

PENETRATION TESTING FOR GROUNDWATER CONTAMINANTS

D.J.Woeller¹, I.Weemees¹, M.Kokan¹, G.Jolly¹, and P.K.Robertson,
M.ASCE²

ABSTRACT: Recent advances in penetration testing technology have produced a variety of new penetration devices to measure groundwater conditions. This paper describes two specially designed devices; a resistivity cone and a chemical testing cone (chemi-cone). The resistivity cone consists of a full seismic cone penetrometer that can record tip resistance, sleeve friction, pore pressure and seismic wave velocity arrivals. Two electrodes, located behind the standard piezo cone unit, are used to measure the bulk resistivity of the surrounding soil. Data are presented to illustrate the potential of the resistivity cone for detecting changes in groundwater resistivity. The chemi-cone also consists of a full seismic cone penetrometer as well pore water testing chamber. The device has the ability to determine water conductivity and temperature. Data are presented to illustrate the potential of the chemi-cone to directly measure some of the chemical properties of groundwater.

INTRODUCTION

The evaluation of groundwater quality has become increasingly important as more industrial and domestic waste comes into contact with groundwater. One method of rapidly and efficiently evaluating contaminated sites is through the use of cone penetration testing. Over the past 40 years extensive world wide experience has been developed using the cone penetration test (CPT). Empirical correlations have been developed to relate CPT data to soil classification and most soil parameters (Douglas and Olsen, 1981; de Ruiter, 1982; Robertson and Campanella, 1983). More recently cone penetrometers equipped to measure electrical properties of soils have been used as aids in evaluating contaminated sites (Zuielberg et al, 1987; Horsnel, 1988; Campanella and Weemees, 1989). The rationale for making electrical measurements is that in many circumstances the electrical properties of the soil will be changed by the presence of contaminants. Therefore, by either measuring soil resistivity or the pore fluid resistivity the lateral and vertical extent of groundwater contamination may be determined. Two specially designed penetration devices have been developed for this purpose, the resistivity cone and a chemical testing cone (chemi-cone).

The resistivity cone penetration test (RCPT) is a continuous test which measures bulk resistivity, while the chemi-cone penetration test (CCPT) measures pore fluid electrical conductivity at discrete intervals. From independent measurements using the RCPT and CCPT certain critical hydrogeological parameters can be determined and

¹Conetec, B.C., Canada ² University of Alberta, Alberta, Canada

subsequently used in analyses relating to problems involving groundwater flow. Based on the recorded values of bulk resistivity and pore fluid conductivity, the location of certain types of contaminant plumes can also be determined. Having the ability to determine basic hydrogeological parameters and delineate certain types of contaminant plumes make the RCPT and the CCPT useful tools for groundwater contaminant studies.

CONE PENETRATION TEST EQUIPMENT

Both the resistivity cone and the chemi-cone include a full 10 ton capacity seismic piezo cone. The cone has a tip end area of 10 sq. cm. and friction sleeve area of 150 sq. cm. The cone is designed with an equal end area friction sleeve and a tip end area ratio of 0.85 (Robertson and Campanella, 1983). A pore pressure filter is located either directly behind the cone tip or on the face of the cone tip. The filter is made of porous plastic and is 5.0 mm in thickness. The cone is pushed hydraulically using a drill rig, with a loading capacity in the order of 10 to 15 tons. The cone is capable of recording the following independent parameters at 5 cm depth intervals: tip resistance, (Q^c); sleeve friction, (F^s); dynamic penetration pore pressure, (U^p); temperature, (T); and cone inclination, (i). Pore water pressure dissipations can be recorded at regular intervals during pauses in the penetration. The seismic piezo cone is also instrumented to record both shear and compressional wave velocities. Full details of the seismic cone are given by Robertson et al, 1986.

Resistivity Cone

Resistivity devices have been added to probes since the late 1960's (Kermabon, et al, 1969; Kroezen, 1981. The resistivity cone developed and used for this study combines a seismic piezo cone with a resistivity module, as shown in Figure 1. The resistivity cone penetration test works on the principle that the measured voltage drop across the electrodes in the soil, at a given excitation current, is proportional to the electrical resistivity of the soil. The stainless steel resistivity electrodes are 15 mm wide and are set 75 mm apart. They are designed to be reasonably wear resistant and have a high electrical conductivity. A smaller electrode separation could give better vertical resolution, but would be measuring the resistivity of a volume of soil closer to the cone and thus more disturbed by penetration. Delrin, a plastic, was used as the insulator separating the electrodes. The probe operates by applying an sinusoidal 1000 Hz current across the electrodes. From the resultant potential difference between the electrodes a resistance is determined. The current is regulated by a downhole microprocessor that adjusts the current when the resistivity changes appreciably to ensure a linear response to the soil. This enables resistivity measurements between 0 and 250 ohm-m to be made with an accuracy of +/-0.2 ohm-m. A 1000 Hz source is used to avoid polarization of the electrodes. Polarization is the process where ions accumulate at the electrodes thus increasing the measured resistance. This frequency also falls within the range (25 - 3000 Hz) suggested by the ASTM (D1125-82) for water conductivity measurements. Weemees (1990) noted that polarization can be observed at frequencies up to 500 Hz.

Resistance is not a material property but a function of the electrode spacing and size. To convert from resistance to resistivity, which is a material property, a lab calibration is necessary. The resistivity module was calibrated in a water tank. Solutions of known resistivity were prepared in the tank and the

resistance across the electrodes was measured. On the basis of the calibration it was found that resistivity was linearly related to resistance. It is necessary to assume that the calibration factor when the cone is advanced through soil will not vary considerably from that determined in an homogeneous isotropic medium. The resistivity of the soil is for the most part influenced by the resistivity of the pore fluid, which in turn is a measure of the groundwater chemical composition. Electrical conduction in saturated soils is largely by electrolytic conduction in the pore fluid although ion exchange within the soil skeleton contributes significantly in clayey soils. The resistivity cone testing procedures used in this study were no different than for a standard piezocone test. No special preparation of the module is necessary and no manual adjustments are needed during the sounding. The resistivity measurements are carried out and recorded on a continuous basis at the same time as the tip, friction and pore pressure.

Chemi-Cone

While the resistivity cone measures bulk resistivity, a more direct, and accurate way of determining groundwater quality is by measuring the pore fluid conductivity (the inverse of resistivity). The chemi cone, as shown in Figure 2, combines the seismic piezo cone and a conductivity module. The conductivity module consists of a remotely operated down hole pump and 30 ml capacity testing chamber which contains the conductivity cell. The conductivity and temperature of the pore fluid sample is measured in the chamber after being drawn in by the pump. The conductivity cell is platinized and operates at frequency of 1000 Hz. Ideally, future versions of this type of tool will have provisions for drawing a pore fluid sample directly to the surface. During pauses in penetration the pump draws in a sample for the conductivity and temperature measurements. After the readings are made the pump is reversed, expelling the fluid completely from the sample chamber. By measuring conductivity an estimate of the total dissolved solids in the groundwater can be made since there is a linear correlation between the amount of dissolved ions and the ability of the pore fluid to transfer electrical current.

SITE INVESTIGATIONS USING PENETRATION TESTS

When considering the use of penetration technology at a site the suitability of the site must first be considered. The RCPT and CCPT, like most cone penetrometers, can be advanced through most soils for depths of at least 10 metres with the exceptions of gravels and cobbles or heavily cemented soils. Thin gravel layers (up to 1 m thick) do not normally present a problem, since isolated dense layers can be drilled out and the soundings can be continued. Even without the addition of the ability to measure bulk resistivity or pore fluid conductivity the piezo-cone test has much to offer in hydrogeological investigations:

- * Piezometric pressures and hydraulic gradients based on equilibrium pore pressure measurements
- * The accurate determination of lithological boundaries including the identification of very narrow soil layers.
- * The determination of soil type from classification charts based on the recorded values of tip resistance, sleeve friction, and dynamic pore pressure.

An example of a recent soil classification chart based on normalized piezo cone data is shown in Figure 3. Also estimates of porosity and the horizontal coefficient of permeability (k_H) can also be estimated from the piezo-cone test. Procedures have been established for the determination of k_H from dissipation tests. Figure 4 shows a compilation of k_H data from a number of sites worldwide. It has been suggested (Robertson and Campanella, 1988) that for hydraulic conductivities of greater than 10^{-3} cm/s that penetration is fully drained. Hence for fully drained soils k_H would have to be estimated on the basis of soil type. Rough porosity estimates may be made on the basis of tip resistance/relative density relationships and by soil classification type. Good estimates of hydraulic conductivity and porosity generally require some local knowledge so that site specific correlations can be developed. In a short period of time a full geological profile of a site can be developed and groundwater gradients can be determined. Also, with estimates of hydraulic conductivity and porosity an initial estimate of advective groundwater velocities may be calculated. The detection of contaminants using the RCPT or the CCPT is based on the premise that contaminants will change the measured electrical properties of the soil or pore fluid. Therefore contaminants can only be identified generically and only qualitative assessments are realistic. Furthermore control soundings are required at a site so that a background resistivity profile can be determined. Nevertheless both positive and negative anomalies in resistivity caused by contaminants can be successfully mapped by the RCPT and the CCPT, horizontally and vertically.

This approach seems particularly promising in detecting the maximum extent of contamination caused by dissolved inorganic species because they travel at the advective groundwater velocity. Figure 5 (MacFarlane et al., 1983), illustrates how discrete conductivity measurements can be made to define the boundaries of a low resistivity contaminant plume, in this case being generated by a landfill. The resistivity cone test and chemi-cone test are able to define the boundaries of a low resistivity contaminant plume in the same way only more rapidly while also supplying stratigraphic, geotechnical and hydrogeological information. Where only non aqueous phase contaminants are present the RCPT would be able to detect such contaminants only if present in large quantities (Weemees, 1990). The RCPT may not be appropriate for detecting small quantities of organic contaminants.

PENETRATION TEST DATA

Resistivity Cone

Resistivity Cone data is presented from two sites. The first, an uncontaminated site in the Fraser River Delta, is meant to show how changes in soil lithology influence bulk resistivity. The second, a contaminant site in western Canada, illustrates how groundwater contamination influences bulk resistivity. While bulk resistivity is primarily influenced by the chemistry of the pore fluid, changes in soil lithology may also change soil resistivity. For this reason the ability of the CPT to note changes in soil lithology is important in establishing if changes in bulk resistivity are caused by either changes in soil properties alone or by changes in pore fluid resistivity. Figure 6 presents a RCPT profile from a site in the Fraser River Delta. As seen in the figure, the clayey silt near the surface has the lowest resistivity. This is due to the presence of clay minerals in the soil. Clay minerals decrease resistivity by providing an alternate method of electrical conduction due to the transfer of cations between exchange sites (Jordan and Campbell,

1986).

Below a depth of 3m the decreasing clay content is marked by a corresponding increase in resistivity, which reaches a maximum in the sand. Bulk resistivity is also influenced by soil porosity. For a given pore fluid resistivity, a dense sand reflected by a higher cone penetration resistance, will have a higher resistivity.

Figures 7 and 8 present resistivity cone data obtained at a site of an organic solvent spill. The contaminant can be classified as a dense non aqueous phase liquid (DNAPL). The product is slightly soluble. Such contaminants can be considered electrically non-conductive, thus increasing the bulk soil resistivity by displacing pore fluid and reducing paths of conduction (Hepple, 1967). A total of 8 RCPT's were performed at the site during one regular 10 hour work day. This illustrates the speed and economy of penetration testing to investigate both the soil and groundwater conditions. Figure 7 shows a typical RCPT profile from the spill site. The site conditions consist of about 2 to 4 m of a fill material consisting of wood waste and sand mixture overlying a deep deposit of clean fluvial sand. The resistivity data clearly identifies the interface between the fill and underlying sand. Groundwater was encountered at a depth of 5 m and piezometric pressures in the sand were essentially hydrostatic as shown in Figure 7. To investigate the lateral and vertical extent of contamination, 4 RCPT's were performed about 200 m downgradient from the contaminant source, across the flow path. One RCPT was performed at the extreme edge of the site approximately 400 m from the spill where there was thought to be no influence of the DNAPL spill. The resistivity values in the sand at this location were very low (20 ohm-m) and were comparable to other values measured for uncontaminated sites in this same geographic region with similar soil conditions. The remaining 3 RCPT's were performed at uniform horizontal intervals of 100 m towards the centre of the spill site. Figure 8 presents a compressed cross section showing the results from the 4 RCPT's. Figure 8 clearly shows the extent of the inferred plume of DNAPL contamination as a zone of high resistivity (Approx, 100 ohm-m). An interesting feature of the resistivity data shown in Figure 8 is the increase in depth of the contamination with increasing distance from the spill. This increase in thickness of contaminated soil is to be expected since the product is heavier than water.

CHEMI CONE

During an investigation in Northern Canada, the CCPT was used to determine the salinity of the pore fluid within both spray ice and soil. The soundings penetrated through the spray ice and foundation soils of an oil drilling well ice island in the Beaufort Sea. The consistency of the spray ice is highly variable, with the strength of the ice being a function of temperature and salinity. The measurement by the CCPT of pore fluid salinity, was based on fluid conductivity and temperature. During the initial phases of this investigation this salinity data was compared to an independent groundwater sampling system, the BAT system (Torstensson, 1984). The BAT system was used to retrieve groundwater samples from specific depths. The samples were then tested in a laboratory for both conductivity and salinity. Both the CCPT and BAT water sampling were carried out at 3 different locations. A comparison of the salinity profiles determined using the CCPT and the BAT sampler are shown in Figure 9. This figure illustrates how the salinity results obtained from the CCPT were corroborated by the direct BAT water sampling method. The CCPT results were obtained directly in the field without

the requirement of time consuming laboratory testing. A good estimate of the salinity can be made by the CCPT because the conductive nature of sea water is mostly due to only two ions, chloride and sodium, whose relative proportions will not change appreciably. Hence, by comparing a single lab measurement of salinity to conductivity a simple relationship between the two parameters can be developed.

CONCLUSIONS

The resistivity cone penetration test and the chemi cone penetration test can rapidly provide accurate determinations of soil stratigraphy and equilibrium groundwater levels and groundwater gradients. In addition, estimates of hydraulic conductivity and soil porosity can be made. Using resistivity or conductivity modules in conjunction with the piezo cone the vertical and lateral extent of certain types of contaminant groundwater plumes can be economically mapped. There appears to be no other single testing technique which can provide the quantity and quality of data presently available from the use of the RCPT and CCPT.

The use of these recent developments in penetration technology, namely the RCPT and the CCPT, have been briefly described in this paper. Continued advances in penetration testing techniques can be expected and, when combined with these recent developments, should significantly improve the ability of engineers to conduct more cost effective assessments of contaminated sites and to rapidly implement detailed monitoring and or remedial measures.

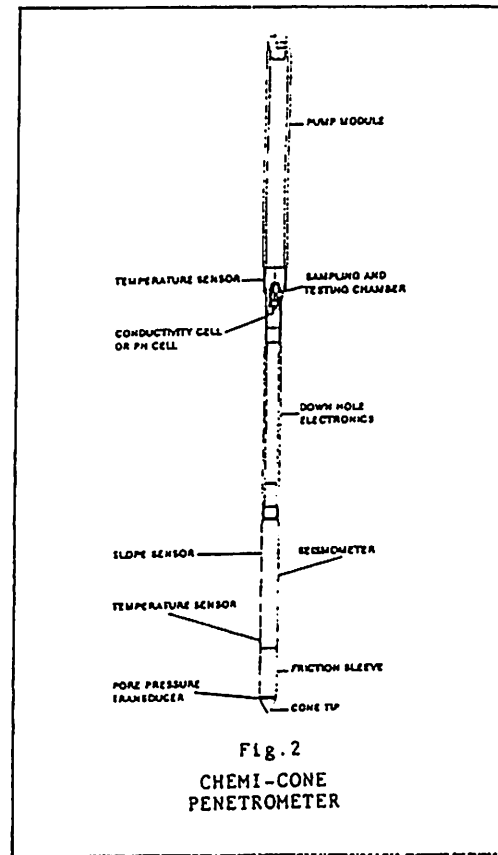
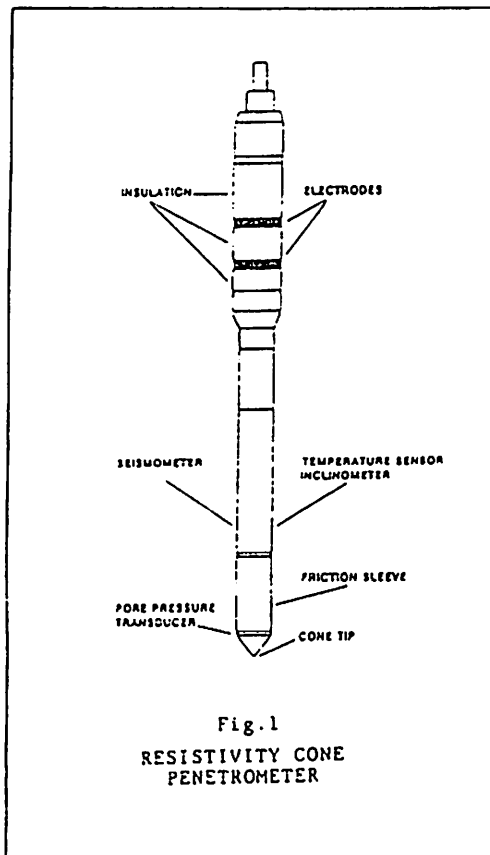
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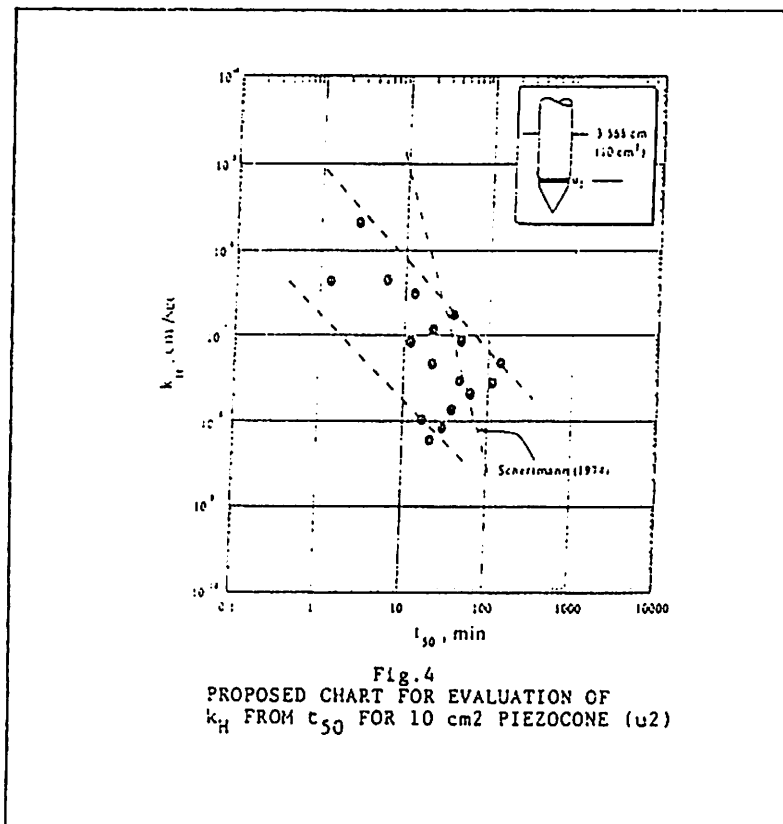
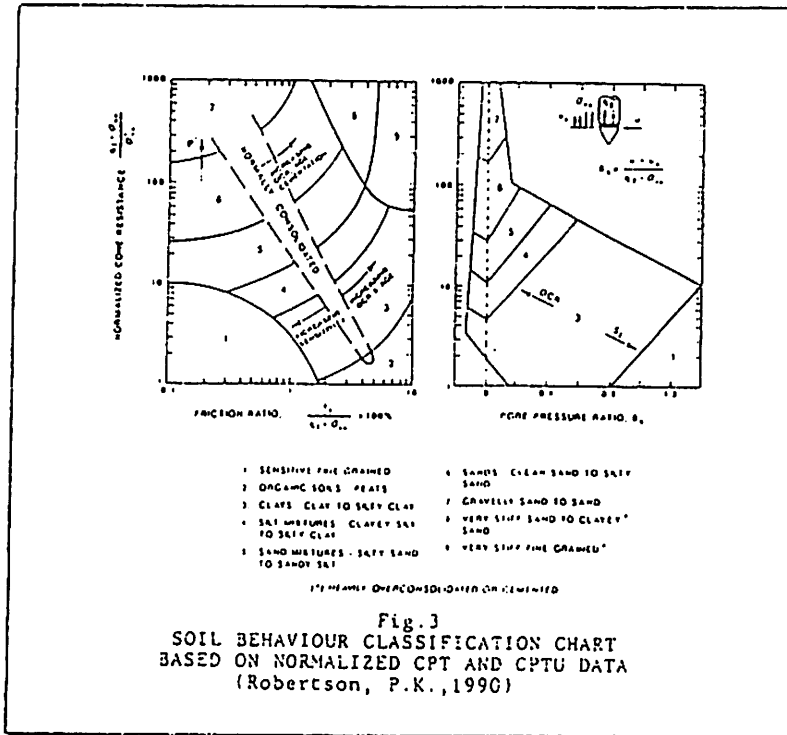
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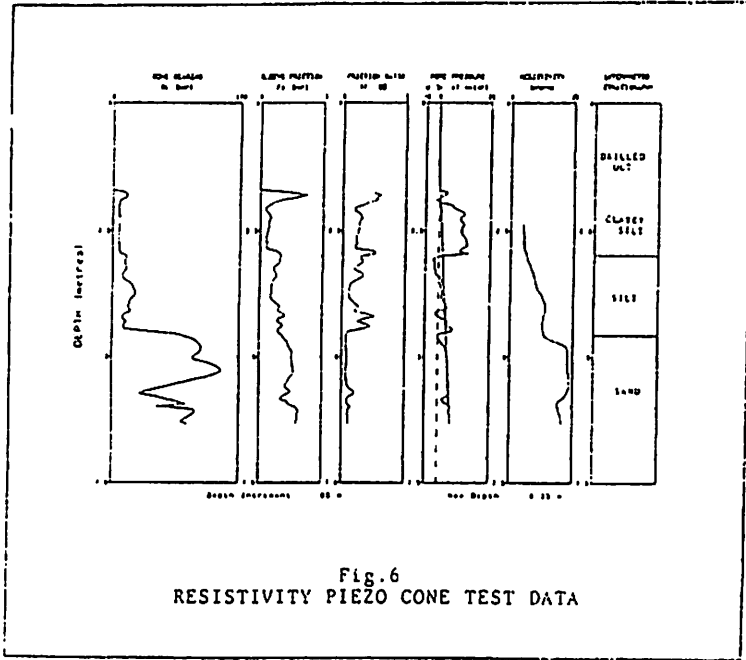
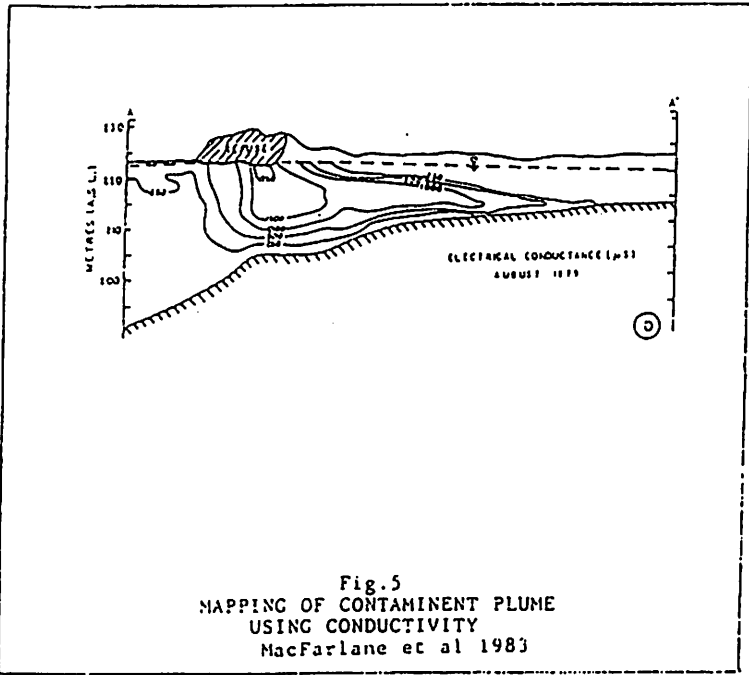
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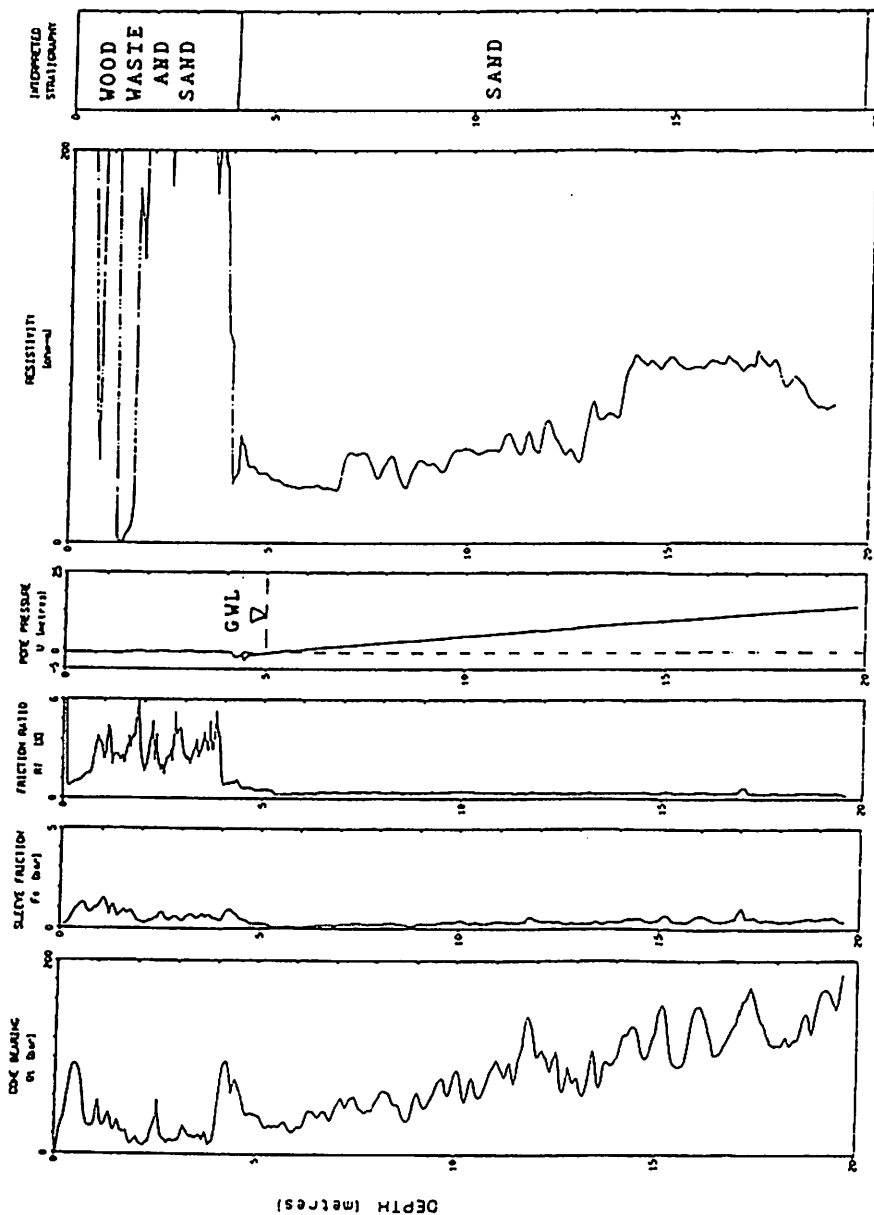


Fig. 7
RESISTIVITY & PIEZO CONE DATA
FROM RCPT AT DNAPL SPILL SITE

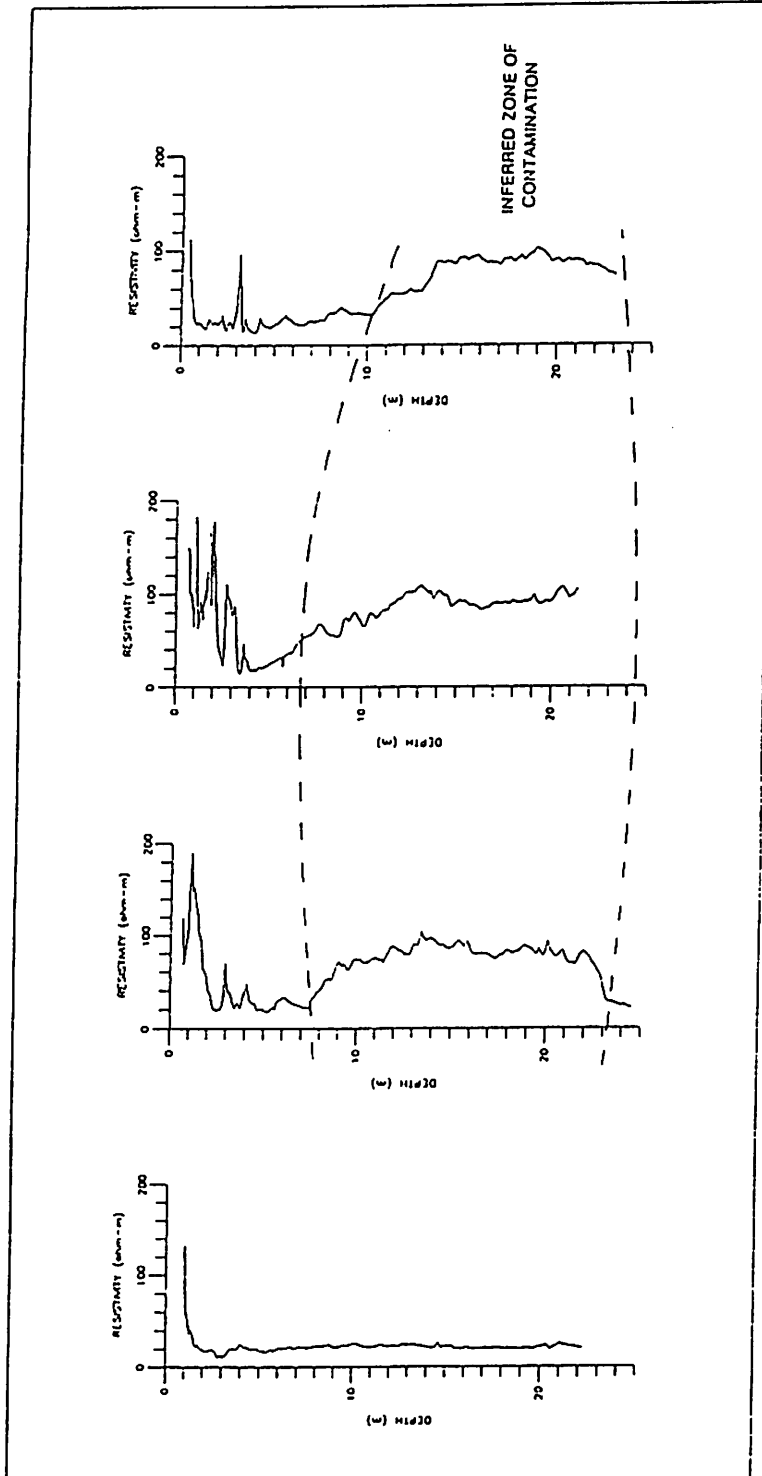


Fig.8
 PLUME DELINEATION USING
 RESISTIVITY AT DNAPL SPILL SITE

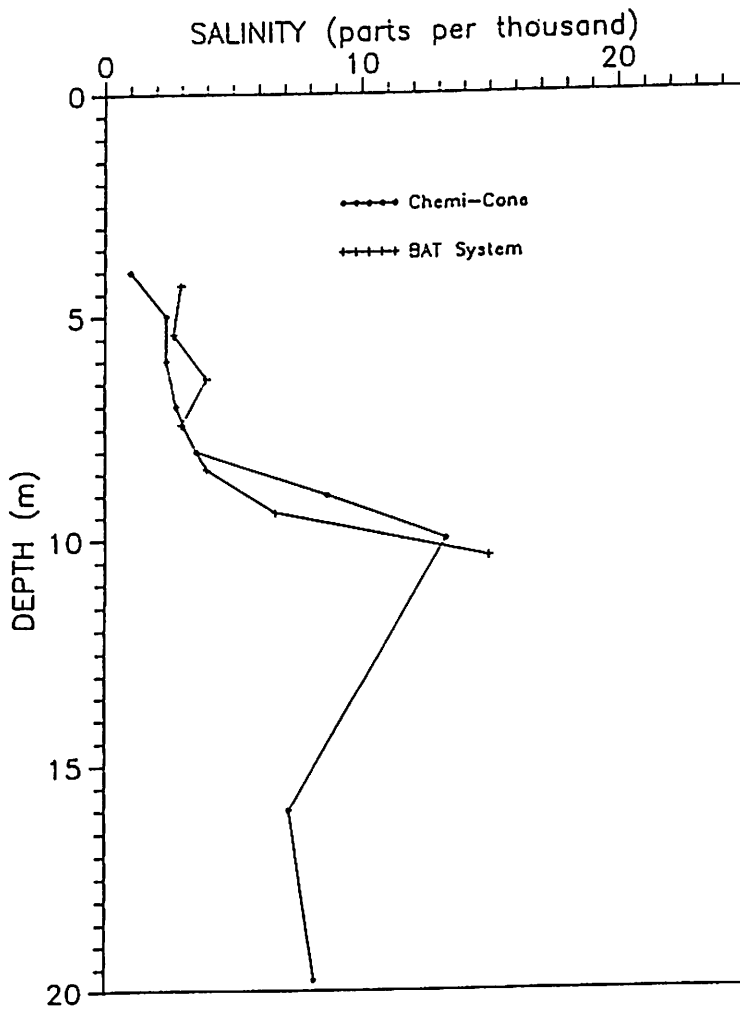


Fig.9
COMPARISON OF CHEMI CONE &
BAT SAMPLER SALINITY DATA