Geo-environmental site characterization

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ABSTRACT: The use of the piezocone to provide detailed stratigraphic information as well as the piezometric and hydraulic characteristics of the soil is discussed. A resistivity module of external electrode rings attached to the piezocone, which was developed at UBC (University of British Columbia) to log and assess groundwater quality, soil porosity and saturation, is also discussed together with basic theory and factors that affect in-situ electrical resistivity. Finally, the combination of the economical and rapid UBC-modified *BAT* groundwater penetration tool to provide 'specific-depth' groundwater samples for chemical and biological analysis and correlation with resistivity will also be explained. Field data from several case histories are presented to demonstrate the use of the resistivity piezocone in combination with groundwater sampling to provide screening data to locate permanent monitoring well systems or to develop remediation scenarios. The examples deal with acid mine drainage, creosote contamination at a pressure treatment plant, sea water intrusion along side a river outlet and seepage through a tailings dam.

1 INTRODUCTION

Geotechnical site characterization requires a full 3-D representation of stratigraphy (including variability), estimates of geotechnical parameters and hydrogeological conditions and properties. While traditional methods like drilling and undisturbed sampling can provide adequate stratigraphic details and estimates of geotechnical parameters, they can not provide useful estimates of hydrologic conditions like gradient and equilibrium pore water pressure. An installation of a network of piezometers would be required to determine pore water transport parameters. Drilling, undisturbed sampling and piezometer installations are all very costly procedures, often prohibitive, resulting in minimal drilling and sampling in most geotechnical projects. Rarely are pore pressure profiles correctly determined, even though an effective stress analysis requires it.

Environmental concerns add the need for also determining geochemical and transport conditions. The determination of the chemical properties of the pore water often requires sampling-wells which are very expensive to install and develop, dilute constituents moving in layers in stratified soils over the length of well screen and are difficult to know where to locate within the property of concern. Furthermore, environmental field studies require decontamination protocols, the use of drilling methods which do not use fluids, the removal of all cuttings to specially designated waste sites and the use of isolation and safety protocols of all equipment and personnel at the site. All of this adds enormously to the cost of geo-environmental site investigations.

In-situ penetration test tools like the resistivity/seismic piezocone and *BAT* specific depth pore water-sampling systems provide particular advantages for a geo-environmental investigation. They displace the soil and do not create any soil cuttings (that must be removed), are relatively small tools causing minimal intrusion, do not require any fluids for penetration, are easily decontaminated, can incorporate continuous grouting to eliminate possible cross-contamination, can sample pore fluid and pore gases at specific depths, and can indicate chemical anomalies with continuous resistivity measurements. These penetration tools accurately and economically meet the requirements for environmental site characterization as set out by the US Environmental Protection Agency (US EPA, 1989), which includes measurement of stratigraphy, water level data, hydraulic conductivity, relative chemical distribution, and sources/receptors for potential and existing contaminants. Also, non-intrusive surface geophysical methods work effectively to guide and supplement data from any site investigation methodology, especially in-situ testing. An example is given in a subsequent case history.

This paper presents a brief review of selected penetration methods for environmental site characterization of soil deposits, and recent developments and experiences in the UBC In-situ testing group. These methods include the piezocone penetration test, the resistivity piezocone and the *BAT* groundwater system. Also presented are several case histories, which demonstrate the advantages of these methods.

2 IN-SITU TESTING

2.1 *Piezocone*

The piezometer cone penetration test (CPTU) involves the penetration of a 60° apex cone of typically 35.7 mm diameter (10 cm^2 area) as shown in Fig. 1. Pushing at a constant 2cm/s (~1m/min) is achieved by hydraulic force supplied typically by either a drill-rig or a specially outfitted cone-pushing vehicle. At UBC, all cone equipment was designed by the author and built in the Civil Engineering machine and electronics shops including the enclosed in-situ testing research truck which supplies the cone-pushing force (Campanella and Robertson, 1981). Davies and Campanella (1995) list typical pushing capabilities through clay and sand soils.

The UBC piezocone measures tip resistance (q_c), friction sleeve stress (f_s), and pore pressure response at up to three locations; on the cone tip face, immediately behind the cone tip and immediately behind the friction sleeve (referred to as U1, U2, and U3, respectively). The U3 location has a more sensitive pore pressure transducer to measure more accurate small dissipations and equilibrium pressures compared to U2 or U1. Most correlations and direct calculations assume measurement at the standard U2 location. Temperature (T) and inclination (I) are also measured simultaneously as the piezocone is advanced into the ground. All channels are continuously monitored and typically digitized at 25 or 50 mm intervals. Campanella and Robertson (1988) outline the piezocone's main advantages, limitations, and standard testing and recommended interpretation procedures. All UBC cones are equipped with either a seismometer or accelerometer to determine shear wave velocity profiles, which is routinely performed in most UBC piezocone soundings. Several studies combining seismic data with piezocone data were presented by Gillespie, 1990.

The piezocone test provides the following advantages for environmental studies:

1) Minimum intrusion with no possibility of cross-contamination.
2) Continuous grouting if necessary and easy decontamination of tools (Lutenegger and DeGrott, 1994).
3) Rapid delineation of site stratigraphy to identify specific depth of coarse layers where water transport is most likely and where water sampling for chemical analysis is needed.
4) Measurement of equilibrium pore pressure at full PPD to quantify vertical hydraulic gradients (single sounding) and groundwater flow regimes (multiple soundings).
5) Estimating hydraulic conductivity, K, from pore pressure dissipation data.
6) Empirical and theoretical correlation of relevant piezocone measurements to soil parameters (ϕ, R_d, and G in sand S_u, OCR and G in clay).
7) K-BAT for water sampling compatible with cone equipment.
8) "Add-on" modules measure resistivity, self-potential, gamma radiation, specific ions sensors, laser-induced fluorescence to detect hydrocarbons like oil and gasoline, etc.

2.2 *Resistivity Piezocone*

The resistivity piezocone (RCPTU) provides the ability to measure the electrical resistance to current flow in the ground on a continuous basis. This ability is extremely valuable due to the large effects that dissolved and free product constituents have on bulk soil resistivity (reciprocal of conductivity). The RCPTU consists of a resistivity module, which is added behind a standard piezocone (Fig. 1). Davies and Campanella (1995) give an overview summary of the RCPTU and its perceived application areas.

Measurements of bulk resistivity trends indicate whether some form(s) of dissolved or free product constituent exist below or above background values. Background values are usually established from on-site testing. The areas where readings are very different (anomalies) from background values are then further evaluated with appropriate groundwater sampling at discrete depths for detailed chemical analyses. Of considerable practical value is the fact that the measured resistivity in *saturated* soil is almost totally governed by the pore fluid chemistry. Soil mineralogy, porosity, and particle size have a limited effect in most circumstances.

Hydraulic and electrical flow laws are similar and given by

- Hydraulic Gradient: $q = K \times h/L \times A$
- Electrical Gradient: $I = C \times V/L \times A$

or $(1/C) \times (L/A) = V/I = R$ (resistance) OHMS (Ω)

$1/C = \rho$ = RESISTIVITY with UNITS of OHM-meter ($\Omega-m$) and is a property of the medium.

Therefore ρ = lab calibrated geometric constant for a given module x measured electrical resistance measured in the field.

Prior to 1990 bulk soil resistivity was only used as a means to determine the in-situ void ratio of saturated sandy soils in combination with pore fluid resistivity and laboratory calibrations (Delft Geotechnical Laboratory). The ring electrodes along the cone shaft allow continuous measurement of resistivity with depth where the electrodes are cleaned during advancement of the cone.

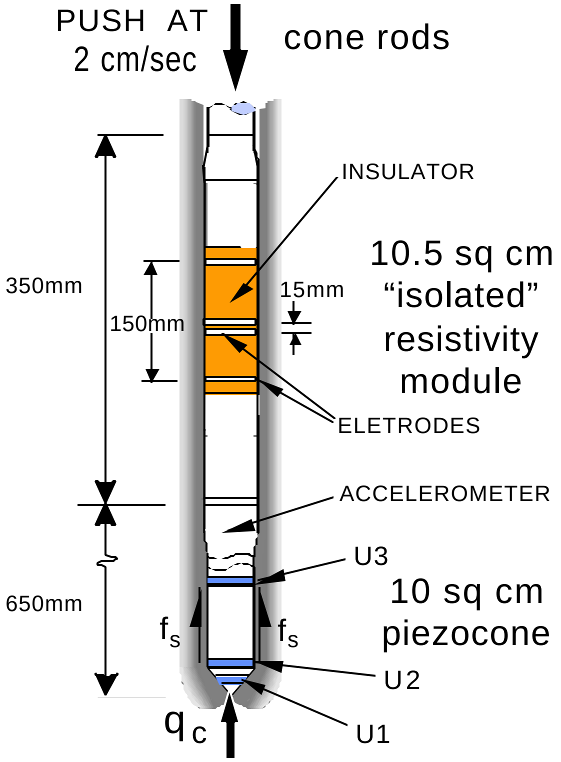


Figure 1. UBC Resistivity Piezocone (RCPTU).

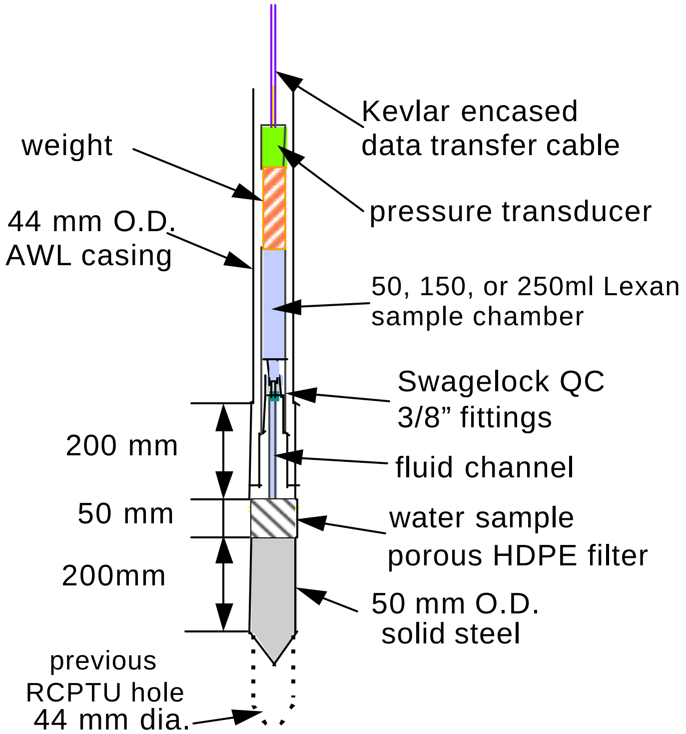


Figure 2. UBC Modified *BAT* Groundwater Tool.

Figure 1 shows the current UBC resistivity module of electrode rings, which is attached behind the standard piezocone. Its excitation and response are electrically isolated from cone electronics, which gives very little current leakage and linear calibrations of resistivity from 0.01 ohm-m to very high values of 500 ohm-m for a given excitation current. The smallest electrode spacing (15 mm) is useful for detection of thin layers of contrasting bulk resistivity, whereas the largest electrode spacing is used for AC current excitation and measurement of average resistivity over a larger depth (150 mm). See Campanella and Weemees (1990) for the research and development of the resistivity module and Daniel et al (2003) for determining engineering properties from resistivity measurements with the isolated module. A comparison of site data and laboratory equipotential data between isolated and non-isolated resistivity measurements will be demonstrated in a subsequent case history.

2.3 *BAT discrete-depth water sampling system*

A modification of the commercially available *BAT* System (named after the inventor, Bengt Arne Torstensson, 1984) is recommended for obtaining in-situ pore fluid samples. The original system consists of a sampling tip that is accessed through sterile evacuated glass sample tubes and a double-ended hypodermic needle set-up pushed through septum seals. The tube sampler is lowered either by cable or electrical wire depending upon whether a pore fluid sample is taken with or without a pressure test being carried out. Figure 2 shows the modifications made at UBC (Wilson and Campanella, 1997) which include using a stainless steel or Lexan sampling carrier, a modified probe to push down a previous cone hole and replacing the hypodermic needle system with Swagelock quick-connect push-on valve fittings. This latter modification allows the direct measurement of permeability in sands and gives much more accurate and feasible sampling in higher TDS environments as experienced, for example, during water sampling in metallic mine tailings. The *BAT* is hydraulically pushed with the same equipment used for cone penetration testing. The surface of the HDPE filter is flush with the outside of the solid stainless steel probe and is effectively cleaned while being pushed through the soil. The 200mm of steel above and below the filter seals off the filter from the previous open RCPTU hole.

The *BAT* probe is also able to take pore gas samples for collecting volatile contaminants. In California, where the water table may be very deep, oil and gasoline spills present a unique challenge. An environmental company using the CPTU developed a snifter cone (HFA Inc., 1994). At a point just behind the friction reducer behind the cone several holes collect air samples to the surface using a venturi where the air is quickly analyzed by a PID (Photo ionization detector) or similar detector sensitive to organic oil vapors. This snifter is used to rapidly identify “hot spots” where remediation can be focused.

The US-EPA and other high conformance requirement groups have adopted *BAT* technology as appropriate and preferred for many environmental characterization applications. The attraction of no drill cuttings and the repeatability of the data are cited as the key reasons for this preference. *BAT* technology has been scrutinized by many investigators and has met with widespread acceptance (e.g., Zemo et al., 1992).

After *BAT* water samples are retrieved to the ground surface, preliminary chemical tests should be conducted on-site and then the sample can be stored for further laboratory analyses. Field measurements should, at a minimum, include conductivity, temperature, and pH. The first sample at a given depth is termed the "purge" or discarded sample and any test data on this sample is only preliminary. Once enough sampling is carried out at a specific depth, the *BAT* probe is then pushed to the next depth and the procedure repeated.

2.4 *BAT hydraulic conductivity or permeability, (K), measuring system*

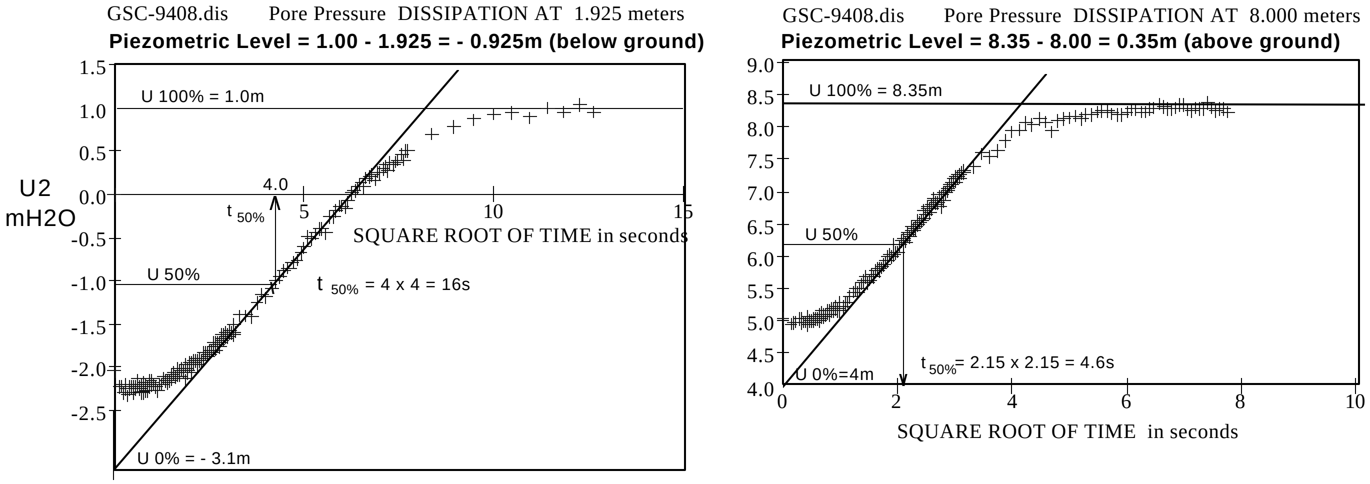
Recent studies at the University of British Columbia (UBC) (Wilson, 1996) have made use of the UBC-modified *BAT* to perform out-flow hydraulic conductivity, K, tests, where sample-vial pressure changes with time are related to volume changes. The analytical solution was verified in comparison testing where the *BAT* tip is made to function as an out-flow slug test. Not only were the results identical, but laboratory tests in 5 m high water columns showed that the current limiting highest K of the measuring system with 50 mm long filter section and 3/8 inch valves was 0.0001 m/s (or a medium sand) as opposed to the original use of hypodermic needles which limited flow to 0.000001 m/s. The limiting K was controlled by the porous HDPE filter material, which had a mean pore size of 125μ. It was also found that high gradients cause turbulence and reduce K, thus controlled gradient tests are required. A recommended procedure is given in Wilson and Campanella, 1997.

An important finding in this study showed clearly that an in-flow K test in sandy soils often gave incorrect and misleading K values which were from one to two orders of magnitude too low due to fines migrating through the sand and plugging the filter. This is usually not a problem in clayey soils. All piezometer/slug testing to measure K in silty, sandy soils must be for outflow conditions under low gradients. Thus, water sampling (in-flow) should not be used to also give K of the soil. K measurement requires an out-flow test.

2.5 *Piezocone hydraulic conductivity and gradient measuring system*

The measurement of CPTU pore pressure dissipation in sandy deposits can also be used to determine the time for 50% dissipation, t_{50}, to estimate K. However, high speed data logging is required in sandy soils where t_{50} can be 5 sec. or less. Figure 3 shows a typical example in a sandy aquifer of rapid dissipation of excess pore pressure to equilibrium at two depths and the interpretation of results. The equation constant, T_{50}, needed to calculate, K, was directly calibrated using the out-flow K-BAT permeability determination at the same locations. This site-specific correlation is required for sandy soils.

Note that for the case in Figure 3, the difference in piezometric levels gave an average vertical gradient indicating upward flow. It should, however, be realized that the gradient would change each time the K value changes. Thus, in stratified soil the gradient, if one exists, would be the average over the measured distance. Any horizontal flow



Upward Gradient = [0.35-(-0.925)] / (8.000-1.925) = 0.21 m/m

$c_h = T_{50}\, r^2 / t_{50}$ & $K = c_h \gamma_w / M$ let $M = \alpha q_t$ and $T_{50} \sim 75$ for $\alpha = 4$ and r = filter radius

Figure 3. High-speed pore pressure dissipation in sand to measure equilibrium pore pressure, gradient and hydraulic conductivity.

Table 1. Summary of typical resistivity measurements of bulk soil mixtures and pore fluid (saturated mixtures only) (adapted from Davies and Campanella, 1995).

Material type	Bulk Resistivity ρ_b, Ω-m	Fluid Resistivity ρ_f, Ω-m
Deltaic sands with saltwater intrusion	2	0.5
Drinking water from sand	>50	>15
Typical landfill leachate	1-30	.5-10
Mine tailings (base metal) & oxidized sulphide leachate	0.01-20	.005-15
Mine tailings (base metal) no oxidized sulphide leachate	20-100	15-50
Arsenic contaminated sand and gravel	1-10	.5-4
Industry site: inorganic contaminants in sand	0.5-1.5	0.3-0.5
Industrial site: creosote contaminated silts and sands	200-1000	75-450
Industrial site: wood waste in clayey silts	300-600	80-200

Note: Conductivity(µS/cm) = 10,000÷[Resistivity(Ohm-m)]

gradients can be evaluated by comparing the equilibrium pore pressure from two adjacent dissipations at the same depth using multiple soundings.

3 RESISTIVITY PIEZOCONE (RCPTU) FOR GEOENVIRONMENTAL SITE CHARACTERIZATION

As summarized by Davies and Campanella (1995), the resistivity piezocone can be used to evaluate the following environmental and geotechnical parameters: soil stratigraphy, soil density, undrained shear strength parameters, hydraulic conductivity, in-situ hydraulic gradients, and relative geochemical nature of pore water. The geochemical nature comes from evaluation of the continuous bulk resistivity signature from the resistivity piezocone compared with chemical analyses on samples obtained with the *BAT* sampling system.

Table 1 presents a small sampling of typical RCPTU bulk soil resistivity measurement values for soils beneath the water table and corresponding measurements of pore fluid resistivity. Note the wide range of values for different pore water chemical constituents.

While there are many other chemical sensors that can be put behind the cone (Lunne et al, 1997), they are always specific for given types of contaminants. The wide measurement range from 0.01 to 5000 ohm-m makes the resistivity a very useful parameter for screening sites for possible contaminants usually presented as anomalies. The practical advantages of the surface electrode rings are simplicity, robustness, direct coupling with soil, self-purging or cleaning of electrodes and continuous measurements.

3.1 *Factors Affecting Bulk Resistivity of Soils*

The measured bulk resistivity of soils is affected by:

1) Pore fluid chemistry
2) Degree of fluid saturation
3) Porosity/Density of soil matrix
4) Temperature
5) Shape of pore space
6) Clay content
7) Mineralogy
8) Dielectric properties may be important.

Archie (1942) proposed the following mixing relationship:

$$F = \rho_b / \rho_f = a\,(n)^{-m}(S_r)^{-s} \tag{1}$$

where: F=formation factor, ρ=resistivity, b=bulk, f=fluid, n=porosity, S_r=degree of saturation, and a, m and s are constants for a given soil. The constants relate to above factors 5 through 8.

The relationship between temperature and electrical resistivity is a constant and all resistivity readings should be corrected to a given temperature like 25°C.

In a recent compaction study of factors affecting bulk soil resistivity, Daniel (1997), showed that it was possible to estimate porosity, n, and degree of saturation, S_r, from RCPTU tests. Lab calibration of two soils compacted over a wide range of densities and water contents yielded the following result:

$$F = \rho_b/\rho_f = 1.84\, n^{-0.5}\, S_r^{-1.45} \tag{2}$$

(highly acid sulphide mineral tailings)

$$F = \rho_b/\rho_f = 0.60\, n^{-2.2}\, S_r^{-1.80} \tag{3}$$

(quartz rock flour)

where: ρ_f = the measured resistivity of the water added for compaction, which had a range of from 1 to 11 ohm-m and ρ_b = measured bulk resistivity of each compacted sample.

It was found that the two very different soils fit Archie's proposed relationship very well, but the constants were very different. This difference is primarily due to very different soil mineralogy. It was recognized, however, that the actual pore fluid resistivity of the tailings might not be equal to the resistivity of the added water (1 ohm-m for the tailings) because of adsorbed soluble ions in the dry tailings.

For a given typical soil and fluid resistivity the change in measured bulk resistivity can be used to estimate degree of soil saturation (e.g., 70 Ω-m at 100% to 4400 Ω-m at 10% saturation) and evaluate density changes after vibro-densification (Campanella and Kokan, 1993,Daniel et al, 1999 and 2003).

The in-situ porosity of a saturated soil is easily determined (Eq. 1) from measurements of resistivity of in-situ bulk soil and pore fluid extracted in-situ from the soil in combination with Formation constants a and m determined from laboratory compaction tests for a particular soil. This, in fact, was the technique used by Delft Geotechnics (page 184, Lunne et al, 1997) to determine in-situ density of loose sea bottom sediments, which were essentially impossible to sample undisturbed.

4 THE USE OF RESISTIVITY PIEZOCONE SITE CHARACTERIZATION IN CONTAMINATED SOILS: CASE HISTORIES

The following examples of geo-environmental site characterization are taken from projects at the University of British Columbia, Civil Engineering Department from about 1990 to 2002. In all of the case histories described the resistivity piezocones were equipped with accelerometers and down-hole shear wave velocity profiles were determined for each sounding. Presentation of that data is outside the scope of this paper and is therefore left out. However, it should be pointed out that the seismic data was necessary and very valuable in order to perform dynamic and seismic stability analyses including liquefaction.

4.1 *Mine tailings (base metal), oxidized sulphide leachate and Acid Mine Drainage (AMD)*

The site, which is relatively flat and consisting of tailings from a sulphide ore-body, had several geotechnical, hydrogeological and geochemical concerns. The old tailings are up to 100 years old and have oxidized leachate, which are highly acidic with pH values less than 1. At this low pH the metallic constituents are soluble and enter the groundwater to become mobile, thereby resulting in what is called acid mine drainage (AMD). The resistivity piezocone and BAT sampling technology were selected for characterizing the site.

Because of the very large extent of the site, a portable surface geophysical tool called a ground conductivity meter (GEONICS™ EM31) was used to obtain a preliminary estimate of the locations of high ionic groundwaters and plumes. A single person walked the site with the meter collecting digital data every 2m in a grid spacing. Figure 4 shows the effective conductivity to a depth of about 5 m in an area 3 km by 3.5 km, which was walked in one day. The higher the apparent conductivity, the higher the ion concentration in the groundwater and the lower the bulk resistivity. In this case the existing 10-year-old observation wells failed to identify the plume or its direction of movement in an old buried stream channel, which is clearly identified by the EM31 survey.

Figure 5 shows a typical resistivity piezocone sounding from the site. From the continuous record of tip stress and penetration pore pressure, the strength and drainage characteristics of tailings could be accurately assessed. The tailings are reasonably free draining and dense. With the additional information of the friction ratio around 1, the tailings were shown to be largely contractant, sensitive fine sand-sized and possessing a high

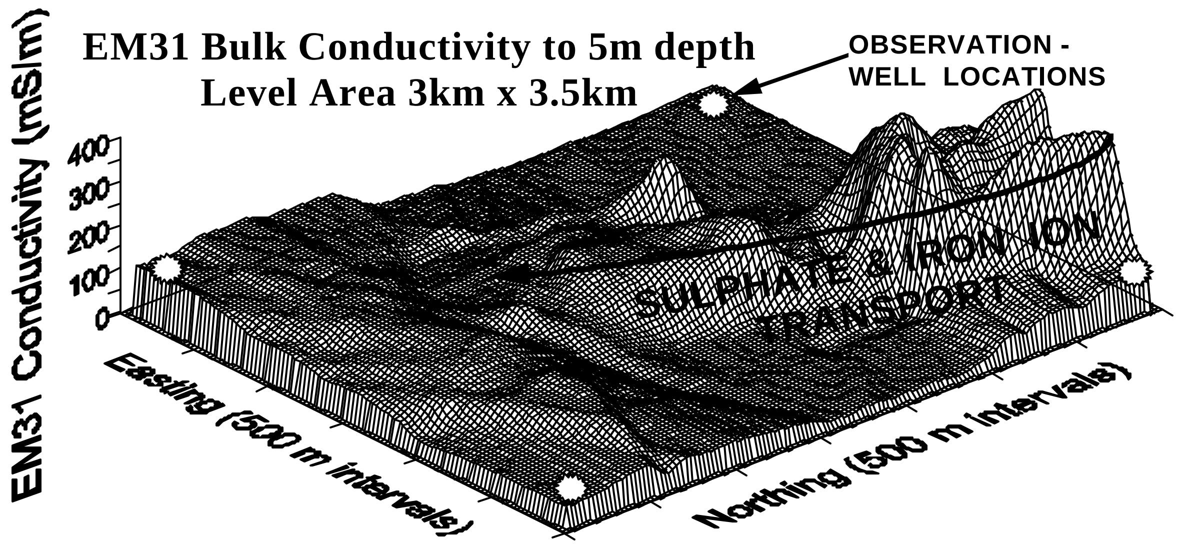


Figure 4. Surface plot of measured average bulk resistivity to a depth of 5m in sulphide mine tailings showing plume. 10-year-old observation wells missed the plume completely. (after Davies, 1999)

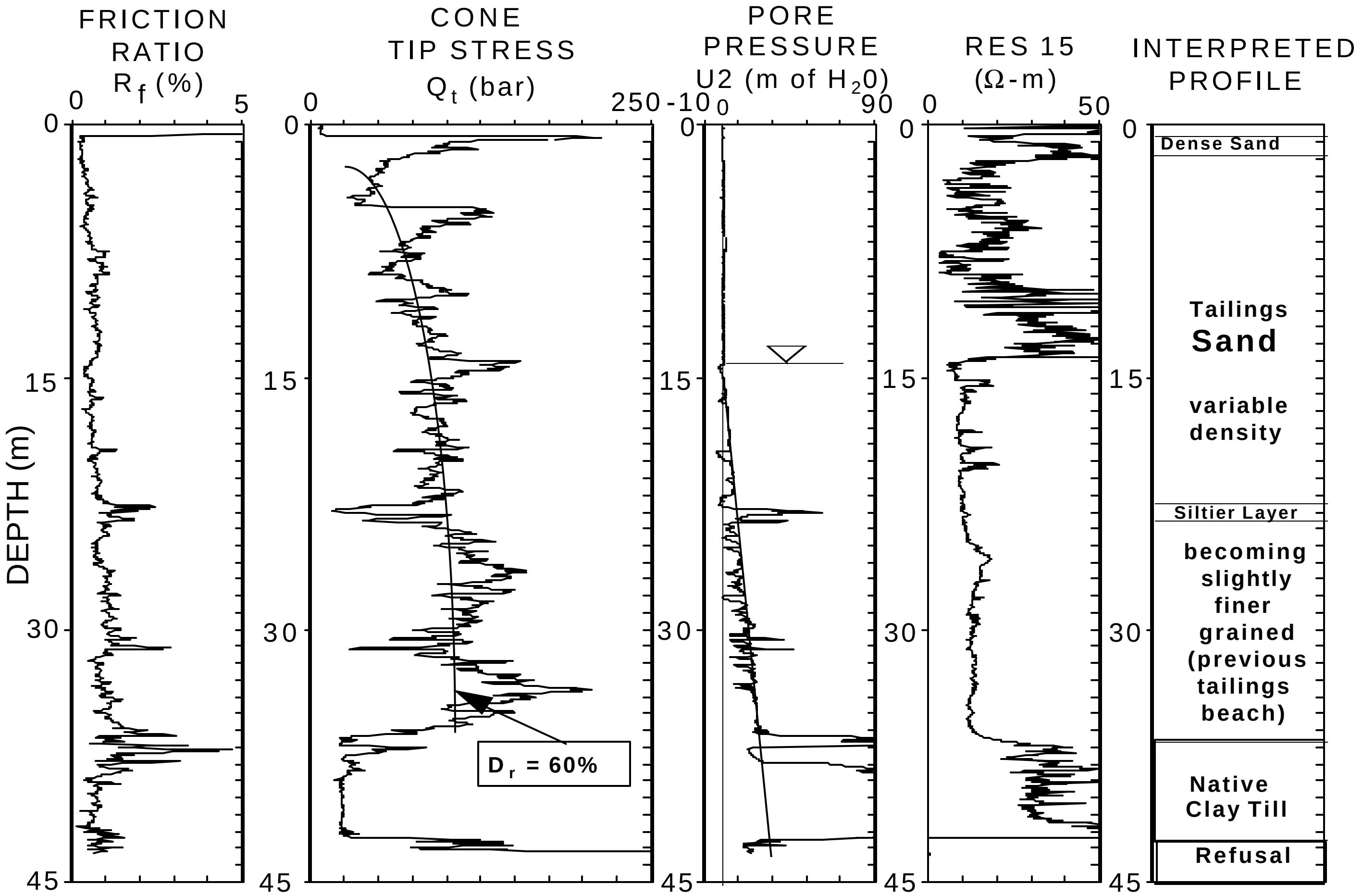


Figure 5. Typical resistivity piezocone sounding profile from sulphide ore mine tailings. Note low resistivity readings even above water table in the high oxidation area leading to acid generation. (after Davies, 1999).

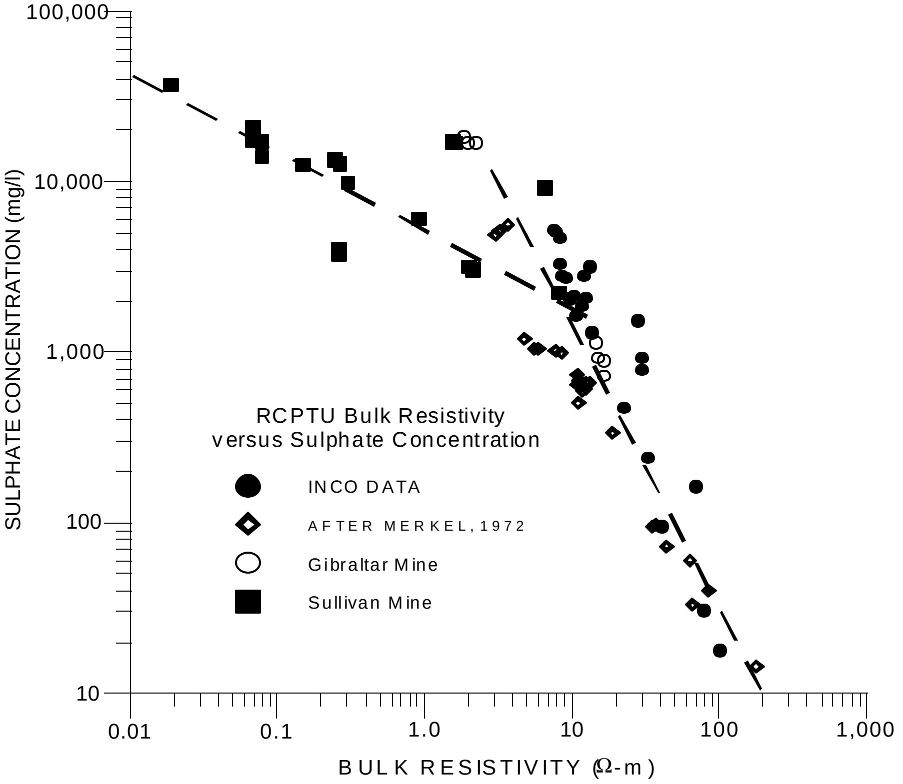


Figure 6. Sulphide ore tailings pore water chemistry of sulphate ion concentration. (after Davies, 1999).

susceptibility to static or dynamic triggered liquefaction. This strength characterization work was used to optimize remedial works (berm placement) that were deemed necessary.

The resistivity profile shows the active nature of the tailings above the water table where oxidation is highest. Resistivity values approach 1 ohm-m in the upper zone, even in a partially saturated environment where saturations less than 100% causes resistivities to increase markedly, thus these very low values indicate the rapid onset of oxidation and subsequent acid generation. The saturated tailings below the water table from 14m to 37m depth have a fairly consistent resistivity value of about 10 ohm-m, have less sulphate concentration and have minimal on-going oxidation.

Geochemically, the UBC-BAT sampling program provided site-specific relationships between bulk resistivity piezocone values and chemical testing of porewater samples for the entire study site. The relationship between total dissolved solids (TDS) in pore water and bulk conductivity in saturated soil is linear. Specific ion correlations with RCPTU bulk resistivity values are most commonly site-specific in nature although sulphate anions and divalent iron have shown remarkable global correlation in our experience to date in mine tailings as shown in Figure 6 for sulphate.

With the aide of the EM31 data, the resistivity piezocone was used to delineate ionic rich plumes whose sampled characteristics included pH values as low as 1 ohm-m and TDS concentrations to 60,000 mg/l (ppm). The delineation from the resistivity piezocone allowed the future optimal spatial placement of regulatory required monitoring wells and the accurate depth location and length of discrete well screens. The site characterization also allowed the location of a cut-off catchment to collect the acid drainage. (See Boyd, 1996 and Davies, 1999 for in-depth site characterization of sulphide tailings and AMD.)

4.2 *DNAPL and creosote contaminated saturated sediments*

This 65-acre site, which is along side a river, has been treating timber with organic preservatives consisting mainly of mixtures of creosote tars, heavy and light petroleum products since 1930 and currently processes about 1.8 million cubic feet of timber per year. Creosote is electrically non-conducting, is not readily dissolved in water, has a density slightly greater than water and a viscosity 50 times that of water. Creosote is a DNAPL (dense non-aqueous phase liquid), which sinks in water and is not readily transported except for its lighter constituents and over long periods. It is toxic to fish and wildlife.

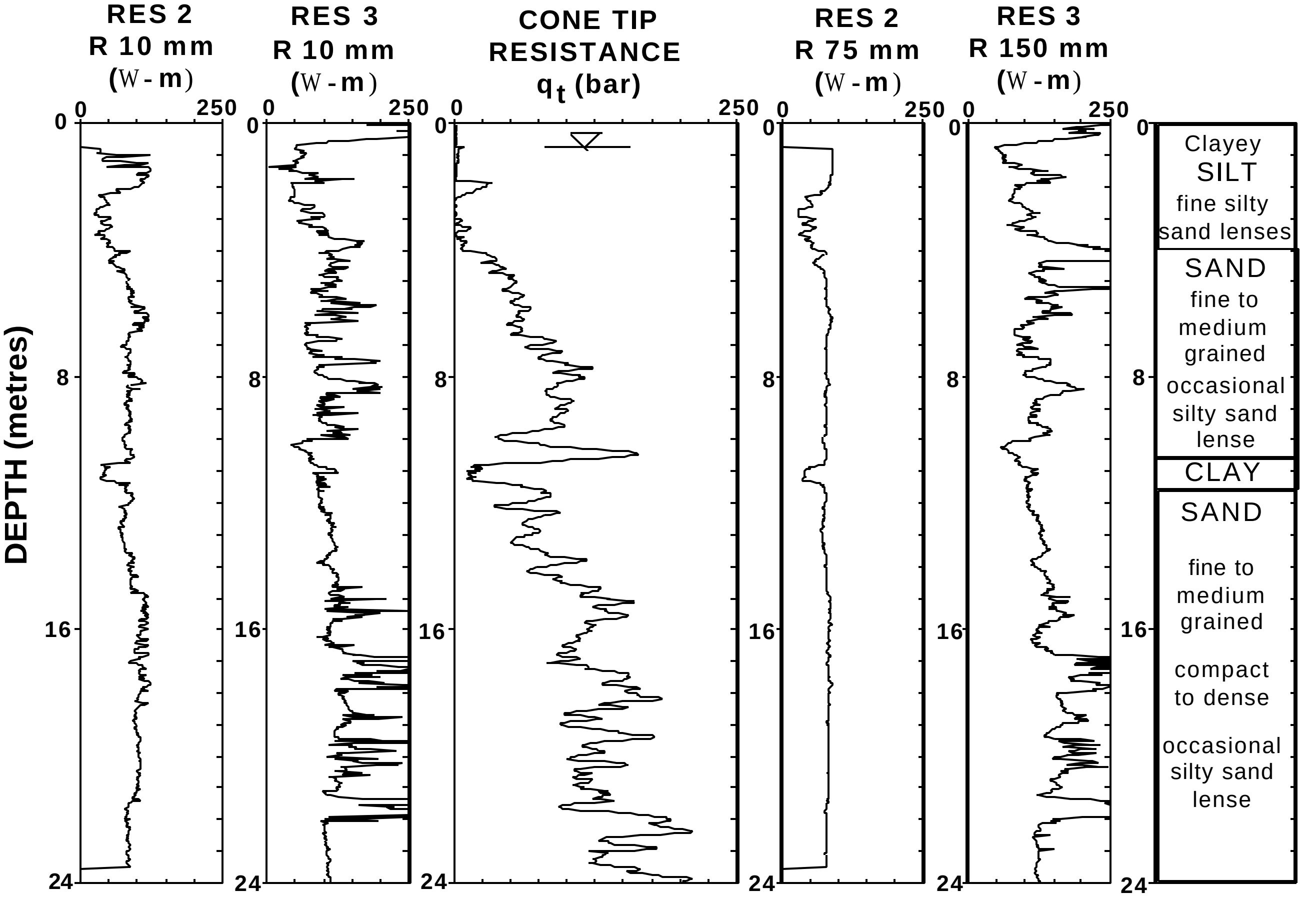


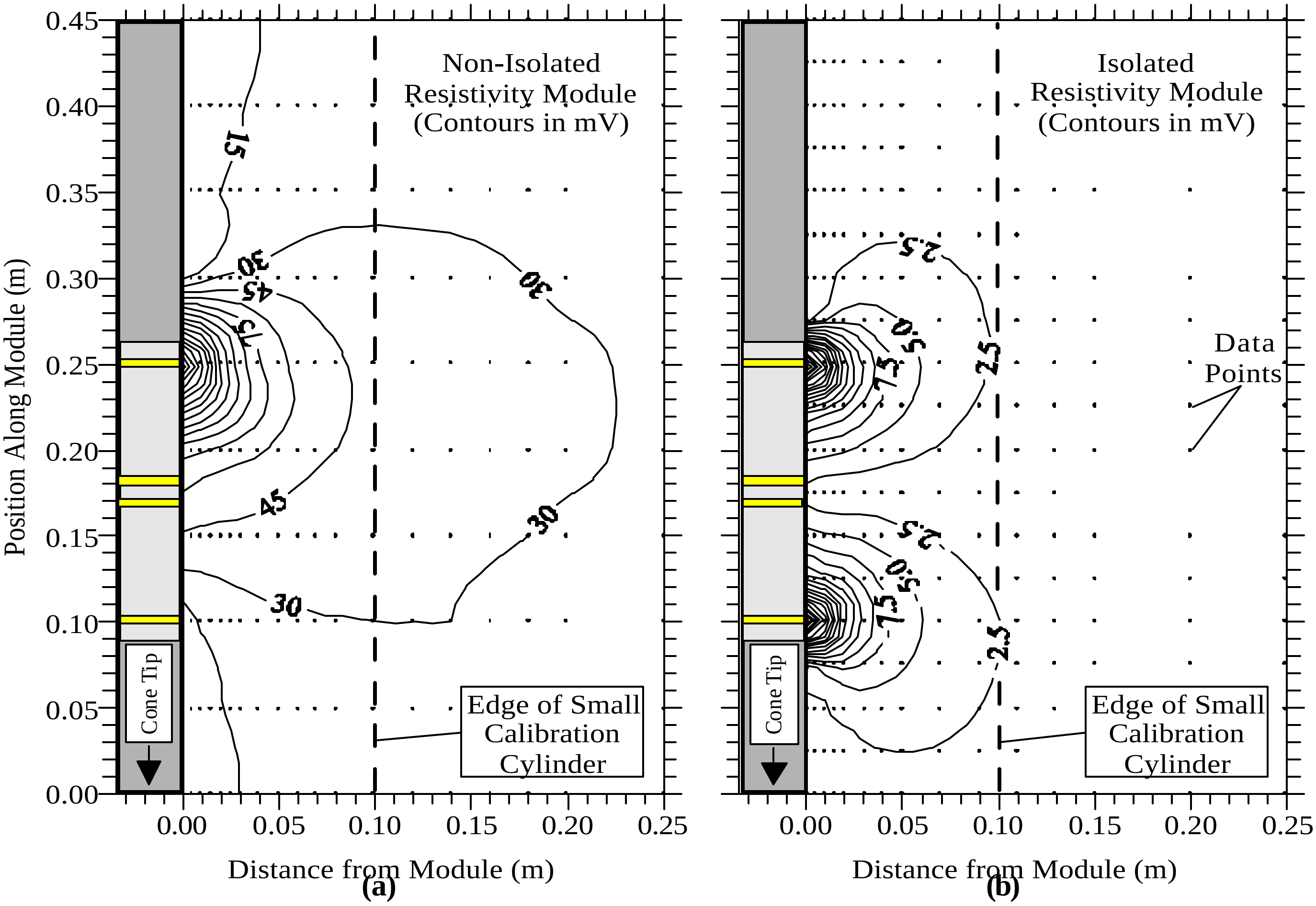
Figure 7. Non-isolated (RES2) and Isolated (RES3) RCPTU at a creosote contaminated site (after Everard, 1995)

Figure 7 shows the results of two resistivity profiles from a similar location. RES 2 at 10mm and 75mm spacing was non-isolated and had a common ground with the cone. RES 3 at 10mm and 150mm spacing was isolated from CPTU electronics. All profiles show the thin clay layer around 10m deep. The saturated sediments are mostly fine to medium sands with lenses of silty sands. The non-isolated RCPTU had values around 100 ohm-m and does not show any clear existence of the creosote. However, the isolated module gives spikes of resistivity values in excess of 250 ohm-m and clearly indicates locations where concentrated creosote had sunk through the sediments and was held on the silty lenses. Subsequent pore fluid sampling yielded pure product at the lens locations.

In an effort to understand the different responses of the resistivity modules, a laboratory test was conducted in a large PVC fish transport container, which measured about 4ft by 6ft and 4ft deep. The tank was filled with 20 ohm-m water using ordinary salt and each resistivity module was in-turn supported horizontally at the center of the tank. The module was excited with the field electronics (1000hz AC) and an AC voltage measuring tip probe was lowered to the mid-height of the module and moved horizontally to obtain the equipotential field. Figure 8 shows the equipotential fields for each module.

Figure 8(a) indicates a fairly high loss of current to the commonly grounded steel cone rod. Because of its inefficiency the linear calibration of output vs. resistivity as shown in Figure 9 only extends to about 75 ohm-m, where the excitation must be reduced to extend measurements to higher values of resistivity. Also, the smaller calibration cylinder interferes with the calibration as seen in Fig. 8(a).

Figure 8(b) indicates a very uniform set of equipotentials for the isolated module with essentially all of the current going between the outer excitation electrodes, totally ignoring the proximity of the steel cone rod. Also, the calibration as shown in Figure 9 is linear to a resistivity of about 500 ohm-m at the capacity of the voltmeter. This range will cover most investigations. It is also satisfying to see that the use of the convenient small cylinder does not affect the calibration.



(a)

(b)

Figure 8. Electric potentials measured in salt-water tub around the UBC (a) non-isolated and (b) isolated resistivity modules. (after Daniel et al, 2003)

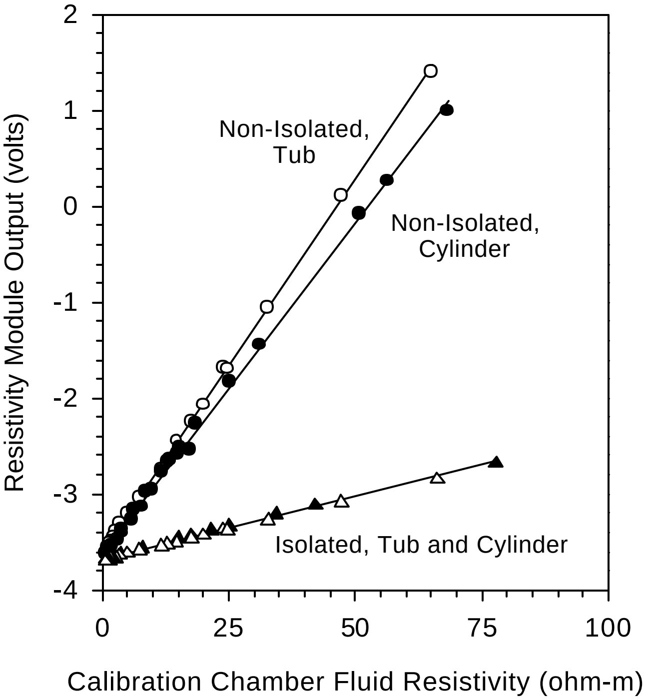


Figure 9. Typical tub and cylinder calibration results for isolated and non-isolated resistivity modules. (after Daniel et al, 2003)

While a non-isolated resistivity module works well in high ionic pore fluids, an isolated module is required to detect electrically non-conducting contaminants.

4.3 *Salt water intrusion*

Figure 10 shows the results of 5 RCPTU profiles along a 500m line along the eastern boundary at the UBC primary field site at the BC Hydro Kidd2 station. This site is used by both the Hydrogeology program in Geological Sciences as well as the Geotechnical program in Civil Engineering for teaching as well as research.

The stratigraphy was determined by the piezocone data. Using the resistivity profile the outline of a salt water wedge is indicated by values of the order of 1 ohm-m. The site is adjacent to and near the mouth of the Fraser River where the salt water has intruded to the bottom of the river where a sand aquifer exists. The salt water being heavier than the fresh water has spread laterally into the fresh water aquifer creating a classic salt water wedge. Over the year the salt water wedge moves in and out of the aquifer depending on the outflow fresh water and its elevation. Also, there is often a small gradient moving river water into the site, as the river level is often higher than the land. Notice the dyke to the right of the figure.

4.4 *Embankment seepage*

Figure 11 shows the cross section of a tailings dam, which was built by the upstream method from cycloned sand tailings. At this stage the embankment is about 175ft high. Although there is no concern for acid mine drainage here, there is concern for the stability of the dam. A major lake is just below the downstream toe and the dam retains highly fluid mineralized tailings.

Because of the high seepage gradients through the embankment an RCPTU investigation was carried out to focus on in-situ pore pressures for stability analysis. In addition, this section had several open and closed piezometers with readings that were confusing to mine personnel who thought they were not working properly.

During penetration the piezocone pore pressures were allowed to come to full equilibrium at penetration pauses each meter when a rod is added. Gradient analyses (similar to Figure 3) were carried out for all piezocone soundings. Since the soil was highly stratified it was necessary to use average values, which yielded gradients from 0.7 to 0.4. The equipotential lines in Figure 11 were determined from all of the piezocone equilibrium pore pressure data supplemented by the in-situ piezometers. All of the fixed piezometers were shown to be working correctly when the gradient field was included in the analyses.

The resistivity profile proved to be very useful in determining the precise depth where saturation takes place. As the resistivity module passes into a saturated soil the reading drops markedly and stays fairly constant. Resistivity was the only method that was able to identify the $u = 0$ water surface.

5 CONCLUSIONS

This paper has briefly summarized the main in-situ tools available for geo-environmental site characterization. The piezocone is used as a *screening* tool and is by far the most useful to determine stratigraphy, estimate strength and stability parameters, and to identify and estimate seepage parameters. The measurement of equilibrium water pressures and gradient field, and K estimates allows a transport model to be developed. The resistivity module, when added to the piezocone, is used to identify chemical anomalies (contaminant plume delineation), particularly in the piezocone identified coarse soil layers where contaminants are mobile and where water sampling is fastest. The original *BAT* concept developed by Torstensson (1984) has been modified by UBC to allow the direct measurement of hydraulic conductivity (permeability) in an outflow test for sands up to a value of 10^{-4} m/sec or 10^{-2} cm/sec. However, the

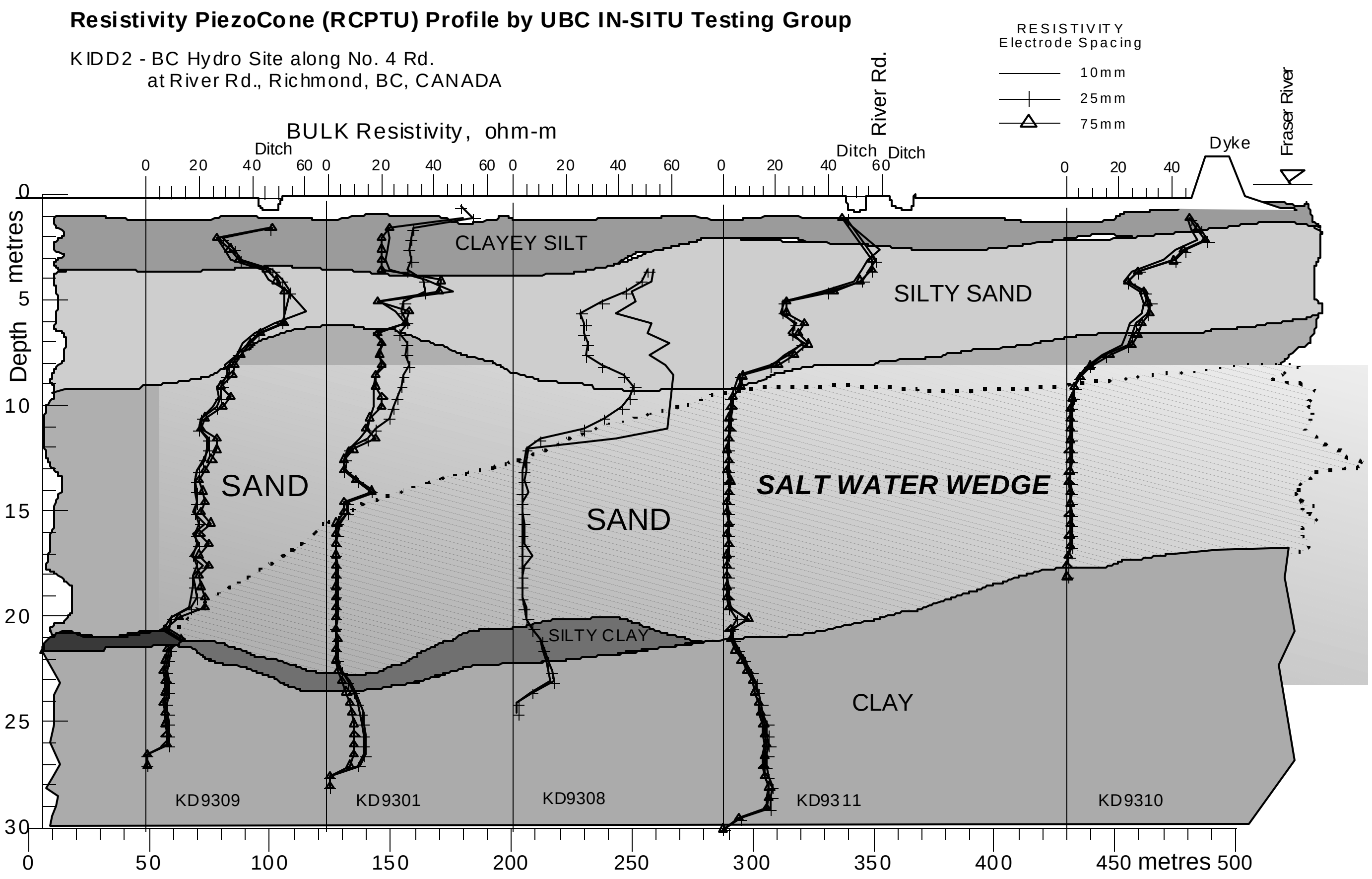


Figure 10. RCPTU profile showing estuary salt water intruding into sand aquifer (after Campanella et al, 1998).

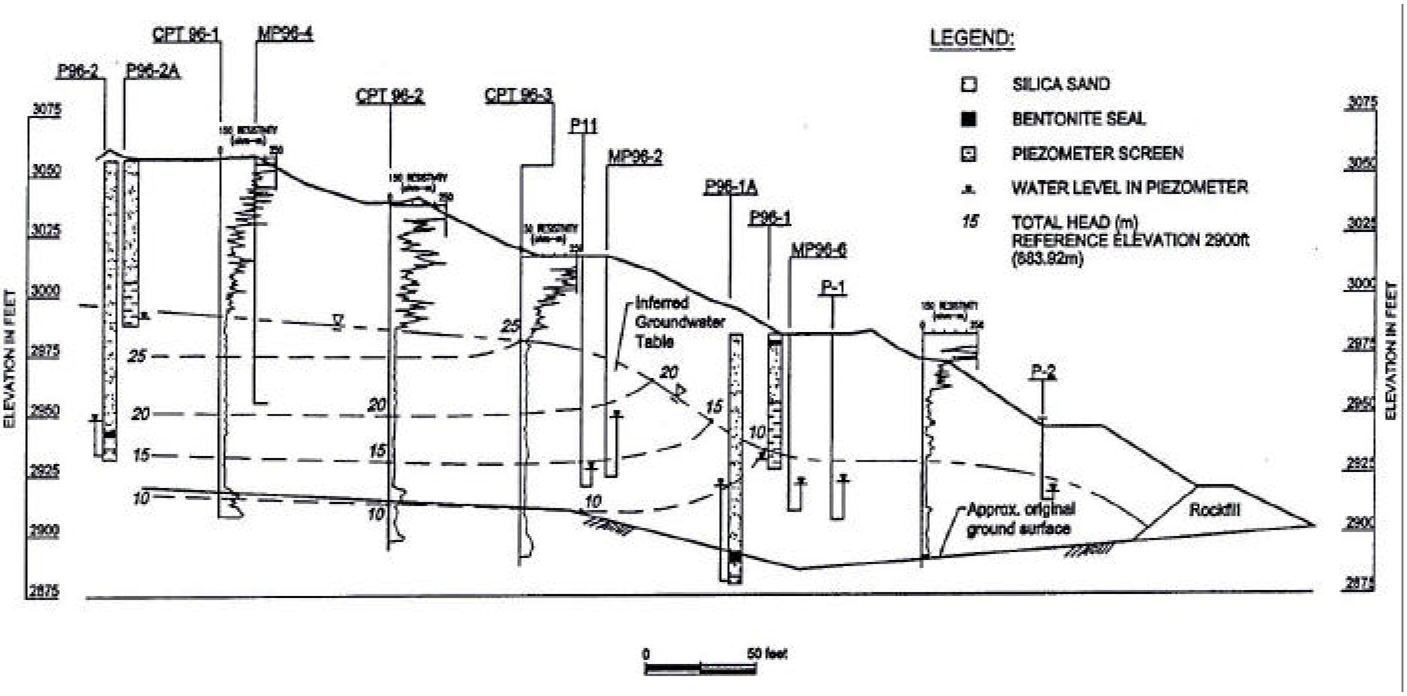


Figure 11. A cycloned sand tailings dam about 175ft high and showing equipotential lines determined from piezocone data where resistivity was the only measurement to indicate full saturation and u=0. (after Davies, 1999).

BAT is used primarily to take water samples for analysis in coarse soils. When it is used to measure K, it is primarily to validate correlations. The resistivity piezocone and *BAT* sampling technology are establishing themselves as the premier geo-environmental tools where ground conditions are appropriate.

Resistivity studies at UBC have also attempted to relate specific ion concentration to complex resistivity at very high frequencies and induced polarization procedures; so far without success (Kristiansen, 1997).

These relatively inexpensive tools provide a simple *In-situ* testing methodology for site characterization of soils for both geotechnical and geo-environmental purposes. These penetration-type in-situ tests cause the least disruption in the groundwater environment and the least risk of extended and cross contamination when compared with traditional and more costly borehole drilling methods and the development of water sampling wells.

Commercially available resistivity piezocone work is readily available in Canada and the USA for roughly $40 per meter or $12 per foot for 3 soundings of about 30 meters each, including seismic in two soundings and all holes grouted. This cost is for a typical deltaic deposit with no special problems like very hard or thick gravel layers. Many environmental characterization projects are carried out each year in materials well suited to the technology presented in this paper.

The addition of seismic to the resistivity piezocone makes a very powerful in-situ tool where one can rapidly profile 5 very repeatable, independent readings (q_t, f_s, u, V_s, ρ_b) in a single sounding (Mayne, 2006). However, it must be remembered that the cone penetrometer is an INDEX tool. Except for shear wave velocity and equilibrium pore pressure, which are directly measured, all other derived soil parameters are estimated from empirical correlations based on theoretical concepts. The best approach is to develop site-specific correlations. Unfortunately, this is often not possible. The use of published global correlations is often problematic and should be used with extreme caution, since they vary with geomorphology, mineralogy, drainage, stress history and undefined measurement errors to name a few; hence, their normal variation is very large.

The development of in-situ testing equipment, procedures and applications at UBC are well documented in theses and papers, which are listed and available for download at the author's home page at www.civil.ubc.ca. Also available as freeware is the final version of CPTINT, the UBC developed cone interpretation program. Alternately, the author may be contacted at rgcampanella@gmail.com.

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