PIEZOCONE TECHNOLOGY:
DOWNHOLE GEOPHYSICS FOR THE GEOENVIRONMENTAL CHARACTERIZATION OF SOIL

Michael P. Davies[1,2] and Richard G. Campanella[1]
[1]*In-Situ Testing Group, University of British Columbia (UBC)*
[2]*Klohn-Crippen Consultants Ltd., Vancouver, British Columbia*

INTRODUCTION

The electronic cone penetration test with pore pressure measurement, commonly referred to as the piezocone test or CPTU, has been established by the worldwide geotechnical community as the premier stratigraphic logging tool for most soil conditions. Besides stratigraphic information, the piezocone also provides accurate estimates of key geotechnical parameters and yields extensive information on the physical groundwater regime. Groundwater parameters assessed include accurate location of the phreatic surface, determination of in-situ gradients, and estimates of hydraulic conductivities.

In recent years, additional geophysical measurement capabilities have been added to the standard piezocone. These additions have included seismic pick-ups (geophone or accelerometer) for downhole and/or cross-hole seismic wave measurements and resistivity modules which can be modified to include induced-polarization measurements. With these additions, current piezocone technology represents an unparalleled means of accurately, rapidly and economically geoenvironmentally characterizing most natural and man-made soil deposits.

This paper introduces traditional piezocone technology and summarizes recent key advances with this geophysical logging tool. A brief case study is presented to demonstrate the technological and economical advantages of the piezocone over more traditional site characterization methods.

PIEZOMETER CONE PENETRATION TEST

Probing with rods through weak soils to locate a firmer stratum has been practiced since the early part of this century. It was in the Netherlands in about 1934 that the Cone Penetration Test (CPT) was introduced in a form recognizable today. The method has been referred to as the Static Penetration Test, Quasi-static Penetration Test, Dutch Sounding test and Dutch Deep Sounding Test. The first electronic cone was introduced in 1948 and vastly improved in 1971 (de Ruiter, 1971) when strain gauged load cells were added.

In the modern cone penetration test, a 60° apex and typically 35.7 mm diameter (10 cm^2 area) cone tip, which resides at the end of a series of rods of the same or lesser diameter as the cone, is pushed into the ground at a constant rate of 2 cm/sec, or roughly a metre per minute. During the test, continuous measurements are made of the resistance to penetration of the cone. Measurements are also made of the resistance to penetration of a 150 cm^2 friction sleeve located just behind the cone tip. Both dimensions and rate of penetration are controlled by rigorous ASTM and International standards.

Gravel layers and boulders, heavily cemented zones and very thick, dense sand layers can restrict the penetration severely and deflect and damage cones and rods, especially if overlying soils are very soft and allow rod buckling. However, in soft to medium dense soils, cone penetration to depths in excess of 100 metres (330 feet) may be achieved provided verticality, which is also monitored, is maintained.

One of the most significant developments in CPT technology has been the addition of pore pressure measurements (CPTU, or more commonly, *piezocone*). The addition of pore pressure sensor(s) to CPT technology has added a new dimension to the interpretation of geotechnical parameters, particularly in loose or soft, saturated deposits. The standard 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 (typically referred to as U1, U2, and U3 respectively). Most correlations and direct calculations assume measurement at the 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 mm intervals. Data is acquired in clear format ASCII files which allow the user to carry out straightforward post-investigation analyses with any number of proprietary and commercial piezocone evaluation software packages. Campanella and Robertson (1988) outline the piezocone's main advantages, limitations, and standard testing and interpretation procedures.

Figure 1 shows a schematic cut-away of a standard piezocone with seismic capability, this capability is discussed later, and of the resistivity piezcone's arrangement also discussed later in the paper.

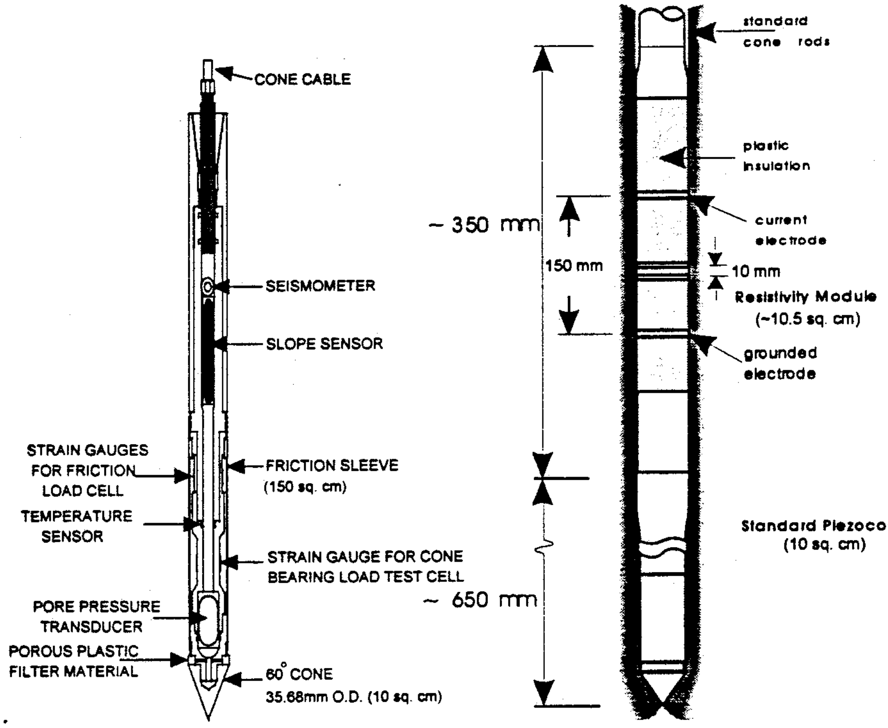
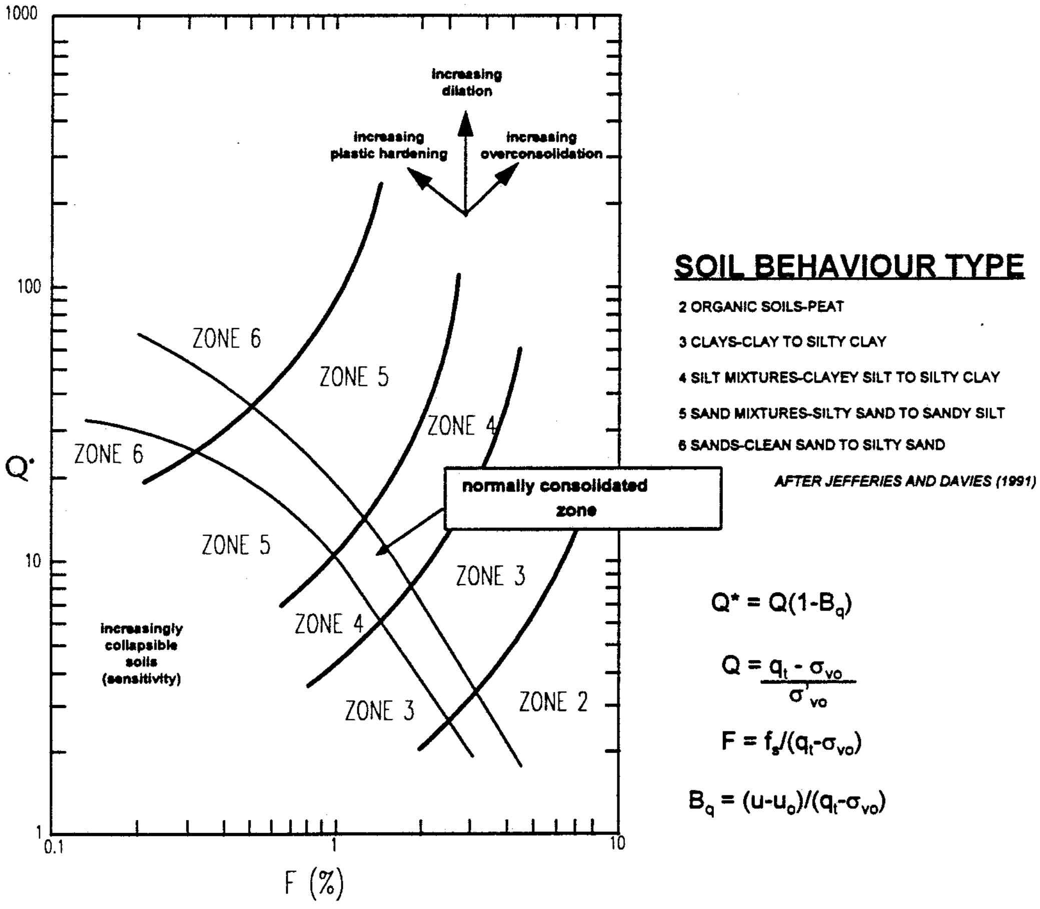


Figure 1. Schematic Piezocone with Seismic Capabilities and Schematic Resistivity Piezocone Arrangement

Stratigraphic logging with the piezocone is one of its primary uses in site investigation work. As the cone is advanced, the forces measured by the tip and the friction sleeve vary with the material properties of the soil being penetrated. The excess pore pressure (Δu) measured during penetration is also useful indication of soil type and provides another excellent means of detecting details in soil stratigraphy. The best interpretation methods combine both the tip and sleeve interpretation with some type of pore pressure interpretation. Combined stratigraphic interpretation using tip, sleeve and pore pressure measurements allows very comprehensive logging with layer discernability in the order of a few centimeters.

Figure 2 shows an example of a stress normalized interpretation chart for soils based on cone bearing and friction ratio (ratio of sleeve friction to cone bearing), both of which are normalized with respect to overburden stress, and dynamic pore pressure. The need to stress normalize piezocone measurements is important where overburden stresses exceed about 200 kPa. Stress normalization of measurements will likely become viewed as state-of-practice within the next few years; particularly for deep soil sites (Jefferies and Davies, 1991).

Excess pore pressure measurements also provide valuable insight into the hydraulic parameters of the porous media. When penetration ceases, e.g. after a 1-metre rod push, any excess pore pressures generated during cone penetration will start to dissipate. The rate of dissipation is dependent upon the coefficient of consolidation, which, in turn, is dependent upon the compressibility and hydraulic conductivity of the soil. Estimates of the coefficient of consolidation, $c_{v,h}$ (where v and h are vertical and horizontal coefficients, respectively), for silty to clayey soils may be obtained by monitoring the rate of dissipation of the excess pore pressure. In addition, pressure head distribution within the saturated zone can be estimated based on the equilibrium pore pressure data for all soil types. Estimates of hydraulic conductivity from piezocone pore pressure decay in sandy material, however, is more difficult because dissipation occurs very rapidly; this rapid dissipation in more granular soils is an area of current research at UBC.



$$Q^* = Q(1-B_q)$$

$$Q = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}}$$

$$F = f_s/(q_t - \sigma_{vo})$$

$$B_q = (u-u_o)/(q_t - \sigma_{vo})$$

Figure 2. Stress Normalized Piezocone Classification Chart (adapted from Jefferies and Davies, 1991)

The piezocone can routinely be used to evaluate the following geotechnical and hydrogeological parameters:

- Drained Penetration (e.g. sands and some silts)
    - relative density, D_R
    - friction angle, ϕ
    - deformation modulii such as M, E and G_{max}
- Undrained Penetration (e.g. clays and most silts)
    - undrained shear strength, s_u
    - sensitivity, S_t
    - stress history, OCR
    - deformation modulii such as M, E_u, G_{max}
- Dissipation of Dynamic Pore Pressures
    - coefficient of consolidation, c_h
    - hydraulic conductivity, K_h
    - equilibrium water pressure
    - hydraulic gradients
- Other Common Uses
    - liquefaction susceptibility (both state-based and empirically derived)
    - equivalent SPT N value
    - pile capacity
    - ground improvement quality control

All parameter estimates listed above are obtained through theoretical considerations and/or correlations with laboratory test results, large chamber test results, and other relevant in-situ tests.

SEISMIC PIEZOCONE

Starting in the mid-1980's, equipping piezocones with seismic pick-ups resulted in a tool, the seismic piezocone, that can be used for a procedure known as the seismic cone penetration test (SCPTU). Small strain wave velocities, and more recently in-situ damping ratio, can be determined in an accurate, rapid and highly repeatable fashion with the SCPTU. Beyond the advantage of retaining all of the information available with the standard piezocone, a further attraction of seismic cone technology is the much lower cost involved than standard downhole geophysical seismic methods. The addition of a seismic pick-up in a standard piezocone was first reported by Campanella and Robertson (1984). The seismic piezocone allows downhole seismic techniques to be carried out with a surface shear source during a pause in cone penetration; typically at the 1 metre rod breaks. The seismic pick-up in a seismic piezocone, either a geophone or accelerometer (depending upon typical application), is located within the standard piezocone as shown schematically in Figure 1.

The typical arrangement utilized for conducting the SCPTU involves a trigger circuit, hammer and a digital oscilloscope or equivalent with recording capability. The down riggers or leveling pads of drill rigs or cone trucks are used as the seismic beam; this beam in either case has excellent ground contact due to the high static load. For damping measurements, a calibrated drop height is required for the hammer. For routine shear (or compression) wave velocity measurements, neither calibrated input energy nor detailed signal processing is required and the velocities can be easily determined from arrival times. However, for damping measurements, it is necessary to evaluate the quality and nature of the signal that the shear wave produces in advance of velocity and other calculations. Signal processing, described later, also leads to a better understanding of the properties of the waves.

Virtually all soils show non-linear stress strain behaviour even at very low strains. Consequently, adequate knowledge of the governing constitutive behaviour is essential for addressing many engineering problems. A typical non-linear stress strain relationship for many soils can be well approximated by a hyperbolic curve; a constitutive relation that can be established with knowledge of the maximum shear modulus and the shear strength. As most soils are strain softening, shear modulus typically decreases with increasing shear strain. However, the shear modulus is almost always constant at shear strains less than 10^{-6} % and is generally referred to as the dynamic shear modulus, G_{max} at these low strains. With the shear strength being determined from the piezocone as noted in the previous section, a rudimentary stress-strain curve can be developed for most soils with the seismic piezocone.

Using elastic theory one relates the maximum shear modulus, G_{max}, shear velocity, V_S, and total mass density, ρ, as:

$$G_{\max} = \rho V_s^2 \qquad (1)$$

The shear wave velocity, V_S, can be calculated by dividing the difference in travel distance between two depths by the time difference between the two recorded signals. The time difference can be found manually by picking the arrival time of the main shear wave pulse or by the *cross-over* technique (Campanella and Stewart, 1992). Alternatively, the time lag can be taken as the time shift of the maximum cross-correlation of the signals. The time can also be calculated as a function of frequency, f, using the phase of the cross spectrum of the signals. Dividing this time into the difference in travel distance gives the velocity as a function of frequency, $V_S(f)$.

Beyond the measurement of shear wave velocity and modulus, the SCPTU can also be used to further evaluate the dynamic response of the ground. In general, the intensity of a seismic wave decreases as distance from its initial source increases due to wave attenuation. Wave attenuation is mainly due to geometric spreading and energy dissipation within the soil mass caused by material damping. Attenuation is most commonly modeled as viscous damping, where the simulated damping force is assumed to be proportional to the velocity within the given soil element. The resulting constant of proportionality is termed the coefficient of viscous damping. The damping ratio, D_s, is defined as the ratio of the coefficient of viscous damping to a critical value of the coefficient where the motion is attenuated within one wave cycle. The subscript, s, is used to indicate that the parameter is used for characterizing the behavior of the shear waves. The damping ratio is an important soil property required for dynamic analyses when simulating the unload-reload behavior of a soil column subjected to transient loading conditions. Campanella et al. (1994) fully explain how to determine D_s from the seismic piezocone.

RESISITIVITY PIEZOCONE

The resistivity piezocone (RCPTU) is another relatively recent development in piezocone technology (Campanella and Weemees, 1990). The ability to measure the resistance to current flow in the ground on a continuous basis is extremely valuable due to the large effects that dissolved and free product constituents have on soil resistivity (conductivity). The RCPTU consists of a resistivity module which is added behind a standard piezocone. Campanella, Davies and Boyd (1993) 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(s) exists at or above background values. Background values are established from either on-site experience or from similar geological environments. The areas where background values are exceeded are then further evaluated with appropriate groundwater sampling at discrete depths for in-depth chemical analyses. This combination of RCPTU screening with discrete water sampling provides a rapid, cost-effective means of carrying out geoenvironmental site characterizations.

The bulk resistivity is not directly measured by the resistivity module, but rather it is determined from the measured AC voltage (V) across an electrode pair at a constant supplied current (I) at 1000 Hz. The bulk resistance of the soil (R) is computed from Ohm's Law:

$$R = \frac{V}{I} \qquad (2)$$

The bulk resistance is not a fundamental property of the soil-pore water system. It is dependent upon the current path length (L) and the cross-sectional area (A) of the effective resistive unit. The bulk resistivity can be computed from the bulk resistance if the following assumptions are made: the soil acts as a homogeneous isotropic media; the measurement electrodes act as perfect conductors; and the resistivity module circuitry acts as a perfect current supply source.

Unlike bulk resistance, bulk resistivity (ρ) is a fundamental property of the porous media and is related to the bulk resistance (R) in the following manner:

$$\rho = \frac{A}{L} \times R = CF \times R = CF \times \frac{V}{I} \qquad (3)$$

The calibration factor (CF) of the resistivity module is dependent upon the geometry of the electrode dimensions and the magnitude of the excitation current. CF is a constant for a given configuration of electrode spacing and excitation current, and is determined by submerging the resistivity module in a temperature compensated buffer solution of known resistivities (conductivities).

When the electrodes are in a homogeneous and isotropic medium they will respond in a similar manner to that observed in the calibration procedure. However, soil is rarely homogeneous and isotropic, so during field testing the response of the electrodes will be dependent on the *state* of the soil and the changes to this state caused by the penetration process. Of considerable practical value is the fact that the measured resistivity is almost totally governed by the pore fluid chemistry and the pore volume. In other words, soil chemistry has a limited effect in most circumstances.

During a RCPTU sounding, the electrodes will not respond fully to a layer unless the layers are completely within the electrode spacing. For minimum layer thickness to be correctly sensed the thickness must be greater than the electrode spacing. Smaller electrode spacings allow for the possible detection of thinner layers of contrasting resistivity. Wider spacings provides an average resistivity over a larger depth and a greater penetration of the electric field into undisturbed soil and should give a more accurate determination of soil resistivity in homogeneous ground.

A schematic of the most recent UBC resistivity piezocone is shown in Figure 1. An excitation current of typically 1000 Hz is supplied to the outer electrodes, and the bulk resistivity of the soil is measured across the two pairs of electrodes. The smallest electrode spacing (10 mm) is useful for detection of thin layers of contrasting bulk resistivity, whereas the largest electrode spacing (150 mm) measures an average resistivity over a larger depth and a greater lateral penetration of the electric field into the undisturbed soil.

Keys (1989) notes that the depth of penetration from this type of logging device is roughly twice the electrode spacing. The resistivity piezocone shown schematically in Figure 1 therefore has penetration capability of about 20 and 300 mm for the inner and outer electrodes respectively. A potential enhancement to this depth of penetration with RCPTU technology is the use of focused resistivity concepts and further research in this area is required. One current enhancement is the inclusion of circuitry which allows a low frequency square-wave input signal to be pulsed on and off so that induced polarization measurements can be made.

Table 1 presents typical values of bulk soil resistivity measurements with the RCPTU and corresponding measurements of pore fluid resistivity. Since conductivity is the reciprocal of resistivity it is easy to convert according to:

$$\textbf{Conductivity}(\mu\textbf{S/cm}) = \textbf{10,000} \div [\textbf{Resistivity(Ohm-m)}] \tag{4}$$

Table 1 gives corresponding values in units of conductivity due to their popular use in the geochemical field.

The results in Table 1 show that the range of resistivity (conductivity) values is very large from about 0.01 (1000000) to about 1000 Ohm-m (10 μS/cm) and is very sensitive to both soluble salts and low solubility organic contaminants.

Table 1 – Summary of typical resistivity (conductivity) measurements of bulk soil mixtures and pore fluid (saturated mixtures only)

Material type	Bulk Resistivity ρ_b, Ω-m	Fluid Resistivity ρ_f, Ω-m	Bulk Conductivity μS/cm	Fluid Conductivity μS/cm
Sea water	---	0.2	---	50000
Drinking water	---	>15	---	<665
McDonald Farm site (Richmond) clay	1.5	0.3	6700	33300
Laing Bridge site (Richmond) clay	20	7	500	1430
Colebrook site (Langley) clay	25	18.2	400	550
TC @ 232 Ave (Langley) clay	8	---	1250	---
Strong Pit (Abbotsford) clay	35	---	285	---
Kidd 2 site (Richmond) clay	14	12.5	715	800
McDonald Farm site (Richmond) sand	5-20	1.5-6	2000-500	6700-1670
Laing Bridge site (Richmond) sand	5-40	1.5-10	2000-250	6700-1000
Colebrook site (Langley) sand	70		143	
Strong Pit site sand	115		89	
Kidd 2 site (Richmond) sand	1.5-40	0.5-21	6700-225	20000-475
Typical landfill leachate	1-30	.5-10	10000-330	20000-1000
Mine tailings site (base metal) with oxidized sulphide leachate	0.01-20	.005-15	1000000-500	2000000-670
Mine tailings site (base metal) without oxidized sulphide leachate	20-100	15-50	145-100	665-200
Arsenic contaminated sand and gravel	1-10	.5-4	10000-1000	20000-2500
Industry site-inorganic contaminants in sand	0.5-1.5	0.3-0.5	20000-6500	33000-20000
Industrial site - creosote contaminated silts and sands	200-1000	75-450	50-10	135-22
Industrial site - organic contaminants in sand	125	---	80	---
BC Place Parcel 2, PAHs (coal gas plant)	200-300	---	50-33	---
BC Place Parcel 2 (wood waste)	300-600	---	33-66	---

The costs per metre of resistivity piezocone testing are essentially the same as for the standard piezocone with an allowance of about 10% to 20% for increased downhole loss exposure and for some increased data reduction.

The relationship between total dissolved solids (TDS) and bulk resistivity is, as it should be, global and 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.

CASE HISTORY

Resistivity Piezocone for Characterizing Sulphide Mine Tailings

The use of resistivity (or conductivity) measurements to delineate zones within sulphide mine wastes where oxidation processes (e.g. acid rock drainage, ARD) are developing or occurring is relatively well documented. For example, King and Sartorelli (1991) show how the high ionic loading of both early stage and low pH, fully developed ARD is well defined by surficial geophysics. The ability to carry out resistivity soundings and dramatically enhance the non-unique solution interpretation of surface geophysics is a large advantage of the RCPTU.

At a large sulphide tailings impoundment in Western Canada, the RCPTU and EM-31 were used together to compare their ability to geoenvironmentally characterize the tailings with respect to more conventional techniques. A total of 15 RCPTU soundings totaling 220 metres and nearly 5000 metres of EM-31 surveying at 3-metre spacings were carried out. The commercial equivalent time for the RCPTU work was 20 hours or roughly $25 per metre; easily less then 1/2 conventional drilling rates and total cost. The EM-31 work was completed by one individual in a long day.

Figure 3 shows a typical RCPTU sounding from the tailings area. Stratigraphic interpretation and geotechnical parameter selection were carried out using routine piezocone techniques and are not discussed herein. As can be seen in Figure 3, the stratified nature of the hydraulically placed tailings is easily discernible with the piezocone. Pore pressure dissipations carried out at every metre rod-break provided an estimate of hydraulic conductivity and showed the presence of a 0.04 downward gradient.

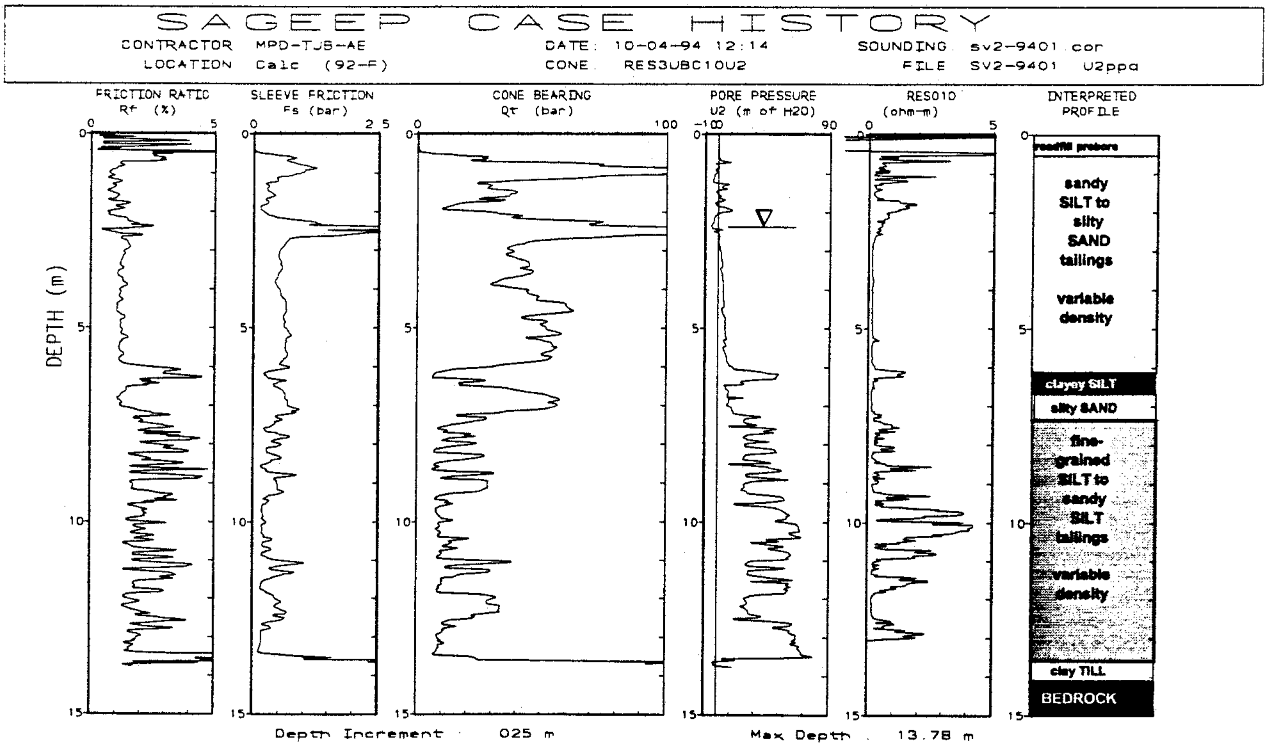


Figure 3. Typical RCPTU Profile from Tailings Area

The bulk resistivity values shown in Figure 3 range from 0.2 to less than 5 ohm-m below the water table; these values indicative of heavy ionic loading. A particularly heavy ionic loading was evident from 2.7 to 6.1 metres.

Figures 4 and 5 show the characterization images for the tailings area using the EM-31 data and RCPTU soundings respectively. Images from the RCPTU were developed at every 0.5 metre depth interval; the image shown in Figure 5 is for the 5.0 metre depth. The combined presentation format of the surface and subsurface conductivity profiles allowed spatial identification of an above-background ionic plume which resulted in optimized sampling locations being identified. Previous conventional drilling and sampling had poorly defined the plume and entirely missed the overall flow direction; all at a cost substantially in excess of the combined RCPTU and EM-31 program.

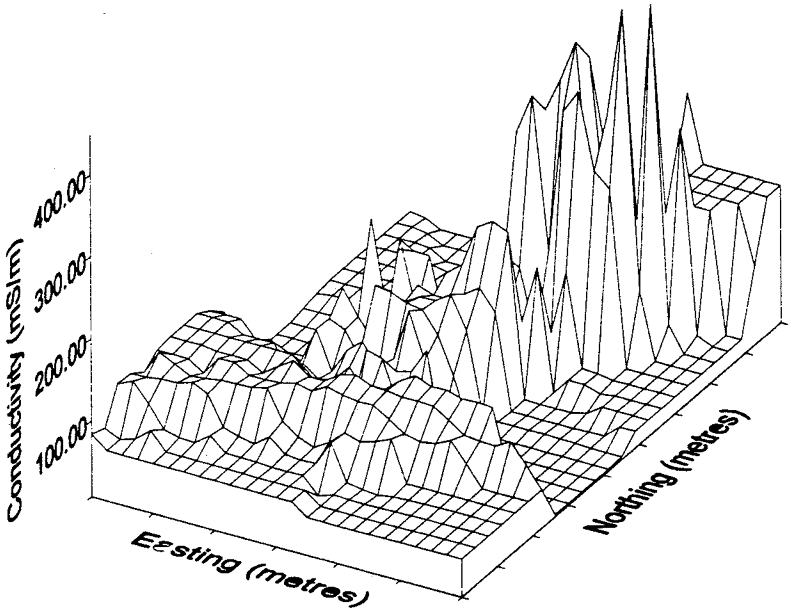


Figure 4. EM-31 Survey Results from Tailings Area

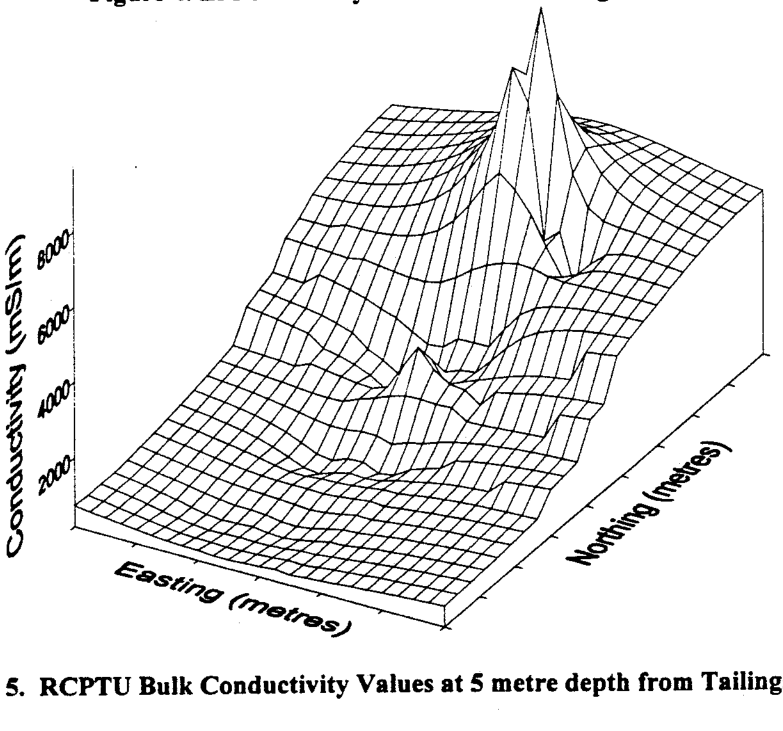


Figure 5. RCPTU Bulk Conductivity Values at 5 metre depth from Tailings Area

A key finding from the case study was the extremely complimentary fashion in which the surface EM-31 survey and the RCPTU soundings operated. For a fraction of traditional investigation methods, our growing experience shows combined surface and downhole geophysical surveys *in addition to* the continuous geotechnical and hydrogeological information obtained at each sounding location via the standard piezocone information provides a very comprehensive geoenvironmental site characterization. Site specific correlations with sulphate concentration were then used to further evaluate the overall rate and nature of upstream tailings oxidation. The results will also be used in optimizing the location of future permanent monitoring well installations.

PIEZOCONE TECHNOLOGY: DEVELOPMENT TRENDS

Piezocone technology is largely downhole geophysics without the requisite pre-drilled borehole and casing concerns. All of the wireline tools are contained within the piezocone itself, including seismic pick-ups, or directly behind the piezocone as is the case with the resistivity piezocone test. There is an increasing amount of applied research to take other geophysical applications and marry them to piezocone technology. One of the most likely to achieve immediate commercial success are the group of fluorescence cones that allow quantification and isolation of PAH contaminants.

The RCPTU has been shown to be able to produce many site-specific and some global correlations with concentrations of individual ionic constituents. However, due to the much more complex manner in which organic constituents dissociate in water, or remain as free product, empirically derived correlations with specific contaminant concentration for organic substances and bulk resistivity/conductivity is not considered likely.

SUMMARY COMMENTS

Table 2 presents a summary of the piezocone technology presented in this paper from a commercial standpoint with respect to geoenvironmental site characterization issues.

Table 2 - Summary of Piezocone Technology for Geoenvironmental Site Characterization

	Cone Type			
Characterization Issue	Electric Cone	Piezocone	Seismic Piezocone	Resistivity Seismic Piezocone
Stratigraphic Interpretation	B	A	A	A
Static Parameters				
• Strength	B	A	A	A
• Modulus	C	B	A	A
Dynamic Parameters				
• Strength	C	B	A	A
• Modulus	C	B	A	A
• Liquefaction Susceptibility	B	B-A	A	A
Hydrological Parameters				
• Hydraulic Conductivity	N/A-C	A	A	A
• Hydraulic Gradients	N/A	A	A	A
• Geochemical Gradients	N/A	N/A	N/A	B
Seismic Wave Properties				
• Shear	C	C	A	A
• Compression	N/A	C	A	A
• Damping	N/A	C	B	B
Bulk Resistivity/Conductivity				
• Total Dissolved Solids	N/A	N/A	N/A	A
• Specific Ion Detection	N/A	N/A	N/A	C-B
• LNAPL Detection	N/A	N/A	N/A	B
• DNAPL Detection	N/A	N/A	N/A	A

A = excellent capability
B = good capability
C = poor to fair capability

The rapid screening ability of the technology as a complement to surface geophysics is shown to be extremely effective as a site characterization tool; especially in light of the stratigraphic, geotechnical and hydrogeological information available at the same time from the standard piezocone. Industry experience with CPTU/RCPTU cost comparisons are generally positive. Typical commercial rates for CPTU/RCPTU work are between \$20 and \$40 per metre depending upon region and project size. To match the RCPTU, a combined drilling and downhole resistivity program can easily exceed $100/metre, or between 2.5 and 5 times typical commercial piezocone rates with less comprehensive and, often, less accurate information.

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REFERENCES

Campanella, R..G., Stewart, W.P., Roy, D. and Davies, M.P. (1994). Low strain dynamic characteristics of soils with the downhole seismic piezocone penetrometer, *ASTM Sym. on Dynamic Geotechnical Testing II*, ASTM STP 1213, Jan., Reno, NV.

Campanella, R.G., M.P. Davies, T.J. Boyd, and J.L. Everard (1994). "In-Situ Testing Methods for Groundwater Contamination Studies", invited preprint to the Asian Institute of Technology, Bangkok, *Symposium on Developments in Geotechnical Engineering, From Harvard to New Delhi, 1936-1994.*, Balkema.

Campanella, R.G., Davies, M.P. and Boyd, T.J. (1993). "The Use of In-Situ Testing to Characterize Contaminated Soil and Groundwater Systems", *Second International Joint ASCE-CSCE Conference on Environmental Engineering*, Publ. by Geotechnical Research Centre, McGill Univ., Montreal, Vol.2, pp. 1497-1505.

Campanella, R.G. and Stewart, W.P. (1992). Seismic cone analysis using digital signal processing for dynamic site characterization, *Canadian Geotechnical Journal*, 29(3), June.

Campanella, R.G. and Weemees, I. (1990). "Development and Use of an Electrical Resistivity Cone for Groundwater Contamination Studies", *Canadian Geotechnical Journal*, 27:5, pp. 557-567, Oct.

Campanella, R.G. and Robertson, P.K. (1988), Current status of the piezocone test, Inv. lecture, *ISOPT 1*, Disney World, Vol. 1, pp. 93-117, Balkema Publ.

Campanella, R.G. and Robertson, P.K. (1984), *Proceedings of 54th Annual Meeting, Society of Exploration, Geophysicists*, Dec. 2-6, Atlanta, GA.

de Ruiter, J. (1971), Electronic penetrometer for site investigations, *J. of Soil Mech. and Found. Engrg.*, ASCE, Vol. 97, SM2, Feb., pp. 457-472.

Ebraheem, A. M., M.W. Hamburger, E.R. Bayless, and N.C. Krothe (1990). A Study of Acid Mine Drainage Using Earth Resistivity Measurements. *Groundwater*, Vol.28, No.3, pp. 361-368.

Jefferies, M.G. and Davies, M.P. (1991). Discussion on soil classification by the cone penetration test, *Can. Geot. J.*, 28(1):173-176.

Keys, W.S. (1989). *Borehole Geophysics Applied to Ground-Water Investigations*. published by National Water Well Association, Dublin, Ohio, 313 pp.

King, A. and A.N. Sartorelli (1991). Mapping Acidified Groundwater Using Surface Geophysical Methods. *Proceedings of second international conference on the abatement of acidic drainage*, Montreal, September, 1991, V3, pp. 451-487

Robertson, P.K., Campanella, R.G., Gillespie, D., and Greig, J., 1986. Use of piezometer cone data. *Proc. of In-Situ-'86*, Specialty Conference, Blacksburg, VA

Woeller, D.J., M.P. Davies, and P.K. Robertson (1989). Use of Recent Cone Penetration Test Technology In Evaluating Geotechnical Properties Of Mine Waste. In proceedings *1989 Vancouver Geotechnical Society Symposium - Geotechnical Aspects of Tailings Disposal and Acid Mine Drainage*.