained from literature is listed in Table 1.

3.2 Electrical Methods

The three main types of electrical methods are spontaneous potential logs, resistivity logs, and induction logs. A spontaneous potential log is a measurement of the self potential between a ground electrode and a recording electrode moving up the borehole. A resistivity log records the resistivity of a circuit by passing a electric current through the geological formation. An induction log is a measurement of formation conductivity. When measuring formation electrical properties, the selection of tools is influenced by the borehole environment as shown in Figure 1. The electrical environment in a borehole changes with the change in the resistivity of the borehole drill fluid (R_m), the resistivity of the flushed/mud filtrate invasion zone (R_{xo}), the resistivity of adjacent beds (R_s) and the resistivity of the formation (R_t).

3.2.1 Spontaneous Potential Logs (SP)

The spontaneous potential (or self potential) log is a measurement of the direct current (DC) voltage differences between the naturally occurring potential of a movable electrode in the uncased drill fluid filled borehole and the potential of a fixed electrode at the ground surface (Doll, 1948). The causes of electrical potential differences in boreholes are:

a) Electrochemical Effect - Charge imbalances can be present between the drill mud and formation water, between two dissimilar rock types, between the mud cake and the borehole fluid, and between the mud cake and the formation water (Guyod, 1944).

b) Electrokinetic Effect or Streaming Potential - It is caused by the invasion of borehole fluid into the formation. This can be a significant factor in a permeable formation when the hydrostatic head differences between the fluid in the borehole and in the formation are large, and

c) Ionic Charge Accumulation or Redox Potential - It is a measurement of the ionic charge accumulation between metallic mineral grains and the fluid adjacent to the grains.

The spontaneous potential log can be used to: 1) identify lithology, 2) detect permeable beds, 3) detect boundaries between permeable beds, 4) determine formation water resistivities (R_w), and 5) determine volume of shale (V_{sh}) in a permeable bed (Asquith and Gibson, 1982).

Hilchie (1979) indicates that the effects of borehole diameter and invasion on the SP log are very small. Since the measurement of the change in potential can be caused by a number of different factors the interpretation of an SP log is very subjective and the log is not quantifiable in any realistic way (Digby, 1997).

3.2.2 Resistivity Logs

The resistivity log is a record of the resistivity measured when passing an electric current through a geological formation. Borehole resistivity measurements depend upon the porosity (fracture and pore space), fluid resistivity, and grain resistivity of the rock. Knowledge of the fluid resistivity and the borehole diameter enables the resistivity measurements to be corrected for borehole effects, resulting in resistivity values that are close to the true resistivity of the rocks. A summary of the typical ranges of resistivities of rocks and soils is presented in Figure 2 (Ward, 1990).

In sedimentary rocks, the resistance log generally follows the variations in resistivity of the formations. Shale and clays generally exhibit low values, sandstones have intermediate values, while coal and limestone beds have high values.

Resistivities in igneous and metamorphic rocks are extremely high when compared to resistivities in sedimentary rocks. Their values are commonly tens-of-thousands of ohm-m. Resistivities of igneous and metamorphic rocks can be altered significantly by the presence of metals, the presence of open fractures, and the presence of altered weathered zones.

Resistivity measurements can be used to correlate stratigraphy, identify lithology, estimate texture, and identify depositional facies (Collier, 1989). Quantitatively, resistivity data can be used to calculate water quality (dissolved solid content and hardness), hydraulic conductivity, and porosity (Alger and Harrison, 1987).

A variety of resistivity tools are available. They can be classified into nonfocused electrode tools and focused electrode tools, as listed in Table 2. Because resistivity tools vary widely in design, response, and application, the choice of a resistivity logging suite should be based on the compatibility of tools and borehole conditions (Collier, 1989). Furthermore varying depths of mud filtrate invasion will affect the measurements. Usually three resistivity curves of varying depths of investigation are necessary to insure that the deep resistivity curve is the formation resistivity. A summary of the depth of investigation of various tools are listed in Table 3 (Collier, 1989).

3.2.2.1 Nonfocused Electrode Tools

There are two types of nonfocused electrode tools. They are the Nonfocused Mandrel Electrode tools and the Nonfocused Microelectrode Pad tools.

a) Nonfocused Mandrel Electrode Tools

The limitation of nonfocused tools is that the current direction of the tools is not controlled (Figure 3). Consequently, the current takes the least resistance path, such as the conductive mud or the conductive adjacent beds, rather than the resistive beds that are intended to be measured by the current electrode. The accuracy of the measurement decreases with the increase in the resistivity contrast between the formation, the drill fluid, and the adjacent beds. Since the 1950's, nonfocused electrode tools have been replaced by focused electrode tools in the petroleum industry. But nonfocused tools continue to be used routinely in the groundwater industry due to the fact that they are the least expensive resistivity tool (Collier, 1989). There are three types of nonfocused mandrel electrode tools. They are the Single-point, the Normal, and the Lateral tools.

The Single-point tool is the simplest type of resistivity tool. The electrode A in the borehole is connected to an AC power source (Figure 4). The tool has a very short electrode length and a very shallow depth of investigation (Collier, 1989).

The Normal tool has three electrodes in the borehole (Figure 5). Electrodes A and B are current electrodes, and M and N are measurement electrodes. The Normal tool has a larger depth of investigation than the Single-point tool.

The layout of the Lateral tool is also shown in Figure 5. It consists of 4 electrodes and it has the deepest depth of investigation of all the nonfocused electrode tools.

b) Nonfocused Microelectrode Pad Tools

The Microlog is a pad type resistivity measuring device that primarily detects mudcake. The pad is in contact with the borehole wall and consists of three electrodes spaced one inch apart. The detection of mudcake by the Microlog indicates that invasion has occurred and the formation is permeable (Collier, 1989).

3.2.2.2 Focused Electrode Tools

Focused electrode tools control the current path by the use of auxiliary current electrodes above and below the primary current electrode (Figure 3). This type of tool is a vast improvement over the nonfocused tools. They were developed in response to the need for a resistivity tool that could handle conductive mud (salt mud), thin beds, and highly resistive formations (Collier, 1989).

a) Focused Mandrel Electrode Tools

There are five main types of focused mandrel electrode tools (Collier, 1989). They are the Guard, Point-electrode, Shallow Investigating, Spherically Focusing, and Dual

Focusing Electrode tools. A schematic diagram of the electrode configurations of some of the tools are shown in Figure 6.

The Guard and the Point-electrode tools are used to measure the formation resistivity. The Shallow Investigation tool and the Spherically Focusing tool have a shallow depth of investigation. They are used to measure the resistivity of the invasion zone. By changing the focus of the electrode of the Dual Focusing Electrode tool, the depth of investigation changes. Thus the tool can be used to measure the resistivity of the invasion zone and the resistivity of the formation.

b) Focused Pad Microelectrode Tools

The focused pad microelectrode tools have electrodes mounted in a pad that is forced against the borehole wall. Microlaterolog tool, Proximity tool and Microspherically Focusing tool shown in Figure 7 are typical focused pad microelectrode tools. These devices have a very shallow depth of investigation, and measure the resistivity of the flushed zone (R_{xo}). The Microlaterolog (MLL) was the first focused pad tool developed. The Proximity tool which is more strongly focused than the Microlaterolog, is designed to investigate greater depth. The Microspherically Focusing tool has a depth of investigation of 12 cm-20 cm.

The Dipmeter is a focused microelectrode pad tool. It consists of three micro-resistivity measuring devices located at 120^o intervals around the probe (Roberston Geologging Ltd., 1997). Responses from the three micro-resistivity measurements are correlated to determine the vertical points of intersection of geologic bed boundaries. The dip of the geologic boundaries is computed from the common signatures occurring at different depths on the three micro-resistivity responses. The accuracy of Dipmeter measurements decreases with smaller diameter drill holes.

3.2.3 Induction Logs

The Induction tool consists of one or more transmitting coils that emits high-frequency alternating current of constant intensity which creates an altering electromagnetic field in the formation. In turn this alternating electromagnetic field induces an eddy current flowing in a horizontal ground loop in the formation (Figure 8). The eddy current creates a magnetic field in the formation that induces a voltage in the receiver coils. The received signals are essentially proportional to the formation conductivity, which is the reciprocal of resistivity. An inter-coil spacing of 50 cm gives reasonable vertical resolution for layered formation measurement while maintaining an adequate radial range of investigation (McNeill, 1990).

The Induction tool was introduced in the 1950's. It was developed for boreholes with non-conductive fluids (oil-based mud, air, or foam). It is the only resistivity tool that will work in non-conductive borehole fluid and in non-metallic casing (no resistivity tool works in steel casing).

The induction tool shown in Figure 8 is a simple unfocused two-coil system. To increase the vertical resolution and depth of investigation, and minimise borehole effects, a focused tool can be used. In a focused tool, multiple coils are used to focus the resistivity measurement. A Dual Induction Log (DIL) consists of a deep-reading induction device, and is similar to an induction log. The dual induction focused log measures the invasion zone resistivity and also the flushed zone resistivity.

Induction logging should be used in non-salt-saturated drilling mud to obtain a more accurate value of true formation resistivity. The accuracy of conventional commercial induction logging systems decreases drastically for high resistivity rocks (often exhibiting a 50% error at 100 ohm-m, and a 100% error at 200 ohm-m), and therefore they are virtually useless in igneous and metamorphic rocks.

Focused induction tools provide accurate resistivity values if environmental corrections are applied and if they are used in the appropriate environment (formation resistivity < 100 ohm-m, with borehole diameter less than 12”, and mud not excessively conductive). In other environments, focused electrode logs (Laterologs and Guard Logs) are more appropriate tools (Collier, 1989).

3.3 Electromagnetic Methods

3.3.1 Ground Penetrating Radar (GPR)

Ground penetrating radar is an electromagnetic sounding method that has been developed to aid in the investigation of shallow subsurface objects that have an electrical properties contrast with the surrounding medium. GPR is a relatively new method for investigating shallow geological, engineering and hydrogeological features. It can also be used to identify fracture zones, lithology contrasts, and to map orientation of individual fracture and fracture zones that intersect or do not intersect boreholes. GPR has been applied to detect bedrock fractures at proposed high level nuclear waste disposal sites, and to delineate contaminated groundwater zones (Stevens et al., 1994, & Lane et al., 1994).

GPR operates on the simple principle that electromagnetic waves, emitted from a transmitter antenna, are reflected from targets and detected at another antenna (Figure 9). This method is analogous to seismic reflection method except for the energy source (Cummings, 1990). Most GPR systems use a time-domain pulse system.

The ground resolution is dependent upon: 1) the amplitude and wavelength of the transmitted pulse, 2) the electrical properties and electromagnetic propagation characteristics of the host material, 3) the complexity of the geology, 4) noise from the manmade objects at, or near, the surface, 5) the depth, shape, and size of the target, and 6) the electrical impedance of the target. The higher frequency antennas have greater resolution but also suffer greater attenuation. They are generally restricted to applications requiring very shallow depth of penetration.

The presence of clay in the formation under investigation will cause loss of signal penetration. Olhoeft (1986) estimates that the addition of just 5% montmorillonite clay decreases GPR signal penetration by a factor of 8. Interpretation of the records requires considerable skill because spurious reflections occur. Misidentifying spurious reflections as real reflections results in error in interpretation.

Most conventional borehole radar instruments use dipole antennas as a transmitter and a receiver. They usually operate within a range of 50-100 MHz, achieving a radar range over 10 m. Their limitations are that they are omnidirectional and also their resolution in the near field is not sufficient for purposes such as crack detection.

A new broad-band directional borehole radar has been constructed by Sato and Tanimoto (1992) for three-dimensional radar measurements. A Discone antenna is used as a transmitting antenna for broad-band radiation. The receiving antenna is a micro array antenna mounted on a relatively thick conducting cylinder. By measuring the induced surface current at several points on the conducting cylinder, the incident angle of the incoming reflected wave can be estimated, and the location of the reflector can be calculated.

For crosshole GPR, the electromagnetic waves emitted from the source located in one borehole are measured by the receiver located at another borehole. Crosshole GPR can be used to detect fracture zones and lithological changes between boreholes (Lane et al., 1994).

3.4 Nuclear Methods

3.4.1 Density Logs or Gamma Gamma Logs

The standard density probe contains a low energy Cs137 (or Co60) gamma ray source sheltered from the detector so that received radiation is only via reflection from the formation. Gamma rays emitted by the source are scattered by electrons in the rock, and the gamma radiation measured at the detector is approximately inversely proportional to the electron density of the rocks. By using two detectors, the extraneous effects of the borehole fluid and borehole wall roughness on the density measurements can be compensated for, yielding a computed density that is equal to the bulk density of the formations. There is a current method which uses a side-walled tool with a collimated gamma ray beam which can be used to obtain a bulk density measurement.

Density logs can be used to determine formation bulk density, derive porosity, and identify lithology. Density logs can also be used to detect bed thickness for beds thicker than half the tool spacing. For thinner beds part of the gamma rays will have traveled into the surrounding beds and the reading obtained will not reflect a true reading (Digby, 1997). Simultaneous interpretation of the density log with other types of geophysical logs can be used to interpret variations in the depositional environment, and to determine porosity variations within a lithological unit.

Caving of the borehole wall results in loss of contact between the sonde and the borehole wall and accuracy of the measurement. The measurement is also affected by the existence of low density fluid or mud between the sonde and the formation. The sensitivity of the log decreases with the presence of casing due to increase attenuation of gamma radiation (British Standards Institution, 1988).

Recently a tool with a small gamma radiation source, the Micro-Density tool, which uses a 3 m Ci source was developed (Digby, 1997). Compared to the standard sonde, this tool provides better safety, easier operation and requires less stringent transportation regulations.

3.4.2 Natural Gamma Logs

The natural gamma ray probe utilizes a scintillation detector to measure the natural gamma radiation emitted by the rocks surrounding the borehole. The principal sources of natural gamma radiation in rocks include the uranium and thorium decay series and potassium-40. The highest content of radioactive minerals in sedimentary environments are contained in shale (or mudstones), while low radioactive mineral concentrations are found in sandstone and calcareous rocks. The natural gamma ray log response in igneous and metamorphic rocks increases with the felsic mineral content. The natural gamma ray response is usually enhanced in porphyritic zones, and altered rocks. Thus natural gamma log is used as the standard lithological log and for correlation purposes.

The occurrence of a significant quantity of non-potassium clays, and the radiation from certain minerals such as k-micas and k-feldspars in sandstones may cause misinterpretation of the results. Thus the interpretation of natural gamma logs should be correlated with driller's logs or core samples.

The nature gamma log response decreases with increase in borehole diameter. The presence of casing and grout will also affect the sensitivity of the measurement.

The quality of natural gamma log has improved with recent improvements in signal transmission and detector efficiency, modern digital logging system, close sampling intervals (preferably 1 cm) and a good knowledge on data interpretation. The natural gamma log can be used universally, giving results above and below water tables and from within plastic or metal casing. Costs can be very low, and equipment can be operated by the geologist or drillers with little specific training or licensing.

3.4.3 Gamma Spectroscopy Logs

The natural gamma spectroscopy log provides detailed analysis of the energies of natural occurring gamma radiation from the formation surrounding a borehole. The discrimination of the different gamma ray energy levels can be used to determine the relative quantities of different natural radioisotopes. For example the identification of the gamma rays from Uranium and Thorium decay as opposed to Potassium decay can be important for determining rock type.

Some of the modern probes can be preset to five energy windows to determine concentrations of potassium, uranium and thorium as continuous measurements. Alternatively, it can function in a stationary mode to identify other spectral peaks (Robertson Geologging Ltd., 1997).

3.4.4 Neutron Neutron Logs

The neutron neutron geophysical logging probe consists of a low energy neutron source (e.g. Am-Be) and one, or two neutron detectors, separated by several centimeters. The neutron log utilizes the principle that neutrons emitted from a source on the probe are scattered and absorbed within the rock, and neutrons measured by a detector on the probe indicate the nature of the neutron absorbers in the rock formation. The primary moderator of neutrons in the earth is the hydrogen atoms contained in water molecules. Therefore, the neutron neutron log response is primary an indicator of the water content of the rock and is an indirect indicator of the porosity of the rock. The log can be used to delineate porous formations.

When other sources of hydrogen such as hydrocarbons are present, corrections to the logs are required. With the assumed porosity of the rocks, hydrocarbon contaminant in the rocks can be detected. The log is very effective at indicating structural changes, including voids, since most logs reflect increased counts with a decrease in porosity.

The presence of casing reduces the log response by positioning the sonde away from the formation. Plastic casing reduces the response due to high chlorine content (British Standards Institution, 1988). The presence of mud cake between the sonde and the formation also affects the measurement.

3.5 Acoustic Methods

3.5.1 Acoustic Borehole Televiewer

The acoustic borehole televiewer was first introduced in 1970 (Zemanek et al., 1970). It is used for imaging lithostratigraphic features and for measuring the orientation and distribution of fractures as well as the orientation and width of stress-induced borehole wall breakouts (Barton et al., 1991). This tool is now available in a size and configuration suitable for most drilling conditions. With increased shots per rotation of the transmitter and a smaller vertical sampling interval, it can provide information even in poor borehole conditions.

The acoustic borehole televiewer probes utilize a piezoelectric transducer that strobes the borehole wall with bursts of ultrasonic energy. The piezoelectric transmitter is also used as the detector of ultrasonic energy. The received signal is the energy reflected from the borehole wall, which has an intensity that is a function of the physical properties of the borehole wall. The acoustic borehole televiewer is a very high frequency logging device that can provide a 360^{o} ultrasonic picture of the borehole wall. A magnetometer is used to determine the rotational position of the logging device. The tilt of the tool is monitored by two inclinometers, and an accelerometer provides continuous data on tool speed. Resolution depends on the hole size and logging speed. The acoustic borehole televiewer typically will provide horizontal resolution of a few millimeters and a one centimeter vertical resolution in a 30.5 cm (12 in) diameter hole. The intensity of the reflected signals is high for smooth surfaces in hard rocks, and low for irregular surfaces (i.e. fracturing).

The acoustic borehole televiewer log represents the borehole wall as if it was split vertically and laid flat. Software have been developed for data interpretation. The program provides an integrated environment for analysing borehole shape and features where images are displayed in false color on a graphics screen and are manipulated by graphics mouse and keyboard commands. The advantages of interactive data analysis is that it gives the geophysicist the ability to (1) interactively manipulate the data to obtain an optimal view of a particular feature, (2) look at the same data interval simultaneously from a variety of perspectives and (3) make decisions as the analysis proceeds.

3.6 Seismic Wave Methods

Seismic wave velocity is one of the important parameters for geotechnical and geophysical site characterisation (Imai & Tonouchi, 1982). Both compression wave (P-wave) and shear wave (S-wave) velocities can be used to calculate the basic elastic material properties, such as shear modulus and bulk modulus, of rock and soil. A summary of the typical seismic velocity values of rocks and soils is listed in Table 4. These parameters are indispensable elements for evaluating seismic ground motion (Kaneko et al., 1990). Furthermore the seismic wave velocities can be used to delineate some type of fracture zones in rock. The seismic velocities of different soils in Japan are summarised in Figure 10. The relationships between shear wave velocity and N-values from standard penetration tests of these soils are shown in Figure 11.

The surface refraction and reflection methods are the most common methods used for the determination of seismic wave velocities. With the advent in borehole receivers and the development of shear wave sources, borehole seismic wave velocity logging methods have now become more practical (Kaneko et al., 1990). Plank hammering is a very simple method for the generation of the seismic source. This yields nicely defined shear waves which can be detected by downhole receivers which are an effective means for downhole shear wave velocity measurement. Using these receivers, it is possible to log waves produced by surface plank hammering to depths of hundreds of meters.

The borehole methods for seismic velocity measurements are summarized in Table 5 (Kaneko et al., 1990). These methods are the downhole seismic, uphole seismic, crosshole seismic, and suspension seismic methods (ISRM, 1988). Because both compression wave (P-wave) and shear wave (S-wave) can be measured simultaneously, these method are sometimes referred to as PS logging.

3.6.1 Downhole Seismic Method

The downhole method is the most commonly used PS logging method. The receiver contains three component geophones (2 horizontal and one vertical) firmly clamped to the borehole wall during each measurement. Surface hammering is usually used as the seismic source. Two shear wave records are obtained by striking the plank horizontally in opposite directions. Thus the shear wave records obtained have reversed polarity. The P-wave record is obtained by measuring the P-wave generated by dropping a weight on the ground surface.

From the P-wave and S-wave records the compression and shear wave velocities can be determined. The elastic properties (Poissons ratio, Young's modulus) of the layer can be calculated. The depth of measurement is limited to 100 to 200 m, and also when a soft layer is overlain by a hard layer, the soft layer may not be measured (Kaneko et al., 1990).

3.6.2 Uphole Seismic Method

In the uphole method, one or more receivers are located on the ground surface and the seismic source is successively positioned at different depths in the borehole.

3.6.3 Suspension PS Logging Method

The most recently developed seismic wave velocities logging method to reach the stage of practical use is suspension PS logging, which uses a downhole probe containing both a seismic source and receivers. The suspension PS method and instrumentation system were originally developed in the mid-1970's by researchers at the Oyo Corporation of Japan (Kaneko et al., 1990) to satisfy the need for a reliable method to measure seismic shear-wave velocity in deep, uncased boreholes. Suspension PS logging can be used to measure shear wave velocity down to depths of over 1 000 m.

Figure 12 shows a schematic of the suspension PS velocity method. The logging system consists of a non-symmetric seismic source and two receivers built into a single probe. The source and receivers spacing is 2 to 3 m and the logging frequency ranges from 100 to 1 000 Hz. The source is acoustically decoupled from the receivers by an isolator that attenuates the direct energy through the probe. The source is a horizontal solenoid which produces a pressure wave in the borehole fluid. At the borehole wall, this pressure wave is converted to seismic body waves (P and S), which travel radially from the borehole wall. At each sensor location, these body waves are converted back to pressure waves in the borehole fluid and detected by the geophones. The seismic wave velocities are calculated from the difference between the arrival time recorded by the two receivers spaced 1 m apart.

This method directly determines the average seismic wave velocity of a one meter thick segment of soil column surrounding the borehole. Higher resolution can be obtained by measuring the velocities in overlapping 1 meter depth segments. A special analysis routine called Simultaneous Iterative Reconstruction Technique (SIRT) performs a least-squares inversion on the overlapping average velocities to calculate the velocities within the overlap intervals (Kaneko et al., 1990). Overlapping measurements with an 80 cm overlap combined with SIRT provides a 20 cm depth resolution.

This method is intended for use in uncased boreholes filled with drilling mud or water. It can be used in cased boreholes if the coupling between casing and surrounding soil or rock is good. However, steel casing often creates problems because large amplitude, high velocity tube waves arrive before the seismic waves. The tube wave problem is smaller with plastic (PVC) casing.

3.6.4 Crosshole Seismic Method

In the crosshole seismic measurements, the source and the receivers are located in different boreholes (Cartmell et al., 1994). This method has become a well established method for site investigation over the past 25 years (McCann et al., 1975).

The rock or soil properties between the boreholes can be determined without having to drill additional expensive boreholes and transport samples to the laboratory. Surveys can be conducted where accessibility is restricted for conventional surface geophysics (i.e. in developed areas), and can also be used to justify inter-borehole interpretation.

The conventional crosshole seismic method provides average seismic wave velocities between the two boreholes. In inhomogeneous rock/soil strata, seismic tomography can be used to delineate the inhomogeneity. By tomographic processing, derived velocity information is calculated within cells in the discretised cross-section. An inversion algorithm can be used to construct the P- and S- wave velocity tomograms. The algorithm is based either on two dimensional ray tracing and simple back projection, or a simultaneous iterative reconstruction technique. An example of the application of crosshole seismic tomography for characterising the rock mass in an underground stope was described by Jessop et al. (1992).

3.7 Optical Methods

3.7.1 Closed Circuit Television (CCTV)

The recent generation of borehole CCTV is equipped with cameras with a range of options, including lighting and remote control of iris and focus. By changing the lens units, either axial or radial views of the borehole can be monitored. In an uncased borehole, orientation is usually provided by a compass viewed by the camera. For a borehole with metal casing, a gyroscope is required to provide the necessary orientation information.

Recently a new camera which is capable of viewing in any direction has been developed. The camera is equipped with a swiveling head. The swiveling head is cased in a hemispherical glass dome.

The use of borehole CCTV for the identification/interpretation of lithological and general geological features is strongly dependent on the borehole environment. Under adverse conditions, such as boreholes with high turbidity fluid or smeared walls, the image obtained will be difficult to interpret. The interpretation of the image is particularly difficult because the colour image frequently looks unnatural due to the lighting system.

4. DOWNHOLE GEOPHYSICAL METHODS PRACTICE IN HONG KONG

4.1 Introduction

In Hong Kong downhole geophysical and optical methods are not commonly used in ground investigation. Among the various downhole geophysical methods, the downhole seismic and acoustic borehole televiewer methods are used most often. The downhole seismic method was used mainly to determine shear zones in rocks and to map cavities within buried marble, and the acoustic borehole televiewer method was used to delineate fractures. Eight applications of downhole geophysical methods in Hong Kong are summarised and presented in the following sections.

4.2 Crosshole Seismic Tomographic Survey - Tsing Ma Bridge Tunnel Anchorage (EGS, 1992b)

The Tsing Ma suspension bridge required a massive anchorage on Tsing Yi Island. As part of the site investigation study for the anchorage site, a seismic tomographic survey was undertaken in December of 1991. The objectives of the survey were to define and delineate any areas of geological variance, such as faulted and fractured zones.

The site is located in the north west corner of Tsing Yi Island. The geological map indicated that the site consists of feldsparphyric rhyolite and coarse ash crystal tuff with north-west to south-east trending igneous dykes. Tomographic surveys were conducted in three boreholes located at or near the top of a large cut slope which was still under construction at the time of the survey. The boreholes were drilled and lined with flush coupled plastic liners. The annulus space between the liners and the borehole wall was filled with cement grout.

An air gun was used to provide the seismic source, and multi-element hydrophones were used as receivers. By firing the air gun at 5 m intervals in one borehole and recording the travel time with the receivers in the other two boreholes, the seismic velocities of the formation between the boreholes were calculated. The survey was repeated by exchanging the locations between the source and the receivers. During the survey, the boreholes were filled with water, and kept full until all of the measurements had been taken.

The calculated seismic velocities increase with depth from about 4.0 m/ms near the top of the sections to approximately 5.0 m/ms near the base of the sections.

The empirical relationship between weathered states of volcanic and granitic rocks of Hong Kong and seismic velocities developed by EGS (EGS, 1992b) is:

State of Weathering	Weathering Grade	Bulk Velocity (m/ms)
Soil and Colluvium	VI	0.3 - 0.6
Completely weathered rock	V	0.3 - 0.8
Highly weathered rock	IV	0.8 - 3.0
Moderately weathered rock	III	3.0 - 4.0
Slightly weathered to fresh rock	II to I	4.0 or more

Based on the calculated seismic velocities the rock mass between the boreholes is classified as mostly slightly weathered to fresh.

The results of the survey were considered to be of a low to medium quality (EGS, 1992b). Such quality could have been caused by poor grouting of the annulus space between the liners and borehole, and the noise from the nearby, 24-hours operating, construction sites. Considering the data quality, features smaller than 5 m thick (in the direction of the sections) would not have been detected by the survey (EGS, 1992b).

4.3 Downhole Seismic Survey - Tak Yi Street, Sha Tin - (Wong et al., 1997)

The downhole vertical seismic profiling method was used in a borehole to measure the shear wave velocities of a site in Sha Tin. The site comprises a fill layer underlain by a layer of marine clay. The marine clay overlies a layer of alluvium, below which is slightly decomposed granite.

The seismic source was generated by a 10 kg hammer impacting on the ground surface adjacent to the borehole. A downhole receiver was anchored to the borehole wall with an inflatable rubber packer, and the other receiver was placed on the ground surface 3 m from the borehole.

A comparison between the shear wave velocities determined by seismic survey and the shear wave velocities estimated from SPT data is presented in Table 6. For the fill and the decomposed granite, the shear wave velocities determined are higher than those calculated from the SPT data. For the marine clay, the shear wave velocities determined are lower than those calculated from the SPT data.

4.4 Crosshole Seismic Tomography Survey - Ma On Shan (EGS, 1992a)

Boreholes drilled for a proposed housing estate at Ma On Shan encountered karst features within marble formations at and below foundation level (EGS, 1992a). To detect the presence of these features within these three housing blocks, a crosshole seismic investigation (P wave) was undertaken in 1992.

Boreholes drilled in the area indicate the bedrock (comprising granite and limestone/marble) is approximately 40 m to 50 m below ground surface.

Upon completion of drilling, the boreholes were lined with flush coupled plastic liners. The annulus space between the liners and the borehole wall was then filled with cement grout to a level at least 1 m above the solid geology. The verticality of each borehole was measured with borehole inclinometer so that the actual borehole separation could be calculated.

An air gun was used to provide the seismic source, and multi-element hydrophones were used as receivers. The spacing between receivers was maintained constant throughout the investigation. By firing the air gun at 2 m intervals in one borehole and recording the travel time with the receivers in another borehole, the seismic velocities of the formation between the boreholes were determined. During the survey, the boreholes were filled with water, and kept full until all the measurements had been taken. The recorded signal to noise ratios were sufficiently large. The ambient seismic noise generally did not present a problem.

The empirical relationship between weathered states of marble of Hong Kong and seismic velocities developed by EGS (EGS, 1992a) is:

Material/Weathering State	Bulk Velocity (m/ms)
Saturated sediments (cavity infill)	1.0 - 2.0
Highly weathered rock	2.0 - 3.0
Moderately weathered rock	3.0 - 4.0
Slightly weathered to fresh rock	>4.0

The calculated seismic velocities along three profiles were in the range 2.0 to 7.0 m/ms. By comparing the borehole logs and the rock mass profiles interpreted from the calculated seismic velocities, it was concluded that no cavities could be interpreted solely based on the evidence presented in the seismic velocity profiles (EGS, 1992a).

4.5 Suspension PS Logging - PWCL (Kwong, 1998)

Three suspension PS logging tests were carried out in three boreholes at a site near the PWCL, Kowloon Bay. The objectives of the study were: 1) to investigate the technical feasibility of carrying suspension PS logging in Hong Kong for site characterisation, and 2) to determine the shear stiffness of the formation at small strain (<0.001%).

The site is located to the southeast of the Public Works Central Laboratory (PWCL). It comprises a fill layer of about 6 m to 16 m thick which is underlain by a layer of marine clay of about 15 m thick. The marine clay overlies a layer of 6 m to 13 m thick alluvium. Below the alluvium is the partially weathered granite of 10 m to 14 m thick. The partially weathered granite generally comprises a matrix of extremely weak, yellowish brown spotted white completely decomposed medium-grained granite and very weak, highly decomposed medium-grained granite.

The logging method and the instrumentation system used were developed by Oyo Corporation, Japan. The borehole probe consists of a seismic source and two receivers. The seismic source is triggered by a solenoid hammer. The hammer hits the borehole wall through the drilling mud and generates the seismic waves. Depending on the stiffness of the ground, the frequency of the shear wave generated by the source is 100 to 1 000 Hz. Each receiver contains two geophones located 1 m apart. One geophone is located vertically for recording the compressive wave, and the other is located horizontally for recording the shear wave.

The three boreholes were supported by steel casings which had to be extracted in stages during suspension PS logging. Local collapse was experienced in two boreholes while the casings were being withdrawn, and which resulted in loss of data. The measurements started from the bottom of each borehole and progressed upward.

The P and S wave velocity profiles along borehole BF6 are presented in Figure 13. The calculated shear stiffness, G_o, and the SPT N value profiles are plotted in Figure 14 (Kwong, 1998). These two figures show that the PS logging method is applicable for determining P and S waves velocity profiles and shear stiffness of weathered granite.

4.6 Acoustic Borehole Televiewer Survey - Hing Wah Estate, Chai Wan Ground Investigation (Bachy Soletanche Group, 1997)

The ground investigations at the Hing Wah Estate site consisted of 10 drillholes, five trial pits and three slope strippings. Borehole televiewer surveys were carried out in eight of the ten boreholes by Robertson Geologging Ltd.

According to the 1:20 000 HGM 20 series geological map of Hong Kong Sheet 11, the site is underlain by fine- to medium-grained granite. The findings of the ground investigation are generally in accordance with the geological map. Impression packer surveys (comprising of one hundred and twelve individual tests in total) were undertaken at predetermined depths in nine drillholes (Bachy Soletanche Group, 1997).

The boreholes were drilled using skid mounted rotary equipment with air foam flushing. The holes were cased from the ground surface to the moderately to slightly decomposed granite. Of the eight boreholes surveyed by geophysical methods, two (BH6 and BH11) were surveyed with a full suite of tests (acoustic borehole televiewer, 4-arm Dipmeter, natural gamma, temperature, and 3-arm Caliper), whilst standard interpretive assessment was made in the case of the remaining six boreholes. The acoustic borehole televiewer used was equipped with 2-axis orientation package and non-magnetic centralisers. The logging speed was a nominal 2 m/min. Caliper (3-arm) logs were also conducted in all boreholes to provide data for control and an aid to interpretation. Since neither the Dipmeter nor acoustic borehole televiewer are able to work in dry boreholes, or above the water level, the holes were artificially charged with fresh water immediately before logging.

Detailed data interpretation for BH6 and BH11 were conducted. The results from the four-arm Dipmeter and the acoustic borehole televiewer do not correlate closely. The explanation was that the two instruments were measuring different formation parameters. The acoustic borehole televiewer is able to "see" features which do not necessarily result in resistivity change in the formation, and features with very high dip angle may not be resolved at all by the Dipmeter.

In the report (Bachy Soletanche Group, 1997) the contractor states that since the impression packer method is always subject to errors of positioning and orientation, no comparison between the impression packer logs and the acoustic borehole televiewer logs was carried out.

4.7 Acoustic Borehole Televiewer Survey - Tuen Mun Road (Maunsell Consultants Asia Ltd., 1997)

The supplementary site investigation work is for the design and construction of the Tuen Mun Road widening at Tai Lam section.

Both vertical and inclined drillholes using triple tube coring techniques were used to obtain cores in order to evaluate the characteristics and locations of all critical weak zones. During drilling, single packer, falling head hydraulic conductivity testing were performed when fracture zones were encountered. Upon completion of the borehole drilling, impression packer tests and acoustic televiewer surveys were used to supplement existing structural discontinuity information. Ten boreholes were surveyed with both impression packer and acoustic borehole televiewer.

In this study, the acoustic borehole televiewer results have been disregarded by the consultant owing to the inconsistent correlation with the impression packer results. Principally this lack of correlation relates to errors in the acoustic borehole televiewer orientation data which may be attributable to magnetic 'drift' in the compass attached to the televiewer orientator, or could result from inaccurate referencing to magnetic datum for the individual holes (Maunsell Consultants Asia Ltd. 1998).

4.8 Borehole Logging Trial - Yuen Long (PW7/2/20.35)

A field trial was carried out in the Yuen Long Scheduled Area to evaluate the applicability of natural gamma, self potential and single point resistivity logging system to delineate the complex geology which consists of marble, meta-sediments and metamorphosed volcanic rock intruded by granite.

The trial was carried out by EGS using an EG&G Mount Sopris Model II logging system. Twenty boreholes were logged. No useful information was obtained from the trials other than that which could be gained from the borehole logs (Koor, 1997).

4.9 Downhole Electromagnetic Wave Survey - Site YLTL464, Yuen Long (Yi, 1989)

The site is located at the junction of Kau Yuk Road and Tai Tong Road, Yuen Long. During foundation investigation karst was found. The objectives of the study were: 1) to determine the distribution of cavities, fragmented marble, dissolution and perfect marble in the northern part of the site, and 2) to determine the continuity of marble in holes and the interface between marbles and completely decomposed rock in the southern part of the site.

Downhole electromagnetic wave survey and crosshole electromagnetic wave survey were conducted in 9 boreholes. These methods were selected over electrical, seismic and sonic methods because of the interference of the electrical noise generated by passing by vehicles.

The apparent attenuation coefficient of the marble in the site was about 2 dB/m and the host rock was about 6d B/m. The JWQ-3A single and double borehole electromagnetic wave system was used in the survey. The operating frequency used was 2 MHz.

In Figure 15, the borehole log and the interpreted ground profiles along borehole AF6 are plotted. This figure shows reasonable comparison between the borehole log and the survey results.

4.10 Discussion

The results of the review of previous local practice show that:

1. The resolution of the downhole seismic and the electromagnetic methods reviewed are too coarse to be used to detect thin clay seams in saprolite.

2. The suspension PS logging method is applicable for determining P and S wave velocity profiles and small strain shear stiffness of weathered granite.

3. Two cases using acoustic borehole televiewer method were reviewed. For both cases, the results obtained by the borehole televiewer method were different from those results obtained by the impression packer method. One contractor claimed that the difference was due to the magnetic ‘drift’ in the compass attached to the televiewer orientator or could result from inaccurate referencing to magnetic datum for the individual holes. The other contractor claimed success of the acoustic borehole televiewer method and discarded the impression packer results based on the reason that the impression packer method is always subject to errors of positioning and orientation. None of the contractors has tried to substantiate their claims by comparing the acoustic borehole televiewer results and the impression packer results to the rock core samples.

4. Since the resolution of the acoustic borehole televiewer method is high, its capability to detect clay seams should be further investigated.

5. PRELIMINARY DOWNHOLE GEOPHYSICAL METHODS SELECTION

5.1 Literature Review Results

The results of the literature review are summarised as follows:

a) Downhole geophysical and optical methods are not commonly used in Hong Kong for ground investigation. In view of the recent rapid development in geophysical and optical equipment, and advancement in data logging technologies, the application of modern downhole geophysical and optical methods to Hong Kong conditions should be explored further.

b) Most of the experience revealed was from the petroleum, mining, and groundwater industries.

c) Methods are available to detect clay layers. However, the thickness of clay layers being detected by these methods are in the range of meters.

d) The resolution of most of the methods revealed depends on the borehole wall conditions. For example, wall collapse may create problems for some of the methods which are sensitive to borehole diameter, and also for other methods which require good contact between the sonde and borehole wall.

e) No record can be found on the specific application of downhole geophysical methods to detect clay seams in saprolite, and

f) Suspension P-S method has been successfully used to determine the small strain stiffness properties of soils and rocks in Japan.

Based on the results of the literature review, relevant downhole geophysical methods that can be used to detect clay zones are compiled in Table 7. This table provides information for the preliminary selection of downhole geophysical methods for future evaluation.

5.2 Method Selection Criteria

From the results of the literature review the following criteria are established for the selection and evaluation of downhole geophysical and optical methods for ground investigation in Hong Kong:

a) The methods should have the capability to detect the properties contrast between the clay seam and the weathered rock adjacent to the clay seam. The physical properties, such as electrical, elastic, and seismic velocity of the weathered rock and clay seam should be determined and used in the final selection of downhole geophysical methods.

b) The methods should have the required vertical resolution. For this study, the thickness of the kaolin seams typically varies from a few millimeters to hundreds of millimeters. Thus some of the methods listed in Table 7 may not have the required resolution.

c) The effect of borehole environment on the applicability of the downhole geophysical methods should be considered in the method selection process. For example electrical methods are not applicable in steel cased borehole. Caving of the borehole wall will change the diameter of the borehole, and also increase the roughness of the borehole wall. It is revealed that the accuracy of most of the methods depends on the borehole wall roughness and borehole diameter.

d) Local regulatory constraints should be considered. For example the gamma-gamma and the neutron-neutron methods use active nuclear sources, a license is required to operate them, and local regulations may prohibit their use in uncased holes. Because of all these regulatory constraints, these methods may be less attractive for use in Hong Kong.

e) The cost and availability of equipment should also be considered in the method selection process.

5.3 Borehole Environment and Preliminary Downhole Geophysical Method Selection

The results of Phase 2 of the *Assessment of Geological Features Related to Recent Landslides in Volcanic Rocks of Hong Kong Study* showed that kaolin is commonly found in two locations within the ground profile. They are:

I) within the PW0/30 rock mass weathering zone (of predominantly Grades IV and V materials) either as infillings of relict joints or more dispersed as veinlets within the weathered rock mass, and also concentrated at and parallel to the often abrupt and planar weathering front in fine grained volcanic rocks as seams or lenses, and

II) along weathered sheeting joints within the predominantly unweathered rock mass.

For simplicity, the ground is ideally subdivided into two regions as shown in Figure 16. The ground in region I is unstable, and requires either casing or drilling mud to keep the borehole open. The ground in region II is stable, and requires no casing to stabilise the hole. Thus in a cased hole environment, the borehole wall along region I will be lined with casing. In an uncased hole environment, both regions I and II will be filled with drilling mud.

Based on the results of the literature review, and the general understanding of the distribution of clay seams, a preliminary list of downhole geophysical methods that are suitable for this study under the cased hole and uncased hole scenarios are summarised in Table 8.

6. CONCLUSIONS

It is important to note that the preliminary list of downhole geophysical methods compiled in Table 8 is based on experience mostly from the petroleum, mining, and groundwater industries. For each method detailed information concerning the availability of equipment, equipment specifications, and past experience is being sought from equipment manufacturers, geophysicists, and geophysics contractors. Once this information is obtained and synthesized, a final list of downhole geophysical methods will be established for future evaluation.

Furthermore, geophysicist, equipment manufacturers, and geophysics contractors are being contacted to obtain up-to-date information on the development of innovative downhole geophysical methods and equipment. All relevant new methods and equipment will be included in the final method selection process.

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Table 1 - Downhole Geophysical Techniques - Summary of Case Histories
(Sheet 1 of 6)

Author	Objective of Survey	Geophysical Method	Remarks
McNeil, 1990	Use induction logger to log conductivity and lithology in 2 monitoring wells.	Induction logger	Successful.
Collier, 1992	Evaluate an aquifer in southwest Texas.	Seismic, Gamma	Geophysical method show high porosity value. Pumping test show low rate of water production. Petrography analysis reveal that the rock has high total porosity and very low effective porosity. Successful.
Zhang, 1990	Exploration for subway construction in Shanghai use crosshole seismic method. The material is unconsolidated sediments.	Crosshole seismic	Successful. Discussion on the effect of noise and buried manmade structures is given.
Crowder et al. 1991	4 cases:		
	1) Use full waveform seismic logs to delineate lithology and permeability of fluvial sediments.	Resistivity, natural gamma, seismic	Resistivity and natural gamma logs failed to identify the features.
	2) Use full waveform seismic logs to determine geological contacts.	Natural gamma, resistivity, seismic	Natural gamma and resistivity failed. Seismic log results confirmed by cores.
	3) Delineate fracture zones with variable permeability with fullwave seismic logs.	Seismic	Good comparison between seismic test results, and field permeability test and cone test results.
	4) Delineate competent, weathered and fractured rock.	Seismic	Good comparison with core data.
Jessop et al., 1992	Assessment of crosshole seismic tomography to detect fractured rock mass at the Colorado School of Mines' experimental mine.	Crosshole seismic tomography	The effectiveness of the tomography method was corroborated by noting that low velocity zones occurred where water was lost in boreholes.
Mwenifambo, 1993	Crosshole characterisation of fractured permeable sandstone by high resolution temperature logs. 5 wells. 4 at 25ft square 1 at centre. By injecting steam, the temperature logs identified the location of interconnected fracture zone.	Temperature log	Good results.

Table 1 - Downhole Geophysical Techniques - Summary of Case Histories
(Sheet 2 of 6)

Samvelson et al., 1994	Use of crosshole seismic measurements and gamma log to evaluate the seismic hazards in Southern and Central Indiana. The holes were PVC grouted monitoring holes. The formation is unconsolidated materials deposited by glacial, glacial-fluvial and fluvial processes during the Quaternary.	1 GS Widco Gamma logging equipment Seismic log	The use of gamma logs in the downhole velocity studies have been found to be very cost effective means. Particularly, the gamma logs can be used to identify layer boundaries within a column where significant acoustic contrasts may occur. Results are good.
Nigbor & Imai, 1994	Several deep (>200m) boreholes were drilled & logged as part of a seismic study of the Golden Gate Bridge. Geological profile consists of many fractured and tilted layers of various granitic and metamorphic rock.	Suspension PS	Excellence agreement between suspension PS and downhole methods. Seismic velocity ranged from 1200 to 2800 m/s.
	Bay Bridge Toll Pass soft bay mud. (150m deep hole) velocity 230-1400 m/s.	Suspension PS	No comparison of results. no measurement at the top 13 m due to casing.
	Savannah River Plant. As part of a study of an ancient earthquake fault. Horizontally stratified and unconsolidated sand, clay, limestone and gravel. P-wave 60-1000 m/s.	Suspension PS	Previous measurement using downhole seismic method limited to 100m depth because of high damping. Agree well with downhole seismic results.
Mack, 1994	Electromagnetic-induction and natural gamma borehole logs were used to delineate the vertical extent of contamination in groundwater at the former plating facility, west of Merricmack River. Specific conductance of groundwater is 300 µs/cm (microsiemen) the contaminated plume had specific conductance of 1000 µs/cm. The soil is glaciolacustrine sediments.	Electromagnetic log & natural gamma log	The plume were identified and checked with groundwater samples. Gamma identified the clayey layers confirmed with borehole logs.

Table 1 - Downhole Geophysical Techniques - Summary of Case Histories (Sheet 3 of 6)

Bauman et al., 1994	Application of electromagnetic (EM) logging to identify permeable zones 4 cases.		
	1) Rocky Mountain Foothills sour gas plant. Geology of the site consists of folded and faulted clastic deposits of Tertiary bedrock, overlain by about 5m of Quaternary deposits of silt till and gravel.	Electromagnetic log Geonics EM39	Identified fractured zones in an otherwise homogeneous cemented sandstone aquifer.
	2) To establish the connectedness of a fracture between 2 monitoring wells.	Electromagnetic log Geonics EM39	Successful.
	3) delineate multiple aquifers in southern California	Electromagnetic log Geonics EM39	Successful.
	4) decommissioned sweet gas plant. To delineate permeable layers/zones of contaminant migration.	Electromagnetic log Geonics EM39	Successful.
Obo & Tornqvist, 1995	To evaluate the accuracy & repeatability of the monitoring of changes in moisture content & density of soils.	PPGR &VPGR, natural gamma, gamma gamma, neutron neutron	
	1) Kokemaenjoki River, Finland. Field repeatability test of radiometric logs from Feb 91 to Jun 92.		Successful.
	2) Uljua Dam Monitoring the dissipation of pore pressure in core.		Successful.
	3) Long term consolidation settlement of railway track in Tottola, Finland.		Successful.
	4) Diagnostics of bearing capacity failure in silt and silty moraine layers.		Successful, disturbed zone identified.

Table 1 - Downhole Geophysical Techniques - Summary of Case Histories (Sheet 4 of 6)

Busby & Peart, 1994	Use azimuthal resistivity and seismic measurements for the determination of concealed sub-vertical fracture orientation. Apply on chalk & limestone at several sites in Southern and Eastern England. 1) Kensworth Chalk Quarry Site. 2) Longwood Limestone Quarry.	Apparent resistivity carried out with 4 electrode co-linear array and seismic refraction where geophones and shots were again co-linear	3 principal fracture/joint sets were recognized and closely matched with 2 of the 3 joint sets from field data. Seismic data poor quality due to excessive plant & traffic noise. Result neglected.
Crowder & Pedler, 1995	Evaluate the complex geologic and hydrologic conditions in basaltic environment - Schofield Army Barracks, Oahu, Hawaii. 4 monitoring well and 1 existing water-supply well.	Caliper, acoustic televiewer, borehole video, neutron, natural gamma, gamma-gamma, spinner flowmeter, fluid electrical conductivity, oxidation-reduction potential, temperature, pH, electrical logs.	Provided information regarding discontinuities (i.e. frequency, orientation, and type of fractures, geological features (i.e. lithologic types, bedding surfaces and basalt textures.) The borehole geophysical logs confirmed the geologic conditions expected to be encountered in this basaltic environment.
Yearsley et al., 1990	To evaluate the continuity of the cement/bentonite grout, position and extent of the bentonite seal, and location of the sand pack of a monitoring well.	Density logs with dual detector (gamma-gamma) and single detector sonde	Borehole density logging is an effective technique above or below fluid level in PVC-cased monitoring wells. Results from laboratory experiments are used to support interpretation of field measurements.
Cartmell et al., 1994	Use crosshole seismic technique to determine seismic velocity and the dynamic elastic properties within the vicinity of the boreholes for a hydro-electric dam project in the Lesotho Highland, South Africa.	Crosshole tomography	5 m^3 air gun pressured to 200 psi used as source. 12 borehole pairs surveyed. Two were unable because of poor data quality. Two other did not provide S-wave velocity because of tube wave caused by air gun interference prevented S-wave's arrival identification.

Table 1 - Downhole Geophysical Techniques - Summary of Case Histories (Sheet 5 of 6)

Sirles & Viksue, 1990	6 case studies on application of crosshole seismic method.		
	1) Casitas Dam - To study dynamic analysis and site liquefaction potential of loose to medium silt and sand.	Crosshole Seismic	Good comparison with SPT results.
	2) Senator Wash Dam - to identify liquefaction potential of uncemented sand & gravel. The bed rock is highly fractured andesite.	Crosshole Seismic	No comparison.
	3) Cold Spring Dam - to identify liquefaction potential of loose sand and dense gravel.	Crosshole Seismic	Compare well with SPT results.
	4) Rye Patch Dam - to identify liquefaction potential of alluvial deposits of sand, silt and clay.	Crosshole Seismic	No comparison.
	5) Steinaker Dam - to identify liquefaction potential of poorly graded fine sand.	Crosshole Seismic	Both shear wave velocity & SPT results identified loose sand layer which has high liquefaction potential.
	6) Jackson Lake Dam - to evaluate the liquefaction potential of alluvial and fluvio-lacastrine deposits consists of silt, sand & gravel with clay lenses.	Crosshole Seismic	Increased in shear wave velocity due to dynamic compaction treatment of the foundation.
Barton et al., 1991	To map fracture and borehole breakout in the Cazon Paso Research well in southern California, and also at the KTB ultra deep well site in Germany.	BHTV, Acoustic borehole televiewer	Good results were obtained.

Table 1 - Downhole Geophysical Techniques - Summary of Case Histories
(Sheet 6 of 6)

Lane et al., 1994	To map fractures and lithologic in 3 sites. 1)Barrington, New Hampshire Bedrock consists of quartz monzorite, granite underlie 3 to 5 m of sandy to clayey till. The fractured bedrock aquifer contaminated by volatile organic compounds. Single-hole radar were conducted in 4 wells. 2)Milliville, Massachusetts Bedrock consists of quartz-diorite gneiss & amphibolite underlies 2 to 6 m of compacted till. Fracture bedrock aquifer contaminated by DNAPL's and VOC's. 2 cross-hole radar surveys were conducted. 3) Byron, Illinois Bedrock consists of dolomite interbedded with shale underlies 3 m of glacial drift and till. Fractured bedrock aquifer contaminated by VOC's, cyanide & heavy metals. 3 cross-hole and 5 single-hole radar surveys were conducted.	Borehole Radar with directional receiver- Single-hole and cross-hole	Successful in identifying fractures zones up to 40 m from wells and the results are confirmed by aquifer tests and other borehole geophysical logs. Successful in identifying fractures zones up to 40 m from wells. Successful in identifying fractures zones up to 25 m from wells.
Stevens et al., 1994	Litho-characterisation in granite rocks. Single-hole radar reflection and crosshole radar tomograph surveys carried out in 2 borehole at AECL's Underground Research Laboratory.	RAMAC borehole radar system	Good correlation between radar reflectors and the fracture-zone interfaces at 10 m to 60m from the boreholes.

Table 2 - Classification of Resistivity Tools (From Collier, 1989)

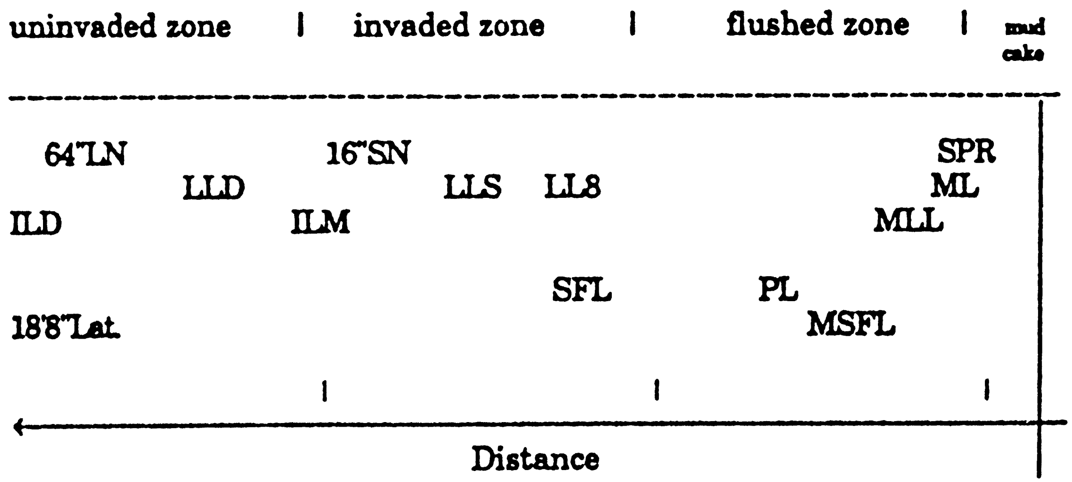
Nonfocused Electrode Tools

- Mandrel
  - Single-point
  - Normal
  - Lateral
- Pad (Microelectrode)
  - Microlog

Focused Electrode Tools

- Mandrel
  - Guard
  - Point-electrode
  - Shallow investigating
  - Spherically focusing
  - Dual focusing
- Pad (Microelectrode)
  - Microlaterolog
  - Proximity
  - Microspherically focusing
  - Dipmeter

Table 3 - Principal Resistivity Value Measured by Different Tools (From Collier, 1989)



PRINCIPAL RESISTIVITY VALUE MEASURED

Key :

SPR	Single-point resistance	MSFL	Microsherically focused log
64"LN	64" Long Normal	PL	Proximity log
16"SN	16" Short Normal	SFL	Spherically focused log
MLL	Microlaterolog	LL8	Laterolog
LLD	Deep Dual focusing electrode	ILD	Induction - deep
LLS	Shallow Dual focusing electrode	ILM	Induction - medium
18'8"Lat.	18'8" Laterolog		

Table 4 - Typical Physical Properties of Rocks and Soils (From Geological Society Engineering Group Working Party, 1988)

	Sand / Gravel	Clay	Sedimentary rocks	Alluvium	Weathered bedrock	Fresh bedrock
Seismic velocity (m/s)	500 - 2100	1000 - 2000	> 2000	< 2000	2200	4000 - 5000
Density (Kg/m^3)	1800 - 2100	1800 - 2200	2000 - 2600	2000	2600	2700 - 2800

Table 5 - Outline of Shear Wave Velocity Logging Methods (From Kaneko et al. 1990)

Method	Number of Boring	Location		Source		Direction of Wave Propagation
		Source	Receiver	P-Wave	S-Wave	
Downhole method	1	surface	hole	weight dropping blasting	plank hammering	vertical (up to down)
Uphole method	1	hole	surface	blasting downhole seismic source	blasting downhole seismic source	vertical (down to up)
Suspension PS logging	1	hole	hole	solenoid hammer	solenoid hammer	vertical (down to up)
Cross-hole method	2~	hole	hole	downhole seismic source blasting	downhole seismic source	horizontal

Table 6 - Shear Wave Velocities of Sha Tin Site (From Wong et al., 1997)

No.	Depth from Ground Level (m)	Soil Type	Shear Wave Velocity* (m/s)		II/I
			I	II	
1	2	Slightly Silty Fine to Coarse Sand, N=7 (Fill)	417	179	0.43
2	4	Slightly Silty Fine to Coarse Sand, N=7 (Fill)	216	179	0.80
3	7	Slightly Silty Fine to Coarse Sand, N=8 (Fill)	225	186	0.83
4	10	Clay, N=4 (Marine Deposit)	100	150	1.50
5	13	Clay, N=4 (Marine Deposit)	136	150	1.10
6	15	Silty Clay, N=6 (Alluvium)	153	170	1.11
7	17	Sandy Clay, N=6 (Alluvium)	153	170	1.11
8	21	Completely Decomposed Granite, N=9	265	193	0.73
9	24	Completely Decomposed Granite, N=23	298	260	0.87
10	26	Completely Decomposed Granite, N=28	332	276	0.83
11	28	Slightly Decomposed Granite	497	-	-
12	32	Slightly Decomposed Granite	744	-	-

* I : Shear wave velocity determined from vertical seismic profiling method
II: Shear wave velocity determined from SPT data and Equation 2

Table 7 - The Applicability and Limitation of Relevant Methods

Information required \ Log measurement	Nuclear				Electrical						Acoustic	Seismic wave		Structure	Electro-magnetic
	Natural Gamma	Gamma Spectroscopy	Gamma Gamma	Neutron-Neutron	Focused Electrode	Focused Induction	Dipmeter	Non Focused Electrode	Single Point Resistance (SPR)	Spontaneous Potential (SP)	Acoustic Borehole Televiewer	Suspension PS	Downhole Seismic	Caliper (3-arm or 4-arm)	Ground Penetratng Radar
Bulk Density			A												
Correlation	A	A	A	A	B/D	B & P	B/D					B/D	B/D		B & P
Diameter / Hole Volume											B/D			B	
Elastic Properties			A									B/D	B/D		
Fluid Flow															
Formation Dip and Direction							B/D				B/D				
Formation Fluid Quality					B/D	B & P		B/D		B/D					
Formation Resistivity					B/D	B & P		B/D							
Fractures							B/D				B/D	B/D	B/D		B & P
Lithology	A	A	A	A	B/D	B & P		B/D		B/D		B/D	B/D		B & P
Permeable Zones						B & P		B/D		B/D				B	
Porosity			A	A	B/D							B/D	B/D		
Shale Content	A	A		A						B/D					
Uranium / Thorium / Potassium	A	A													
Water Level					B/D				B/D						

LEGEND :

A	No restrictions on hole
B	Open hole
B & P	Open hole or with plastic casing
D	Fluid filled hole

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Updated on : 30 Jun 1998

Table 8 - The Preliminary Selected List of Downhole Geophysical Methods

Area with casing	Area without casing
Natural Gamma	Natural Gamma
Gamma-Gamma	Gamma-Gamma
Neutron-Neutron	Neutron-Neutron
	Dipmeter *
	Caliper
Induction ++	Induction
	Resistivity *
GPR ++	GPR
Crosshole GPR ++	Crosshole GPR
Suspension PS * ++	Suspension PS *
Crosshole seismic *	Crosshole seismic *
	Acoustic borehole Televiewer *
	CCTV **

* only when the hole is filled with fluid
** Only when the hole is dry or filled with clear water
++ Plastic casing

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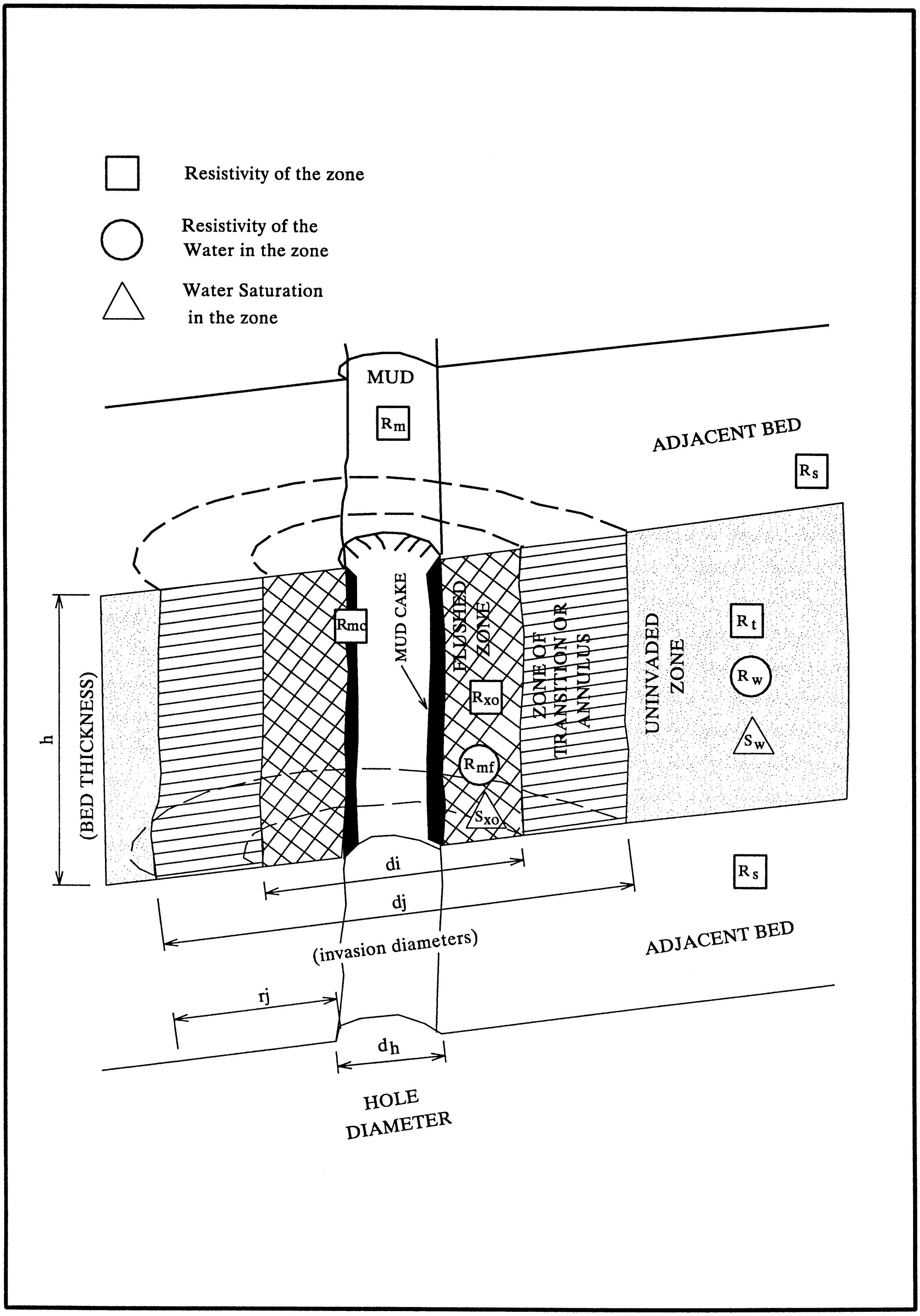


Figure 1 - Schematic Diagram - Borehole Environment (From Acquith and Gibson 1982)

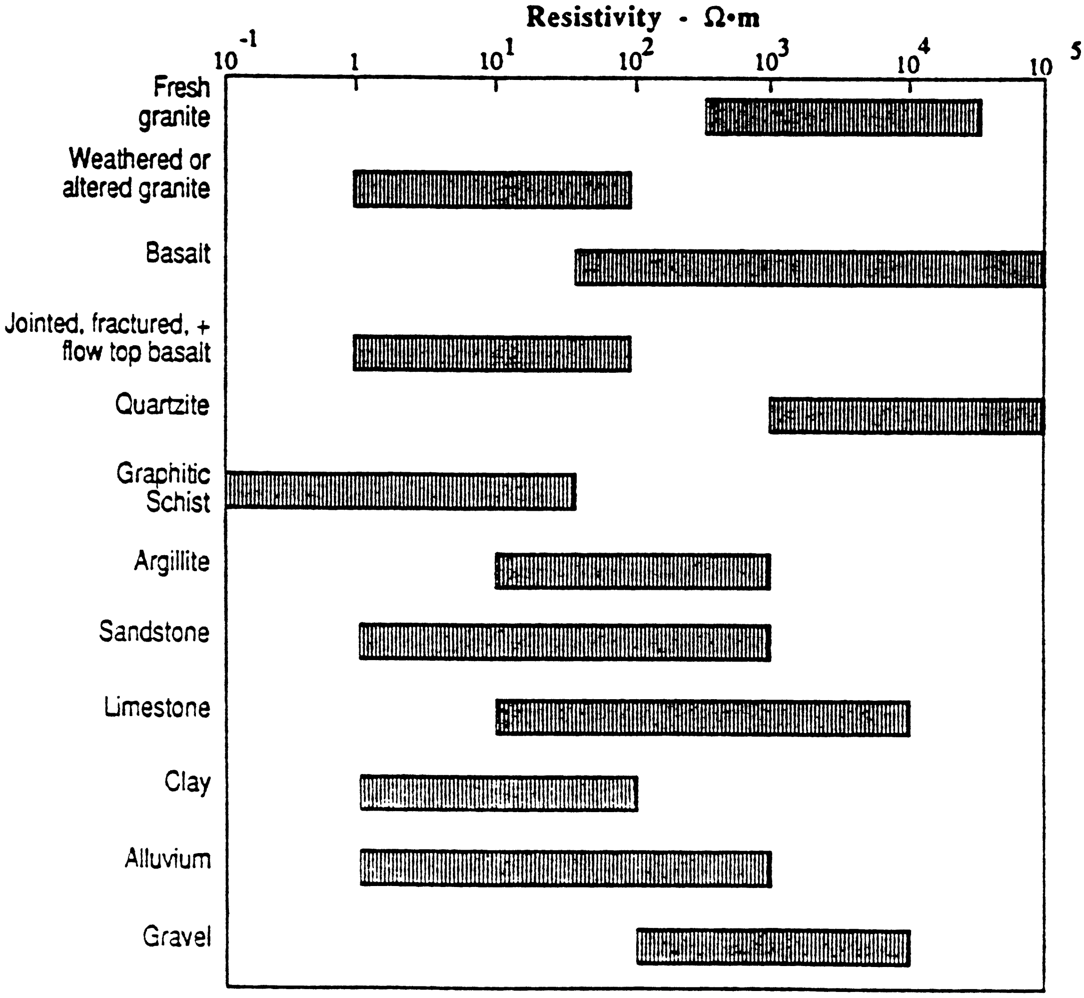


Figure 2 - Typical Ranges of Resistivities of Rocks and Soils (From Ward,1990)

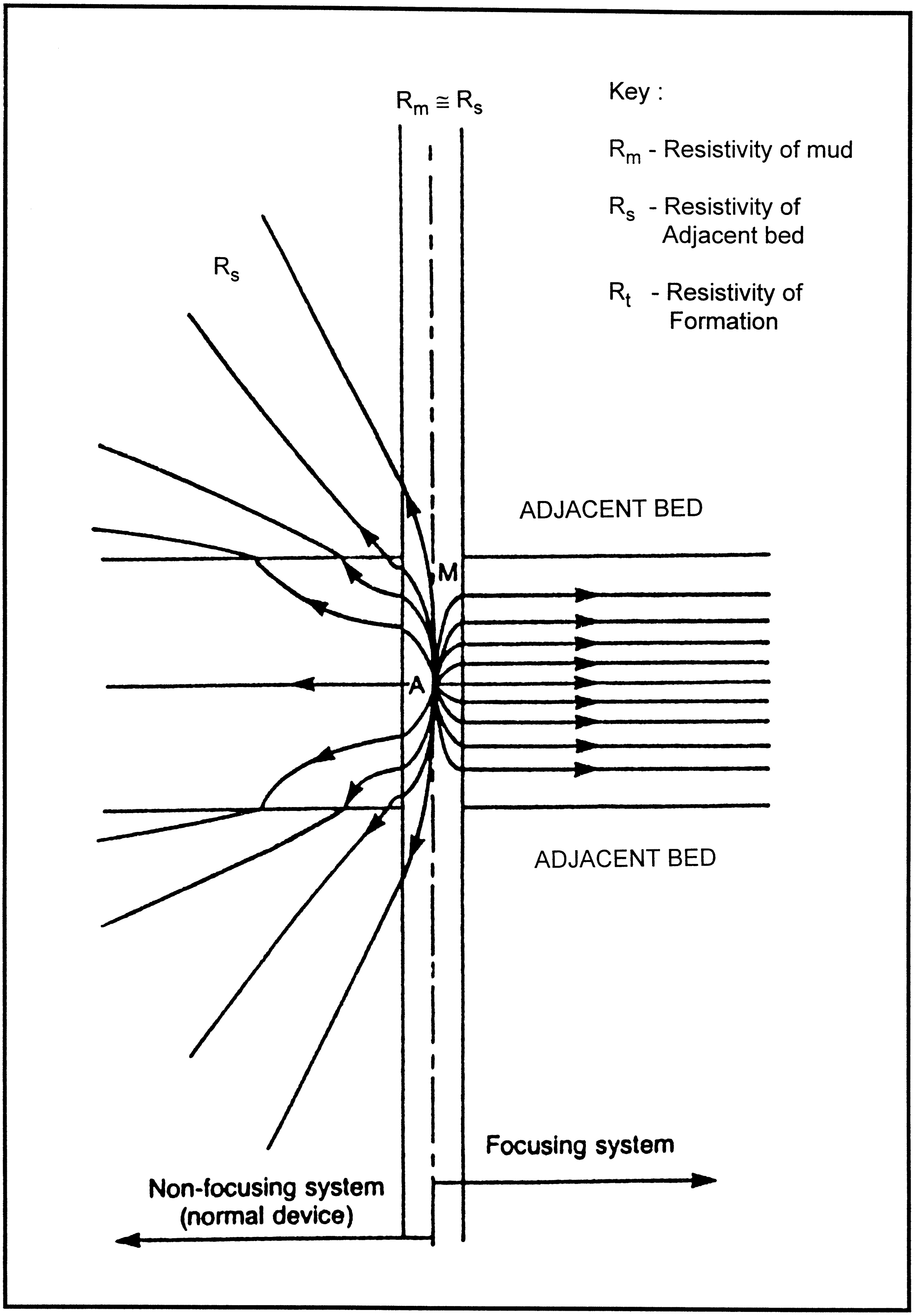


Figure 3 - Generalized Schematic Comparing Current Distribution in a Resistive Bed Opposite a Nonfocused and a Focused tool (From Helander, 1983)

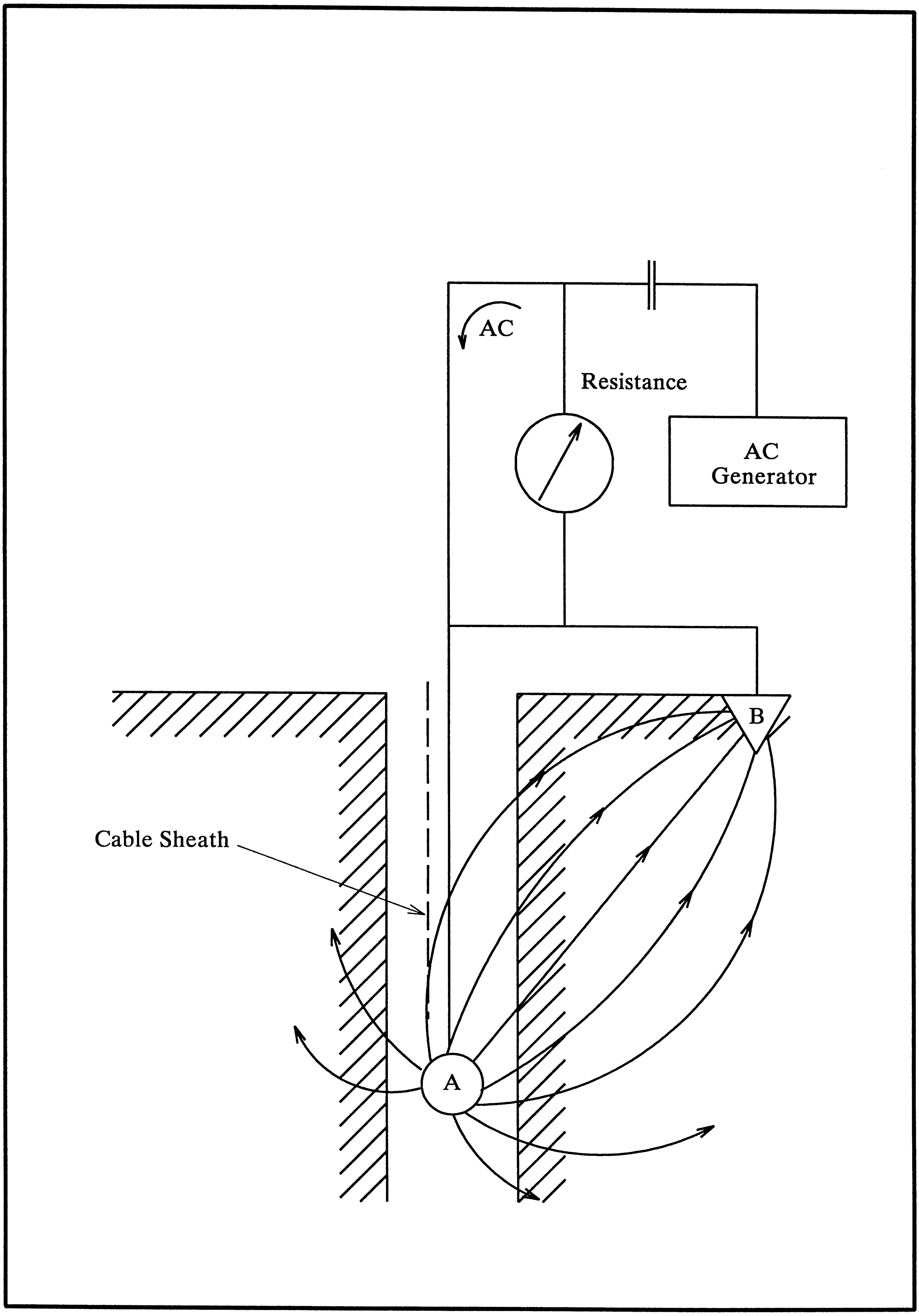


Figure 4 - Electrode Arrangement of a Single-point Tool (From Keys and MacCary, 1971)

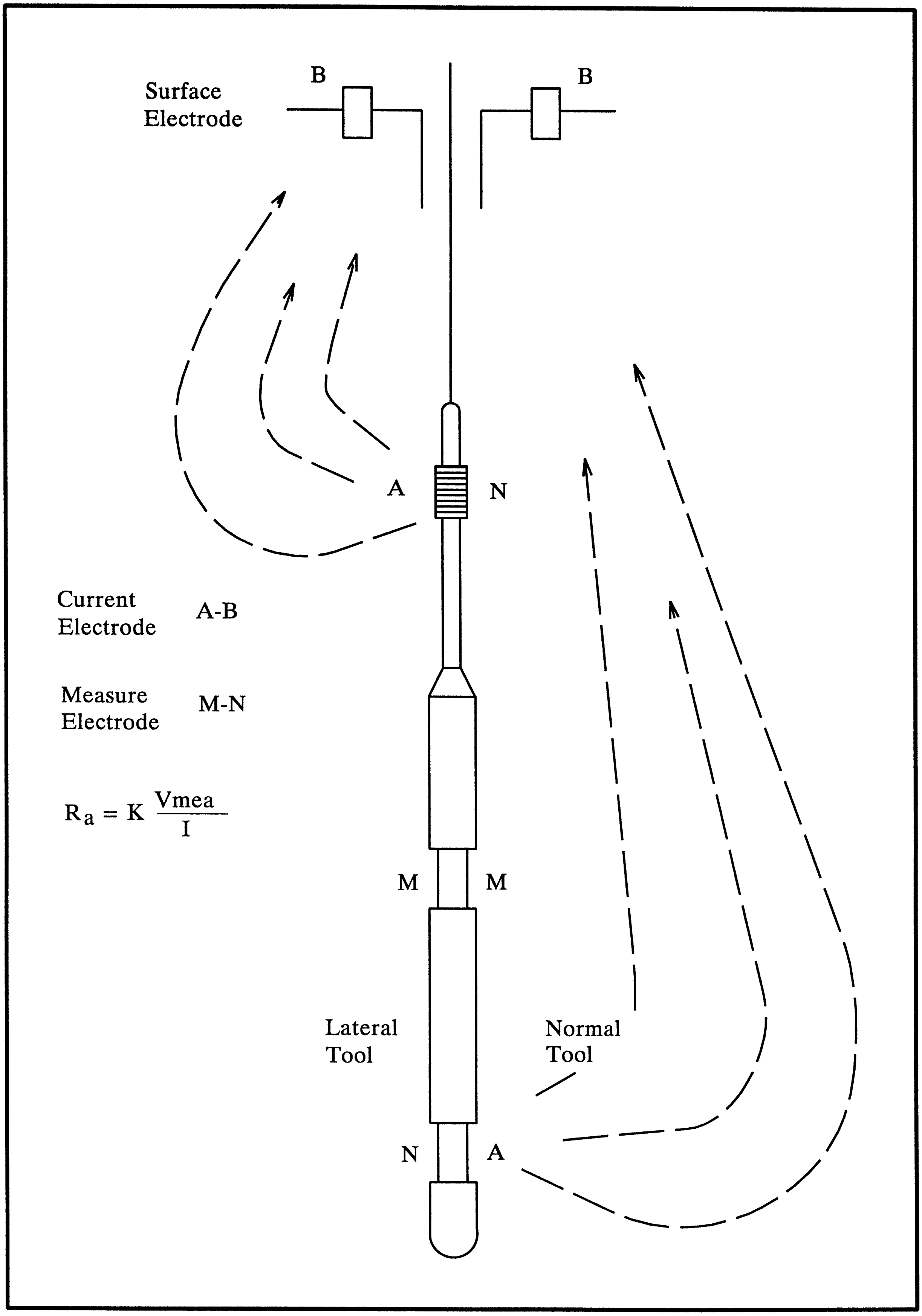


Figure 5 - Generalized Schematic of Lateral and Normal Tools (From Collier, 1989)

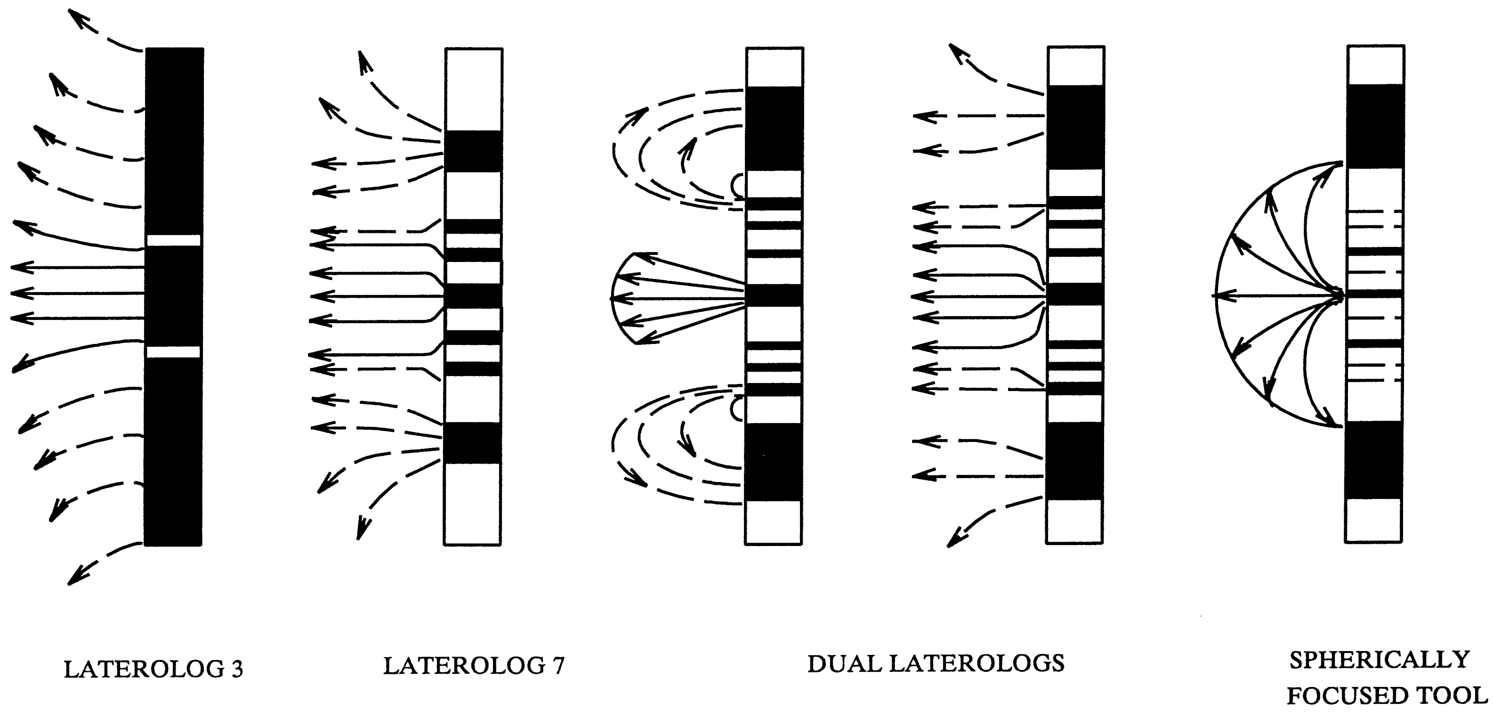
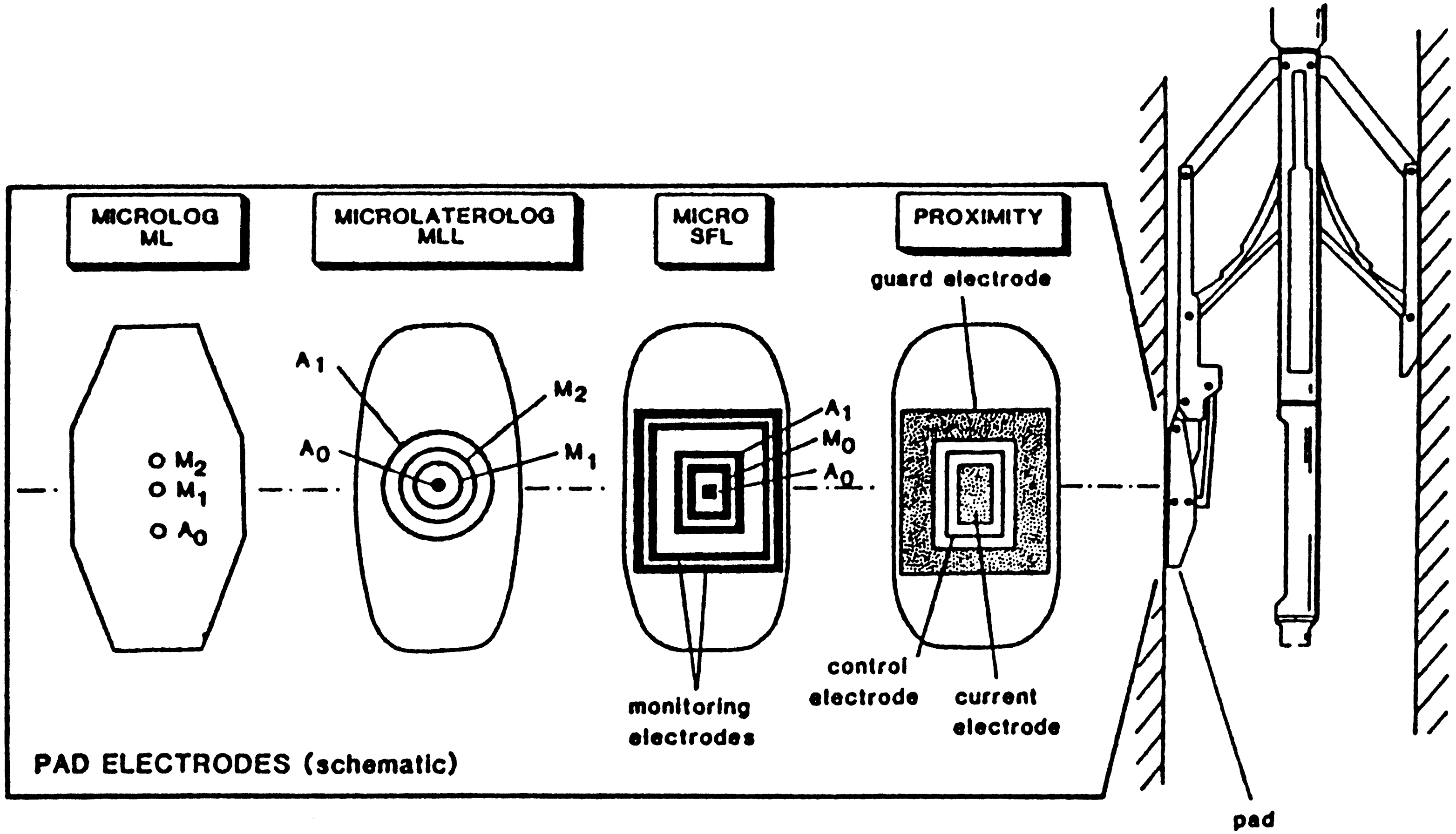


Figure 6 - Schematic Electrode Configuration in Several Schlumberger Focused Mandrel Resistivity Tools (From Collier, 1989)



A and M are Electrodes

Figure 7 - Schematic Electrode Configuration of Focused Pad Microelectrode Tools (From Rider, 1986)

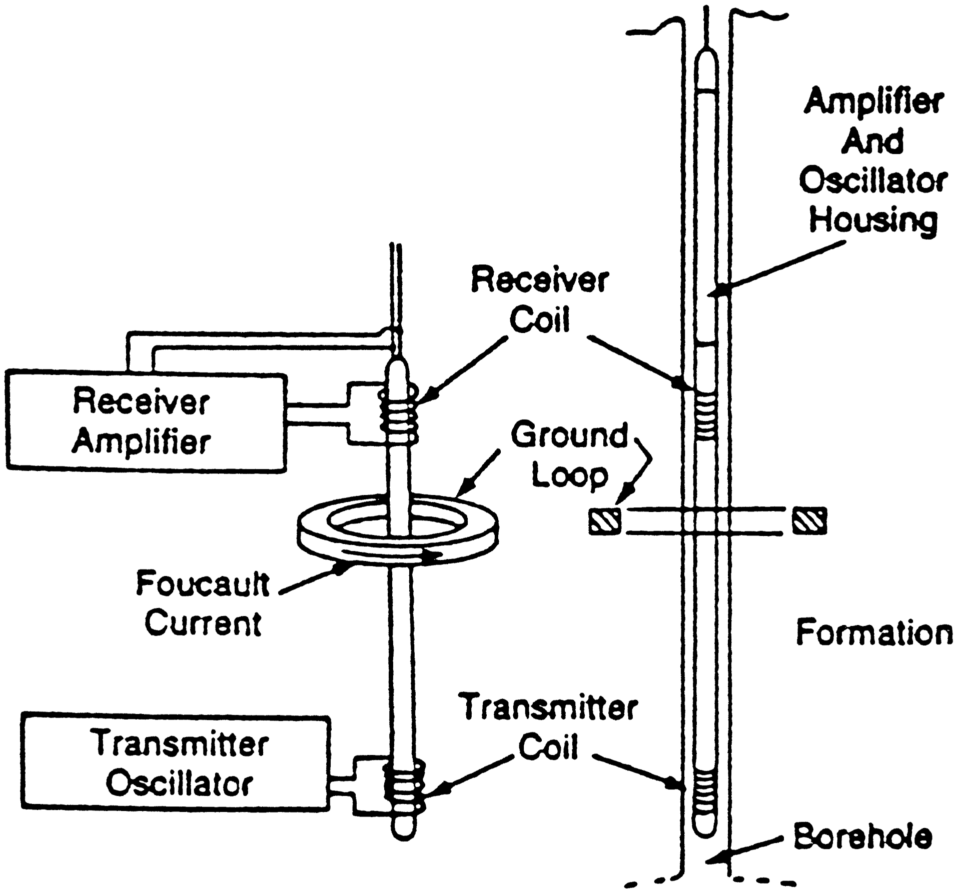


Figure 8 - Basic Two-coil Induction System (From Schlumberger, 1987)

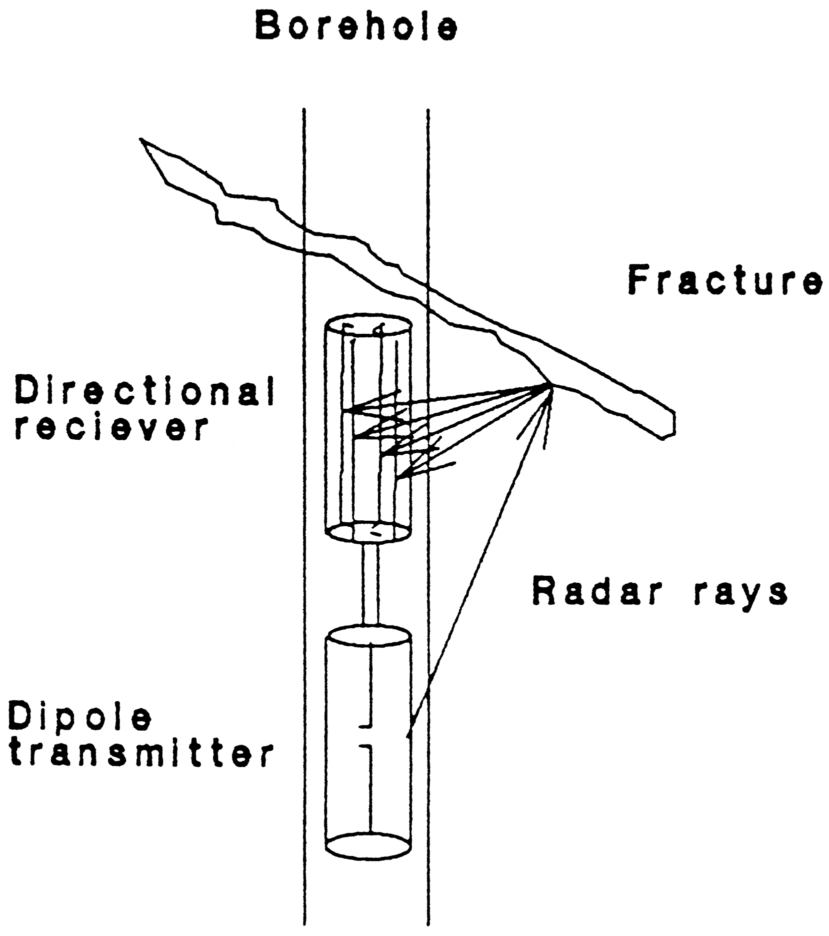


Figure 9 - Schematic Diagram of Reflections Received from Single hole Reflection Surveys
(From Lane et al., 1994)

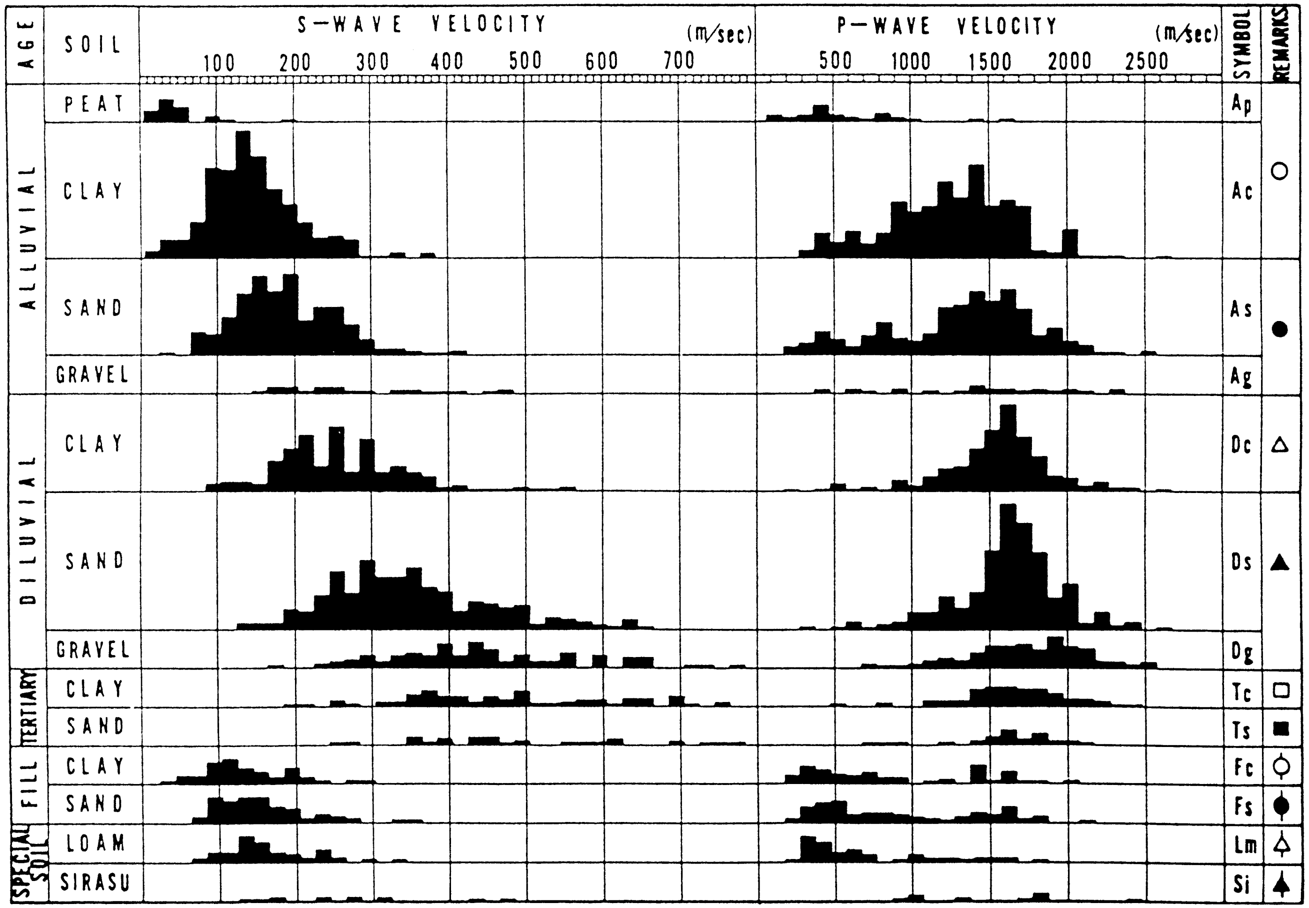
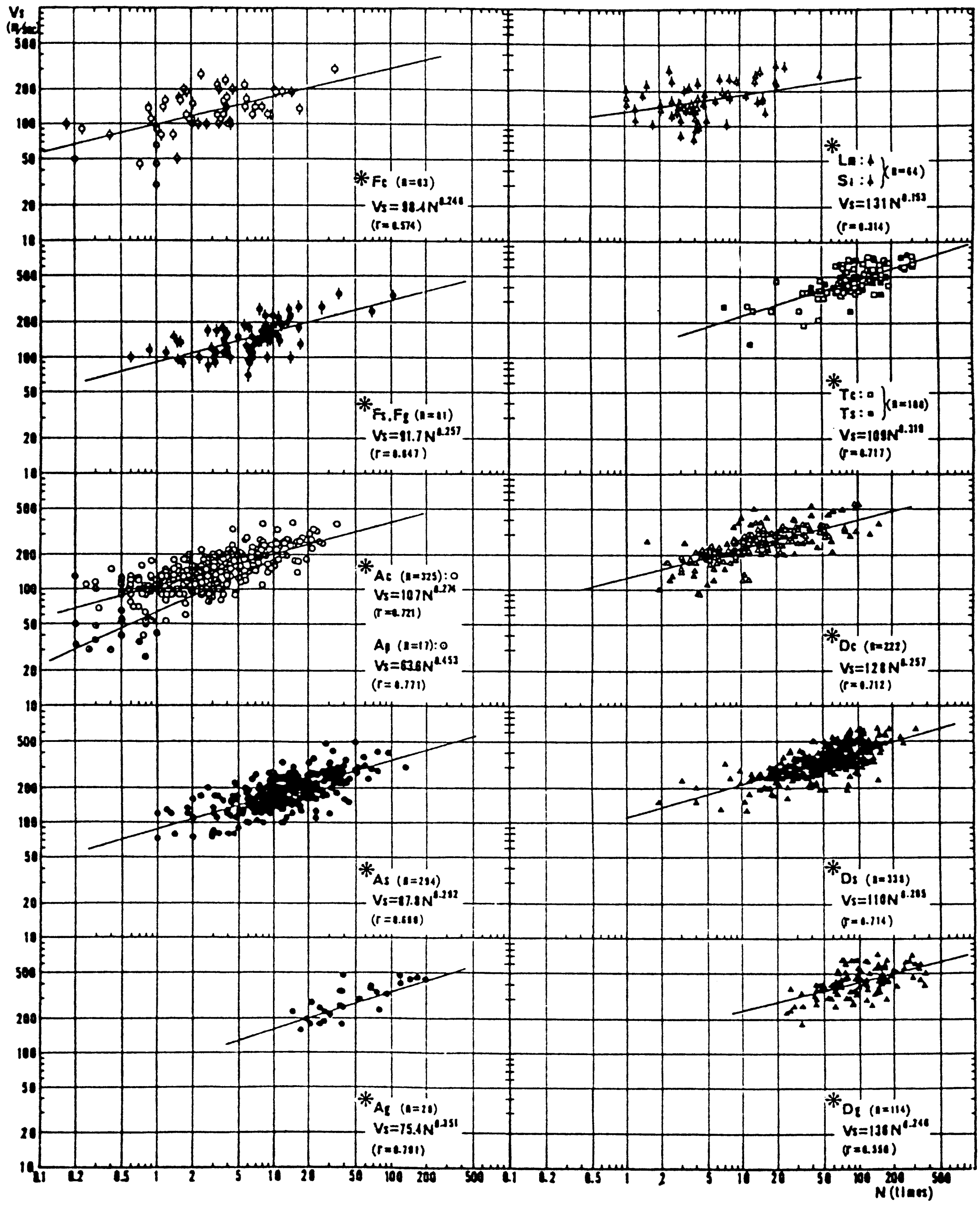


Figure 10 - Example of Wave Records by Suspension PS Logging in Different Soils in Japan (From Kaneko et al., 1990)



* The symbols for the soil types are explained in Figure 10

Figure 11 - S-wave Velocity and N-value of Different Soils in Japan
(From Imai & Tonouchi, 1982)

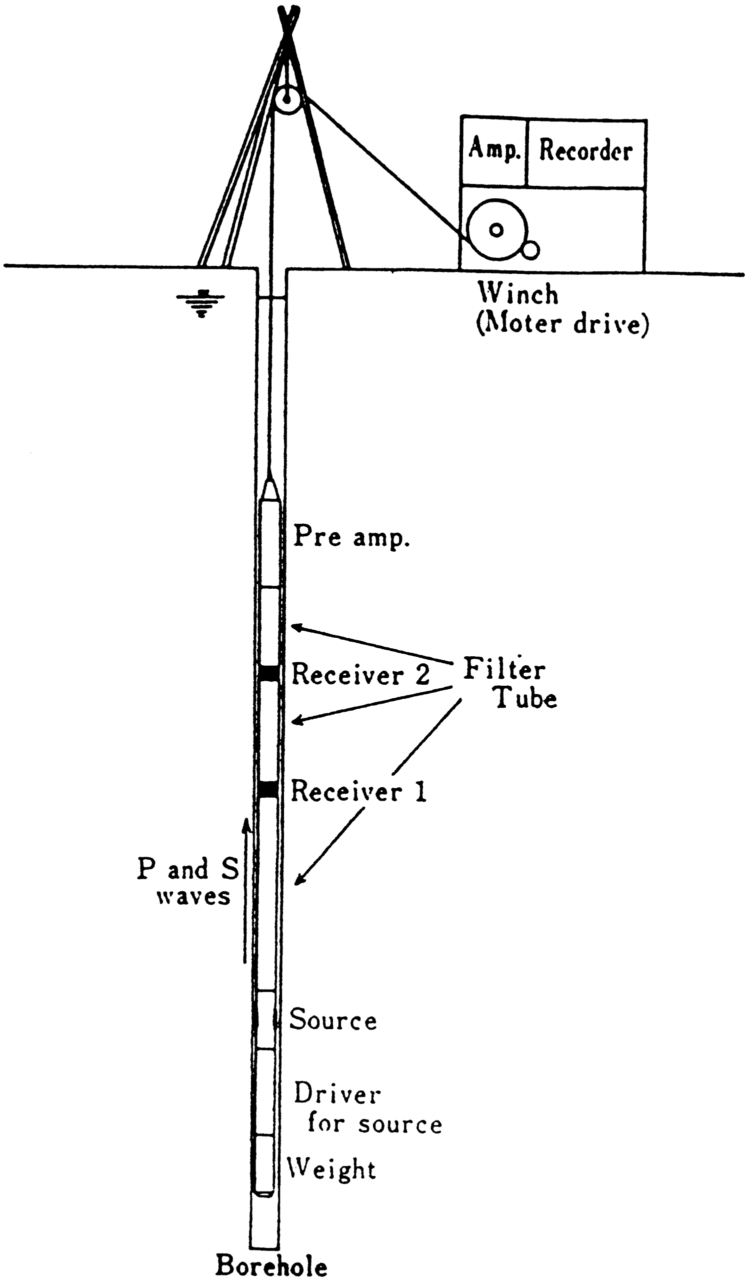


Figure 12 - Measuring System of Suspension PS Logging (From Kaneko et al., 1990)

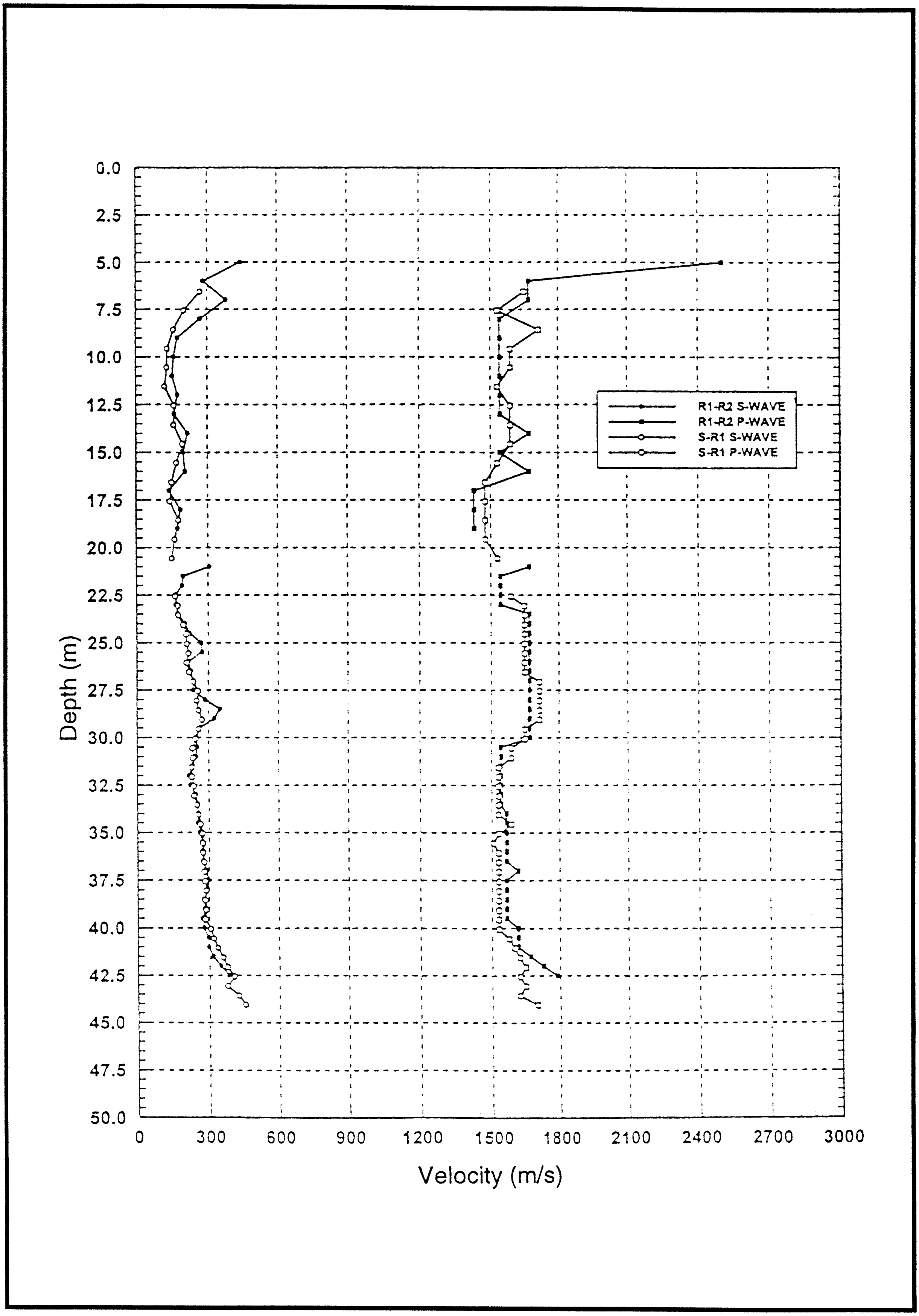


Figure 13 - P and S Wave Velocities for Borehole BF6 (Kwong, 1998)

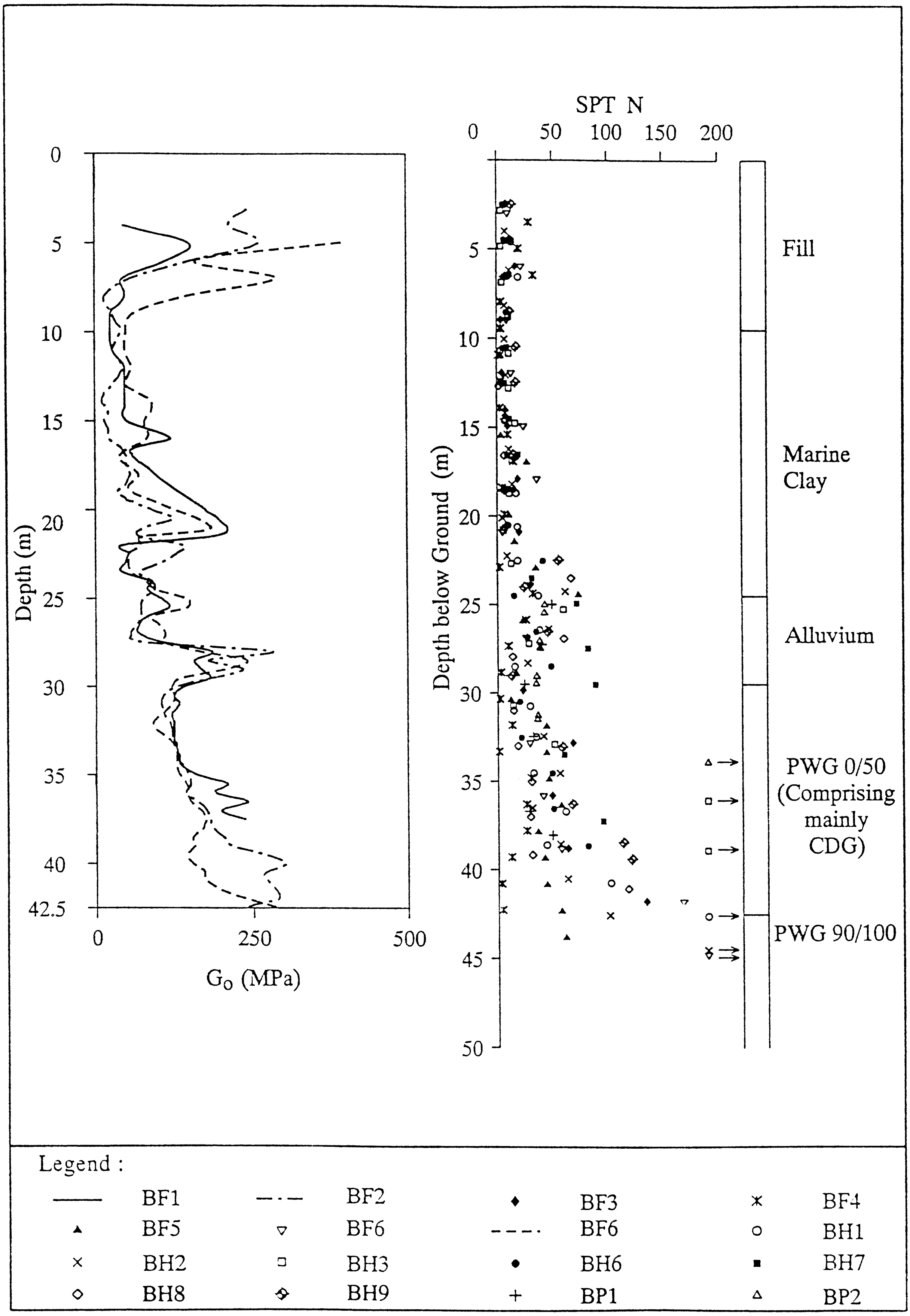


Figure 14 - Comparison of SPT N Value Profile with G_o Profile (Kwong, 1998)

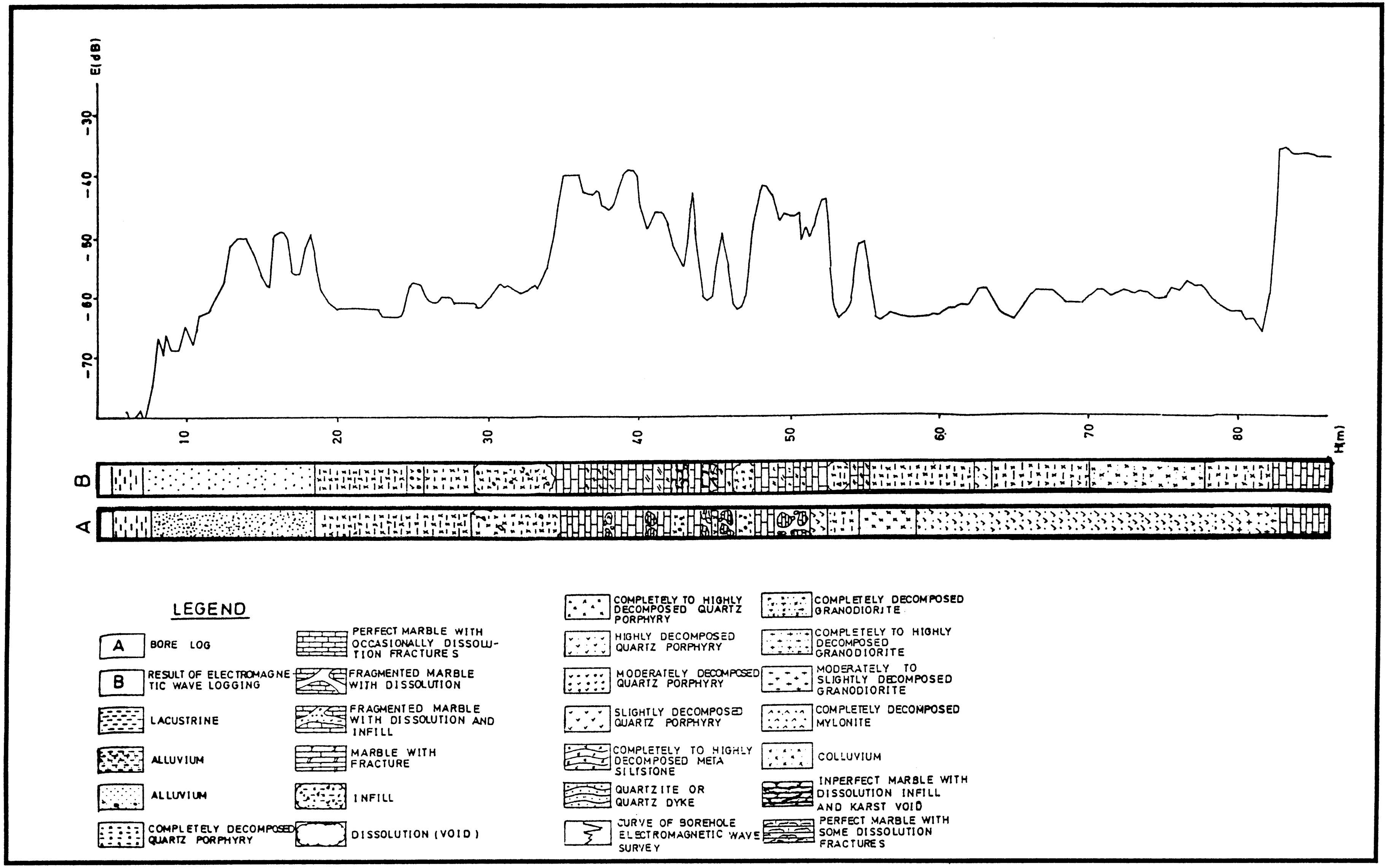


Figure 15 - Electromagnetic Wave Logging in BH AF6 (From Yi, 1989)

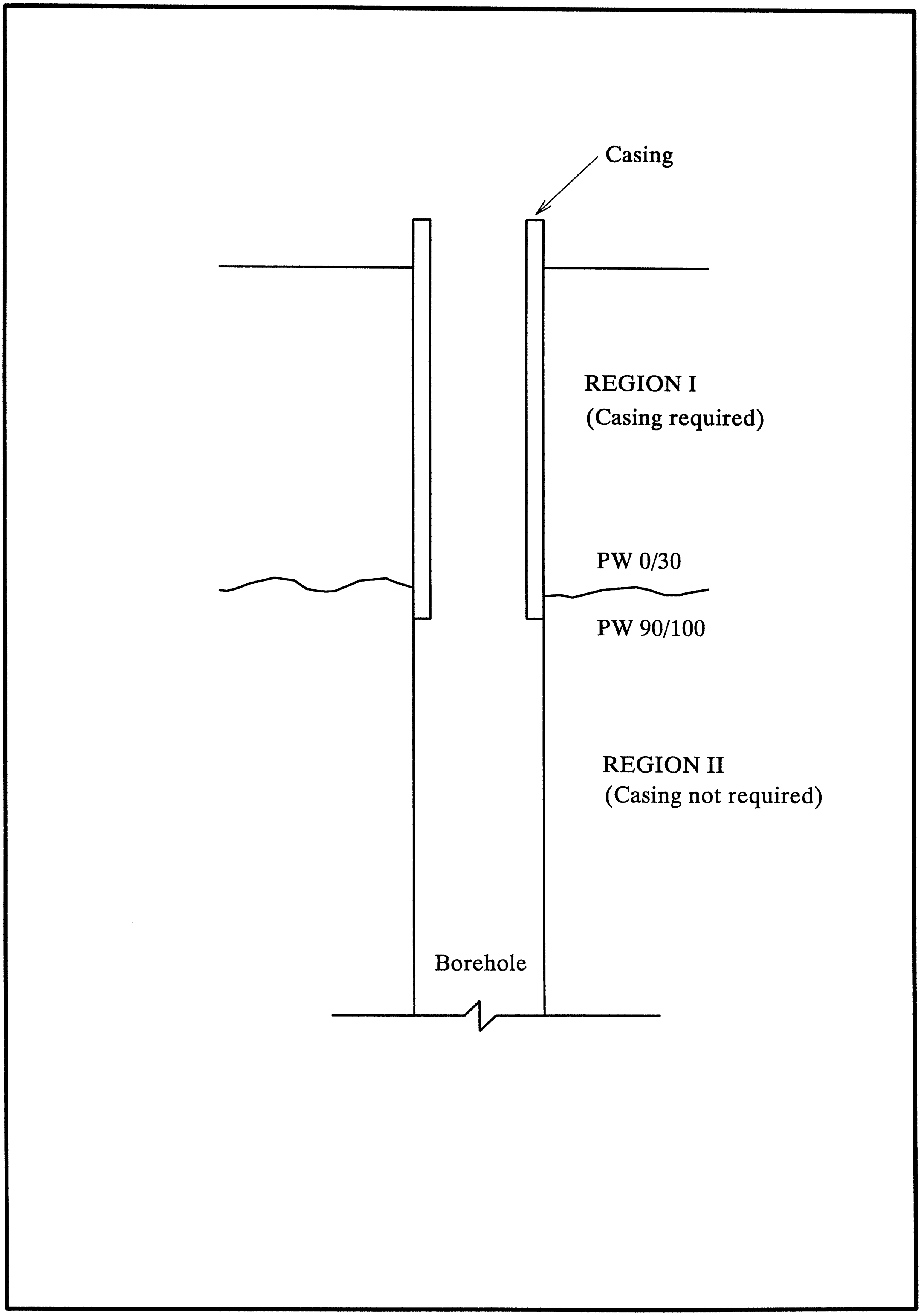


Figure 16 - Idealised Ground Conditions and Casing Requirement