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Characterizing Contaminated Soil and Groundwater Systems with In-Situ Testing

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Abstract

The key component of any subsurface assessment of environmental conditions is the method of site characterization. Traditional methods of limited drilling and discrete sampling followed by selected laboratory testing are expensive, time-intensive and provide an extremely small statistical sample of the system of interest. In-situ testing, using sophisticated instrumented and mechanical devices, offers a technically superior and cost effective alternative for site characterization.

This paper presents an introduction to some of the in-situ tools currently available for contaminated soil and groundwater characterization. The paper will concentrate on the resistivity CPT and will include case study examples of site characterization. The paper will also present a synopsis of planned research activities for the In-Situ Testing Group over the next few years including investigating contaminated aquifers, assessing acid rock drainage in mine wastes and effective and economic means of water sampling at mines and other heavy industrial sites.

Introduction

With any subsurface assessment of environmental conditions, the method of site characterization is the key to the quality of the information obtained. Traditional methods of limited drilling and discrete sampling followed by selected laboratory testing provide an extremely small statistical, and often poor quality, evaluation of the system of interest. What makes in-situ testing attractive for environmental site characterization is that an accurate and repeatable information that is available on a near continuous basis can be obtained in a fast, cost-effective manner.

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In-situ testing also provides a huge advantage over conventional drilling in that soil cuttings are not produced. On many contaminated sites the costs related to handling and disposing of these cuttings can be extremely high and tends to limit the amount of subsurface investigation ultimately carried out.

The University of British Columbia's (UBC) In-Situ Testing Group has been conducting applied characterization research for nearly 15 years. The main focus of this research has been to not only expand the knowledge base in the field but to provide the practising engineer with reliable, repeatable and economical in-situ testing tools, procedures and evaluation methodologies to solve an extreme variety of engineering problems. The main area of research for the first 10 years of the Group was in the applied geotechnical engineering field. Since that time, the geotechnical research has continued but is being augmented with the development of in-situ methods to facilitate practical environmental characterization.

The key items that must be characterized in order to evaluate contaminated soil and groundwater systems are:

- the stratigraphic profile;
- the relative geotechnical properties of each stratigraphic unit;
- the hydraulic properties of the aquifer and aquitard materials; and
- the nature of the pore fluid/gases that are present in the materials.

Currently available in-situ methods allow estimates of the above to be made in most soil conditions. The actual pore/gas fluid chemistry is carried using in-situ sampling methods, and some laboratory testing, not described in this synopsis paper, but which are a large part of current characterization research at UBC.

<u>In-Situ Testing</u>

Cone Penetration Test

The electronic piezocone (CPTu) is increasingly being used by practising engineers as an effective means of geotechnical classification. The method provides a fast, economical, and accurate means of delineating soil stratigraphy and determining geotechnical parameters. The cone has a standard 10 cm^2, 60° conical tip, a friction sleeve with an area of 150 cm^2 and pore pressure transducers which allow the CPTu to measure tip resistance (q_c), friction sleeve stress (f_s) and pore pressure dissipations at three locations (U_1, U_2, and U_3). There are extensive relationships available between the various CPTu channels, and combinations thereof, that provide soil behaviour type (often equivalent to stratigraphy), geotechnical strength parameters and hydraulic parameters. Temperature (t) and instrument inclination (i) are also measured simultaneously. In addition, a seismic model of the cone has been developed to measure low strain dynamic properties of the soil.

The CPTu is generally regarded as the most effective and cost efficient tool for stratigraphic logging of soils by the geotechnical community (Robertson et al., 1986). The cone is pushed into the ground at a constant 2 cm per second by a hydraulic pushing source; often a drill rig or a specially outfitted research vehicle. As the cone is advanced, pore pressures are generated around the cone tip and sleeve. The measurement of these excess pore pressures which are generated during penetration provides insight into the hydraulic parameters of the porous media. Since most groundwater contamination has advective transport as its major component, developing a continuous profile of hydraulic parameters is a key step in characterizing contaminated sites.

When penetration ceases, e.g., after a 1-metre rod push, the excess pore pressure decay with time is used in cohesive soils to calculate the coefficient of consolidation, $c_{v\ (or\ h)}$ (where v and h are vertical and horizontal coefficients, respectively). Knowing $c_{v,h}$, the hydraulic conductivity (K) can be computed using:

$$K_{v,h} = c_{v,h}\, m_{v,h}\, \gamma_w \qquad (1)$$

where $m_{v,h}$ is the coefficient of volume compressibility in either the vertical or horizontal plane, which can be estimated from CPTu data, and γ_w is the specific weight of water. In addition, pressure head distribution within the saturated zone can be determined based on the equilibrium pore pressure data for all soil types.

Empirical correlations between hydraulic conductivity and relative density (D_r) provide an acceptable estimation technique for the hydraulic conductivity in cohesionless soils. Relative density can be determined directly from the CPTu tip resistance. The form of the empirical correlations between K and D_r is:

$$\log (K) = a - b\ (D_r) \qquad (2)$$

where *a* and *b* are the empirical constants. For many clean sands, an initial estimate of K (cm/sec) can be obtained for a = 0.5, b = 0.05 and D_r is in %. For example, a sand with D_r = 60%, K would be estimated as 3 x 10^{-3} cm/s. The anisotropic ratio, K_v/K_h, can also be estimated from the CPTu profile using some judgement. More field and laboratory data are needed before a comprehensive relationship can be developed for cohesionless soils, although equation 2 appears to provide a very good first order estimate of a parameter that is rarely known to within better than about an order of magnitude.

Resistivity CPT (RCPTu)

The resistivity cone penetration test (RCPTu) is a modification of the standard piezocone test (CPTu). All of the downhole electronic equipment used was designed and built at UBC.

The ability to measure the resistance to current flow in soils, has been one of the more recent developments in penetration technology at UBC. Several models of resistivity cones have been developed with varying number and types of electrodes and other modifications. A five electrode array resistivity module, which is located behind the piezocone , is shown in Figure 1. The most current research tool has a total of seven electrodes. With the addition of a resistivity module, the RCPTu has the advantage of continuous resistivity measurements <u>and</u> all of the traditional CPTu data.

The electrode separation currently varies from 8 mm to 150 mm providing different depths of lateral penetration. The outer electrodes are the current supply electrodes, but are also used as measurement electrodes. 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. A constant peak current AC source, set at 1000 Hz, can be adjusted in amplitude according to the resistivity of the of the soil to allow voltage measurements across the electrodes during penetration. Data is logged using the UBC in-situ testing digital data acquisition system.

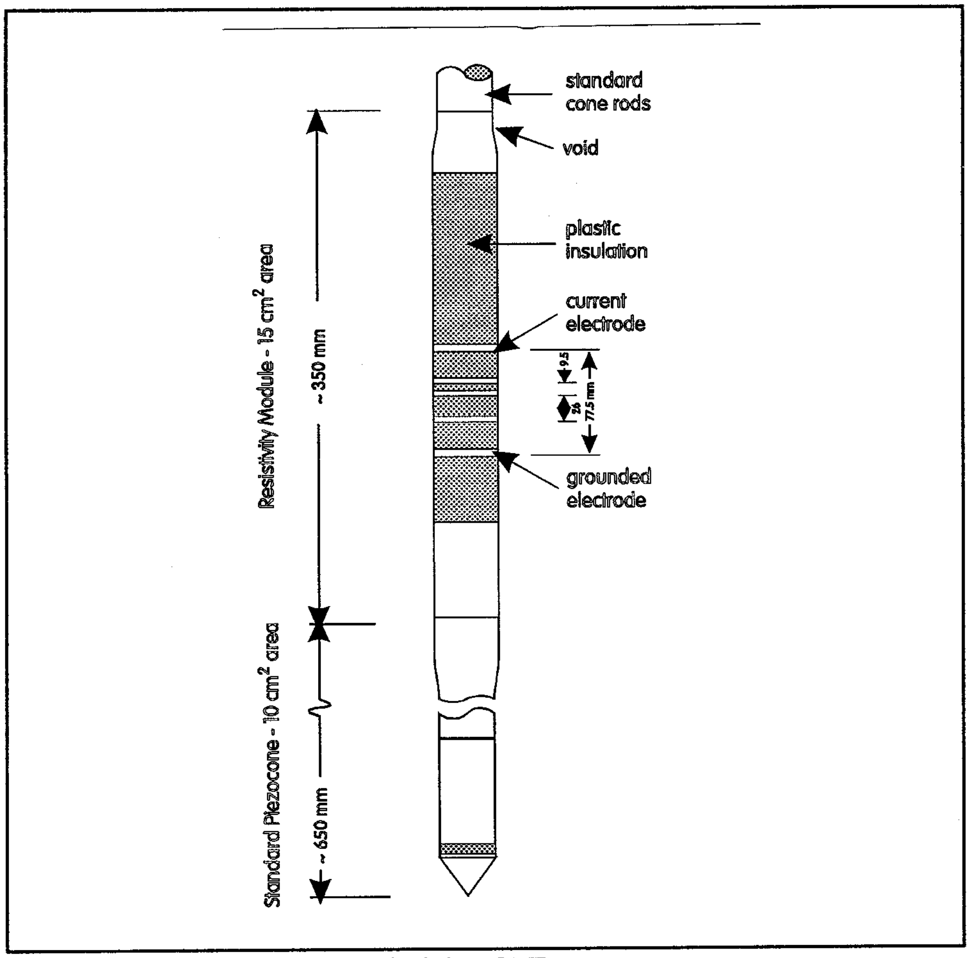

Figure 1 - Schematic of Resistivity CPTu

When the electrodes are in a homogeneous and isotropic medium, they should respond in a similar manner to that of water immersion. However, soil is rarely homogeneous and isotropic, so 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 will not respond fully to a layer [redacted] unless the layers are completely within that layer, so to be correctly sensed layers must have a thickness greater than a given electrode spacing.

Campanella and Weemes (1990) provide a much more thorough discussion on the design and the development of the UBC RCPTu.

Site Characterization with RCPTu

Profiling Capability

Besides providing the standard CPTu profile of stratigraphic and geotechnical information, the resistivity cone is ideal for rapidly determining cross-sectional profiles of groundwater quality. This groundwater profile would typically be carried out to delineate the boundaries of a contaminant plume. For an illustrative example, the McDonald Farm site in Richmond, British Columbia, is presented. Although not a contaminated site, McDonald Farm does provide a site where data can readily be disclosed and a similar situation to groundwater contaminant delineation exists - a salt water to fresh water interface. The salt water, due to its higher density will tend to behave like a DNAPL and migrate below the fresh water. The RCPTu profile for the McDonald Farm site is shown in Figure 2.

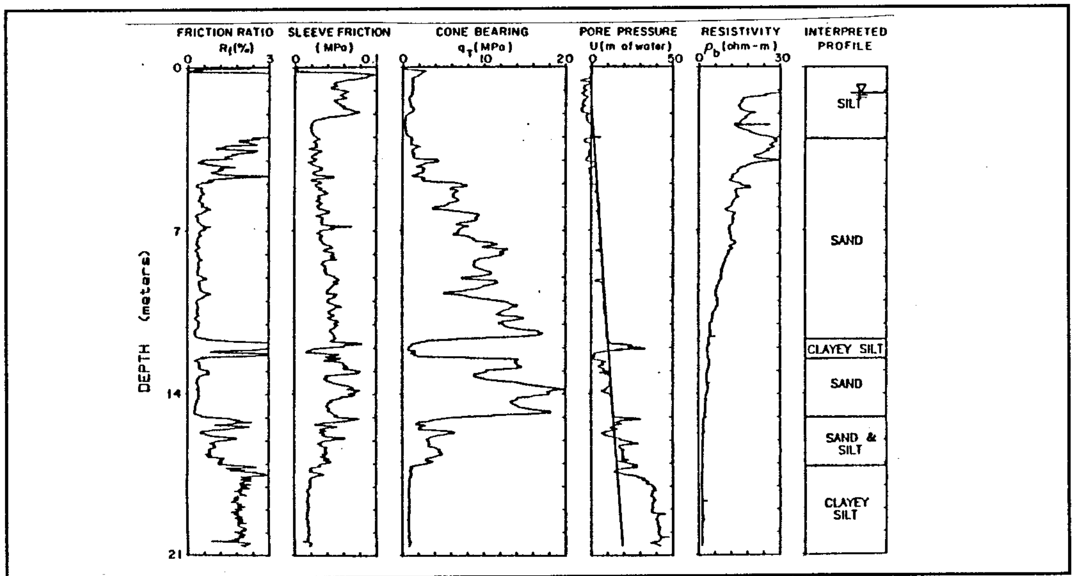

Figure 2 - RCPTu Profile of McDonald Farm, Sea Island, British Columbia

Figure 3 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 4 day period from March 6 to 10, 1989. A 6 Ω-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 (seasonal variations excluded). 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.

Application to Contaminant Assessment

Results to date clearly demonstrate the capability of the RCPTu to produce repeatable and accurate profiles of resistivity. To be successful 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.

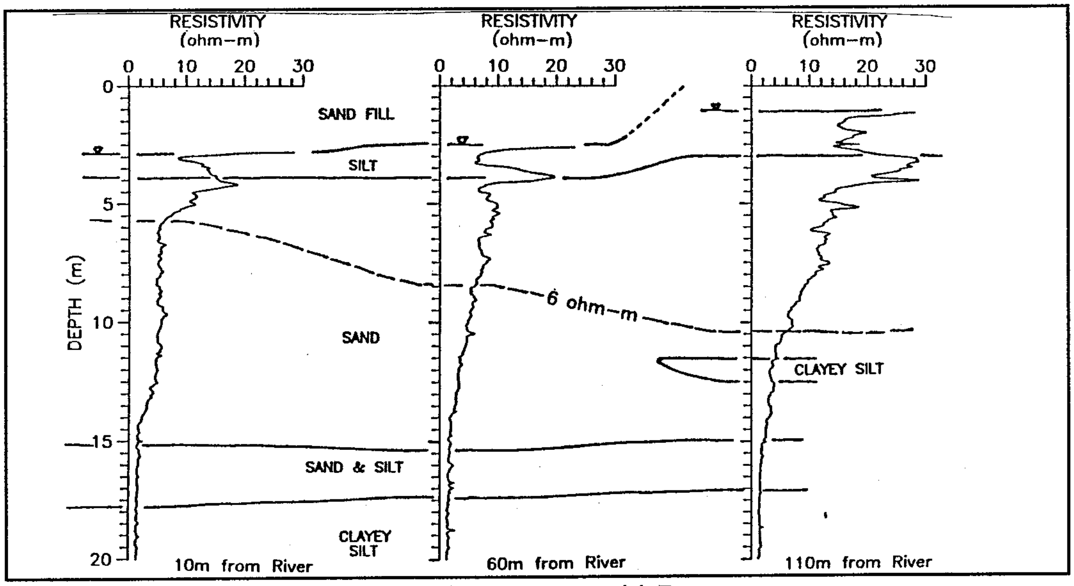

Figure 3 - Resistivity Cross-Section, McDonald Farm

A summary of typical resistivity measurements of fluids and bulk soil-fluid mixtures are 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 work at UBC, Kokan (1990) reports that at a site contaminated by industrial wastes of the polycyclic aromatic hydrocarbons (PAH's) type, the resistivity cone clearly mapped the distribution of the contaminants. Resistivity as high as 600 Ω-m were recorded for the contaminated bulk soil in comparison to 40 Ω-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.

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

	ρ_f, Ω-m (fluid)	ρ_b, Ω-m (bulk soil)
Seawater	0.2	-
Drinking Water	>15	-
McDonald Farm Clay	0.3	1.5
Colebrook Site Clay	18.2	25
401 @ 232 Ave., Railway Site Clay	N/A	8
B.C. Highway Strong Pit Clay	N/A	35
Typical Landfill Leachate	1.5-6	5-20
Colebrook Site Sand	N/A	70
Strong Pit Sand	N/A	115
100% Ethylene Dichloride (ED)	20,400	
50% ED/50% 150 Ω-m fluid in Wedron 7020 sand	-	696
30% ED/70% 150 Ω-m fluid in Wedron 7020 sand	-	335
17% ED/83% 150 Ω-m fluid in Wedron 7020 sand	-	273

In the case of the detection of insulating contaminants the resistivity cone may be used to detect such contaminants when present in proportions as 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 and the usually high resistivity contrast of the conducting media.

As noted earlier, 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. Furthermore, having a knowledge of the bulk and pore fluid resistivities, the porosity can be determined with empirical relationships. 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. Based upon our experience, the RCPTU is the ideal tool to evaluate and even control site remediation procedures.

Current Trends and Research

The In-Situ Research Group at UBC plans to use the RCPTu and other related tools investigating two distinctly different contaminated site issues in 1993. These tools will be used to investigate acidic groundwater which has been contaminated by acid rock drainage. The goal will be to delineate the extent and nature of the acidic drainage in the soil aquifer and also within the mine tailings themselves. Also, the RCPTu will be used to characterize an unconfined groundwater aquifer in British Columbia where a well-documented case of agricultural nitrate contamination exists.

The challenge in carrying out any in-situ tests lies in the interpretation of the data. To accurately delineate a contaminant plume, the movement of the contaminant in time and space must be accurately mapped. The field investigation programs planned by UBC are being designed such that the testing yields enough information so that a realistic three-dimensional characterization can be developed.

For the 1993 programs and all future investigations, UBC is using three-dimensional, relational, spatial and temporal data bases that allow storage, retrieval and presentation of environmental site data.

Conclusions

This paper has briefly presented an overview of in-situ testing for characterizing contaminated soil and groundwater systems. The paper has focused mainly on the CPTu and RCPTu although other related tools are used and form an integral part of the characterization efforts by UBC.

The RCPTu has been introduced as a key tool to characterize contaminated sites. The strength of the RCPTu lies in its ability to effectively measure geotechnical parameters and environmental quality at a given site. The duality of the tool is technically appealing when it also produces reliable, repeatable data at a reasonable cost, the appeal is enormous.

In-situ testing has become, and will continue to grow as, a key method of characterizing contaminated sites. The penetration tests do not produce cuttings and provide nearly continuous information on soil type, hydrogeological information (including pore fluid pressure) and chemical information from resistivity measurements. When these tools are combined with specialized soil/gas/water sampling equipment, accurate and cost effective site characterization can be realized.

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