DEVELOPMENT AND USE OF AN ELECTRICAL RESISTIVITY CONE

FOR GROUNDWATER CONTAMINATION STUDIES

by

R.G. Campanella* and I. Weemees**

ABSTRACT

The evaluation of groundwater quality has become increasingly important as more industrial waste and solid domestic refuse comes into contact with groundwater. One method of detecting contaminated groundwater is by noting the electrical resistivity of the contaminated soil. This method has been applied at UBC by the development and use of a new resistivity cone. The resistivity cone (RCPTU) consists of four circumferencial surface electrodes contained in a separate module behind a 15 sq.cm piezocone (CPTU). The cone has the capability of providing a continuous record of resistivity with depth.

Initially, a laboratory testing program was carried out using a simplified probe design to ensure the feasibility of the project. On the basis of favourable lab results the module was constructed, calibrated in the lab, and then field tested. The paper describes the design and operation of the RCPTU, theory and laboratory calibration and test results from three sites in the lower mainland of B.C. The results of the testing program provided evidence of the reliability of the instrument and illustrated its application in determining changes in groundwater quality. Factors affecting results and applications of the resistivity cone in contaminant site investigations are discussed.

Key Words: Electrical, Resistivity, Cone, Groundwater, Contamination, Plumes, Mapping, In-Situ Testing, Soil.

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INTRODUCTION

Contaminants influence the bulk resistivity of soil because they change the electrical properties of the groundwater. The electrical resistivity of the groundwater will decrease with an increase in dissolved solids, and increase if insulating contaminants are present in the groundwater. In many instances most 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 greater than that of non-conducting contaminants. Sources of such plumes could be acidic sludge from oil reclamation (Greenhouse and Slaine, 1986), sanitary landfills (MacFarlane et al, 1983), and acidic leachate from mine waste (Morin et al, 1982).

Surface methods are commonly used to measure soil resistivity, 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. The use of a resistivity cone is particularly appealing since the cone can measure resistivity to a higher resolution (±1%) and at the same time note changes in lithology.

Unfortunately, very little information is reported in the technical literature concerning the use of bulk soil resistivity or conductivity probes, even though they have been in use by Delft Soil Mechanics for more than 13 years. Delft uses several pairs of both excitation and measurement electrodes in order to measure in situ density and porosity of sands and silts (Van de Graff and Zuidberg, 1985). Fugro-McClelland use a simple two electrode system for applications dealing with corrosion potential determination and the extent of soil and groundwater pollutant detection (Horsnell, 1988). A simple summary of the concepts involved in the use and application of the resistivity cone measurements is provided in the following sections.

ELECTRICAL CONDUCTION IN SOILS

The electrical resistivity of the soil is determined by first measuring the electrical resistance of the soil. This is done by measuring the voltage across a pair of electrodes at a known current level.

[1] $R = V/I$

where: R = resistance, ohm
      I = current, Amp (RMS value at 1000 Hz, UBC cone)
      V = voltage, Volts (RMS value, UBC cone)

However, the measured resistance is not a unique material property, but is a function of the cross-sectional area and length of the electrical conductivity material being measured. Resistivity, ρ, can be defined as

[2] $\rho = (A/\ell) * R = (conductivity)^{-1}$

where: ρ = resistivity = $(conductivity)^{-1}$, ohm-m
      A = cross-sectional area, m^2
      ℓ = length, m
      R = resistance, ohm

For the case of a pair of electrodes in a homogeneous, isotropic conducting media there is a linear relationship between resistance and resistivity

[3] $\rho = K * R$

with the probe constant K being a function of the geometry of the electrode pair.

The measured bulk resistivity of the soil is a function of both the resistivity of the pore fluid and the soil particles, and their arrangement. The dominant mechanism of conduction is the transfer of charge through porewater by electrolytic conduction, i.e., physical movement of ions in the response to the application of an electric field. In general, the more ions present in the pore fluid the less is the resistivity and the greater the conductivity. Another factor relates to the viscosity of the pore fluid which affects the conductivity of a particular ion in an electrolyte. The most important factor affecting viscosity and hence conductivity, is the pore fluid temperature.

Contaminated soil is usually a multiphase system with the components being: 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 their interaction with each other. The difficulty is identifying which components cause changes in the resistivity.

Formulas that relate the resistivity of the different components to the bulk resistivity of the conducting medium are referred to as mixing laws and the simplest of these is Archie's Formula (Archie, 1942, and Telford et al, 1976). Archie's Formula assumes that bulk resistivity is directly related to porewater 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

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

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

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

Archie's Formula has been recognized to be an oversimplification of the relation between bulk soil resistivity and pore fluid resistivity but is still valid under the condition that the pore fluid resistivity is relatively low and there is only a small quantity of 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 such as surface conduction in clay minerals. For this reason the measured formation factor is referred to as the apparent formation factor. An understanding of the formation factor is important if estimates of the pore fluid resistivity based on bulk resistivity measurements are desired.

DESIGN CONCEPTS

In the measurement of resistivity two modes of conduction must take place, electrolytic conduction through the pore fluid and ohmic conduction across the metallic electrodes. It is assumed that no conduction takes place through mineral grains. Charge transfer between the electrodes and the pore fluid takes place by oxidation-reduction reactions. The measured resistance between the electrodes is a function of the flow of ions in the pore fluid and the resistance to the transfer of charge from the electrolyte to the electrodes. Given this point the design of a resistivity module requires the consideration of (1) the number of electrodes on the module and operating excitation frequency, and (2) the geometric configuration of the electrodes.

If, in the case of a 2 electrode module, a direct current is applied there will be electrochemical changes in the electrodes since the oxidation-reduction reactions are not being reversed which causes a buildup of ions at the electrodes (Keller, 1982). This continuing buildup of ions, referred to as polarization, causes changes in the measured resistance or impedance in the soil-porewater system (Olhoeft, 1985). This polarization effect is most important for DC and low frequency excitation (Lockner and Byerlee, 1985).

A four electrode array where measurements are only made with the inner electrodes minimizes the effect of polarization since the current drawn through the measurement electrodes is very small so there is no appreciable buildup of ions at the electrodes. Thus, a four electrode probe module can operate at very low frequencies without becoming polarized. The UBC resistivity module has four electrodes and makes use of both outer and inner electrode measurements of resistance. To avoid polarization of the outer or constant current excitation electrodes a frequency of 1000 Hz was deemed appropriate in the design of the UBC Resistivity Cone. This frequency is in the range 25-3000 Hz suggested by ASTM (D1125-82) for conductivity measurements of water. At frequencies higher than 3 kHz, inductive effects influence resistance measurements.

Smaller distances between the electrodes allow for the possible detection of thinner layers of contrasting resistivity. Wider spacing provides a greater penetration of the electric field into undisturbed soil and thus should give a more accurate determination of soil resistivity in homogeneous ground.

RESISTIVITY MODULE DESCRIPTION

The resistivity module, as shown in Fig. 1, 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 electrodes are 5 mm wide and spaced at 25 mm center to center. Simultaneous and continuous measurements of voltage are made across the inner and outer electrodes. Conversion of the
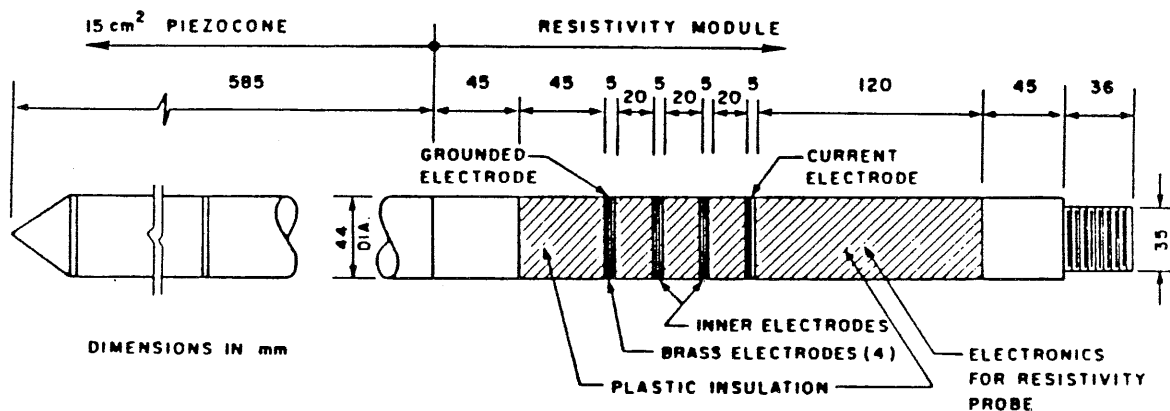
Fig. 1. UBC Resistivity Cone.

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 grounded electrode, the electrode closest to the tip. The constant peak current power source at 1000 Hz is controlled from the surface. Since the peak applied current is very small, typically in the order of 150 μA, the potentials measured across the electrodes must be amplified downhole to the point where they fall into the range usable by the data aquisition system. The maximum expected average voltage gradient across the outer electrodes is only in the order of 0.13 RMS V/cm. A more comprehensive description of the UBC Resistivity Cone is given by Weemees (1990).

CONE CALIBRATION

The (RCPTU) measures electrical resistance between the electrodes, which is related to the resistivity of the media being penetrated and the geometry of the electrodes. The measured resistance will increase if the electrodes are set farther apart or if the electrode surface area is decreased. The resistivity is a fundamental soil parameter and thus its value is independent of a probe's electrode geometry.

To convert from resistance to resistivity a lab calibration was made for both the outer and inner electrode pairs. To minimize edge effects the RCPTU was placed in an open cylindrical chamber that completely surrounded the module. The chamber was filled with water and potassium chloride (KCl) was added 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 resistance measured by the cone. 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. 1 the calibration factor, K (Eq. 3), was found to be 0.100 m for the

outer electrodes and 0.838 m for the inner electrodes at 15 µa peak current at 1000 Hz.

TESTING PROCEDURES

The preparations involved in testing are similar to those involved with any other piezocone sounding (Robertson and Campanella, 1988). The only additional consideration is the connection of a signal generator to the data aquisition system to control current level and frequency for electrical resistance measurements. The input current level must be set with some regard to the expected resistivity. If highly resistive soil is expected, a lower current should be applied. A frequency of 1000 Hz was maintained for all tests. Data is collected using the UBC in-situ testing digital data acquisition system which has the capability to simultaneously record eight channels. All channels (bearing, friction, pore pressure, inclination, resistivity 1, resistivity 2, etc.) are digitally recorded during penetration at depth intervals of 25 mm. The depth interval can be adjusted to a value as a small as 1 mm if required.

TEST RESULTS

Test results from three sites in the Fraser Valley are discussed in detail. The first test site presented is the UBC McDonald Farm research site situated in the Fraser River delta, at the Vancouver International Airport. The other two sites were in glaciomarine deposits.

McDonald Farm, situated on the north side of Sea Island, is part of the prograding Fraser River delta. The lowlands in this area are underlain by complex sequence of 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 a depth of 1 to 2 metres depending on rainfall and tidal influence.

An interpreted resistivity cone profile representative of the site is presented in Fig. 2. Typically at this 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 distributary channel sand and silty sand which can be highly variable, spatially and with depth. The sand is medium to coarse grained with thin layers of medium to fine sand and at this location showed a thick lens of clay silt at 12 m. At a depth of 15 m the sand becomes finer and grades into a relatively uniform clayey silt.

The resistivity profile indicates a high salinity in the porewater. Bulk soil resistivity values below approximately 50 ohm-m for the UBC-RCPTU in sand correspond to total dissolved solids (TDS) in excess of 500 mg/ℓ (typical water quality standard) and a value of about 0.5 ohm-m equates to sea water. This high salinity at the site (25 to 2 ohm-m) is due to the infiltration of the brackish water found near the mouth of the Fraser River. The salinity of the porewater 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 clearly indicated by the sudden drop in resistivity at 1.2 m.

GLACIOMARINE DEPOSITS

The current surficial geology of the Fraser Valley is dominated by glaciomarine clay deposited during the Fraser deglaciation. At the time of deposition the lowland areas were estimated to be depressed by more than 200 m by the weight of the cordilleran ice sheet. During deglaciation the glaciomarine deltaic soils of the Capilano and Fort Langley Formation were deposited. The proximity of the Fort Langley sediments to the decaying glacial ice front resulted in a lower depositional salinity than for the sediments of the Capilano formation (Clague and Luternauer, 1982).

A resistivity cone profile at the Strong Gravel Pit site near Aldergrove, B.C. is shown in Fig. 3. This site is located in the central Fraser Valley in the Fort Langley glaciomarine deposits. The profile can be divided into three zones. The first 1.5 m consists of freely draining outwash sandy gravel (Sumas Formation) which was originally about 10 m thick at the site. Below the sandy gravel is overconsolidated stoney clay. The boundary between the gravel 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 contact. The presence of a harder dessicated 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 fluid filled 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 in the clay. This is 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 layer in the profile is a medium density sand. In the sand the resistivity is higher due to the lack of conducting clay minerals but more so due to the higher porewater resistivity. In the sand, the denser parts of the layer (higher Q_c) have the highest resistivities.

Capilano sediments in the area of the Colebrook site, located at Colebrook Road and King George Highway in White Rock, B.C., consist of glaciomarine clay overlying proglacial deltaic sand and gravel. A resistivity cone profile from the site (Fig. 4) shows that the stratigraphy consists mainly of marine clay overlying sand. At the surface there was 0.5 m of topsoil. In the clay the resistivity is fairly constant at a value of about 25 ohm-m. From the water table to 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 an upward flow through the clay layer with the surface being a zone of groundwater discharge. However, it is more likely that the lower resistivity is due to the high organic content in the upper few metres of the profile. Peat and organic silt was noted in the extrusion log of a bore hole on the site to a depth of 3 m. It is likely that the increase in resistivity would be due to the decrease in organic content. Soils with organic material have low resistivities for two reasons: (1) such soils, especially fibrous peat, have high water contents; and (2) organic soils tend to have a very high cation exchange capacity (CEC) which promotes easier conduction of ions through the soil. Leaching of the clay would explain the relatively high resistivity when compared to other clay sites in the Lower Mainland. The low porewater salinity in the clay silt causes it to be very sensitive.
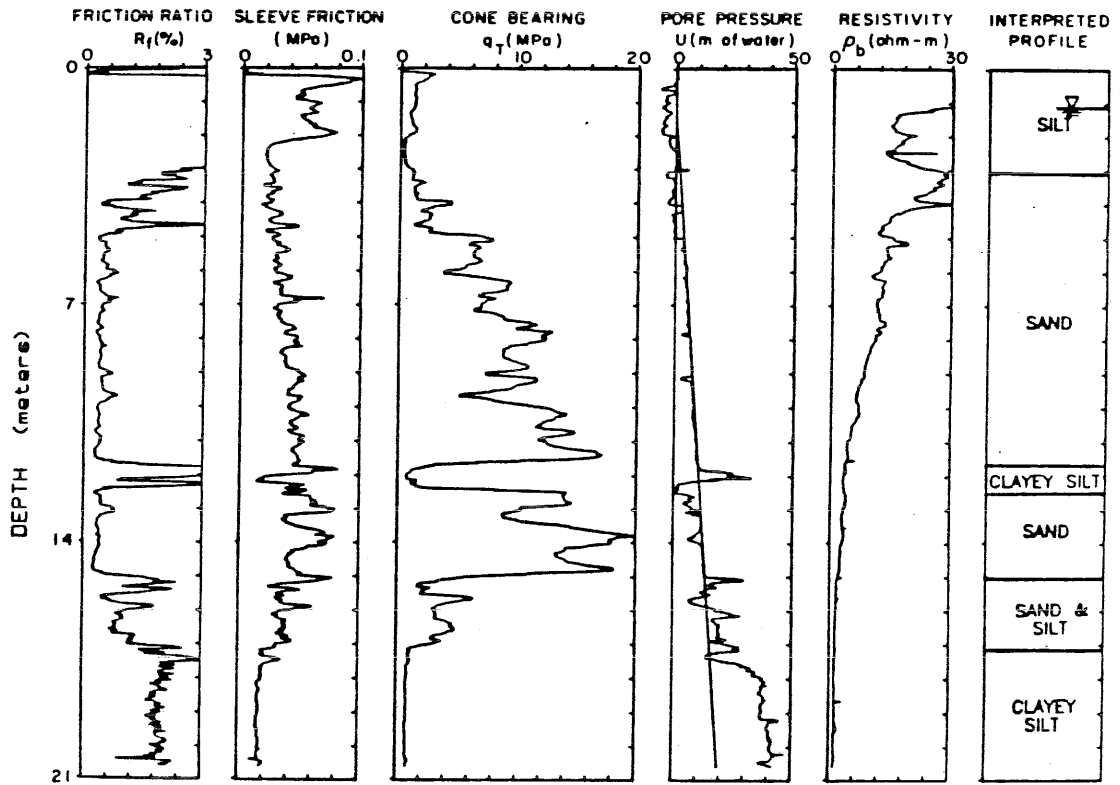
Fig. 2.   Resistivity Cone Sounding at McDonald Farm, Vancouver International
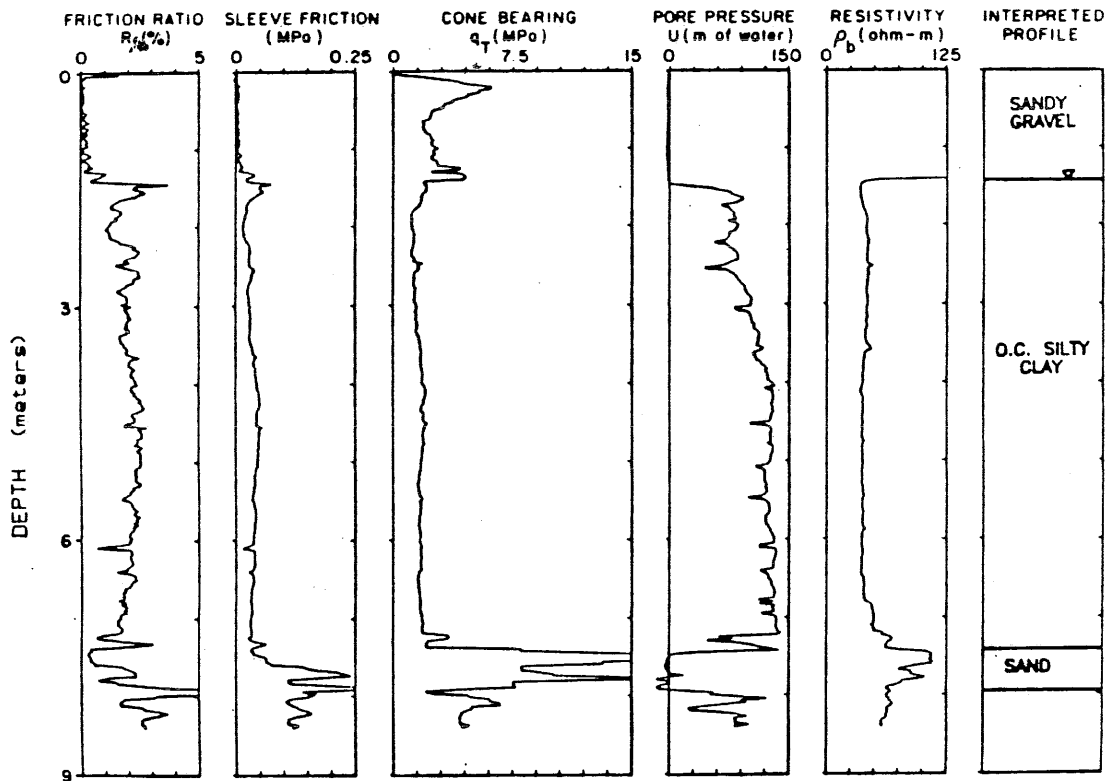   Airport, B.C.

Fig. 3.   Resistivity Cone Sounding at Strong Pit, Aldergrove, B.C.

INTERPRETATION AND DISCUSSION OF RESULTS

EFFECT OF SOIL LITHOLOGY

As discussed in the section on electrical conduction in soil a number of different factors affect the bulk resistivity of the soil. By far the most important factor is the resistivity of the pore fluid. At low porewater resistivities the effect 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 porewater conduction. At McDonald Farm (Fig. 2), 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 porewater where the resistivity was only about 4 ohm-m.

When the porewater resistivity is higher the effects of surface conduction become more apparent. This was particularly true at both the Strong Pit site (Fig. 3) and the Colebrook site (Fig. 4) where the clays have bulk resistivities of 35 and 25 ohm-m, respectively, and sands have values of 110 and 70 ohm-m, respectively, showing a high contrast. In clay minerals surface conduction is related more to the CEC of the soil than porosity. Soils with high CEC are clays, and organic soils (Olheoft, 1985). More active clays will have a greater CEC.

The resistivity measurement can also be indicative of groundwater flow regimes. At the Colebrook site recharge from groundwater with a low amount of total dissolved solids results in high bulk resistivities in the leached soils which gives a distinct difference between clay and sand resistivities. This was just the opposite at McDonald Farm where leaching with brackish porewater gives very low resistivities resulting in almost no difference between sand and clay resistivity.

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 soundings separated by 0.7 m 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 Figs. 5a and 5b. These profiles indicate good repeatability for both the inner and outer electrodes. The profiles shown in Figure 5 only deviate in the upper clayey silt which is due to water content variations caused by rainfall at the site between the time the two soundings were made. The groundwater table, indicated by the abrupt drop in resistivity near the surface, moved closer to the surface due to rainfall over the period. Because of 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.
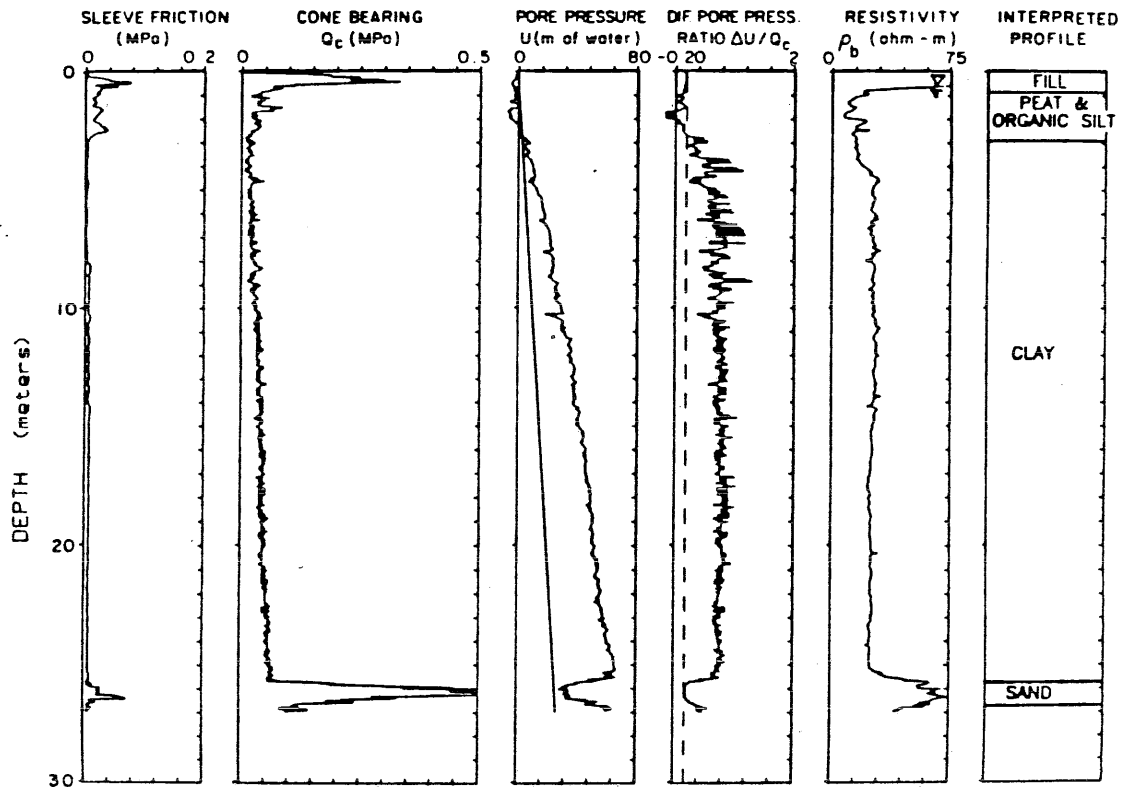
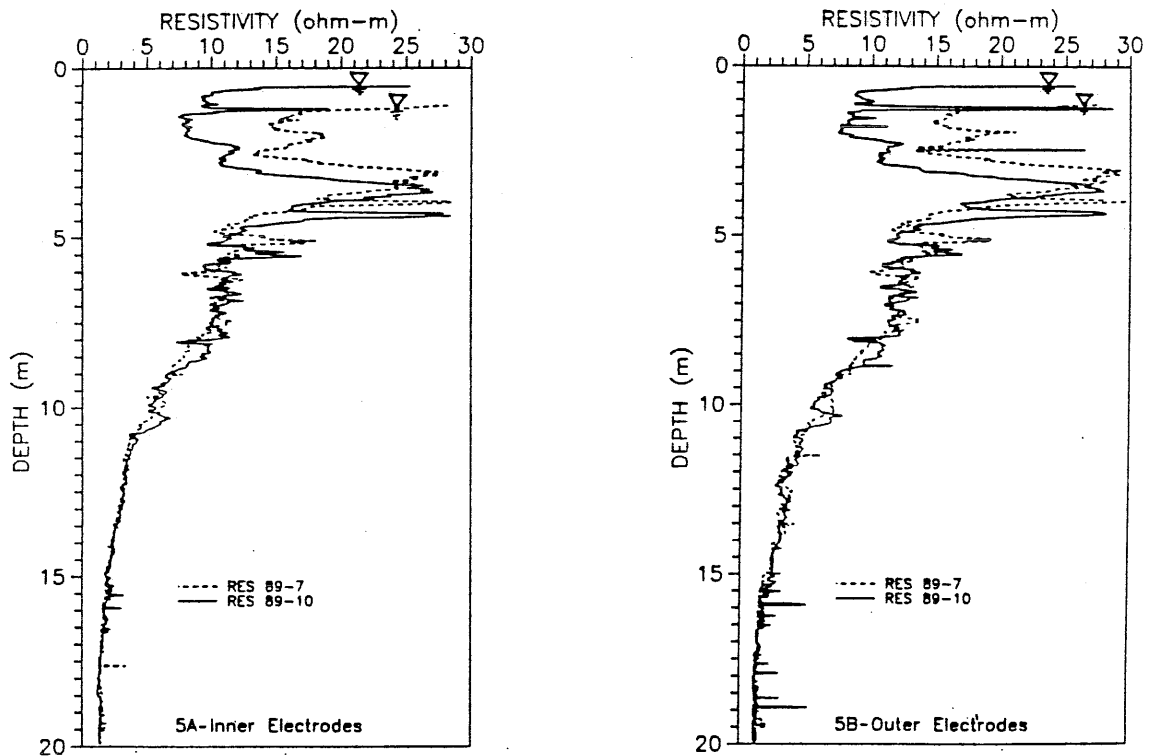**Fig. 4.**   Resistivity Cone Sounding at Colebrook Road at King George Highway, White Rock, B.C.

Fig. 5.   A Comparison of Two Adjacent Resistivity Logs Made 11 Days Apart for (a) The Inner Electrodes, and (b) The Outer Electrodes.

PORE FLUID RESISTIVITY

Pore fluid samples were extracted from the soil using the BAT ground water sampling system developed by Torstensson, 1984. This system was designed to have a filter tip pushed into soil sediments with cone penetration equipment. A hypodermic syringe system is lowered through the rods, penetrates a rubber septum at the tip and extracts a fluid sample. The small tip volume is quickly purged and a second sample taken, from which the conductivity is measured using the Omega CDH-30 portable conductivity meter.

Figure 6 shows a series of fluid conductivity measurements taken at McDonald's Farm over depths of 6 to 14.5 m in the sand and compared to bulk soil resistivity measurements with the cone. The pore fluid resistivity

RESISTIVITY (ohm-m)

McDONALD FARM
- - - - INNER ELECTRODES
——— OUTER ELECTRODES
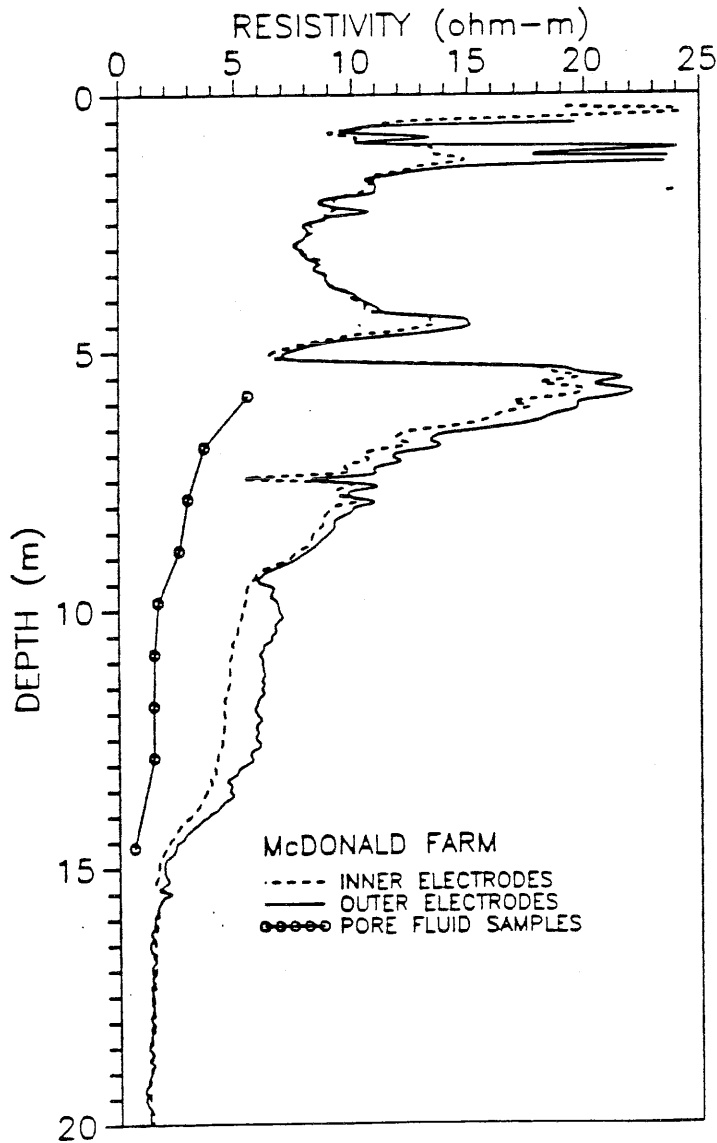o-o-o-o-o PORE FLUID SAMPLES

Fig. 6   A Comparison Between the Resistivity of Pore Fluid Samples and the Resistivity Measured by the RCPTU.

measurements were made on April 3, 1989, 5 days after the cone resistivity sounding. The fluid resistivity shows a consistent relationship with both inner and outer electrode resistivity measurements for the bulk soil.

To evaluate this trend the apparent formation factor, F (Eqn. 4), was calculated and plotted against the corresponding average cone bearing values normalized by dividing by the estimated horizontal effective stress. The cone bearing was normalized in order to eliminate the effect of overburden and changing density. The results in Fig. 7 show a well defined trend for the outer electrodes with values of formation factor from 3 to 4 in the sand. The inner electrode measurements, however, show no definite trend and suggest a constant formation factor of about 3.2. This important difference will be discussed in a later section. The measured formation factors, F, of 3 to 4 are within the usual values for sand. Delft report measurements of F in the range from 3 to 5 in sands in density logging applications (de Graf and Zuidberg, 1985).

It is therefore possible to make reasonable estimates of pore fluid resistivity from the resistivity cone. The pore fluid resistivity may be
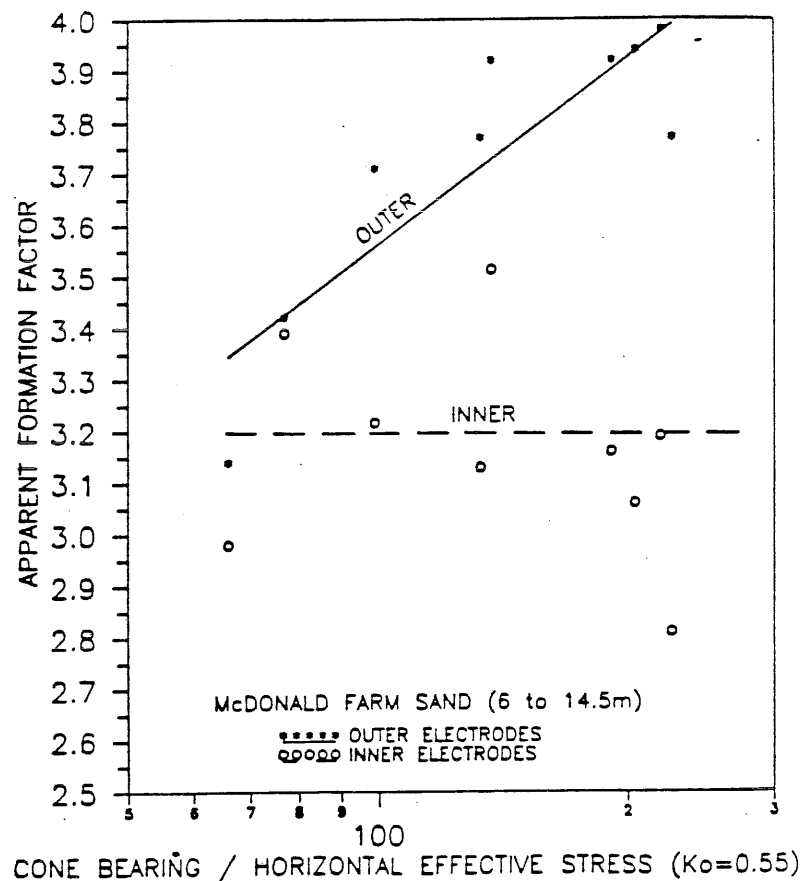

Fig. 7. Observed Relationship Between Apparent Formation Factor and Cone Bearing Normalized with Respect to Horizontal Effective Stress.

estimated by using the formation factor determined by either (1) site specific correlations between soil and pore fluid resistivity (Figs. 6 and 7), or (2) based on Archie's Formula (Eq. 4) assuming an accurate estimate of the soil porosity and constants are known.

The estimation of pore fluid resistivity in clay is more difficult due to the effects of mineral surface conduction. In clay the apparent formation factor is very dependent on the pore fluid resistivity, clay mineral content and type. From the Colebrook site 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 clayey silt at McDonald Farm had an apparent formation factor of 4 to 5, which agrees with Archie's relationship for a = 1 (Eq. 4), which gives a formation factor equal to 4 for a void ratio of 1.0 and assuming m = 2. At Colebrook where n = 0.6, and assuming m = 2, the intrinsic formation factor is calculated as 2.8 by Eq. 4 but was measured to be 1.43. This difference is due to surface conduction because of the presence of clay minerals.

COMPARISON BETWEEN INNER AND OUTER ELECTRODES

When the electrodes are in a homogeneous and isotropic medium the electrodes should respond in a similar manner to that 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. The electrodes won't respond to a layer fully unless the electrodes are completely within that layer so that minimum layer widths correctly sensed must have a thickness greater than the electrode spacing.

At McDonald Farm the outer electrodes tended to measure a greater resistivity than the inner electrodes in the dense sand (Fig. 6). In looser and siltier sands the difference is less apparent. In typical clayey silt and highly plastic and sensitive silty clay the outer and inner electrodes give almost exactly the same result. This has been repeatedly observed at all sites studied (see, for example, Fig. 6 below 15 m).

In dense sands there is likely a narrow zone of dilation or loosening adjacent to the cone. For loose sands there is a narrow zone of compression or densification adjacent to the cone. If there is a 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 as was observed for McDonald Farm sand (6-14 m) in Fig. 6. In any case the larger the spacing between the electrodes the greater the radial width of electrical influence and the more representative the resistivity measurements should be of the undisturbed soil.

Evidence that wider spacing of the electrodes decreases the effect of disturbance was shown for the McDonald Farm medium dense sand (Fig. 7) for the formation factor-cone bearing relationship. For the outer electrodes there was a good correlation with density (or normalized cone bearing), but for the inner electrodes there was no correlation at all. Thus, the closely spaced inner electrodes tend to remove the effect of varying soil porosity on

resistivity and measure a bulk resistivity associated with a constant volume or critical state condition for the sand.

If one assumes that remolding of the soil does not change the pore fluid resistivity, there is likely a direct correlation between fluid and bulk resistivity for a given soil which is independent of density variations. Thus, where one is only interested in estimating pore fluid resistivity in groundwater contamination studies, the electrodes should have as close a spacing as is practical. This is a very important point which needs further verification.

CONE PARAMETER RELATIONS TO SOIL RESISTIVITY

The cone provides information with respect to both lithology and geotechnical parameters. Since these parameters also relate to soil resistivity the relation between cone parameters and measured soil resistivity is examined.

Cone bearing in sands has been shown to be related to horizontal effective stress, soil compressibility, and relative density (Robertson and Campanella, 1983). Relations between relative density and cone bearing normalized by dividing by horizontal effective stress have been proposed so it should be reasonable to expect that there is a similar correlation between formation factor and normalized cone bearing, since the formation factor is related to soil porosity (Eq. 4). In low resistivity soil this relationship has been shown to be quite accurate. Resistivity cone data and pore fluid resistivity data (Fig. 6) was used to determine a relationship between apparent formation factor and cone bearing normalized with respect to horizontal effective stress. The relation between these parameters as illustrated in Fig. 7 shows that increased cone bearing, which implies an increased relative density, will increase the formation factor.

The friction ratio, 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 sand grains. Decreasing porosity has the effect of increasing the resistivity; and (2) the presence of fines in the soil may indicate the presence of conducting clay minerals, which would result in a decrease in the resistivity.

The results of two RCPTUs from McDonald Farm illustrate that there is a relationship between friction ratio and resistivity (Fig. 8). Peaks or increases in friction ratio are generally matched by troughs or decreases in the resistivity. This effect becomes less apparent as the resistivity decreases. The relation between friction ratio and resistivity was noted by ERTEC (1987). They normalized their conductivity data with a function of the friction ratio to remove the effects of lithological change from their data. Any such relation would also have to be dependent on resistivity. It is appropriate to understand why the resistivity changes throughout the profile due to changing lithology so that changes due to porewater resistivity can be detected. However, the complex nature of soil resistivity make the application of such corrections uncertain.
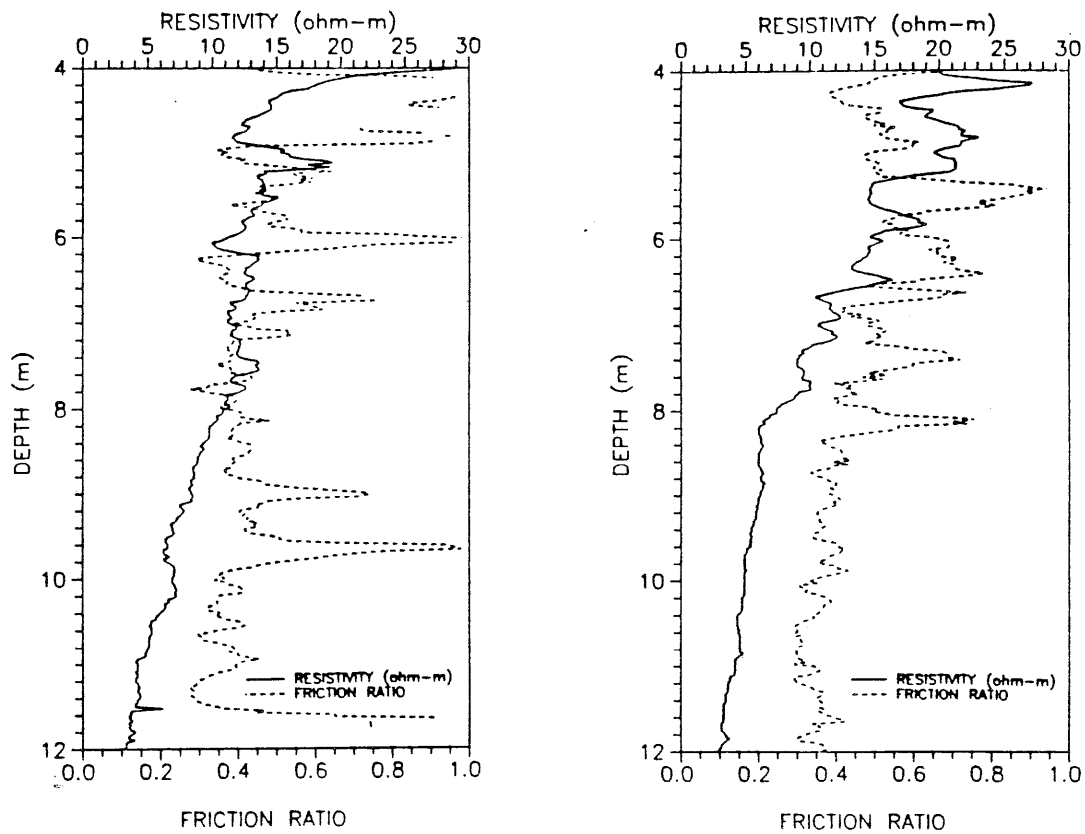
RESISTIVITY (ohm—m)

RESISTIVITY (ohm—m)

Fig. 8. A Comparison of the Resistivity (Outer Electrodes) and the Friction
Ratio for Two Soundings from the McDonald Farm Site.

RESISTIVITY
(ohm—m)
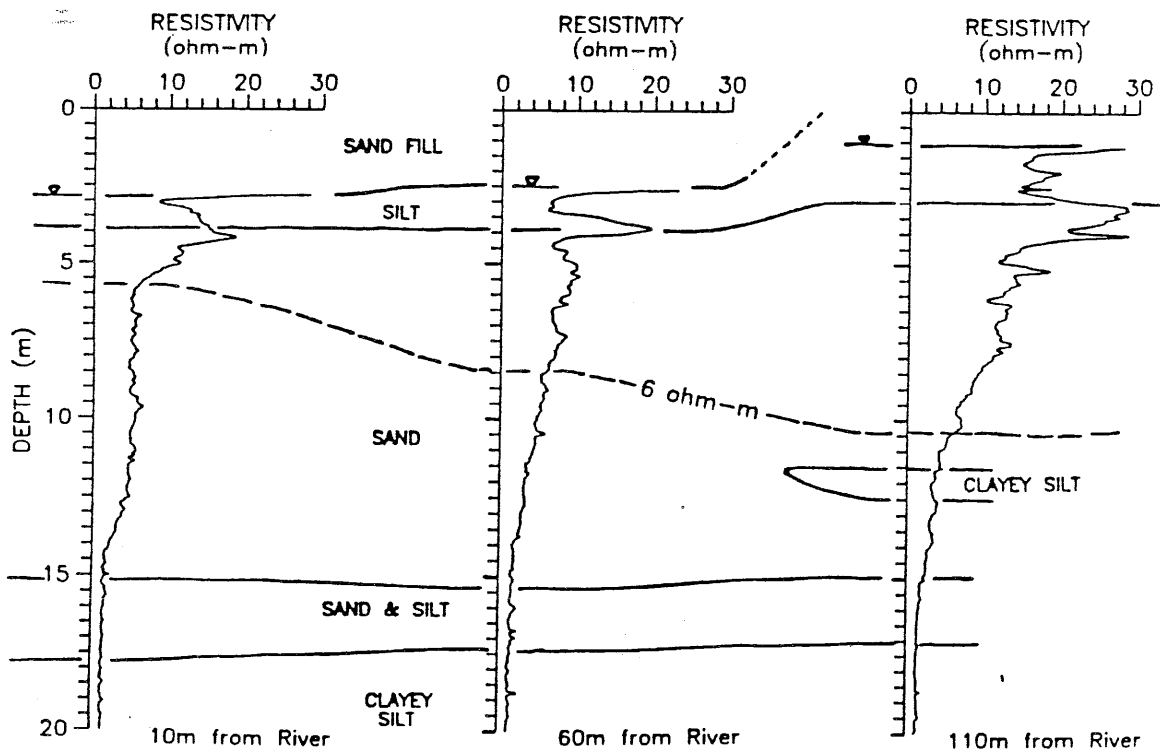
RESISTIVITY
(ohm—m)

RESISTIVITY
(ohm—m)

SAND FILL

SILT

SAND

SAND & SILT

CLAYEY
SILT

6 ohm—m

CLAYEY SILT

10m from River

60m from River

110m from River

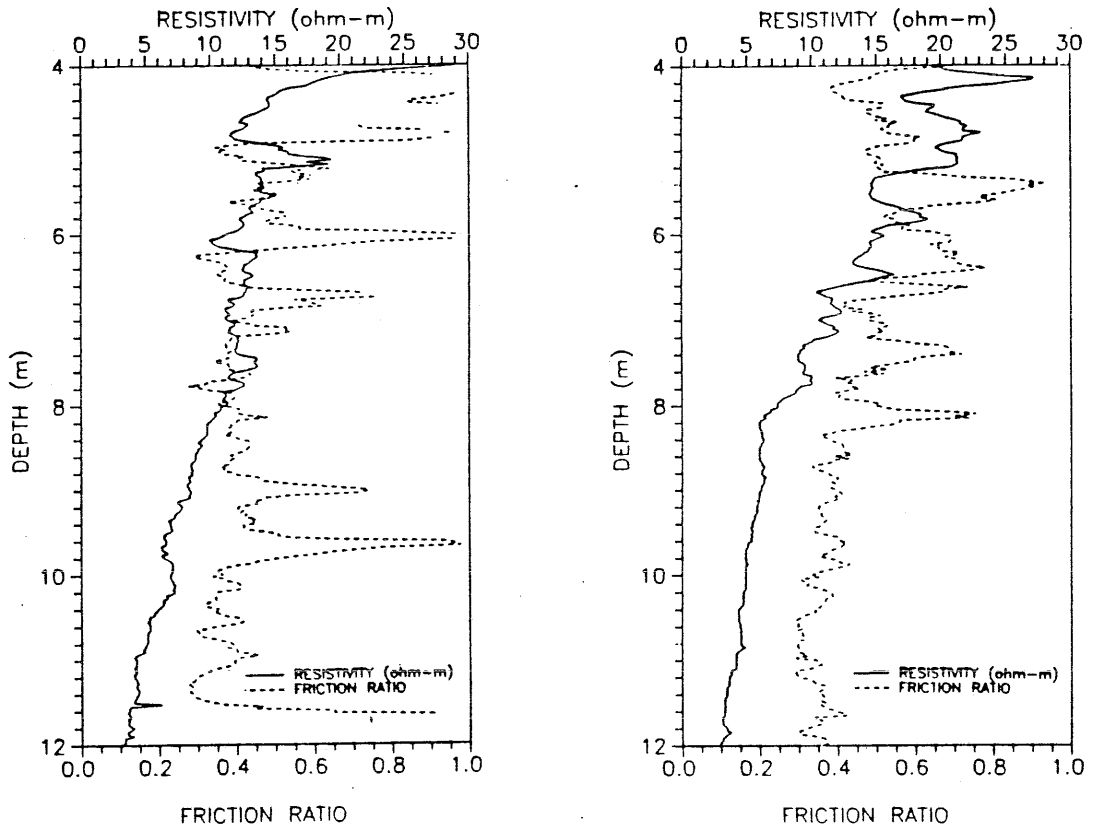Fig. 9   Stratigraphic and Resistivity Profile of McDonald Farm Site.

Fig. 8. A Comparison of the Resistivity (Outer Electrodes) and the Friction Ratio for Two Soundings from the McDonald Farm Site.
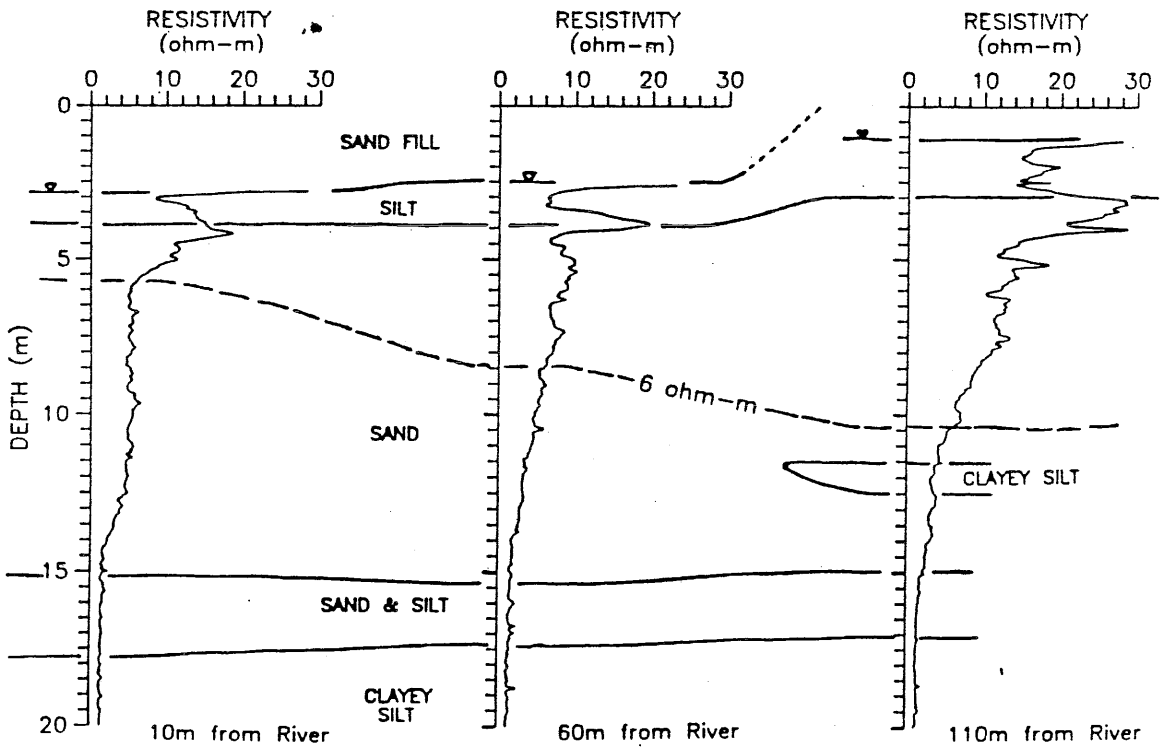

Fig. 9 Stratigraphic and Resistivity Profile of McDonald Farm Site.

The pore pressure parameter is also very useful when describing lithological changes in undrained and partially drained soils. A change from a silt to a clay which would cause a decrease in resistivity would also be detected by a rapid increase in the pore pressure parameter.

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.

At McDonald farm a salt water intrusion situation exists but it is complicated by seasonal fluctuations in river salinity. During periods of low flow in the Winter the river water at McDonald Farm becomes very brackish (ρ_f = 0.64 ohm-m in early February) with a salinity in the order of that of sea water (ρ_f = 0.2 ohm-m, sea water average, Telford et al, 1976). When the river flow is increased due to either prolonged rainfall in the Winter or snowmelt in the Spring and Summer, the salinity drops considerably (ρ_f = 14.8 ohm-m measured on May 9, 1989). This variability in salinity would be rapidly reflected in the groundwater adjacent to the river but farther away from the river the salinity of the groundwater would not have that much seasonal variability.

Figure 9 illustrates a cross-section through three RCPTU soundings, each separated by 50 m, in a line perpendicular to the bank of the Fraser River. Sounding RES89-8 is closest to the river, approximately 10 m from the river shore. This figure shows the resistivity for each sounding and the stratigraphy. All soundings were done within a 5 day period from March 6 to 10, 1989. A 6 ohm-m contour is superimposed on the profile to illustrate the general trend across the site. 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 indicating there was very little groundwater movement below this depth. The resistivity of the clayey silt does not vary at all across the whole site. Near the surface, there tends to be an increase in the resistivity with depth in the overbank silt below the water table. This may be due to decreasing amount of conductive clay minerals with depth in the overbank deposit.

APPLICATIONS TO CONTAMINANT ASSESSMENT

Results to date clearly demonstrate the capability of the cone to produce repeatable and accurate profiles of resistivity. To be successfully applied the resistivity method requires that there be a contrast between background and contaminated soil resistivities. This prerequisite can be satisfied in the case of (1) non-organic conductive aqueous phase liquids (APLs) that decrease the bulk resistivity; and (2) insulating organic non-aqueous phase

liquid (NAPLs) that increase bulk resistivity by blocking paths of conduction through the pore space of the soil.

A summary of typical resistivity measurements of fluids and bulk soil-fluid mixtures is shown in Table 1. These results show the wide range of bulk soil resistivity measurements especially for organic contaminants like Ethylene Dichloride. In a recent study, Kokan (1990) reports that at a site contaminated by industrial wastes of the polycyclic aromatic hydro-carbons (PAH's) type, the resistivity cone clearly mapped the distribution of the contaminants. Resistivities as high as 600 ohm-m were recorded for the contaminated bulk soil in comparison to 40 ohm-m for low or uncontaminated areas, thus providing a high contrast in resistivities.

The resistivity cone can also be used where there is contamination of the groundwater that will disassociate to produce ions. Some examples of such cases are (1) leachate from domestic landfills; (2) acidic mine leachate created by the oxidation of sulphide minerals; and (3) industrial waste.

In the case of the detection of insulating contaminants the resistivity cone may be used to detect such contaminants when present in proportions as

Table 1. Summary of Typical Resistivity Measurements of Fluids and Bulk Soil-Fluid Mixtures

	ρ_f,ohm-m (fluid)	ρ_b,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 Landifll 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

low as 2-5% of the pore fluid. This lower limit is more than adequate for the detection of dense NAPLs that pool on low permeability layers. It is also possible to detect light hydrocarbons that float on top of the water table, because of the close electrode spacing, the usually high resistivity contrast of the conducting media.

In addition to the use of resistivity in a site investigation, the piezocone test provides pertinent hydrogeological information. In an initial site assessment the CPTU may be used to make estimates of (1) steady state head distribution; (2) hydraulic conductivity; and (3) porosity. Hence the goal of a site investigation using the RCPTU would be to: (1) define the boundary of a contaminant plume; (2) determine the stratigraphy at the site; and (3) determine basic hydrogeological parameters. On the basis of this information a site remediation program could be formulated. Of course, the RCPTU is the ideal tool to evaluate and even control site remediation procedures.

SUMMARY AND CONCLUSIONS

Field testing of the resistivity cone showed that this instrument performed reliably and provided a reasonably accurate determination of bulk resistivity. The results of testing at McDonald Farm illustrated the capability of the RCPTU to produce a detailed profile of bulk resistivity which is representative of changes in the amount of total dissolved solids in the groundwater. It was noted that soil resistivity could be related to measured cone parameters in sandy soils. This shows that the state of soil with respect to porosity, and amount of fines can influence the bulk resistivity. The designed four electrode module with simultaneous measurements of resistivity from the outer and inner electrodes showed that changes in soil density caused by penetration do affect bulk soil resistivity measurements. Comparing the results of the inner and outer electrode measurements it can be concluded that two electrodes excited at 1000 Hz are adequate for resistivity measurements. On the basis of results presented it appears that the speed, economy, and reliability of the RCPTU make it ideal for many contaminant site investigations in unconsolidated soil. It is important to realize, however, that the resistivity cone is an Index Tool that must be correlated or calibrated to site specific soil measurements through water and soil sampling and laboratory testing.

ACKNOWLEDGEMENTS

REFERENCES

1. Archie, G.E., 1984. The Electrical Resistivity log as an Aid in Determining Some Reservoir Characteristics. Trans. Amer. Inst. Mineral Metallurgy Eng. 146, pp.1 54-62.

2. ASTM (D1125-82), Standard Test Methods for Electrical Conductivity and Resistivity of Water, Section 11.01, Water, pp. 149-156.

3. Bear, J. and Verruijt., A., 1987. Modeling groundwater flow and pollution. D. Reidel Pub. Co., Dordrecht, pp. 196-198.

4. Benson, R.C., Turner, M.S., Volgelsong, W.D. and Turner, P.P. 1985., Correlation between field geophysical measurements and laboratory water sample analysis. In Proceedings of NWWA Conference on Surface and Borehole Geophysical Methods in Groundwater Investigations, pp. 178-197.

5. Clague, J.J. and Luternauer, J.L., 1982. Field excursion guide book 30A: Late quaternary sedimentary environments, southwestern British Columbia. Presented at 11th Int. Congress on Sedimentology, pp. 24-35.

6. Earth Technology Corporation., 1987. Report on conductivity CPT. Long Beach, California.

7. Greenhouse, J.P. and Slaine, D.D., 1986. Geophysical modelling and mapping of contaminated groundwater around three waste disposal sites in southern Ontario. Canadian Geotechnical Jour., Vol. 23, pp. 372-384.

8. Horsnell, M.R., 1988. The Use of Cone Penetration Testing to Obtain Environmental Data. Penetration Testing in the U.K. Institution of Civil Engineers, pp. 289-295.

9. Jackson, P.D., Taylor-Smith, D. and Stanford, P.N. 1978., Resistivity-porosity-particle shape relationships for marine sands. Geophysics, Vol. 43, No. 6, pp. 1250-1268.

10. Keller, G.V., 1982. Electrical properties of rocks and minerals. In R.S. Carmichael (ed.) Handbook of Physical Properties of Rocks, CRC Press, Boca Raton, FL, pp. 217-293.

11. Kokan, M.J. 1990., Evaluation of Resistivity Cone Penetrometer in Studying Groundwater Quality. B.A.Sc. Thesis in Geological Engineering University of British Columbia.

12. Lockner, D.A. and Byerlee, J.D., 1985. Complex resistivity measurements of confined rock. Jour. of Geophysical Research, Vol. 90, No. B9, pp. 7837-7847.

13. Morin, K.A., Cherry, J.A., Lim, T.P. and Vivyurka, A.J., 1982. Contaminant migration in a sand aquifer near an inactive uranium tailing impoundment, Elliot Lake, Ontario. Canadian Geotechnical Jour., Vol. 19, pp. 49-62.

14. MacFarlane, D.S., Cherry, J.A., Gillham, R.W. and Sudicky, E.A., 1983. Migration of contaminants in groundwater at a landfill: A case study: Part 1. Groundwater Flow and Plume Delineation. Journal of Hydrology, 63, pp. 1-29.

15. Olhoeft, G.R., 1985. Low-frequency electrical properties. Geophysics, Vol. 50, No. 12, pp. 2492-2503.

16. Robertson, P.K. and Campanella, R.G., 1988. Guidelines for geotechnical design using CPT and CPTU. Soil Mechanics Series No. 120. Dept. of Civil Engineering, University of British Columbia.

17. Robertson, P.K. and Campanella, R.G., 1983. Interpretation of cone penetration tests, part I, (sand), Canadian Geotechnical Journal, Vol. 20, No. 4, pp. 718-734.

18. Telford, W.M., Geldart, L.P., Sheriff, R.E. and Keys, D.A., 1976. Applied Geophysics. Cambridge University Press. Cambridge, pp. 442-457.

19. Torstensson, B.A., 1984. A new system for ground water monitoring. Ground Water Monitoring Reviews, Vol. 4, No. 4, pp. 131-138.

20. Weemees, I., 1990. Development of a resistivity cone for groundwater contamination studies, M.A.Sc. thesis, Dept. of Civil Engineering, Univ. of British Columbia.

21. Van de Graff, H.C. and Zuidberg, H.M., 1985. Chapter 2, Field Investigations, The Netherlands Commemorative Volume, ED. de Leeuw, 11th Int. Conf. on Soil Mech. and Found. Engng., pg. 35.

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