

DEVELOPMENT OF AN ELECTRICAL RESISTIVITY CONE FOR
GROUNDWATER CONTAMINATION STUDIES

By

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B.A.Sc., The University of British Columbia, 1987

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES
Department of Civil Engineering

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

September, 1990

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ABSTRACT

The evaluation of groundwater quality has become increasingly important as more industrial waste and solid domestic refuse comes into contact with groundwater. Often the quantity and extent of contamination is determined by direct sampling of the groundwater and soil. An alternative method of detecting contaminated groundwater is by noting the electrical resistivity of the contaminated soil. The feasibility of logging resistivity while conducting cone penetrometer testing has been investigated in this research. To this end a two stage program was devised, consisting of lab testing and then field tests of a working tool.

Lab testing was carried out using a prototype probe designed to evaluate the feasibility of the project. The lab testing consisted of determining the resistivity of a number of different soil, electrolyte, and organic contaminant mixtures while varying the configuration of the probe. On the basis of lab testing the necessary requirements for the module dimensions and electronics were chosen and were fine tuned by field tests. The module itself consists of an insulated four electrode array and is mounted behind a standard 15 sq cm piezo-cone (CPTU).

Upon completion of the development phase the instrument was tested at four different sites. From field testing it was determined that the resistivity cone (RCPTU) was able to accurately map changes in groundwater chemistry on the basis of

resistivity measurements. The results of the resistivity testing were verified by groundwater sampling. It was also found that changes in lithological properties, as determined by the cone penetration test (CPT), could influence the resistivity. Basic guidelines for the use of the RCPTU in contaminant investigations are presented.

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ACKNOWLEDGEMENTS

I wish to thank Dr. Campanella for this choice of a research project and his continued interest in this project.

I would like to thank my fellow students in the In-situ Testing Group: Dave Brown, Ross Hitchman, John Sully, Damika Wickremesinghe, and from Geological Engineering, Mark Pritchard for their assistance in carrying out the necessary field work for this thesis.

Many thanks to Harold Schrempp for his work in machining the resistivity cone module and especially Scott Jackson, who designed and built the circuitry for the excitation, measurement and data logging of the resistance measurements for the resistivity cone module. I would also like to thank Art Brookes for his continual role in maintaining the in-situ testing vehicle, without which none of the field work would be possible.

I wish to acknowledge the financial support of the Natural Sciences and Engineering Research Council, Canada, in the form of a research assistantship.

1. INTRODUCTION

1.1 Rationale for Resistivity Cone Development

The detection of contaminated soil and groundwater has become an important aspect of both the groundwater and geotechnical industry. The degradation of groundwater quality has a direct effect on the quality of life in a region by possibly threatening both the health of the local population and of wildlife habitats. Therefore, the rapid detection and containment of contaminated soil is of wide interest. Examples of potential contamination sources are: acidic sludge as a byproduct from oil reclamation (Greenhouse and Slaine, 1986), leachate from sanitary landfills (MacFarlane et al, 1983), acidic leachate from mine tailings dumps (Morin et al, 1982), or accidental spills.

Contaminants may be detected by either direct sampling and analysis of groundwater and soil samples or by indirect methods that operate on the premise that the presence of contaminants will change some other measurable soil or groundwater property. A common indirect method is the measurement of the subsurface electrical conductivity. The electrical conductivity is a measure of the ease that an electrical current may be passed through a medium, in this case soil. Often these measurements are presented in terms of soil resistivity (or bulk resistivity), which is the inverse of soil conductivity.

In most cases contaminants influence the bulk resistivity of the soil because they change the electrical properties of the groundwater. The electrical resistivity will decrease with an increase in dissolved solids, and increase if insulating contaminants are present in the groundwater. Generally for non-cohesive soils virtually all the electrical conduction takes place through the pore fluid with the soil matrix acting as an insulator. In many instances contaminant sites contain a mixture of aqueous phase (usually conductive) and non-aqueous phase (insulating contaminants). Usually such mixtures will produce highly conductive plumes since the influence of the conductive contaminants is generally greater than that of the non-conducting contaminants.

Given that soil resistivity measurements are a valid method of detecting contaminants it becomes necessary to choose what method is most suitable to make such measurements. Generally, there are two methods, galvanic measurement, and electromagnetic (EM) induction. Galvanic measurements are made by direct contact with the ground while for EM measurements no contact with the ground is necessary. Both can be employed from the surface or in boreholes. EM measurements have the advantage of being able to make measurements in plastic cased holes.

The objective of this research is to make rapid and accurate measurements of soil resistivity using a modified cone penetrometer. The cone penetrometer test (CPT) has gained wide acceptance as the most applicable logging tool for soil in the

geotechnical industry (Campanella and Robertson, 1982). With the addition of the resistivity logging capability it is likely that the CPT will see more use for hydrogeological investigations. A cone penetrometer with the capabilities of resistivity logging would be appealing for the following reasons:

1) By being pushed into the ground the measuring electrodes are in intimate contact with the ground, as opposed to the case where a resistivity probe is deployed in a mud filled borehole.

2) Direct measurements are more accurate than surface measurements. Surface methods are commonly used to measure electrical soil resistivity (Telford et al, 1976), but require at least a 5 to 10% electrical contrast between contaminated and uncontaminated soil to successfully map a contaminant plume (Benson et al, 1985), assuming that there are no lithological variations. A resistivity cone can measure resistivity to a resolution of 1% and at the same time record changes in lithology.

3) The development of instrumentation for measuring galvanic resistivity is much easier to design and implement than for electromagnetic induction.

4) Valuable information from the cone penetrometer is also recorded in addition to the resistivity data.

1.2 Scope of Research

Very little published technical literature is available concerning the design and use of electrical resistivity cones though both Delft (Van de Graff and Zuidberg, 1985) and Fugro-McClelland (Horsnell, 1988) have successfully operated such probes. Delft have used their resistivity cone for density measurements in offshore sands. The Fugro-McClelland resistivity cone has been used to profile conductive contaminants (Horsnell, 1988) and also used in the determination of corrosivity potential. With there being such little published work on the operation and interpretation of resistivity data, the purpose of this research is to fill this gap and independently determine how applicable the resistivity cone penetration test (RCPTU) is for detecting the presence of contamination.

To meet this objective a research program was developed and is summarized as follows:

1. Gather available literature regarding electrical conduction in soil and water and also resistivity testing methods, specifically downhole tests.
2. Set up a simplified lab resistivity testing apparatus to aid in the selection of a final design for the resistivity cone. This step is meant to check the viability of making accurate resistivity measurements and to minimize the number of changes

that would be needed for the eventual field prototype.

3. Field test the resistivity cone to ensure it is collecting accurate data and then compile data from various sites.

4. Determine how the resistivity measurements are affected by different soil types and groundwater conditions.

5. Outline the application of the resistivity cone to contaminant studies and for other purposes.

Each of these steps are examined in the following chapters of this thesis. Conclusions and recommendations for further work are also presented.

2. ELECTRICAL CONDUCTION PHENOMENA

2.1 Introduction

An electric charge can be transferred by three different processes (Telford, 1976). The first, being the most familiar, is the transfer of a charge by the flow of free electrons in a metallic conductor. This charge transfer is referred to as electronic, or ohmic conduction. Another method of charge transfer is electrolytic conduction, the transfer of charge by the migration of cations and anions in an electrolyte in response to an electrical field. This method of charge transfer is dominant at the frequencies used in galvanic resistivity measurements. The final method of charge transfer is referred to as dielectric conduction. With dielectric conduction a current is produced due to changing electronic, ionic or molecular polarization caused by the application of a time varying electric field. Conduction, in the most general terms, may be described by the following relation (Hearst, 1985).

$$[2.1] \quad J = [\sigma + \omega \epsilon + i(\sigma - \omega \epsilon)] E$$

where:

- J - current density (A/m^2)
- E - electric field strength (V/m)
- σ - conductivity (S/m)
- ϵ - dielectric permittivity (F/m)
- ω - angular frequency
- i - $\sqrt{-1}$

The form of the above equation can be simplified depending

upon the excitation frequency. Both the conductivity and dielectric permittivity are complex quantities that are frequency dependent. In the case of low frequency resistivity measurements the relation between the applied electric field and the current density simplifies to the following relation:

$$[2.2] \quad J = \sigma E = E/\rho$$

where: ρ = resistivity (ohm-m)

This relationship will be valid at low frequencies, up to several kilohertz, providing the charges are not bound. Using this relationship the low frequency resistivity (which is sometimes referred to as the DC resistivity), or conversely conductivity may be determined. The factors which influence resistivity at low frequencies in pore fluid and in saturated soil will be examined in the following sections.

2.2 Electrical Conduction in Pore Water

At low frequencies conduction in pore water takes place by electrolytic conduction. A current is produced when the ions migrate due to the application of an electric field. In general, the more ions present in the pore fluid the greater the conductivity. However, a number of other factors affect the conductivity of a particular ion in an electrolyte. Keller (1982) points out that the acceleration of ions in an electric field is opposed by viscous drag. This limits the maximum velocity of the ions, hence its conductivity. The amount of drag is a function of temperature, ionic concentration, ion size, and

valence. Since fluid viscosity is a function of temperature, the conductivity of a particular ion will increase as the temperature increases. While conductivity increases with increased ionic concentration there is an increased tendency towards collisions which retard the migration of ions to some extent. It would seem reasonable that smaller ions would be more conductive since there would be less viscous drag. However, Hearst (1985) states that the relationship between size and mobility is not that simple since charged ions tend to solvate (attract a layer of water molecules). Conductivity is also dependent on the valence of the ion. The greater the valence the more charge transferred per ion, resulting in a higher conductivity. Viscosity also decreases with pressure so that conductivity will increase at higher pressures, however this is a negligible consideration with the pressures involved in cone testing.

By assuming a linear relationship between the concentration of ions and conductivity, a reasonable estimate of the total dissolved solids (TDS) in a solution can be made. (CRC, 1982).

$$[2.3] \quad C = \sigma K$$

where: C - concentration of total dissolved solids (mg/l)
 σ - conductivity ($\mu S/cm$)

and K is a constant with the following ranges.

$K < 0.55$ high salinity (TDS > 2g/l, 6 < pH < 9)
 $K = 0.55 - 0.7$ low salinity (TDS < 2g/l, 6 < pH < 9)
 $K > 0.7$ for highly acidic or caustic pore waters

The high value of K for low pH pore fluids is due to the high mobility of hydrogen ions in comparison to other ions.

Different ions have different conductivity factors, the conductivity factor being the relative contribution to the total conductivity of a solution. Using conductivity factors the concentration of each constituent may be estimated if the relative quantities of contaminants in the groundwater are not changing

2.3 Electrical Conduction in Multi-Phase Systems

A study by Urish (1983) determined that bulk conductivity of uncontaminated soil is a combination of a number of factors: conductivity of the matrix and pore fluid, porosity, tortuosity (which is dependent on the geometric packing and shape of the grains), the total interstitial surface area of the pores per unit pore volume of the sample, the specific surface conductivity of the grains (which is dependent on the pore water resistivity), ionic composition of the pore water, pore water pH, cation exchange capacity (CEC) of the matrix minerals. The bulk conductivity in a contaminated multi-phase system becomes more complicated since four components must be considered: soil particles, aqueous phase liquids (APL), non-aqueous phase liquids (NAPL), and air. The measured bulk resistivity of the soil is a result of conduction (or lack of conduction) through the above mentioned components and how the components interact with each other.

If each specific contributor to conductivity was considered the relationship between fluid conductivity and bulk

conductivity would be extremely complicated. Formulas that describe the resistivity in multi-phase systems are referred to as mixing laws. Fortunately simplifying assumptions can be made. Air, NAPLs, and sand can be considered equivalent with respect to their conductivity, in most cases they are considered insulators. Therefore the simplest case is the assumption that all conduction takes place through the pore fluid. This assumption is the premise of Archie's Formula (Archie, 1942, and Telford et al, 1976), the simplest of the mixing laws. Archie's Formula assumes that bulk resistivity is directly related to pore water resistivity and the geometry of the pore spaces in the soil (or rock). A term commonly used to relate soil resistivity to pore fluid resistivity is the formation factor, which is a function of the pore geometry. Archie's Formula is given as:

$$[2.4] \quad F = \rho_b / \rho_f = a n^{-m}$$

where: F = intrinsic formation factor
 ρ_b = bulk resistivity (ohm-m)
 ρ_f = fluid resistivity (ohm-m)
 a, m = constants for a given soil
 n = porosity

For unconsolidated soil $a \approx 1$, and m is dependent on soil type. For sands the value of m is approximately 1.5, and for various clays authors have found that $m = 1.8$ to 3 (Jackson et al, 1978).

Archie's Formula has been recognized to be an oversimplification but is still valid under the condition that the pore fluid resistivity is very low or there are no clay

minerals present in the soil. This is because the bulk resistivity can be a function of factors, other than pore geometry and fluid resistivity, which would tend to decrease the observed formation factor. For these reasons the measured formation factor is referred to as the apparent formation factor. The intrinsic formation factor of a soil is a function only of the pore geometry, which has been found to be a function of particle shape. Jackson et al. (1978) researched the effect of particle size, distribution and shape on the formation factor and found m to be only a function of grain shape. Thus, m is a measure of pore tortuosity, with m increasing as the soil particles become more elongated.

Other more complicated mixing laws have been formulated to consider the effect of mineralogical conduction due to the presence of clay. An excellent summary of these relations may be found in Jordan and Campbell (1986). These relations are difficult to put into practice due to the necessity of measuring the cation exchange capacity of the soil. However an awareness of these relationships is important in understanding what factors may influence resistivity. The effect of surface conduction is important in clayey soils and organic material which have a high cation exchange capacity.

Attempts have been made by some authors to use resistivity as a method of determining hydraulic conductivity. The rationale being that if porosity can be estimated from resistivity measurements then hydraulic conductivity could also

be estimated. If the Kozeny - Carmen equation is used as a representation of the factors that influence hydraulic conductivity it can be seen that hydraulic conductivity depends, to some extent, on the square of the pore radius, a specific surface term and the representative grain size. All these factors are measures of pore size, hence there should be some relation to the formation factor. However relations developed between formation factor and hydraulic conductivity have been contradictory. The fact that the apparent and intrinsic formation factor are often different makes this approach of determining hydraulic conductivity unfavorable.

2.4 Frequency Dependent Behavior

Frequency dependent electrical behavior in soils may be ascribed to two different polarization processes. The first being induced polarization, and the second dielectric polarization. Both effects result in a current out of phase with the voltage therefore requiring the conductivity, or permittivity to be described as a complex quantity. Induced polarization is noted at frequencies of less than one hertz while dielectric polarization is noted in the mega-hertz range.

2.4.1 Induced Polarization

At low frequencies complex conduction may occur due to the polarization of ions. Polarization takes place due to zones of unequal ionic transport properties (Hearst, 1985). Clays have

fixed negative charges so that the conduction of cations in clayey soils is favored over that of anions. This leads to zones of unequal charge distribution. In soils containing clay this leads to what is referred to as the membrane polarization. When a current is applied to a clayey soil ionic concentration gradients develop in regions where clay partially blocks pore spaces. This behavior is indicative of variable clay content. The relationship between polarization and the state of the clay is complex. Bodmer et al. (1968) noted that polarizability increases to a maximum at 5 to 9 percent clay content and then decreases.

Besides confirming the presence of clay minerals in the soil polarization is also indicative of contamination in soils that have an initial high polarization. Increased pore fluid salinity will decrease the polarizability since conductive paths will be chosen over capacitive paths of current flow. Bodmer et al (1968) noted that in sand clay mixtures that the polarizability is roughly proportional to the cation exchange capacity (CEC) of the clay. The presence of contaminants that would decrease the CEC capacity of the clay could be noted by observing a decrease in polarizability of the soil. Examples of such contaminants are hydrocarbons (Olhoeft, 1985), water soluble organic cations (Hughes, 1986), and also chlorides (Scott-Fleming et al. 1983).

Measurements of polarization are accomplished in either the time domain or frequency domain (Telford, 1976). In the time

domain, once the source voltage is removed, the observed voltage decay curve is integrated. In the frequency domain two measurements of resistivity are made at low frequencies one decade apart. Another method, referred to as complex resistivity, uses resistivity measurements over a large frequency range. Using the complex resistivity method Towle et al (1985) noted an inverse relationship between grain size and a critical frequency, which is defined as the peak in the complex resistivity spectrum.

2.4.2 Dielectric Polarization

At low frequencies conduction of free electrolytes is independent of frequency. As the frequency is increased an increasing proportion of the charge transfer in pore fluid is due to displacement currents. In the mega-hertz range the dielectric permittivity of water, and other polar fluids, is frequency dependent due to time dependent orientation of dipoles. At higher frequencies the dielectric permittivity is a function of frequency due to various resonances of atoms and electrons.

As previously noted displacement currents dominate conduction currents at high frequencies, the frequency range where displacement currents dominate depends on the conductivity of the soil. The advantage of measuring the dielectric permittivity of the soil is that it is closely related to the water content of the soil. The dielectric constant of water is

weakly influenced by salinity and temperature for most soils. This is because of the very high dielectric permittivity of water, being highly polar, in comparison to the dielectric constant of the soil matrix. Thus the in-situ measurement of the dielectric constant of the soil could be used to determine water content, and hence void ratio is cohesionless soils.

3. INSTRUMENT DEVELOPMENT

The successful development of the resistivity module was contingent on two factors: (1) understanding the underlying principles of conductivity in soils and; (2) the completion of the lab testing program. This chapter commences with a brief outline of currently availability resistivity cone technology. Available literature concerning these tools was so sparse that a lab testing program was necessary to determine an appropriate design for the UBC resistivity cone. The lab testing apparatus will be described and results from that program will be used in the section of this chapter concerning design criteria.

3.1 Existing Resistivity Cone Technology

Electrical measurements of soil and pore water have been used successfully in a number of instances to map changes in groundwater composition. Normally, surface resistivity surveys are carried out to measure soil resistivity. Surface methods require at least a 5 to 10% electrical contrast between contaminated and uncontaminated soil to successfully map a contaminant plume (Benson, 1985), assuming there are no lithological variations. By measuring resistivity during cone penetration testing much more accurate determinations of resistivity can be made while obtaining lithological information. The recognition of this has led to the development

of a small number of resistivity cone penetrometers. However, there has been little published about their use at different sites and of their actual description. The following is a brief description of these cones.

1) Delft: This cone was developed in 1970's to be used in conjunction with water sampling to determine soil porosity (Van de Graff and Zuidberg, 1985). The cone has 8 electrodes. It is presumed that there are two set of four electrodes. Data is collected at discreet intervals of 20 cm to provide a profile of resistivity with depth. The input signal is at a frequency of 10 hertz.

2) Fugro: The Fugro cone contains two circular electrodes set five cm apart (Horsnell, 1988). The electrodes are isolated from the rest of the cone body by a ceramic material. The excitation signal is applied at an unspecified low frequency.

3) ConeTec: This module has two 10 mm wide electrodes set 7.5 cm apart. The excitation current is applied at 1000 Hz. It is a modular design built to be fitted on a standard Hogentogler piezocone. The probe is a fully digital, microprocessor controlled unit. This module was developed after the UBC resistivity cone.

3.2 Lab Testing Equipment

The lab testing equipment was quite simple but effective in

making resistivity measurements. The probe part consisted of four rings that slid along a plastic cylinder. This allowed the electrodes to be placed at varying distances to note the effect of changing the electrode spacing. The source was basically the same constant current circuit that was in the final unit, with the power being supplied from a signal generator. This allowed for measurements over a wide frequency range to study the effect of varying the frequency. The voltage output from the electrodes was noted on an oscilloscope. The electrode assembly was submerged in a large tank of water and Potassium Chloride (KCl) was added to the water in the tank to create solutions of different conductivity.

3.3 Design Requirements and Considerations

The following is an outline of the requirements for the resistivity probe. Options in the design are considered and the benefits and problems involved with each option are considered in the light of the results obtained from the lab tests.

3.3.1 Number of Electrodes

Most resistivity probes have used either two or four electrode arrays. Usually surface resistivity methods use four electrodes, with the current applied at the outermost electrodes and the potential measured with the inner electrodes. With a two electrode probe the potential is measured across the electrodes applying the current. For the UBC probe it was

decided to use a four electrode design while measuring potential across the inner and outer electrodes. The purpose of this configuration was to observe if there was any difference in the results between the two sets of electrodes. The four electrode probe also has the advantage of being able to make low frequency measurements without the inner electrodes becoming polarized. Polarization occurs due to a buildup of ions at the electrodes which produces an impedance in series with that of the surrounding soil. At the electrodes oxidation-reduction (redox) reactions must take place for there to be a transfer of charge. (Keller, 1982). The redox reaction rates are controlled by the concentration of reactions that accumulate as the current is transferred. As the ions cannot react they accumulate at the electrodes causing the polarization. Since polarization is a function of current the problem may be ameliorated by decreasing the current passing through the electrodes. This can be done by employing a second set of electrodes to measure voltage. Since the impedance through the voltage measuring circuit is high the current passing through the electrodes is very small. Therefore, such an array can be operated at low frequencies without becoming polarized. The effect of polarization is illustrated in Figure 3.1 where the resistivity, normalized with respect to the resistivity measured at 1000 Hz, is plotted versus frequency for three different electrode configurations. Using a four electrode system, with the electrodes set 3.5 cm apart, the output is independent of frequency, showing that there is no polarization of the inner electrodes. The two electrode configuration shows a frequency dependent output characteristic

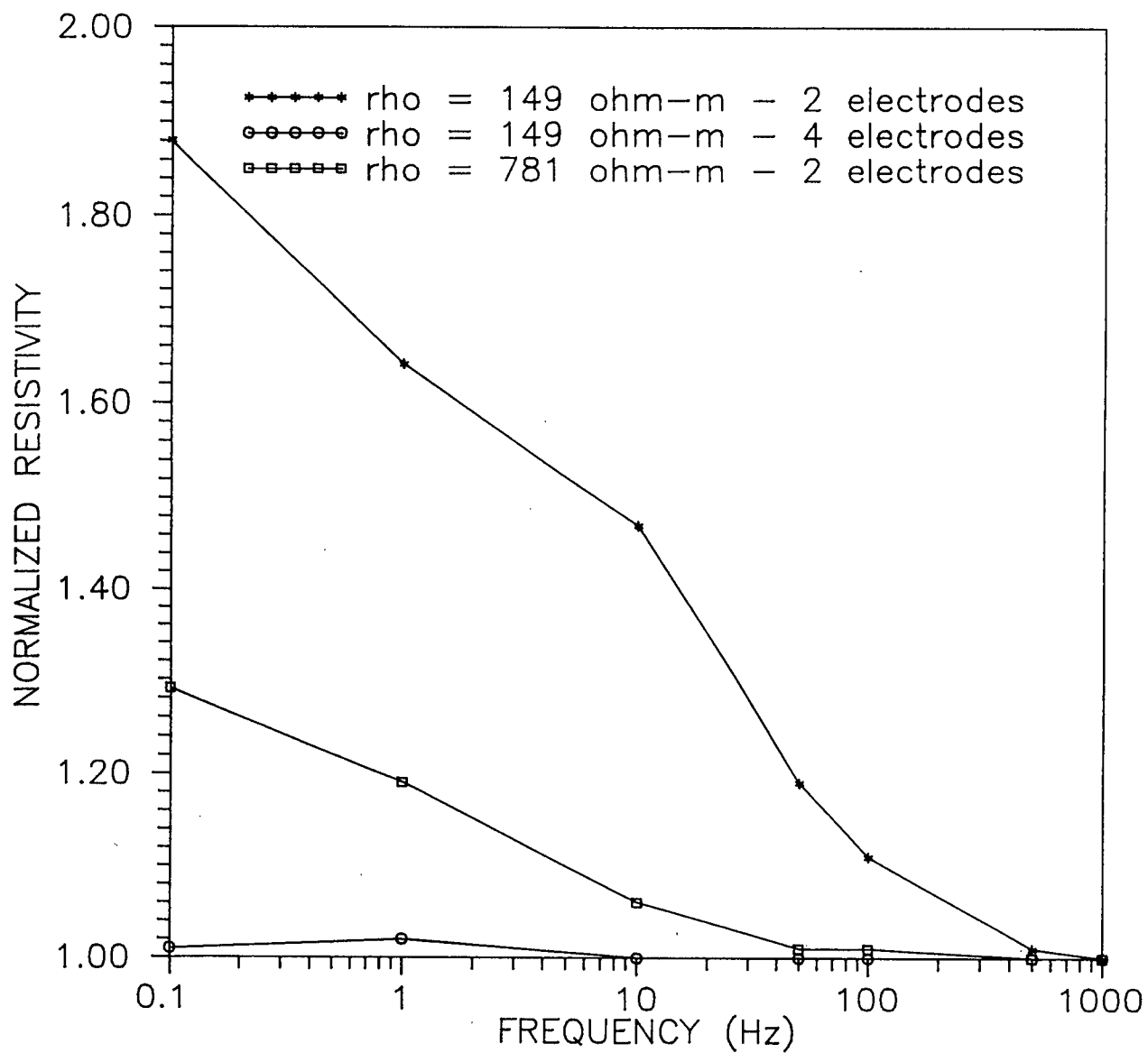


Figure 3.1 Inner and outer electrode normalized resistivity measurements versus frequency

of electrode polarization. As 1000 Hz is approached the effect of polarization decreases, this is because the ions do not have time to accumulate at the electrodes. Therefore, a two electrode configuration can be successfully employed if the excitation frequency is adequate. The advantage of a two electrode configuration over a four electrode probe is ease of fabrication.

3.3.2 Electrode Spacing

Three factors are involved when determining the spacing used. Smaller distances between the electrodes allow for the possible detection of thinner layers of contrasting resistivity. Wider spacing provides a greater penetration into the soil and should give a more accurate determination of in-situ resistivity. With a four electrode array, if the distance between the potential and current electrodes is too small the potential electrodes will become polarized if a very low excitation frequency is employed. From a number of lab tests at different electrode spacings it was found that for 5 mm wide electrodes, spacings as small as 15mm from centre to centre were adequate in providing accurate determinations of resistivity.

3.3.3 Excitation Frequency

Alternating current excitation supplies are used in order to avoid electrode polarization. An upper limit to the frequency chosen for the probe is a few thousand hertz to avoid inductive

coupling. A few practical limitations were also encountered. Sixty hertz should be avoided since noise from power sources may affect the instrumentation. The frequency must high enough to ensure accurate AC to RMS conversion. As seen from Figure 3.1 this frequency must be high enough to avoid electrode polarization of the outer electrodes. It is also notable that the effect of electrode polarization is different for varying fluid resistivities. The frequency chosen for the probe was one kilo-hertz. This frequency meets all the desired criteria and is also within the range 25-3000 Hz suggested by the ASTM (D1125-82) for conductivity measurements of water.

3.3.4 Measurement Range

Electrical resistivity of the ground can vary over a range of many orders of magnitude. With both conducting and insulating contaminants being considered a wide measurement range is necessary. With very conductive contaminants the measured voltages across the electrodes may be too small to accurately determine changes in resistivity, due to a low signal to noise ratio. The maximum input current is limited by the power supply.

3.3.5 Probe Materials

The material from which the probe is constructed must be resistant to abrasion and able to withstand reactive chemicals. The parts must also be easily replaced. The electrode material

must be reasonably durable, have a high conductivity, and be non-oxidizing. Lab and field testing was done with a number of different metals: brass, aluminum, copper, and beryllium copper. It was found that the results from the first three of the formentioned metals were essentially the same. The beryllium copper electrodes however became easily polarized due to the formation of an oxidized surface. Brass was chosen as it is reasonably abrasion resistant and is a good conductor. Aluminum and copper are not durable enough for field use. It is likely that stainless steel would also be adequate as an electrode material since it is both very durable and a good conductor.

3.4 Resistivity Module Description

The resistivity module, as shown in Fig. 3.2, consists of a four electrode array. The electrodes are made of brass and are isolated by plastic insulating sections and are sealed by O-rings. The insulation and the electrodes are field replaceable. The spacing between the centre of the electrodes is 25 mm, with the width of the electrodes being 5 mm. Simultaneous and continuous measurements are made with the inner and outer electrodes. Conversion of the measured AC voltage to RMS voltage takes place downhole. The electrode furthest from the tip is the current source. This electrode is set at the centre of the insulation to maximize the distance from the cone body. The cone body is grounded and will tend to draw some current towards it. Ideally all the current should go to the ground electrode, the electrode closest to the tip. The magnitude of

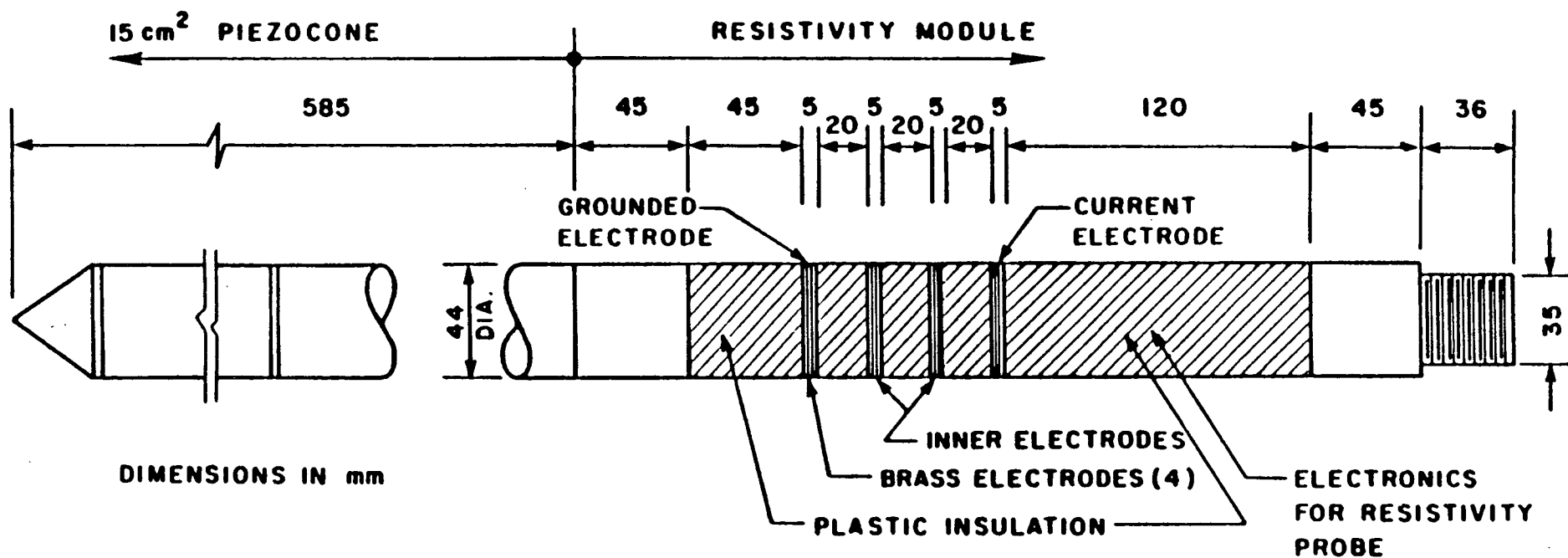


Fig. 3.2 UBC Resistivity Cone.

the constant current source, operating at 1000 Hz, is controlled from the surface. Since the peak applied current is very small, typically in the order of 150 micro-amps, the potential measured across the electrodes must be amplified downhole to the point where they fall into the range usable by the data acquisition system.

3.5 Resistivity Cone Calibration

The RCPTU measures electrical resistance between the electrodes. The resistance will increase if the electrodes are set farther apart or if the electrode surface area is decreased. The resistivity is the actual soil parameter and thus its value should be independent of the probes electrode geometry as long as the probes insertion into the soil does not change the in-situ resistivity. To convert from resistance to resistivity a lab calibration was made for both the outer and inner electrode pairs. This was accomplished by placing the probe in an open cylindrical chamber that completely surrounded the module. The chamber was filled with water and potassium chloride (KCl) was added in quantities such that measurements of resistance could be made at a number of different electrolyte concentrations. The resistivity of the solution was noted with a portable conductivity meter (Omega CDH-30) and the values were compared to the resistances measured by the probe. The conductivity meter was calibrated with a 0.01 M solution of KCl and then checked with a 0.10 M solution. From the calibration of the cone a linear relation between the resistance and the

resistivity was derived. For the dimensions given in Fig. 3.2 the calibration factor, K , (Eq. 3.3), was found to be 0.100 m for the outer electrodes and 0.838 m for the inner electrodes. In an Ertec (1987) report they note that K is dependent on the penetration of the electric field into the ground, or alternatively stated K will vary with different soil types. One way of providing some level of confidence as to the validity of the calibration factor is by comparing the resistivity results determined by both the inner and outer electrode sets. Differences in measured resistivity values between the two electrode sets will be discussed in Chapter 5. For cohesive soils lab resistivity measurements could be made on tube samples for comparison.

3.6 BAT Water Sampling System Description and Use

Besides making measurements of the resistivity of tube samples the only other way of gauging the reliability of the resistivity cone is to measure the conductivity of the pore fluid at the site of a RCPTU test. The easiest way of doing this was with the BAT ground water sampling system developed by Torstensson (1984). This system was designed to have a filter tip pushed into the soil sediments with cone penetration equipment. In this case a steel BAT tip, coupled with a friction reducer was pushed into the soil with AWL rods. At one metre intervals a hypodermic syringe sampling system is lowered through the rods, penetrating a rubber septum at the tip, and extracts a sample. The small tip volume is quickly purged and a

second sample is taken, from which the conductivity is measured by using an Omega CDH-30 portable conductivity meter. The BAT and RCPTU resistivity values should correlate quite well as they are both approximately sampling a similar volume of soil. In the case of the cone the outer electrodes are 7.5 cm apart and for the BAT tip the length of the porous filter is approximately the same distance. If measurements of the conductivity are made immediately after the water sample is drawn from the ground no temperature corrections are necessary to compare the resistivity of the pore water to that measured by the RCPTU. If the samples are stored and the conductivity measured at a later time the in-situ temperature at that depth must be known so that the resistivity values may be corrected to a common temperature.

3.7 Field Testing Procedures

All the field work involved in the research was carried out from the UBC in-situ testing vehicle, of which a description is provided by Campanella and Robertson (1981). Cone data was collected using the UBC in-situ testing digital data acquisition system, which has the capability to simultaneously record eight channels. Seven channels (bearing, friction, lower pore pressure, upper pore pressure, temperature, resistivity1, resistivity2) were recorded during penetration at intervals of 25 mm. The preparations involved in resistivity testing are the similar to those involved with the standard piezocone test. These procedures are outlined in Robertson and Campanella (1988). The only additional preparatory step for the RCPTU is

that the AC excitation voltage is set. This excitation voltage controls the amount of current supplied to the electrode array according to the relation:

$$[3.1] \quad I = V / 47.5k\Omega$$

where: V = input voltage (RMS volts at 1kHz)
 I = excitation current (RMS amps)

Hence, an appropriate choice of voltage must be made based on the desired range of resistivities to be measured, where the resulting resistivity will follow the relations:

$$[3.2] \quad R = V / (I * A)$$

where: R = resistance (ohm)
 I = current (RMS amp)
 V = output voltage (RMS volt)
 A = amplifier gain (50 for outer electrode pair, 500 for inner electrode pair)

$$[3.3] \quad \rho = K * R = (1/\text{conductivity})$$

where: ρ = resistivity (ohm-m)
 K = calibration factor

The maximum allowable input voltage is 10 V without corrupting the sinusoidal nature of the output signal. This results in a maximum allowable input current of 210 μ A. The allowable input voltage can be also limited to a lower value if the resistivity output voltage from the DAS exceeds 7.5 V RMS. Therefore, during testing, if the output voltage starts to exceed 7 V RMS penetration should be stopped and the input voltage should be lowered to an appropriate level. Care must be taken to note the input voltage prior to each test and then any subsequent changes. From the sites investigated for this research it was found that an input voltage 5 V RMS provided the

best accuracy without exceeding the range of the DAS. This resulted in a possible range of measurement of 0 to 119 ohm-m. If higher resistivities were expected at a site a lower input voltage should be chosen. The frequency of the input signal must be maintained at 1000 Hz since a variation in the frequency will alter the observed calibration of the electrodes. This is because the behavior of the electronics is frequency dependent due to the capacitive coupling of the electrodes to the probe circuitry.

Ideally the resistivity module should be regularly maintained. This entails cleaning the electrodes after each test and periodically cleaning and inspecting the O-ring seals. After prolonged use the insulation and the electrodes should be replaced due to abrasional reduction in their outer diameter which may affect the repeatability of the resistivity measurements.

3.8 Data Reduction

In addition to the normal corrections necessary to cone data some data manipulation must be done to the resistivity data. For purposes of plotting, the resistivity data must be offset 71 cm upward to the same datum as the cone tip. The resistivity data from the cone is in the form of a measured voltage from across the electrodes. The voltage is converted to a resistance based on the constant current chosen for the particular test. The conversion to resistivity is based on the calibration done

in water. The resistivity provided from this calibration should be fairly representative of the in-situ calibration factor. The applicability of the calibration factor is discussed later in the results. Resistivity is also temperature dependent. The results in this research have not been corrected to a common temperature for comparison. The temperature changes between sites are not large enough to significantly change the results. Water sample resistivity values have been corrected to the same temperature as the in-situ resistivity measurements.

No temperature calibration has been made. It is assumed since that almost all conduction is electrolytic that the same temperature correction for a fluid solution holds for any particular soil (2% /degree Celsius). This could be tested for different soils by forming samples around the cone in the calibration chamber. When penetration takes place the probe does heat up due to friction, but the temperature of the probe will not affect the measurements. If comparisons of resistivity at a site are being made over a long period of time the in-situ temperature should be noted if seasonal soil temperature conditions change appreciably.

4. RESEARCH SITES AND FIELD RESULTS

All field testing was done from the UBC in-situ testing vehicle. Testing started on Oct 31, 1989. The first six tests were needed to fine tune the probe electronics. The first test with the final working configuration was RES 89-7. A table showing the test schedule is presented in Table 4.1. A map showing the location of the test sites is shown in Figure 4.1. Most of the testing was done at the nearby McDonald Farm research site. The final three tests were conducted in deposits of glacial origin in the lower Fraser Valley. A description of each site is provided along with a description of the stratigraphic and resistivity profile from each site.

4.1 McDonald Farm

4.1.1 Site Description

This site is located at an abandoned farm on the north side of Sea Island as shown on the area map (Figure 4.1). A more detailed map of the site showing the location of the various tests is presented in Figure 4.2. The elevation of the site is +1.6 m with variations in elevation of no more than 0.5 m. The area is mostly covered with low grass and light deciduous vegetation.

Sea Island is part of the prograding Fraser River delta. The lowlands in this area are underlain by a complex sequence of

Table 4.1 In-situ testing program

Site	Test No.	Date	Coordinates
McDonald Farm	RES 89-5	Feb 21/89	210.4, 28.7
	RES 89-7	Mar 6/89	29.5, 0.2
	RES 89-8	Mar 6/89	29.5, -99.9
	RES 89-9	Mar 6/89	29.5, -50.2
	RES 89-10	Mar 17/89	29.5, -0.5
	RES 89-11	Mar 29/89	214.1, 2.2
	RES 89-12	Mar 29/89	141.0, 0.2
	RES 89-13	Mar 29/89	424.3, -16.1
	BAT 89-2	Apr 3/89	215.1, 2.2
Strong Pit	RES 89-14	Apr 6/89	n/a
Langley	RES 89-15	Apr 6/89	n/a
Colebrook	RES 89-16	Apr 18/89	n/a

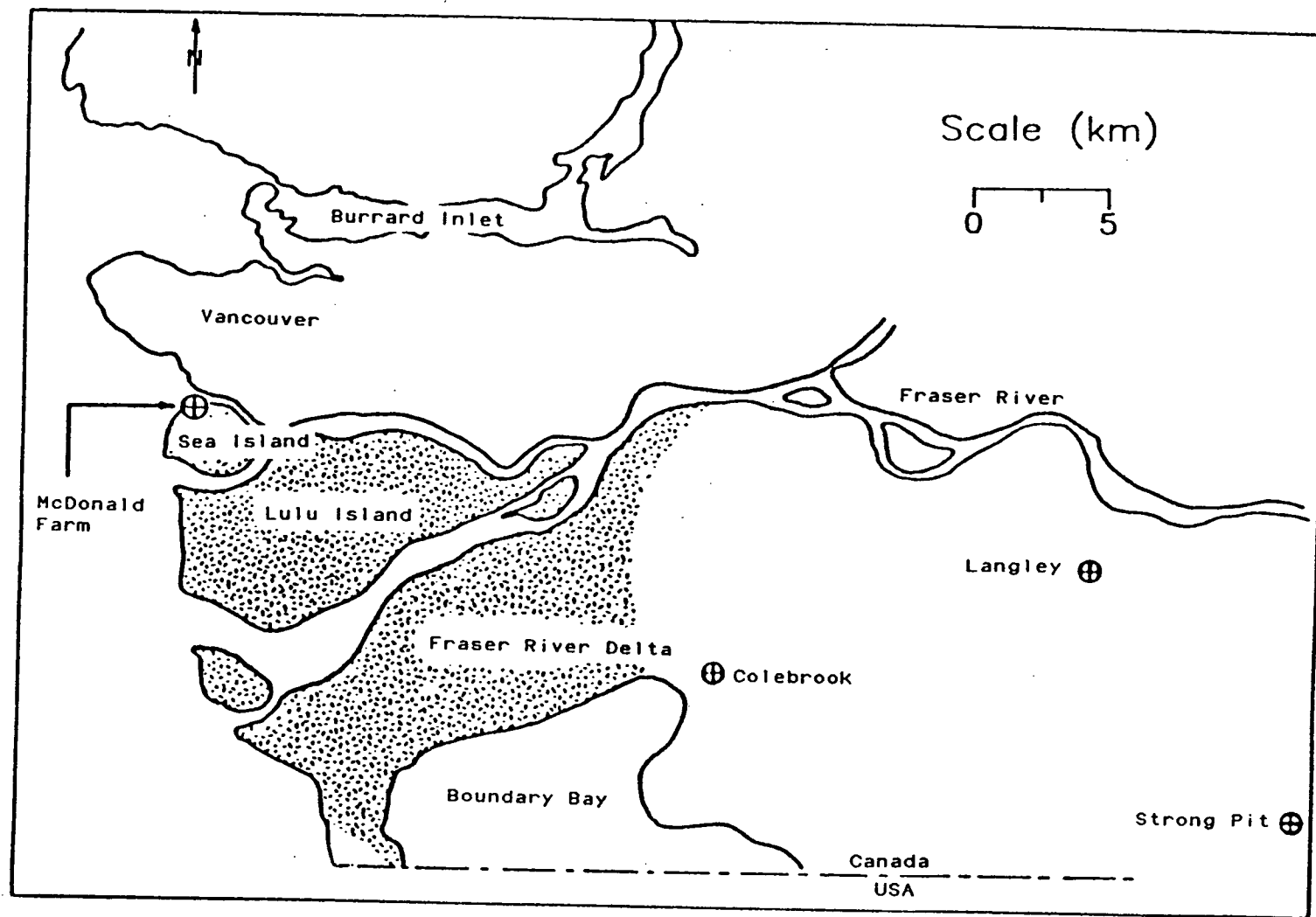


Fig. 4.1 General Location of the U.B.C. Research Sites

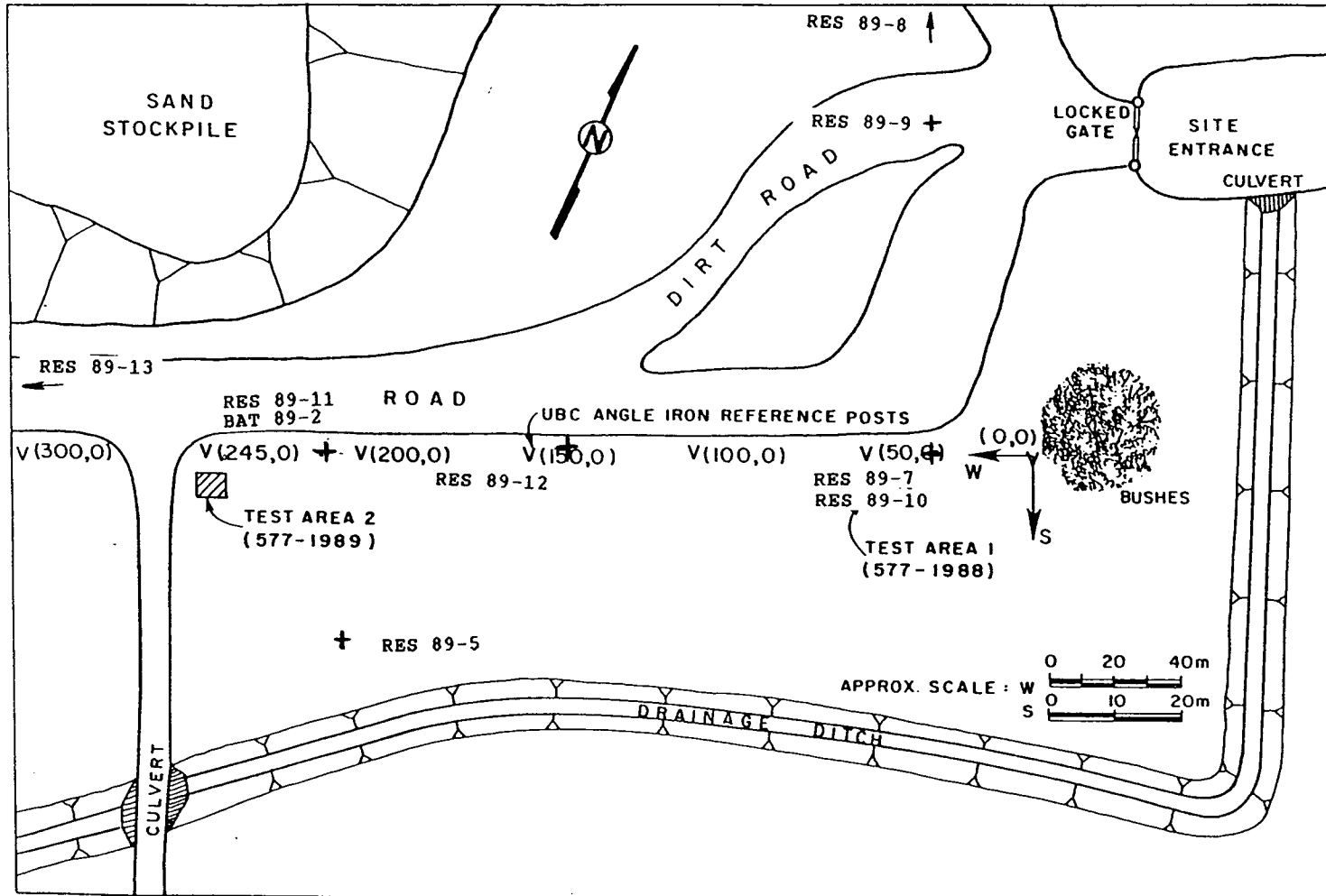


Figure 4.2 McDonald Farm research site

glacial, fluvial, and marine deposits up to a depth of 300 m, with the more recent Fraser River sediments accounting for up to 200 m of this sequence. The groundwater table at the site varies from 1 to 2 metres depending on rainfall and tidal influence. During the winter some surface ponding occurs due to the low permeability of the surface overbank silt deposits, thus limiting vehicle access.

4.1.2 Stratigraphic and Resistivity Profile

An interpreted resistivity cone profile (RES89-7) representative of the site is presented in Figure 4.3. Typically on the site from the surface to a depth of 2 to 4 m overbank sandy to clayey silt can be expected. This is followed by a sand horizon to a depth of 15 m. This horizon consists of deltaic and distributory channel fill sand and silty sand. This has resulted in a highly variable soil relative density, horizontally and vertically across the site. The sand is medium to coarse grained with thin layers of medium to fine sand. Sieve analysis from a nearby SPT show that the sand is coarse grained with increasing fines content near the surface. At a depth of 15 m the sand becomes finer and is occasionally interbedded with silt. This transition layer grades into a clayey silt.

From the resistivity profile the high salinity of the pore water is evident (25 to 2 ohm-m). This is due to the infiltration of brackish water found near the mouth of the

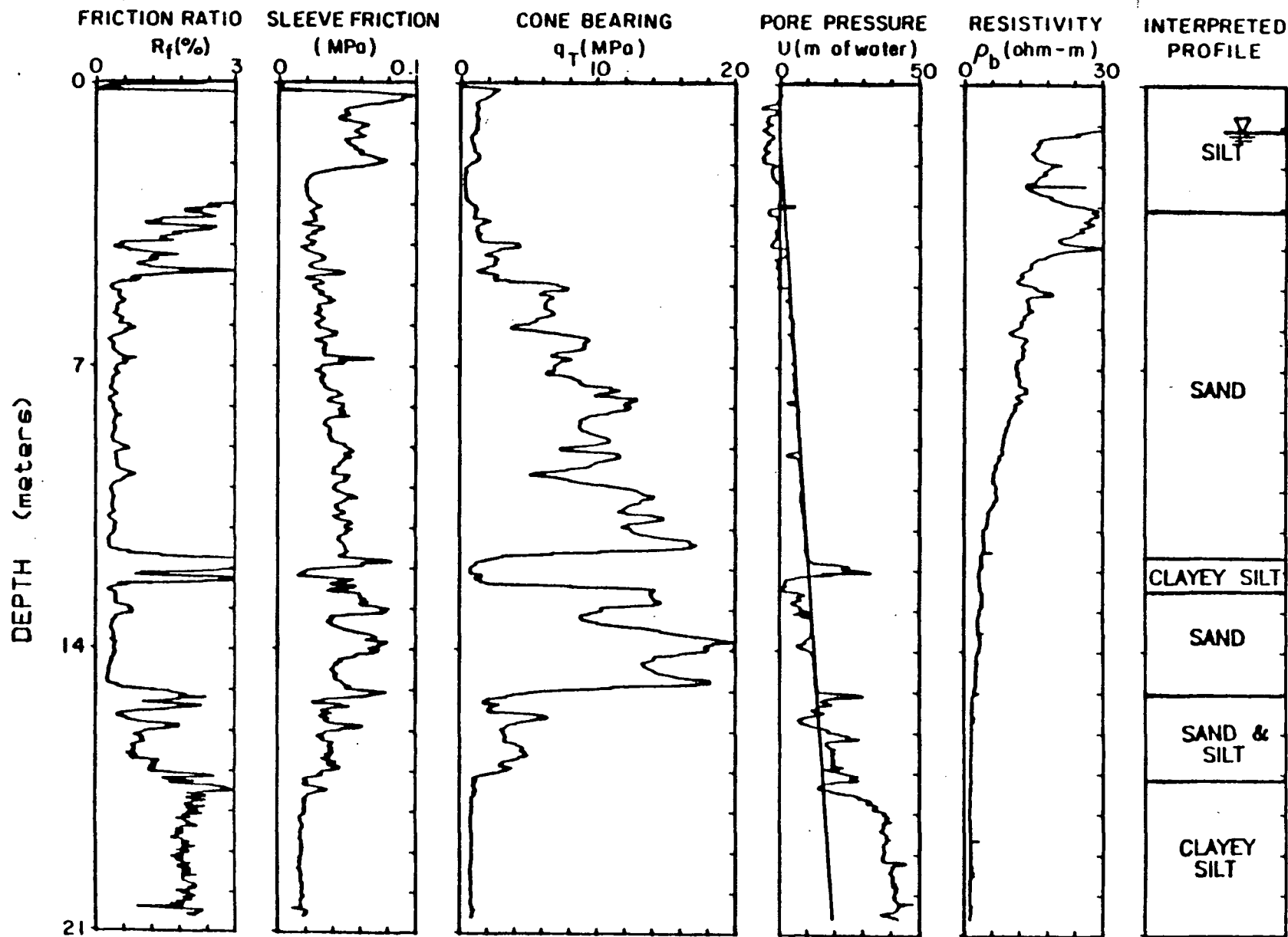


Fig. 4.3 Resistivity Cone Sounding at McDonald Farm, Vancouver International Airport, B.C.

Fraser River. The salinity of the pore water increases with depth, as illustrated by the decreasing resistivity, until reaching a limiting value in the clayey silt of about 2 ohm-m. The groundwater table is noted by the sudden drop in resistivity at 1.2 m.

4.2 Fraser Valley Glaciomarine Deposits

The current surface geology of the Fraser Valley is dominated by glaciomarine clay deposited during the Fraser Deglaciation. At the time of deposition the lowland areas were depressed by more than 200 m by the weight of the cordilleran ice sheet. During the recession glaciomarine deltaic deposits of the Capilano and Fort Langley Formation were deposited.

While the two formations were deposited at the same time there are some features that make them distinct (Clague and Luternauer, 1982). The deltaic deposits of the Capilano Formation were deposited from melt water from the Coast Mountains so their mineralogy is dominated by granitic rock types. Fort Langley deposits were derived from rock of the Cascade Mountains to the east of the Fraser Valley. Capilano sediments, which contain no ice contact sediments, were deposited in a more saline environment. The Capilano sediments consist of raised deltas, intertidal and beach deposits and glaciomarine sediments. With the resultant uplift of the land and leaching these clays would have a greater tendency to become very sensitive. The Fort Langley glaciomarine clays were

deposited closer to the decaying glacial ice front and thus tended to have an originally lower salinity. The farther east in the Fraser Valley the lower the salinity of the depositional environment.

4.2.1 Strong Pit

4.2.1.1. Site Description

The Strong Pit research site is located within an abandoned gravel pit approximately 4 km west of Abbotsford Airport (see location on Figure 4.1). The site is on the north side of a valley which is occupied by Pepin Creek. The valley was incised by glacial outwash and contains outwash sand and gravel and ice contact deposits of the Sumas Formation. The south side of the valley contains ice contact deposits, implying that site was just west of the farthest local advance of Sumas Ice during the Fraser Glaciation. Immediately to the north of the site Fort Langley glaciomarine stoney clay and sand is present at the surface. The close proximity of the Fort Langley clay to the site would suggest that the clay tested at the site belongs to the same formation. The variable depth to clay throughout the site may be due to irregular erosion by the Sumas melt water.

4.2.1.2 Stratigraphic and Resistivity Profile

The RCPTU profile, as shown in Figure 4.4, can be divided into three zones. The first 1.5 m consist of freely draining

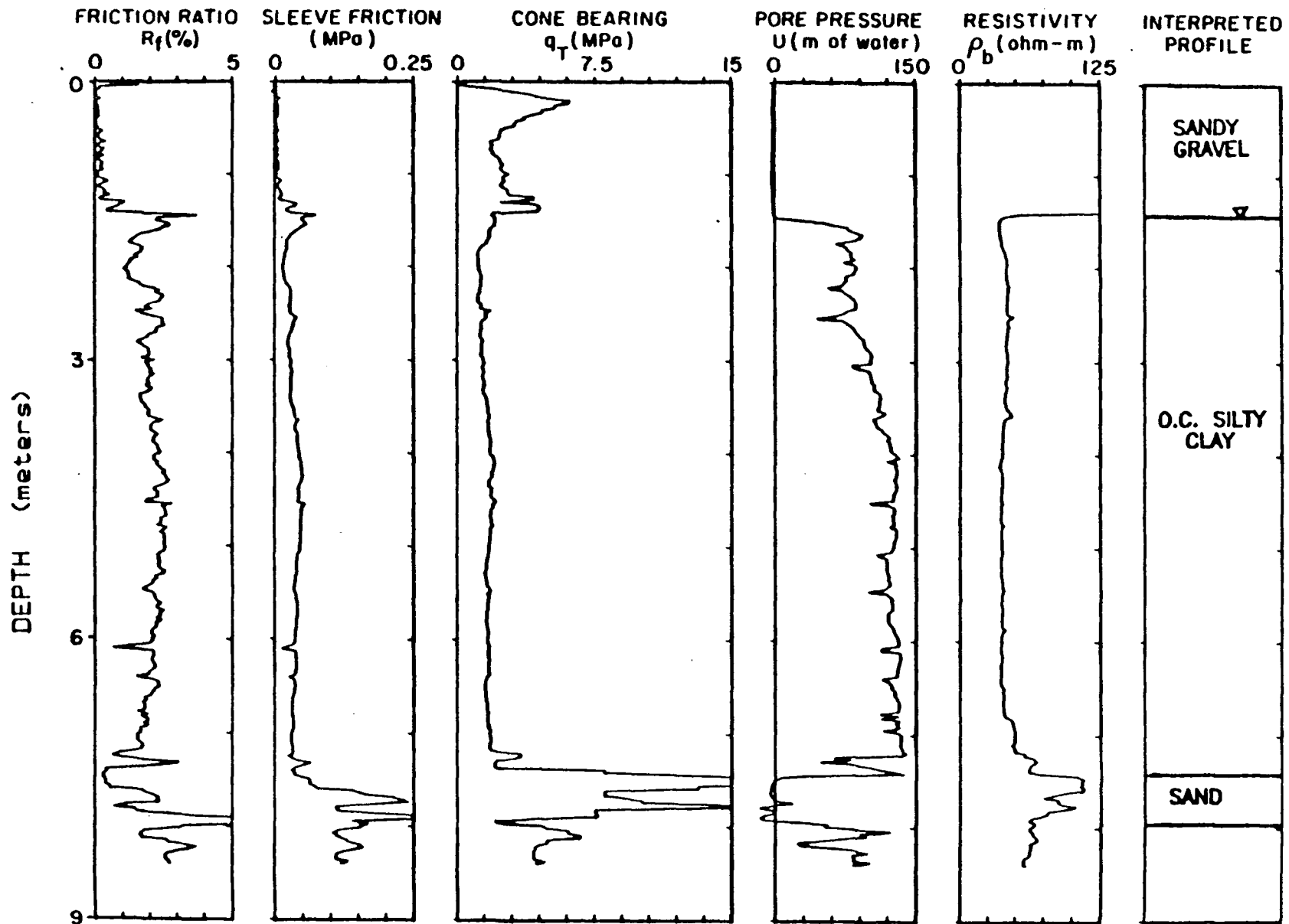


Fig. 4.4 Resistivity Cone Sounding at Strong Pit, Aldergrove, B.C.

sand and gravel which was originally 10 m thick at the site. Below the fill is overconsolidated stoney clay. The boundary between the fill and the clay is clearly marked by the sudden increase in pore pressure and drop in resistivity. There is a perched water table at this point. The presence of a harder desiccated layer at the surface of the clay (1.5 to 1.8 m) results in a higher cone bearing and slightly lower resistivity. The lower resistivity could be due to surface water filling of small fissures in the clay. From 1.8 to 6.8 m the resistivity is fairly constant at a value of 35 ohm-m. At 6.8 m there is a distinct increase in the resistivity of the clay. This would be due to the proximity of the sand layer. The sand layer contains fresher water and thus would tend to leach the adjacent clay to some extent. The last unit in the profile is a medium dense sand. In the sand the resistivity is higher due to the lack of conducting clay minerals but more so due to higher pore water resistivity. In the sand layer the more denser parts of the layer, higher Q_c , also have the highest resistivities.

4.2.2 Langley

4.2.2.1 Site Description

The Langley site is located approximately 100 m west of the B.C. Rail overpass along the Trans Canada Highway in the municipality of Langley. This area is part of the Surrey upland. The area is underlain by Capilano sediments consisting of glaciomarine clay with numerous thin interbeds of silt and

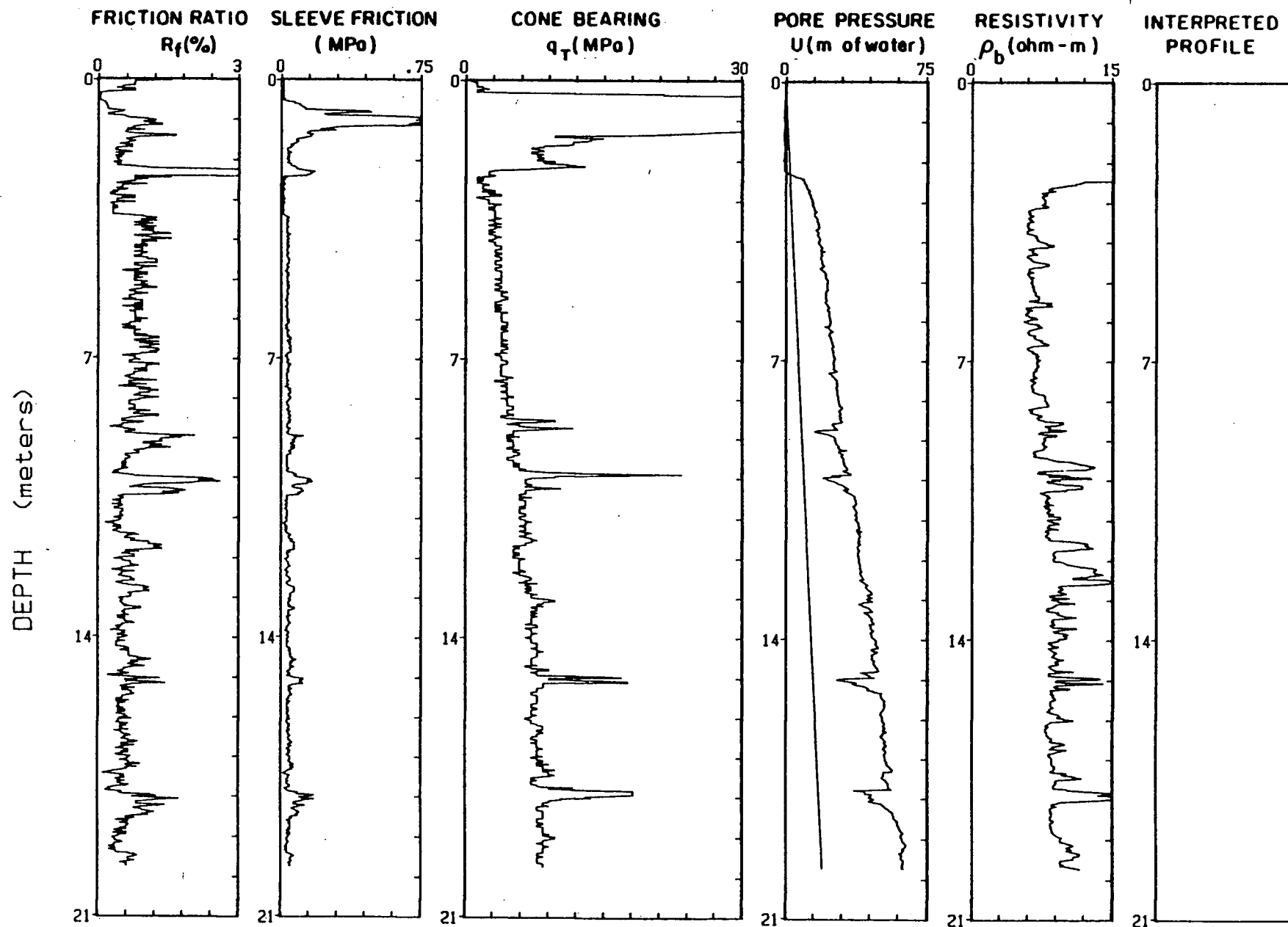


Fig. 4.5 Resistivity cone sounding at Langley.

fine sand.

4.2.2.2 Stratigraphic and Resistivity Profile

A resistivity cone profile is presented on figure 4.5. The site stratigraphy consists of clay overlain by 2.3 m of fill and desiccated clay. The beginning of the clay layer is marked by an increase in pore pressure and drop in resistivity as the soil becomes saturated. Generally the resistivity falls between 6 and 9 ohm-m, increasing with depth, with occasional peaks of up to 15 ohm-m. The clay is normally consolidated with occasional narrow interbeds of fine sand. These thin layers are noted by increased cone bearing and low pore pressures. These sand layers also produce pronounced increases in the resistivity. The sand layers noted by bearing and pore pressure do not account for all the resistivity highs, such as at 12.5 m. These high values are most likely due to lower pore water salinities in the clay or could be sand layers that are too narrow for the cone bearing resistance to respond to.

4.2.3 Colebrook

4.2.3.1 Site Description

The Colebrook site is located immediately west of the south abutment of the Highway 99 railway overpass. The area is located within the Nicomekl-Serpentine Valley at an elevation of several metres above sea-level. The valley has been subjected to marine

sedimentation throughout most of the Quaternary Period (Armstrong, 1984) with the Capilano Formation being the most recent. The Capilano sediments in this area consist of glaciomarine clay overlying proglacial deltaic sand and gravel.

4.2.3.2 Stratigraphic and Resistivity Profile

A resistivity cone profile from the site (Fig. 4.6) shows that the stratigraphy consists mainly of marine clay overlying dense sand. At the surface there is 0.5 m of topsoil. In the clay the resistivity is fairly constant, perhaps with a small tendency toward decreasing, between 4.5 and 25 m. The resistivity from 4.5 to 14 m has some minor variability, while from 14 to 25 m the profile is very uniform. From the water table to a depth of 4.5 m the resistivity is much lower suggesting either a change in lithology or a change in pore fluid resistivity. This layer of lower resistivity may be due to deposition of dissolved solids since the surface is a zone of groundwater discharge. The sand layer below the clay has artesian pore pressures therefore there would be some component of upward flow through the clay layer. The upper clay could also have a greater organic content. Organic soils tend to have a very high CEC, and higher CEC soils are more conductive. Leaching of the clay by this process would explain the relatively high resistivity for this soil, considering the original saline depositional environment. A lowered pore water salinity may cause the clay to be very sensitive.

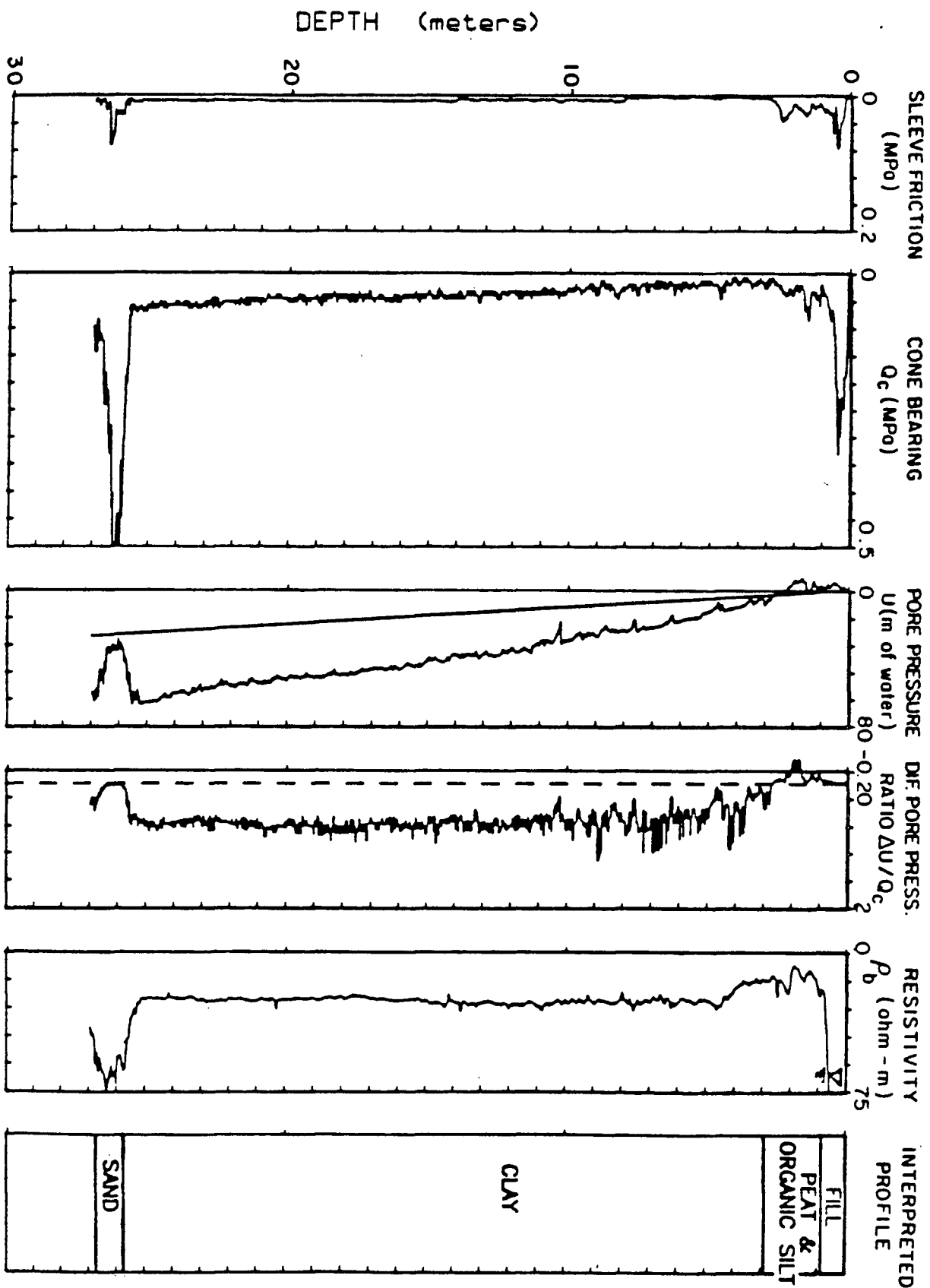


Fig. 4.6 Resistivity Cone Sounding at Colebrook Road at King George Highway, White Rock, B.C.

5. INTERPRETATION AND DISCUSSION OF RESULTS

A number of observations may be made on the basis of the resistivity cone profiles collected from the research sites. Questions regarding; (1) The repeatability of the RCPTU, (2) The profiling capability of the instrument, (3) The effect of changing soil lithology on resistivity, (4) The determination of pore fluid resistivity from bulk resistivity, and (5) The effect of electrode spacing on the measured resistivity, will be examined in this chapter.

5.1 Repeatability of Results

With the development of new instrumentation it is important to verify the validity of the results by checking the repeatability of the measurements. Repeatability provides confidence in the results, enabling the comparison of reasonably small changes in groundwater quality from different test locations.

Two tests, one metre apart, were conducted at McDonald Farm eleven days apart. The resistivities measured from the two holes by both the inner and outer electrodes are superimposed on Figure 5.1a and 5.1b. These profiles indicate good repeatability for both the inner and outer electrodes. The profiles shown in Figure 5.1 only deviate in the upper clayey

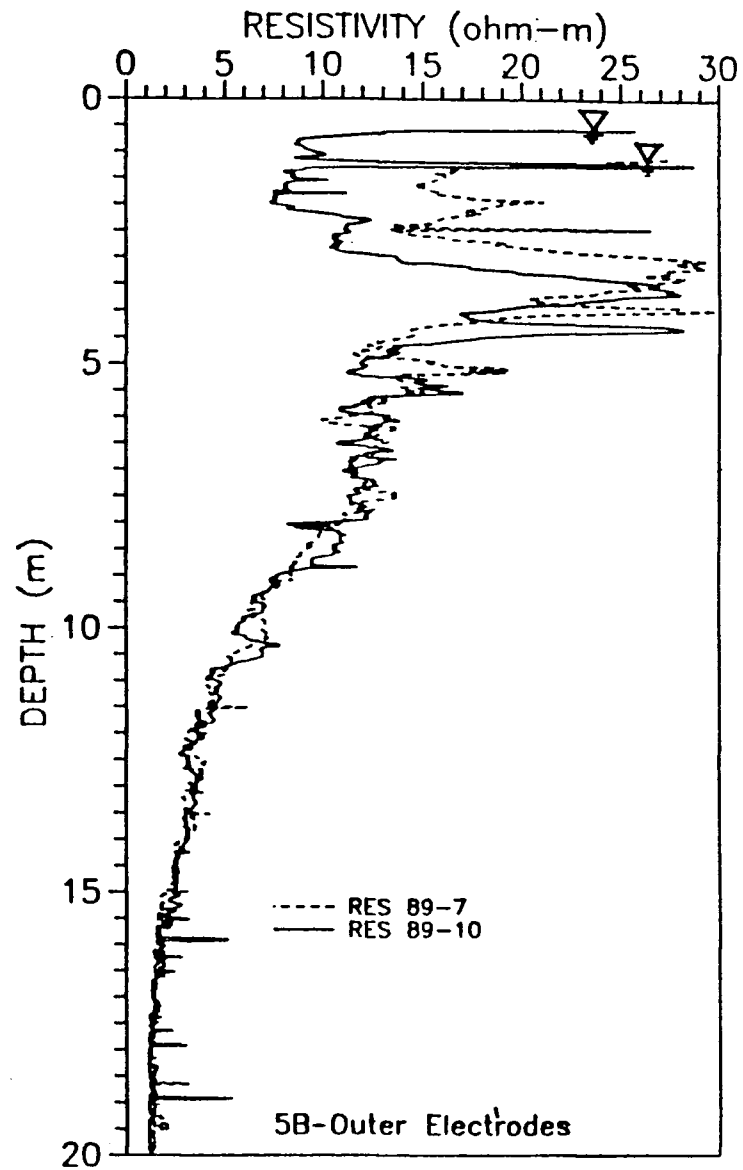
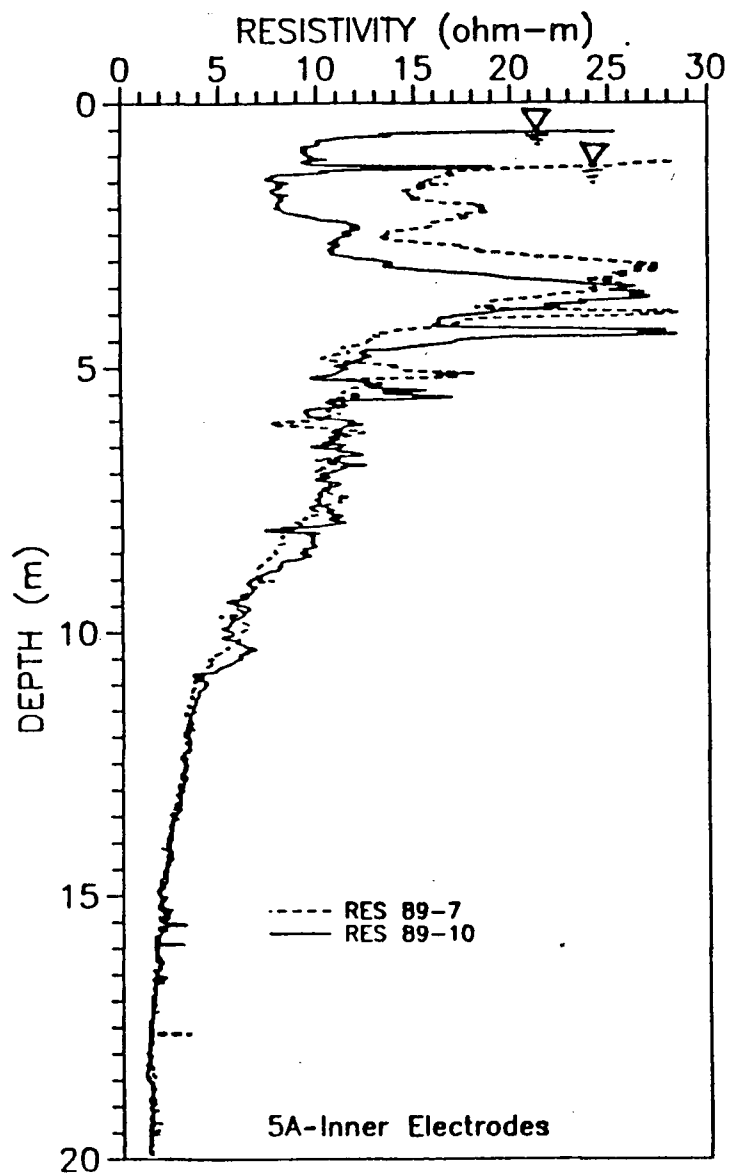


Fig. 5.1 A Comparison of Two Adjacent Resistivity Logs Made 11 Days Apart for (a) The Inner Electrodes, and (b) The Outer Electrodes.

silt, this is due to water table fluctuations from rainfall at the site between the time the two soundings were made. The groundwater table is closer to the surface for RES 89-10. There is also a sharp peak for RES 89-10, where the groundwater table for RES 89-7 was. Due to the highly variable nature of the sand at the site the two profiles do not completely match up but the same peaks and troughs are evident from both tests.

5.2 Profiling Capability

The resistivity cone is ideal for rapidly determining cross sectional profiles of groundwater quality. Typically this would be done to delineate the boundaries of a contaminant plume. While there is no contaminant plume as such at McDonald Farm the site does provide a similar application - a salt water to fresh water interface. The interface between salt water and fresh water is not distinct. There is a zone of hydrodynamic dispersion (Bear and Verruijt, 1988) which results in a more gradual transition between fresh and brackish water. The salt water, due to its higher density will tend to migrate below the fresh water.

The salt water to fresh water interface at McDonald Farm is further complicated by seasonal fluctuations in river salinity. During periods of low flow in the winter the river water at McDonald Farm becomes very brackish ($\rho = 0.64$ ohm-m in early February) with a salinity in order of that of sea water ($\rho = 0.2$ ohm-m, sea water average, Telford et al, 1976). When the river

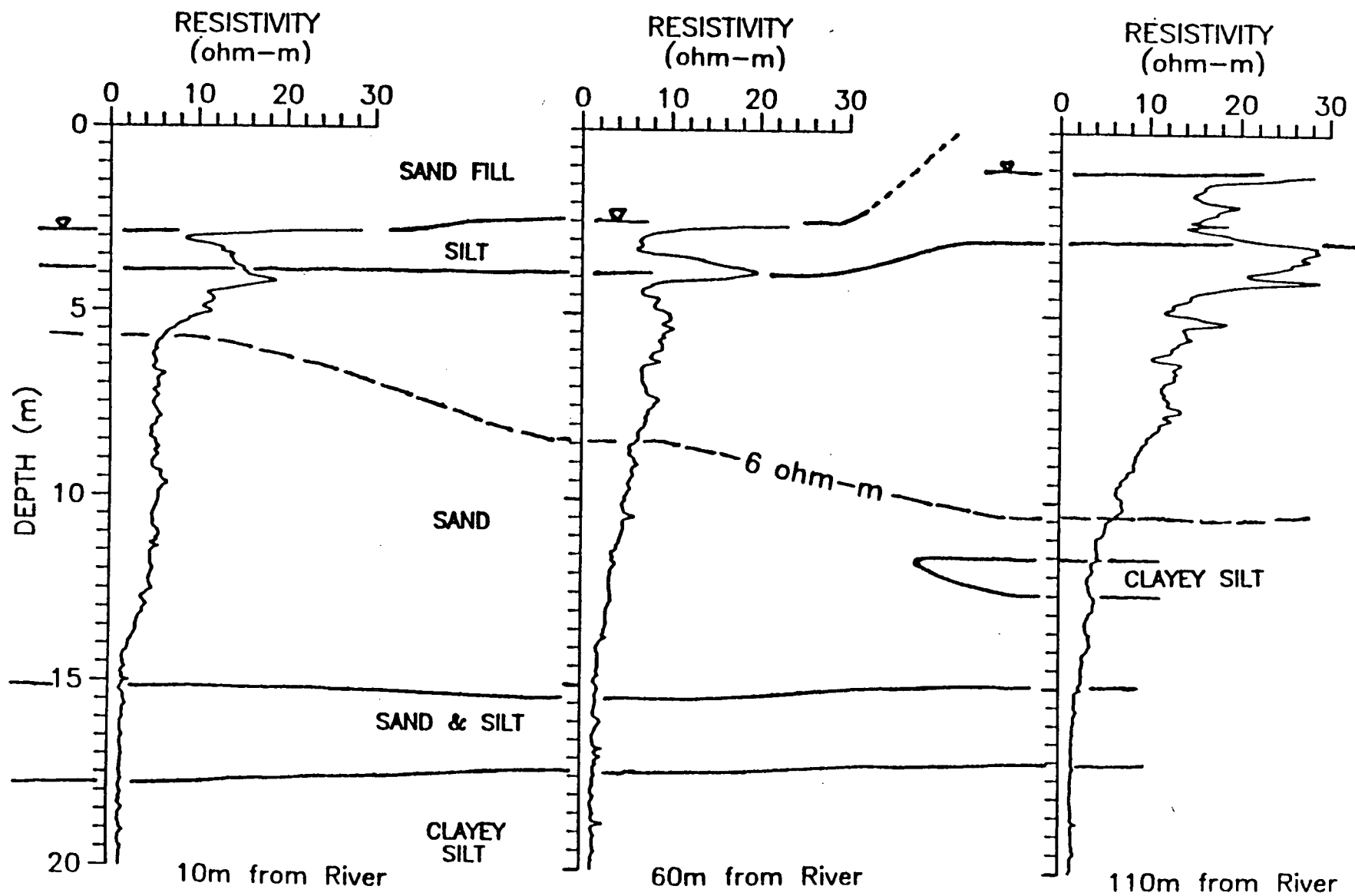


Fig. 5.2 Stratigraphic and Resistivity Profile of McDonald Farm Site.

flow is increased due to either prolonged rainfall in the winter or snow melt in the spring and summer the salinity drops considerably ($\rho = 14.8$ ohm-m measured on May 9, 1989). This variability in salinity would be rapidly reflected in the groundwater adjacent to the river. Farther away from the river the salinity of the groundwater would not have that much seasonal variability.

Figure 5.2 illustrates a cross section through three RCPTU soundings, each separated by 50 m, in a line perpendicular to the river bank. The figure shows the resistivity for each test along with a 6 ohm-m contour and the stratigraphy. The location of the holes (RES 89-7,8,9) is shown on the site map (Fig. 4.2). As illustrated by the cross section there is a decrease in the resistivity as the river is approached, as would be expected for the case of salt water intrusion. Below a depth of approximately 11 m there is very little difference between the resistivities from the three tests. This would be the case if there was very little groundwater movement below this depth. The resistivity of the silty clay does not vary at all across the whole site since it was deposited in a marine environment and there has been no subsequent groundwater flow through the clay. Near the surface, there tends to be an increase in the resistivity with depth of the overbank silt below the water table. This may be due to decreasing amount of conductive clay minerals with depth in the overbank deposit.

5.3 Effect of Soil Lithology

5.3.1 General Aspects

As discussed in the section on conduction in soil-pore fluid systems a number of different factors affect to bulk resistivity of the soil. By far the most important factor is the resistivity of the pore fluid. At low pore water resistivities the affect of surface conduction is insignificant in comparison to electrolytic conduction in the pore fluid. The situation is analogous to the total resistance measured by two resistors in parallel, where the resistors represent surface conduction and pore water conduction. For example, at McDonald Farm (hole RES 89-7), the clayey silt layer at 11.8 m does not provide an appreciable resistivity contrast with the sand bounding this layer. This is because a much greater proportion of conduction in both soils takes place through the pore water where the soil resistivity was only about 4 ohm-m.

When the pore water resistivity is higher the effects of surface conduction become more apparent. This was particularly true at the Strong Pit site and the Colebrook site where the clays have bulk resistivities of 35 and 25 ohm-m respectively, and the sands have values of 110 and 70 ohm-m. In clay minerals surface conduction is related to the CEC capacity of the soil. Soils with high CEC are clays, the more active clays will have a greater CEC, and organic soils (Olhoeft, 1985).

The resistivity measurement is also indicative of ground water flow regimes. At the Colebrook site recharge from ground water with a lower amount of dissolved solids than in the clay layer results in a greater resistivity. This was just the opposite at McDonald Farm where brackish pore water gives very low resistivities resulting in almost no difference between sand and clay resistivity.

5.3.2 Cone Parameter Relations to Soil Resistivity

With the simultaneous measurement of cone bearing, friction, and pore pressure, comparisons may be made with the resistivity to see how changes in mechanical soil properties affect the resistivity.

5.3.2.1 Friction Ratio Relationship

The friction ratio (R_f), sleeve friction stress divided by cone bearing stress expressed as a percentage, will increase with increasing K_o and increasing fines content. In sand deposits where K_o is constant R_f may be used to note increases in fines content. The presence of fines in a sandy soil may affect the resistivity in two ways: (1) increased fines content will decrease porosity since the fines will occupy void space between the sand grains. Decreasing the porosity has the effect of increasing the resistivity; and (2) the presence of fines may indicate the presence of conducting

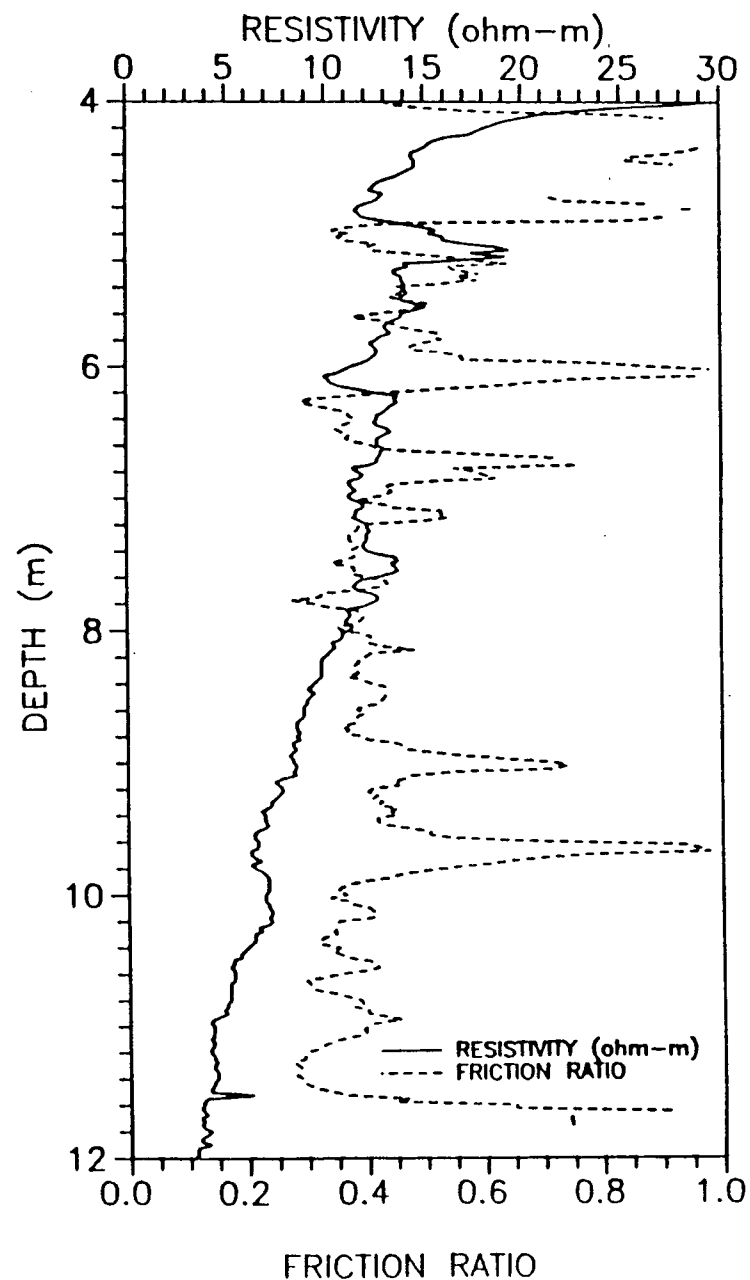
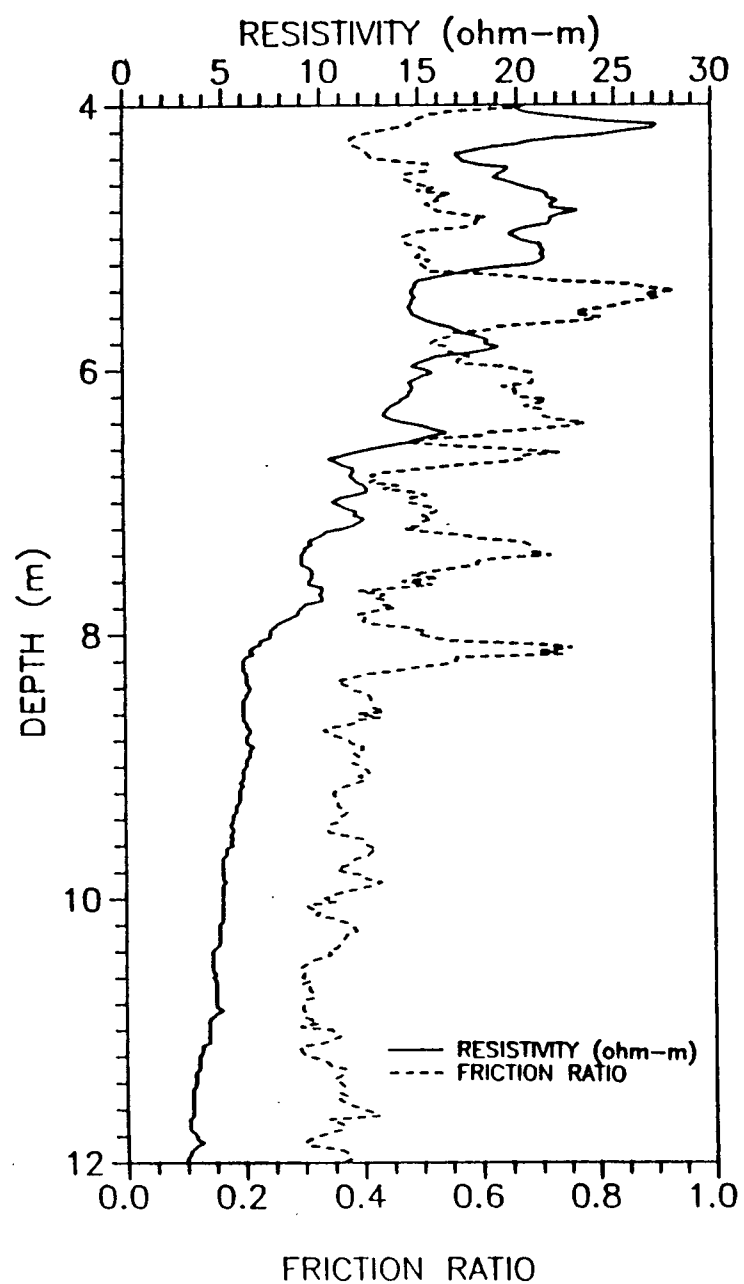


Fig. 5.3 A Comparison of the Resistivity (Outer Electrodes) and the Friction Ratio for Two Soundings from the McDonald Farm Site.

clay minerals, which would result in a decrease in resistivity. Figure 5.3 (McDonald Farm, RES 89-5,7) illustrates that increased friction ratio in sandy soils will tend to decrease the resistivity. Generally the peaks in the resistivity match the troughs in the friction ratio. This would suggest that, at least at this site, that fines in the sand will decrease the resistivity. As the resistivity decreases this effect becomes less pronounced, this being due to the domination of pore fluid conduction over other conduction mechanisms at low resistivities. The relationship between friction ratio and resistivity was noted by ERTEC (1987). They normalized their conductivity data as a function of friction ratio to remove the effects of lithological change from their data. However, the complex nature of soil resistivity make the application of such corrections uncertain.

5.3.2.2 Cone Bearing Relationship

Cone bearing in sands has been shown to be related to horizontal effective stress, compressibility, and relative density (Robertson and Campanella, 1988). Relations between relative density and cone bearing normalized by horizontal effective stress have been proposed so it should be reasonable to expect there is a similar correlation between formation factor and normalized cone bearing, since the formation factor is related to soil porosity by Archie's Formula. In low resistivity soils this relationship has been shown to be quite accurate (Jackson, 1978). Figure 5.4 relates apparent formation

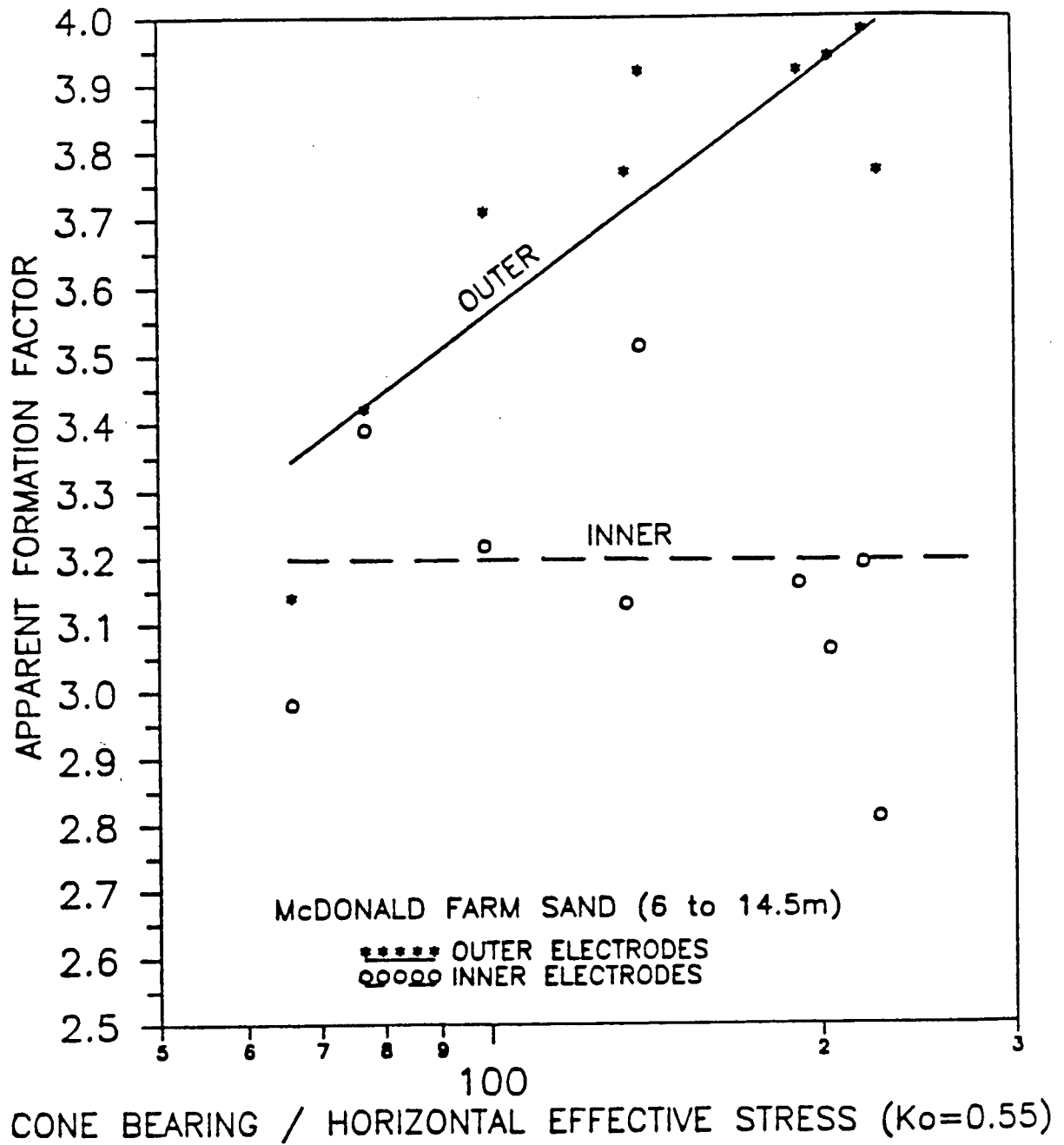


Fig. 5.4 Observed Relationship Between Apparent Formation Factor and Cone Bearing Normalized with Respect to Horizontal Effective Stress.

factor to the normalized cone bearing. While the relationship is not that strong it still illustrates that increased cone bearing, or decreased relative density will increase the formation factor.

5.3.2.3 Pore Pressure Relationship

No direct relationship between any pore pressure parameters and resistivity has been made. In general high pore pressures are indicative of a high fines content, thus a lower resistivity. In normally consolidated clayey soils, dilative behavior, which would be indicative of sand layers, may also be reflected by changes in the resistivity.

5.4 Determination of Pore Fluid Resistivity

From Figure 5.5 it can be seen that the pore fluid resistivity determined from BAT samples and the bulk resistivity measured from the cone relate quite well, with a formation factor between three and four. This correlation is expected on the basis of Archie's Formula. Given this, it should be possible to make reasonable estimates of pore fluid resistivities from the resistivity cone. The two quantities are related by the formation factor. Therefore, the pore fluid resistivity may be estimated by determining the formation factor by either: (1) site specific correlations between soil and pore fluid resistivity; or (2) Archie's Formula assuming that an accurate estimate of the soil porosity is known.

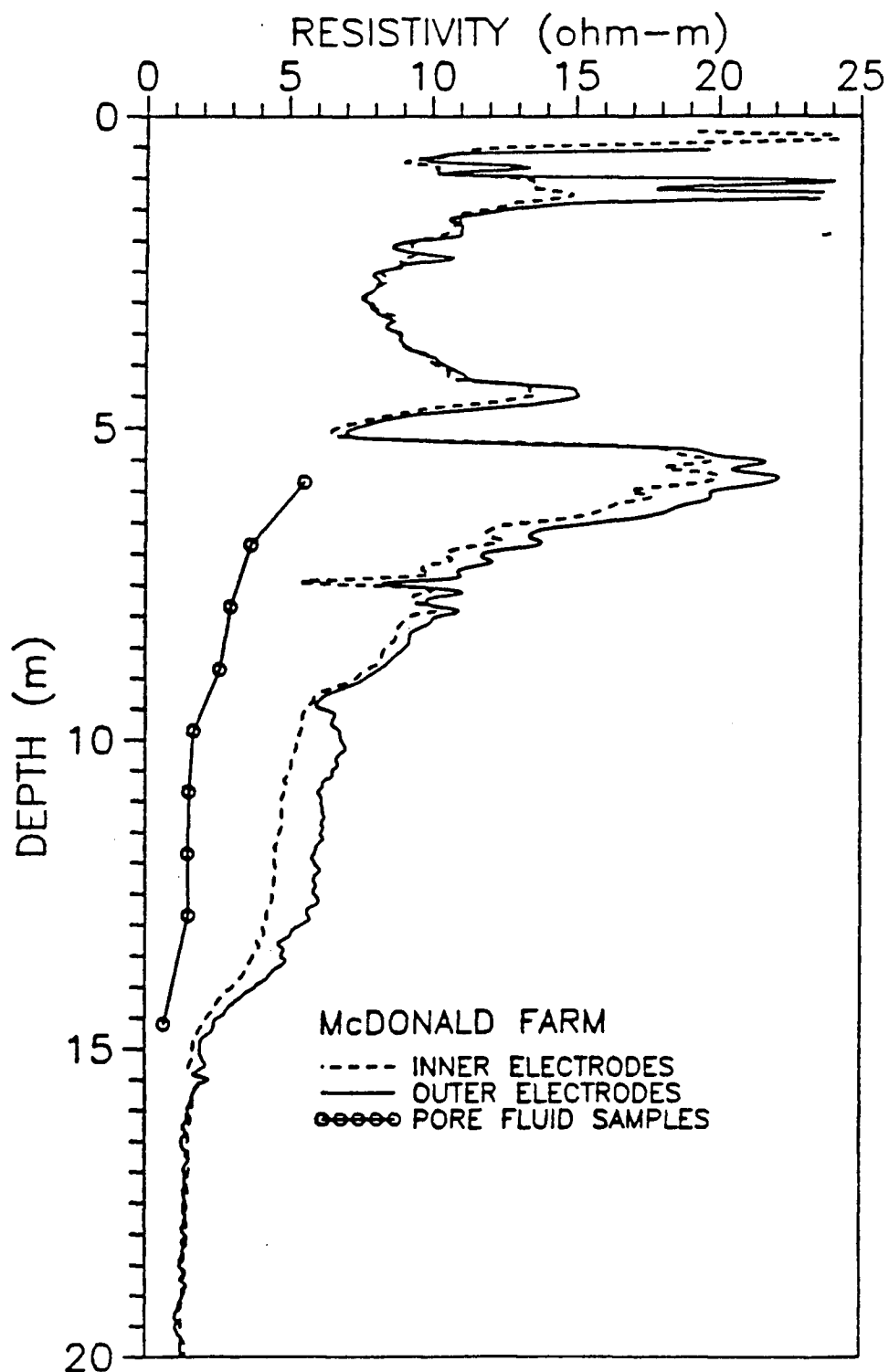


Fig. 5.5 A Comparison Between the Resistivity of Pore Fluid Samples and the Resistivity Measured by the RCPTU.

The estimation of pore fluid resistivity in clay is more difficult due to the effects of surface conduction. In clay the apparent formation factor is very dependent on the pore fluid resistivity, clay mineral content and type. From Colebrook the apparent formation factor was found to be 1.43 at a depth of 10.6 m on the basis of a water sample obtained from a BAT probe. This is considerably lower than the range of 3 to 4 that was noted in the sand at McDonald Farm. The silty clay at McDonald Farm has an apparent formation factor of 4 to 5. According to Archie's Formula the formation factor for a clay with a void ratio of 1 should be 4, assuming $m=2$. So that at the McDonald Farm site Archie's Formula was applicable since the pore fluid resistivity was very low. For $n=0.6, m=2$, $F_{\text{intrinsic}} = 2.8$ for Colebrook as compared to the $F_{\text{apparent}} = 1.43$. This difference is due to clay mineral surface conduction.

5.5 Influence of Electrode Spacing on Measured Resistivity

The UBC resistivity cone has been equipped to make simultaneous measurement of resistivity from the inner and outer electrodes. This section deals with the comparison of the results of the inner and outer electrodes and suggests why there should be differences between the two measurements in different soil types.

When the electrodes are in a homogeneous - isotropic medium the electrodes should respond in a similar manner to that of the

case of water immersion. However, soil is rarely homogeneous and isotropic, so that the response of the electrodes will be dependent on the state of the soil and the changes to the soil caused by penetration. When the electrodes enter a layer of contrasting resistivity the full response due to the change in resistivity will not be noted until the probe has fully penetrated the layer.

Comparisons have been made between the magnitude of the results of the two electrode pairs and their responsiveness to narrow layers. The following observations were made at the test sites and are presented in Figures 5.6 to 5.9. In these figures the resistivities determined from the inner and outer electrodes are superimposed and compared to the soil type, since it is the soil type that appears to cause the differences in the results. On the basis of these observations some suggestions are presented as to why there should be a difference between the two resistivity measurements.

1. Clean sands at McDonald Farm (Fig. 5.6): The resistivity measured by the outer electrodes is greater in the medium dense sand. In silty sands there appears to be very little difference at McDonald Farm.

2. Langley (Fig. 5.7): The inner and outer electrodes give almost exactly the same result in clay with narrow sand interbeds.

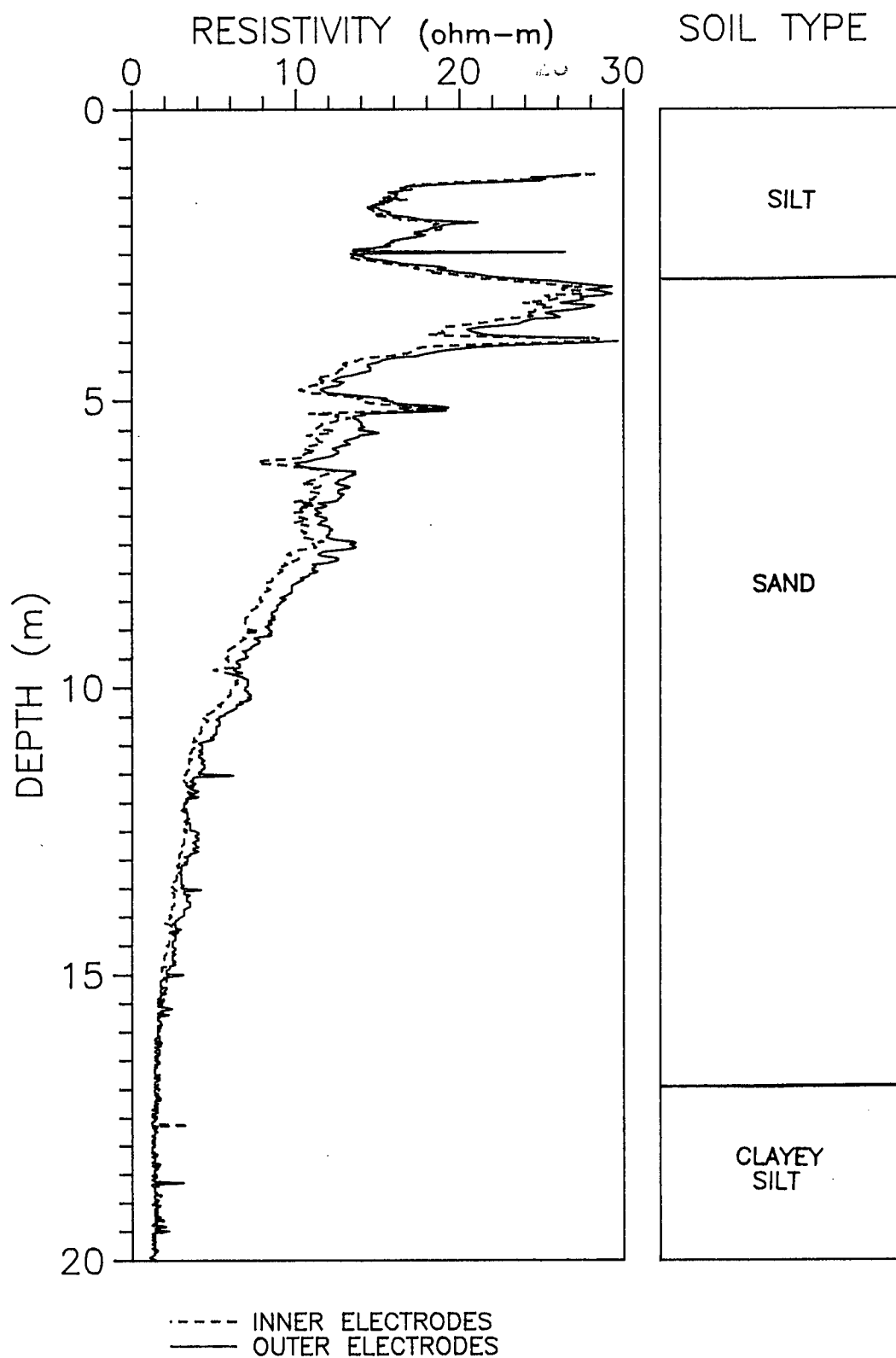


Fig. 5.6 A comparison between the resistivity measured by the inner and outer electrodes at McDonald Farm.

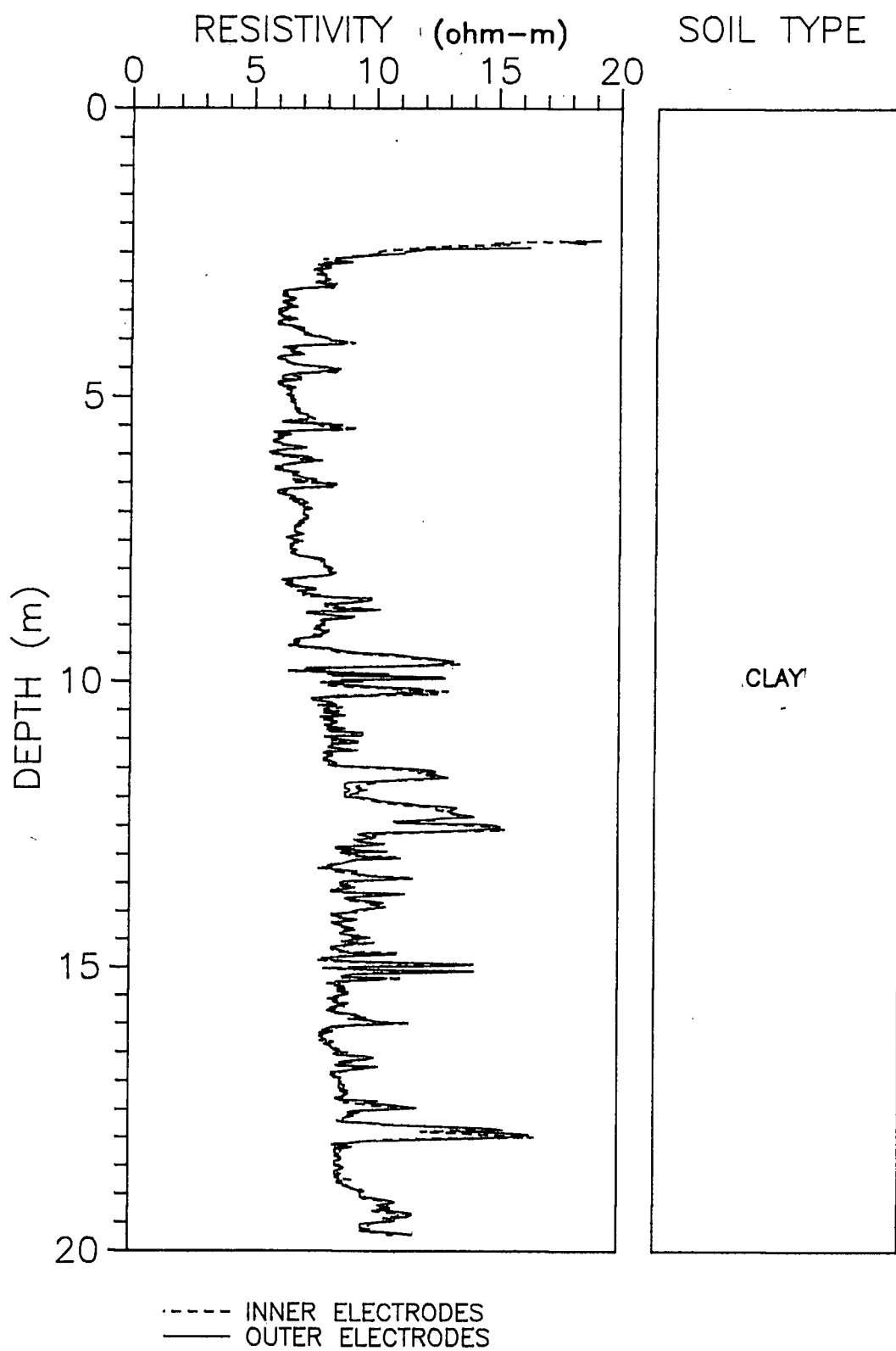


Fig. 5.7 A comparison between the resistivity measured by the inner and outer electrodes at Langley.

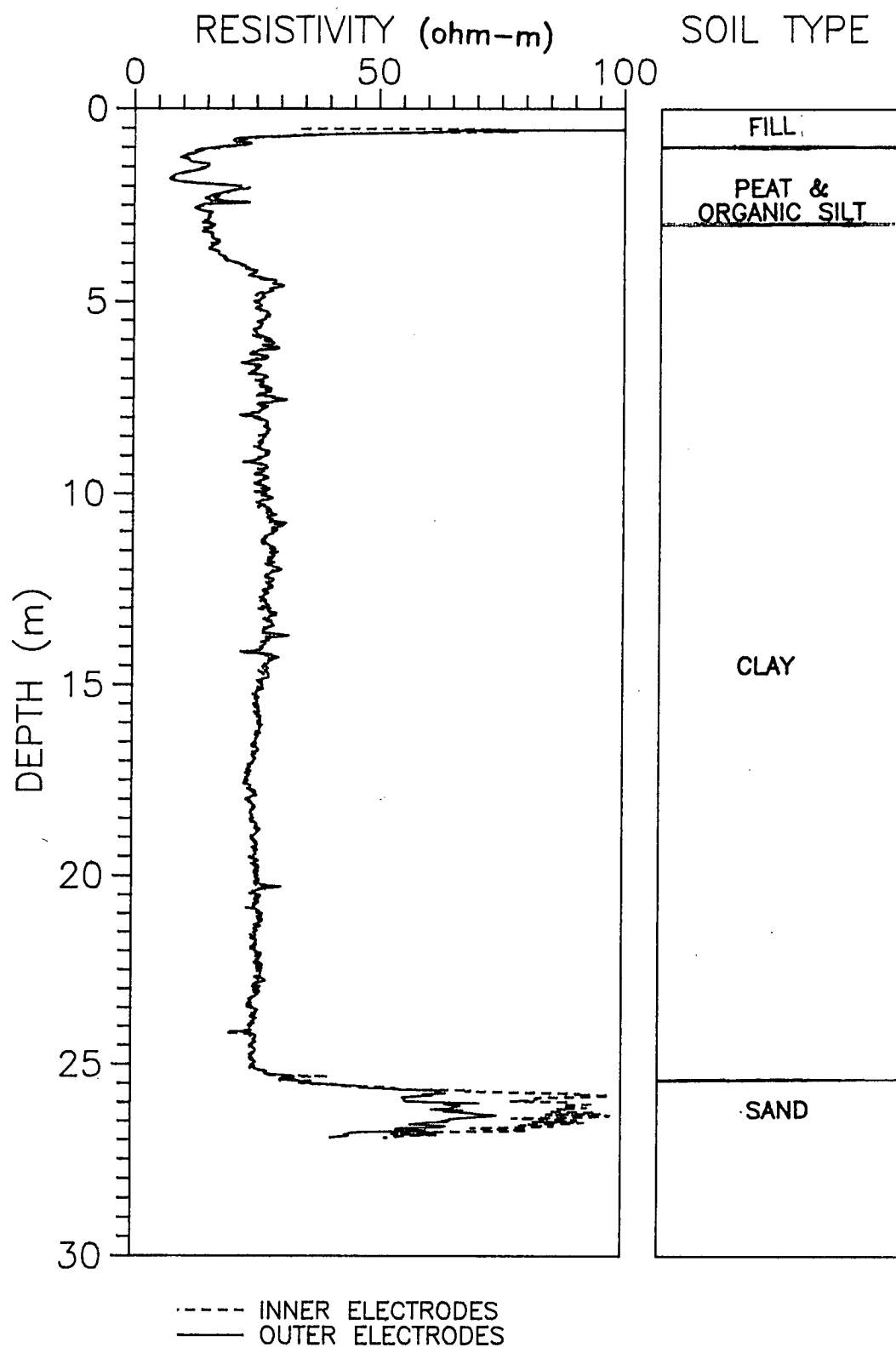


Fig. 5.8 A comparison between the resistivity measured by the inner and outer electrodes at Colebrook.

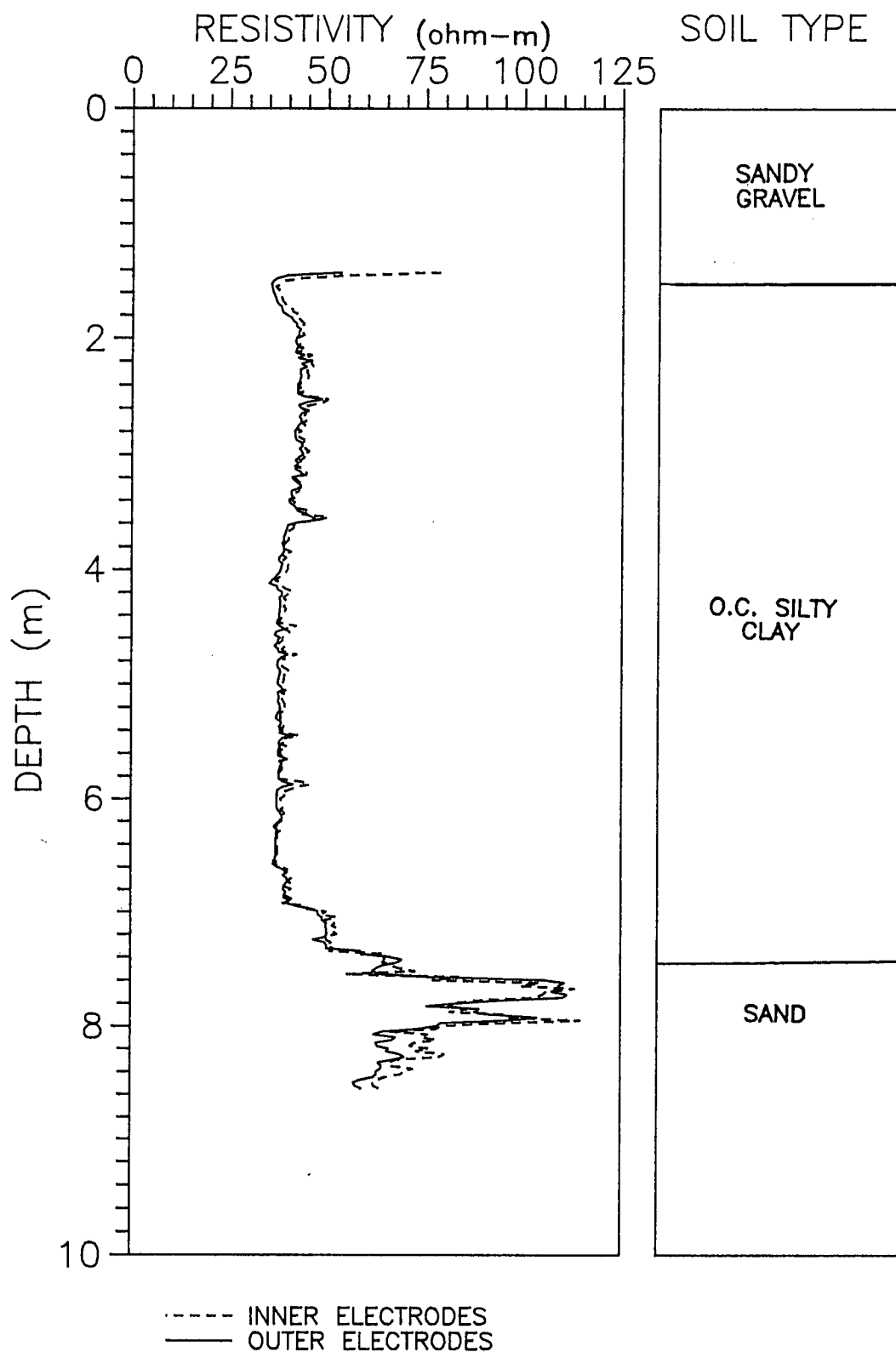


Fig. 5.9 A comparison between the resistivity measured by the inner and outer electrodes at Strong Pit.

3. Colebrook (Fig. 5.8): The results of the two electrodes are the same in clay. However the inner electrodes give substantially greater resistivity in the loose sand layer.

4. Strong Pit (Fig. 5.9): The results are the same in clay and the sand layer with the exception of the last 40 cm, where the sand is looser, the inner electrodes give a higher resistivity.

In dense sands there is a narrow zone of dilation adjacent to the cone. For loose sands there is an increase in density adjacent to the cone. If there is densification in the sand adjacent to the cone the resistivity measured by the inner electrodes would be greater. For the case of a dense sand the inner electrodes would measure a lower resistivity. In any case the larger the spacing between the electrodes the greater the penetration of the electric field into the soil and the more representative the resistivity measurements should be of the undisturbed soil.

It has been observed that in silt and clay, both NC and OC, that the inner and outer electrodes give consistent resistivity results. Adjacent to the cone, when pushing through clay, there is a zone of remolding. This remolding of the clay is at constant volume and hence constant water content. Since the water content of the soil is constant the resistivity should not change. This is in fact the behavior noted in all the silty clays tested at the four sites. By measuring resistivity at a

number of different spacings one can use the resistivity measurements to note the affect of sand disturbance by the cone. Figure 5.5 suggests, for the inner electrodes, that disturbance has caused the formation factor to be more uniform.

In general, for clays, closely spaced electrodes will give true values of undisturbed resistivity. In sands the value of the resistivity is affected by soil disturbance from penetration. This effect decreases with increased electrode spacing because more of the current travels through undisturbed soil further from the cone. Therefore, for contaminant studies it is preferable to have close electrode spacing. This is because the narrow spacing will indicate the presence of narrow layers and the influence of sand density is reduced, making it easier to estimate pore fluid conductivity on the basis of measured soil resistivities.

6. APPLICATIONS OF THE RESISTIVITY CONE

The purpose of this research was the development of a resistivity cone for contaminant detection. Due to difficulties in accessing such sites no testing at contaminant sites was done. The following section outlines for what types of contaminants the resistivity method would be applicable and describes how the RCPTU should be deployed in a site investigation. The resistivity cone can be used for other applications which are described at the end of this chapter.

6.1 Applicability of Resistivity for Contaminant Detection

There are two general groups of contaminants; 1) Aqueous phase liquids (APLs); and 2) Non-aqueous phase liquids (NAPLs). Aqueous phase liquids consist of both conducting (ionic) and soluble organic (insulating) contaminants.

The easiest contaminants to detect by the resistivity method are conducting aqueous phase liquids. Sources of such contamination may be landfills (industrial, sanitary, fly ash) or mine tailings. Pyrite produces acid water when oxidized, releasing Fe^{3+} and H^+ . The best conductors are solutions of most inorganic salts, acids, and bases. Contamination may also be due to salt water infiltration of aquifers. Non-ionic aqueous phase liquids will not be detected by the resistivity

method.

Non-aqueous phase liquids (NAPLs) are insulating organic contaminants. The presence of NAPLs decreases the bulk resistivity by blocking pathways of conduction through the pore space of the soil. NAPLs can be either classified as DNAPLs, contaminants that are denser than water, or floating NAPLs, that have a density less than that of water. DNAPLs will sink under a gravity gradient to some low permeability layer or will remain in residual saturation. Light NAPLs will float on the surface of the water table and may be difficult to detect since the resistivity above the water table would be very high regardless of the presence of contamination. However, field work at an appropriate test site would be necessary to evaluate the effectiveness of the RCPTU at detecting such contaminants. By assuming NAPLs are insulators Archie's Formula (Equation 2.4) can be used to approximately estimate the amount of contamination by assuming the resistivity of the contaminant is equivalent to that of air. For the resistivity method to note a sufficient change there would need to be at least 5% NAPL saturation.

However, in most cases conductive contaminants will be the target of a site investigation. This is because most industrial waste will have a large component of dissolved solids along with possible NAPLs. Very small amounts of some organic chemicals are very hazardous. If such contaminants are the only source of contamination the resistivity cone would not be able to detect

Table 6.1 Summary of Typical Resistivity Measurements of
Fluids and Bulk Soil-Fluid Mixtures

	$\rho_f, \text{ohm-m}$ (fluid)	$\rho_b, \text{ohm-m}$ (bulk soil)
Seawater	0.2	-
Drinking Water	>15	-
McDonald Farm Clay Colebrook Site Clay 401 @ 232 Ave., Railway Site Clay B.C. Highway Strong Pit Clay	0.3 18.2	1.5 25 8 35
McDonald Farm Sand Colebrook Site Sand Strong Pit Sand	1.5-6	5-20 70 115
Typical Landfill Leachate	0.5-10	
100% Ethylene Dichloride (ED)	20400	
50% ED/50% 150 ohm-m fluid in Wedron 7020 sand		696
30% ED/70% 150 ohm-m fluid in Wedron 7020 sand		335
17% ED/83% 150 ohm-m fluid in Wedron 7020 sand		273

them. The resistivity cone is used for determining contrasts in resistivity. If the natural groundwater is very brackish, such as in a marine delta, it may be difficult to detect conductive contaminants. On the other hand if the natural groundwater is highly conductive it becomes easier to detect insulating NAPLs. Table 6.1 provides a convenient summary of resistivities of a number of soil types, soil contaminant mixtures, and fluids. Having a knowledge of the soil type and contamination at a site one can use this information to help decide if the resistivity method is appropriate.

6.2 Use of the RCPTU in Contamination Problems

By itself the RCPTU is a valuable tool in contamination site investigations. Besides providing information on the extent of groundwater contamination the cone may also be used for determining: hydrogeological properties, stratigraphic profiles, and geotechnical properties. The following is a suggested outline for an RCPTU investigation.

The CPTU can quickly determine steady state pore pressures in drained soils. Given that the CPTU provides accurate measures of pore pressure, soundings should be periodically stopped to allow an accurate determination of the equilibrium pore pressure. In sandy soils equilibrium will be reached almost instantaneously thus allowing many such measurements to be made. Dissipation of excess pore pressure in non-plastic silty soils is fairly rapid. In plastic clays it would not be

practical to determine the equilibrium pore pressure due to the low permeability of such soils. By repeating this procedure in a number of holes at a site the direction and magnitude of the hydraulic gradient may be determined.

The hydraulic conductivity can be determined for fine grained soils by pore pressure dissipation. Details on this procedure may be found in Robertson and Campanella (1988). This procedure works well for normally consolidated silty clays and clays. In the case that such soils are encountered it would be worthwhile doing a dissipation test since it is a cost effective method of determining hydraulic conductivity. For drained soils an initial estimate of hydraulic conductivity can be made on the basis of soil type classification determined from the CPT parameters. Porosity may also be estimated from soil type classifications and relative density estimates. Alternatively the porosity may also be determined by using a mixing law. In the case of low resistivity sand Archie's Formula may be used to determine porosity providing the resistivity of the pore fluid is also known.

A rapid assessment of the three dimensional extent of groundwater contamination can be made after a series of cone tests. Sections showing stratigraphy and resistivity should be prepared. By comparing the resistivity at certain points to contaminant concentrations determined from direct water sampling the resistivity values may be used semi-quantitatively to give an indication of contaminant concentrations at other points.

The highly accurate stratigraphic profile that the CPT provides allows for the identification of soil layers with high hydraulic conductivities that may be pathways for contaminants. Also soils with low hydraulic conductivities which may act as aquitards are also identified. At the same time the information obtained from the CPT can also be used to determine geotechnical parameters.

On the basis of an initial investigation with the RCPTU planning for other forms of investigation, such as piezometers and sampling wells, can be made. The RCPTU can also be used for periodic monitoring of a site to note the advance of any contaminants. If baseline resistivity tests are done changes in the groundwater chemistry can be easily noted.

6.3 Other Possible Applications of the RCPTU

While the resistivity cone was designed with the the purpose of contaminant detection it may be applied to other areas. Three applications are briefly outlined in the following section.

6.3.1 Corrosion Assessment

Soils with low resistivities have high concentrations of dissolved solids which would accelerate corrosion. A standard adopted in the United Kingdom (Geological Society Engineering Group Working Party, 1988) defines severely corrosive soil as having a resistivity of less than 10 ohm-m, and moderately

corrosive soils having a resistivity in the range of 10 to 100 ohm-m. Soils with a resistivity of greater than 100 ohm-m are of little concern with respect to corrosion.

6.3.2 Water Quality Assessment

As noted earlier there is a strong linear relationship between TDS and fluid conductivity. By using a mixing law the pore water resistivity may be estimated from the direct measurement of the bulk resistivity. For sands, by using a formation factor of 3.5, an initial estimate of the pore fluid resistivity can be made. The limit of total dissolved solids for potable water is 500 mg/l (water resistivity aprx = 12 ohm-m) hence for most sand aquifers the minimum bulk resistivity should be in the range of 35 to 50 ohm-m.

6.3.3 Soil Classification

The resistivity cone can be used as a tool for soil classification where soil horizons have different salinities or water contents. The high water content of peats may make resistivity measurements an ideal method of differentiating such soil from other soils with lower water contents. Resistivity measurements are ideal for detecting the presence of frozen ground. There can be no mobility of electrolytes in ice, therefore it acts as an insulator and ice content could perhaps be inferred by using Archie's Formula. Resistivity measurements would also be sensitive to the presence of gas in soil.

7. CONCLUSIONS AND RECOMMENDATIONS

It was found, through extensive field tests, that the initial design of the UBC RCPTU was successful in rapidly and accurately determining resistivity. The repeatability of the measurements and the favorable comparisons to direct groundwater sampling proved the validity of the results.

While in this research no actual contaminated sites were tested the testing done at the McDonald Farm site served well to show the ability of the RCPTU to make a detailed profile of the bulk resistivity, which is representative of changes in the amount of total dissolved solids in the groundwater. It was noted that changes in soil porosity and fines content could influence the bulk resistivity. The four electrode module with simultaneous measurements of resistivity from the outer and inner electrodes showed that penetration causes localized changes in soil density which in turn influences the measured bulk resistivity of sandy soils.

Due to the electrically insulative properties of organic contaminants they should also be detectable by the resistivity method. Besides being a tool for contaminant detection the RCPTU may also be used for corrosion assessment, drinking water quality assessment, and as an aid in stratigraphic logging.

On the basis of the results presented it appears that the speed, economy, and reliability of the RCPTU make it ideal for many contaminant investigations in unconsolidated soil. Lab and field testing with simultaneous measurement of resistivity across two sets of electrodes showed that a two electrode probe operating at a frequency of no less than 1000 Hz is adequate. For contaminant applications close spacing between the electrodes is desirable as it gives good resolution of thin layers and tends to reduce the influence of soil porosity in measurements of sand resistivity.

It is recommended that further field work at different sites with various soil conditions coupled with a more comprehensive water sampling program be undertaken. Testing in different soil types will give an indication of what background resistivities could be expected when testing at a contaminant site. Ideally, testing should take place at a well documented site of organic contamination to prove that the resistivity method is viable way to detect the presence of contaminants. Further research will legitimize the RCPTU as a practical tool in contaminant investigations.

Further resistivity field testing coupled with soil sampling would allow for comparisons between changes in resistivity and changes in soil water content, percentage of clay, and clay type.

Numerical modeling could be used to determine the distance

the electrical field penetrates into the soil. Modeling could be useful in illustrating the influence of soil disturbance and of electrode spacing on observed resistivity measurements.

Research into the subject of the corrosion of buried structures would be appropriate since the measurement of bulk resistivity is one way of assessing soil corrosion potential.

Research into the viability into making in-situ dielectric permittivity measurements could be examined. Dielectric measurements have application in both contaminant detection and the determination of soil water content. This former application would be a practical approach in determining in-situ void ratio of cohesionless soils.

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