

# Resistivity Piezocone (RCPTU) Data Interpretation and Potential Applications

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**ABSTRACT:** The resistivity piezocone penetration test (RCPTU) provides standard piezocone data as well as measurements of the electrical resistivity of the soil around a module behind the piezocone. The sensitivity of the empirical relationship proposed by Archie between bulk soil resistivity, pore fluid resistivity, porosity and degree of saturation is reviewed. Typical qualitative applications of RCPTU data are reviewed and some recent approaches to more quantitative data analysis are presented.

**KEYWORDS:** Resistivity, Piezocone, Archie's Law, Densification, Partially Saturated

## 1 INTRODUCTION

Resistivity is a material property that quantifies the resistance to electron flow in a conductor. Resistivity is measured in (ohm-m) and, unlike electrical resistance, is independent of geometry. UBC began performing piezocone tests with electrical resistivity measurements (RCPTU) in 1989. The RCPTU has proven to be a simple, useful screening tool for geo-environmental applications. Applications have included accurately locating groundwater tables and delineating plumes of contaminated groundwater. Resistivity modules have also been used to estimate soil porosity with only moderate success.

Recent research efforts at UBC confirm that potential exists for using the RCPTU to characterize pore fluid resistivity, soil porosity and degree of saturation beyond the screening level. This paper presents some of the preliminary findings of these studies and discusses future trends.

## 2 RESISTIVITY PIEZOCONES PENETRATION TEST (RCPTU)

RCPTU equipment consists of a resistivity module mounted behind a piezocone. They are pushed vertically into the ground at a standard rate of 2 cm/s (Figure 1). Standard

CPTU measurements of tip bearing ( $q_c$ ), sleeve friction ( $f_s$ ) and pore pressure behind the tip ( $U_2$ ) are typically recorded every 2.5 or 5 cm. These three parameters, in various combinations such as friction ratio ( $R_f = (f_s/q_c)100\%$ ), are used to delineate site stratigraphy.

The UBC resistivity module consists of two pairs of brass ring electrodes spaced at 150 and 15 mm within an insulating plastic. The outer electrodes establish a 1000 Hz excitation current of either 0.025, 0.25 or 2.5 mA (excitation magnitude is controlled during the sounding by the operator). The output signal from the module is proportional to the root mean square (RMS) voltage required to establish the selected current. Linear calibration factors for correlating the output signal to bulk soil resistivity are developed by immersing the module in water baths of various resistivities and measuring the module output. The inner electrodes passively measure the field established by the outer electrodes and are calibrated in the same manner.

Figure 2 shows calibration data obtained with two UBC resistivity modules in both a 2 x 2 x 1.5 meter tub and a 0.25 meter diameter cylindrical container. The modules, referred to as isolated and non-isolated, differ in their electronic design and will be discussed further in Section 3.2.

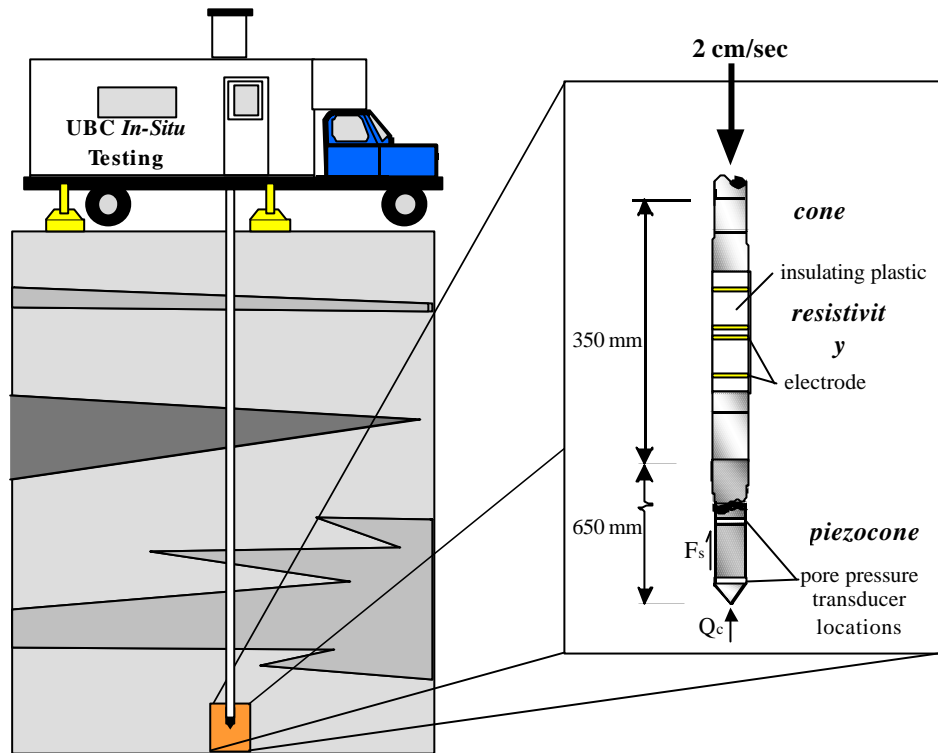


Figure 1. The UBC cone truck and resistivity piezocone.

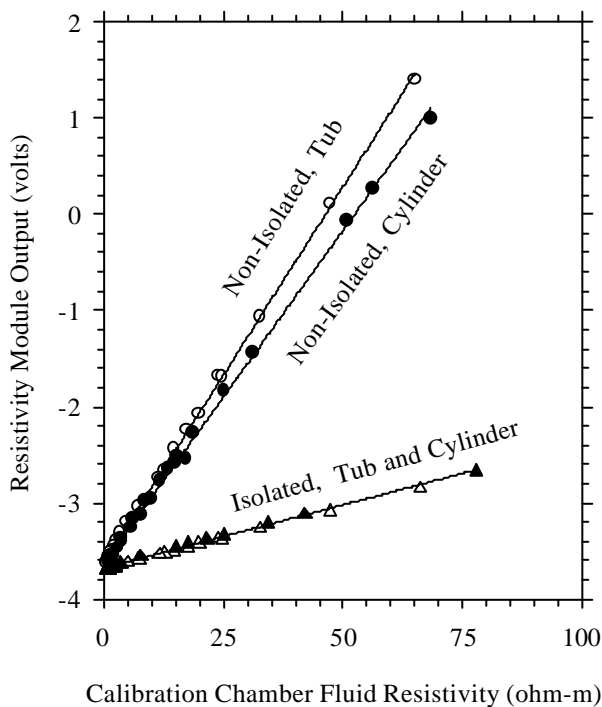


Figure 2. Typical tub and cylinder calibration results for the UBC Isolated and Non-Isolated resistivity modules.

### 3 APPLICATIONS OF BULK SOIL RESISTIVITY MEASUREMENTS

Archie (1949) identified the pore fluid resistivity ( $\rho_f$ ), soil porosity ( $n$ ):

$$n = (\text{volume of voids}) / (\text{total volume}) \quad (1)$$

and degree of saturation ( $S_r$ ):

$$S_r = (\text{water volume}) / (\text{volume of voids}) \quad (2)$$

as the three dominant factors affecting the bulk resistivity ( $\rho_b$ ) of granular soils with non-conductive grains. Based on empirical observations, Archie proposed the following relationship, commonly referred to as "Archie's Law":

$$\rho_b = \rho_f \cdot n^{-m} \cdot S_r^{-s} \quad (3)$$

where:  $m$  and  $s$  are soil constants which must be determined experimentally. The sensitivity of Archie's Law can be studied by considering the practical range of the parameters ( $n^{-m}$ ) and ( $S_r^{-s}$ ). Published values of ( $m$ ) range from 1.3 to 2.2 and Table 1 summarizes typical ranges of ( $n$ ) for various soil types. Table 1 also lists the minimum

(n) value to the power (-1.3) and the maximum (n) value to the power (-2.2), which yield the maximum and minimum possible values of ( $n^m$ ), respectively. The degree of saturation can vary between zero and one so the parameter ( $S_r^{-5}$ ) ranges between one and infinity. This is a much larger range than the ranges of ( $n^m$ ) shown in Table 1.

Table 1. Typical porosity (n) ranges for various soil types and corresponding ranges of ( $n^m$ ) using m values of 1.3 and 2.2.

Soil Type	n min – max	$\frac{n_{min}}{n_{max}}$	$n^m$ min-max
Fraser River Sand	0.41 – 0.52 (determined in laboratory)	0.79	2.3 – 7.1
Gravel Sand	0.25 – 0.40	0.63	3.3 – 21
Silt	0.25 – 0.50	0.5	2.5 – 21
Clay	0.35 – 0.50	0.7	2.5 – 10
	0.40 – 0.70	0.57	1.6 – 7.5

Early RCPTU work focused on geo-environmental screening applications using the direct relationship between bulk resistivity and fluid resistivity to assess groundwater quality. Monitoring groundwater quality, soil porosity or degree of saturation using RCPTU data requires assumptions about the parameters not being monitored as well as variables such as grain conductivity in clays that are not considered in equation (3). The following sections describe some of the assumptions and preliminary results of recent research into these types of monitoring.

### 3.1 Monitoring Groundwater Resistivity

Groundwater resistivity is a function of ion concentration and mobility. For groundwater quality screening applications, the engineer is interested in the former. The following study indicates that ion mobility, which is a function of groundwater temperature, is not a critical consideration.

Figure 3a shows the temperature of the electrode closest to the cone tip during an

RCPTU at a site scheduled for ground densification work. The electrode temperature steadily increased as each 1 meter rod was pushed and then decreased while additional rods were added to the rod string. Figure 3b shows the range of temperatures recorded before and after densification at the same site. The post densification temperature range is larger as higher frictional forces occur while penetrating the densified soil. The low end of the pre and post densification temperature ranges are roughly equivalent, indicating that the time required to add a rod to the drill string is sufficient for the electrode temperature to decrease to the local ground temperature.

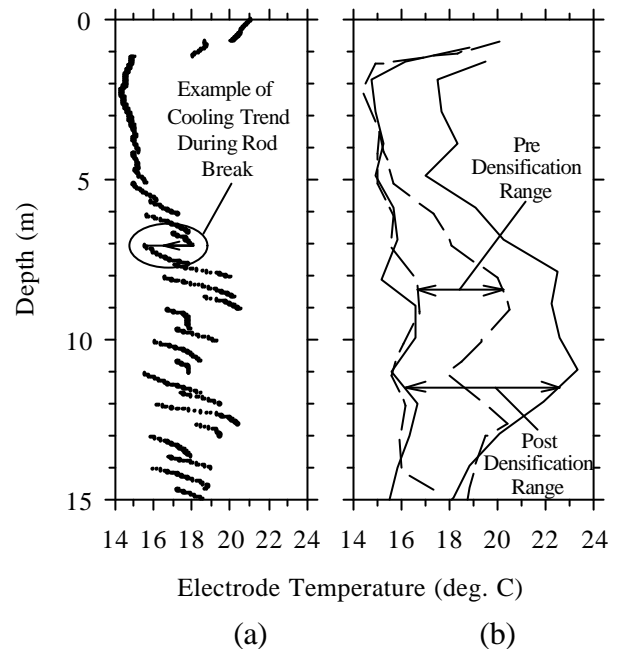


Figure 3. (a) Pre densification electrode temperature and (b) pre and post densification temperature ranges from the ground densification site.

The resistivity of salt-water decreases at roughly 2.5 % per degree of temperature increase between 0 °C and 25 °C. Despite the significant amount of electrode cooling which occurred during rod breaks (up to 7 °C in Figure 3b), experience at UBC is that there are no discontinuities at corresponding depths in the resistivity profiles. This observation suggests that the pore fluid is not heated as much as the electrodes of the

module during penetration. This can be explained by considering that the ratio of the heat capacity (the amount of energy required to produce a unit temperature rise in a unit mass) of water to brass is 112 and the mass of water available to adsorb frictional heat is much greater than the mass of the electrode. Thus, it is reasonable to assume that the temperature of the pore fluid follows natural temperature gradients, which are essentially constant between soundings and apparently simple to measure.

The RCPTU output in Figure 4, from a well-characterized site on the Fraser River delta near Vancouver, Canada, illustrates how ion concentration affects resistivity. Horizontal lines in the ( $R_f$ ), ( $q_c$ ) and (U2) plots separate depth ranges within which the measured parameters are judged to be constant or following a uniform trend. Soil types and characteristics were assigned to these stratigraphic layers based on empirical correlations such as those described by Campanella and Robertson (1988).

The resistivity recorded by the outer electrode pair (R-150) in Figure 4 varies with soil type because of porosity variations between the silts and sands and grain conduction effects in the silts and clays. There is also a significant decrease in resistivity between roughly 13 and 21.5 meters depth within uniform Fraser River sand. This anomaly has been attributed to the intrusion of a salt-water wedge within the sand (Campanella et. al., 1998). Using the RCPTU to quickly locate such major changes in fluid resistivity increases the efficiency of environmental groundwater sampling programs.

Campanella et. al. (1998) also describe the development of an empirical correlation between sulfate concentration and bulk resistivity for saturated mine tailings. The effect of porosity variations on measured resistivity was negligible compared to the effect of sulfate concentration but this will not be true for all ion-specific correlations. Ion-specific correlations are also limited by

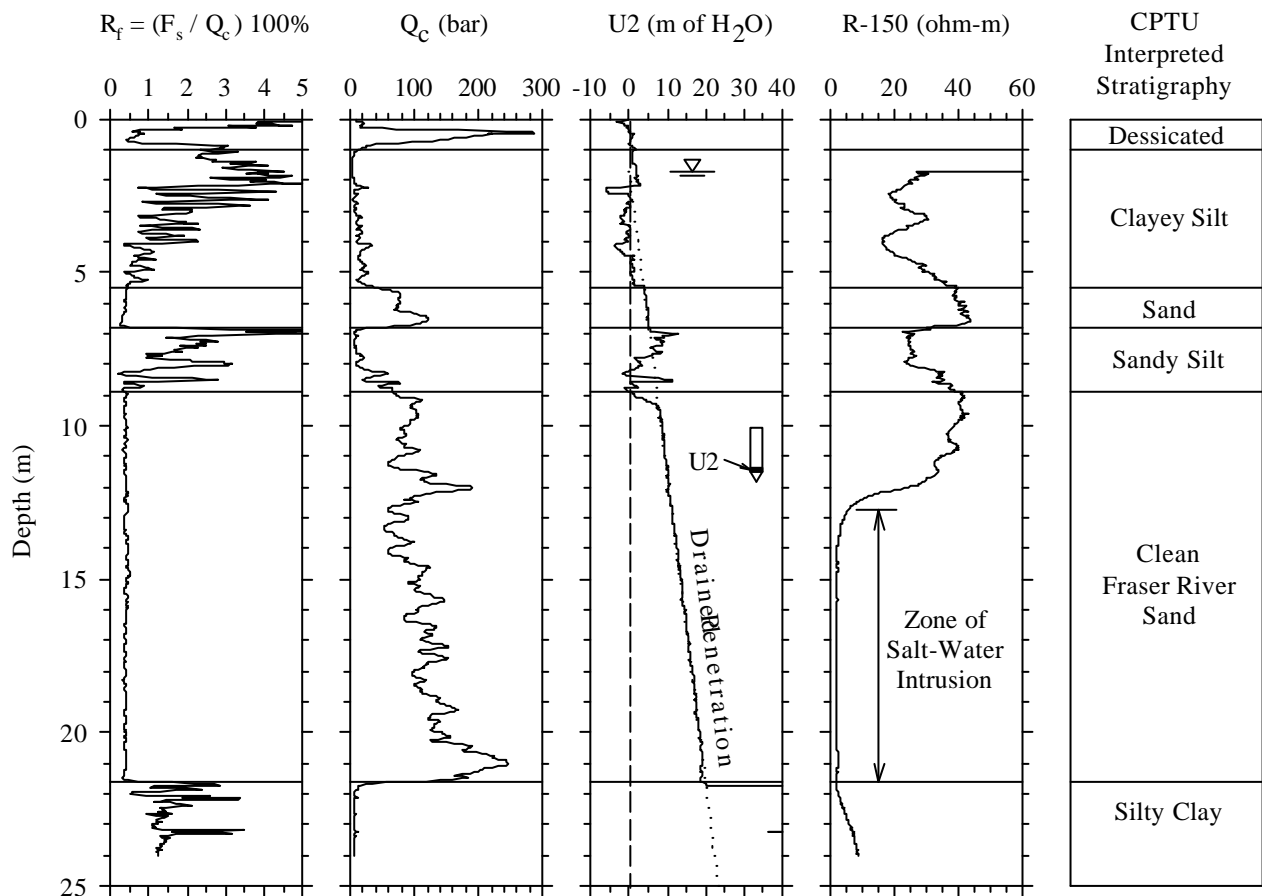


Figure 4. Interpreted RCPTU profile showing effect of salt-water intrusion on measured resistivity.

the required assumption that the concentration of the ion being monitored is primarily responsible for the observed resistivity response or consistently proportional to the concentration of the ion(s) causing the response.

### 3.2 Monitoring Soil Porosity

Equation (3) can be used to estimate porosity below the water table ( $S_r=1$ ) using bulk soil and fluid resistivity measurements and an estimated value of the soil constant ( $m$ ). This application has proved to be difficult due to the time consuming nature of water sampling. One way to avoid extensive water sampling is to use the ratio of bulk resistivity measurements from two electrode pairs at different spacings. The bulk resistivity measurement from the wider spaced pair will be representative of a larger mass of soil. The volumetric strain in the disturbed zone around the module grades to zero with increasing distance from the module. Depending on whether the soil contracts or dilates when it is sheared by the piezocone, the resistivity measurement from a widely spaced electrode pair will be higher or lower, respectively, than the resistivity

measured by a closer spaced electrode pair (Kokan, 1992). The ratio of the two values eliminates groundwater considerations because fluid resistivity is a constant.

The authors describe a similar ratio based approach applied at a vibro-replacement ground densification site in Daniel et. al. (1999). Rather than using two electrode spacings, the ratio of post to pre densification porosity ( $n'/n$ ) was estimated from the corresponding ratio of bulk resistivities. Calculation of the resulting "porosity ratio" requires the assumption that vibro-replacement does not affect the fluid resistivity (this assumption was shown to be valid by water sampling at a similar vibro-replacement site). Figure 5 shows the measured resistivity, calculated porosity ratio and interpreted stratigraphy of the site. Two porosity ratio profiles are presented to show the effect of changing the ( $m$ ) value. The pre densification resistivity is actually higher than the post densification resistivity above the crossover indicated in Figure 5 at 3 meters depth. This has been attributed to partial saturation of the fill sand prior to densification. Idealized pre and post densification resistivity profiles were used to calculate porosity ratio because minor depth misalignments of background trends

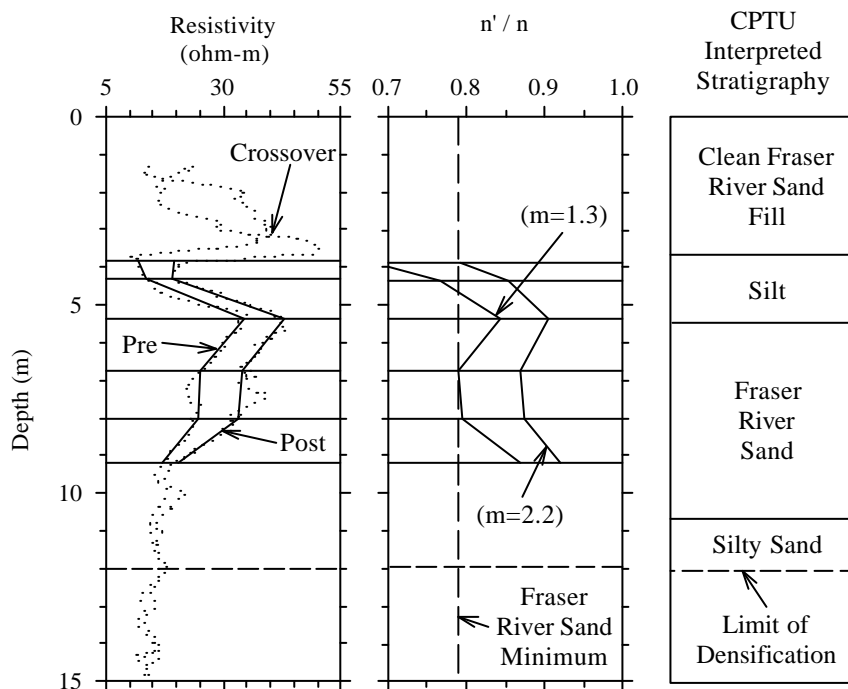


Figure 5. Pre and post densification resistivity data and calculated porosity ratio from a densification site (After Daniel et. al., 1999).

in the data yield unreasonable values. The porosity ratio profiles for both (m) values within the Fraser River sands are above the minimum possible porosity ratio of 0.79 listed in Table 1 and suggest that the porosity was reduced by at least 10% or, for the range of porosities listed in Table 1, by at least 0.045.

While soil disturbance around the piezocone and module is the basis of the approach described by Kokan and others, the authors identified such disturbance as a major cause of uncertainty in the porosity ratios calculated at the densification site. It is known that the magnitude and distribution of volumetric strain in the soil around the cone and module varies with soil density and mean stress, both of which are increased during the ground densification work. Quantification of the effect on RCPTU data of varying the degree of soil disturbance can be approached theoretically or empirically.

As a first step towards theoretical quantification, the authors sought to quantify the volume of soil from which the two UBC

modules derive resistivity measurements. The electric potential was measured at points on a grid pattern in the large water filled tub normally used for calibrations. The contoured results for the two modules, shown in Figure 6, are quite different in appearance because the potentials measured around the non-isolated module are relative to the electrode closest to the cone tip while measurements around the isolated module are relative to the metal body of the module. One result of the different grounding points for the measurements was that the background potentials (i.e. the potentials measured in the tub at greater than 1 m from the modules) were different (25 and 1.5 mV for the non-isolated and isolated modules, respectively).

Figure 6 shows that the non-isolated module resistivity values are derived from a larger volume of soil than the isolated module values. The contour at the boundary of the small calibration cylinder is almost at the background level for the isolated module (2.5 versus 1.5 mV) but significantly higher

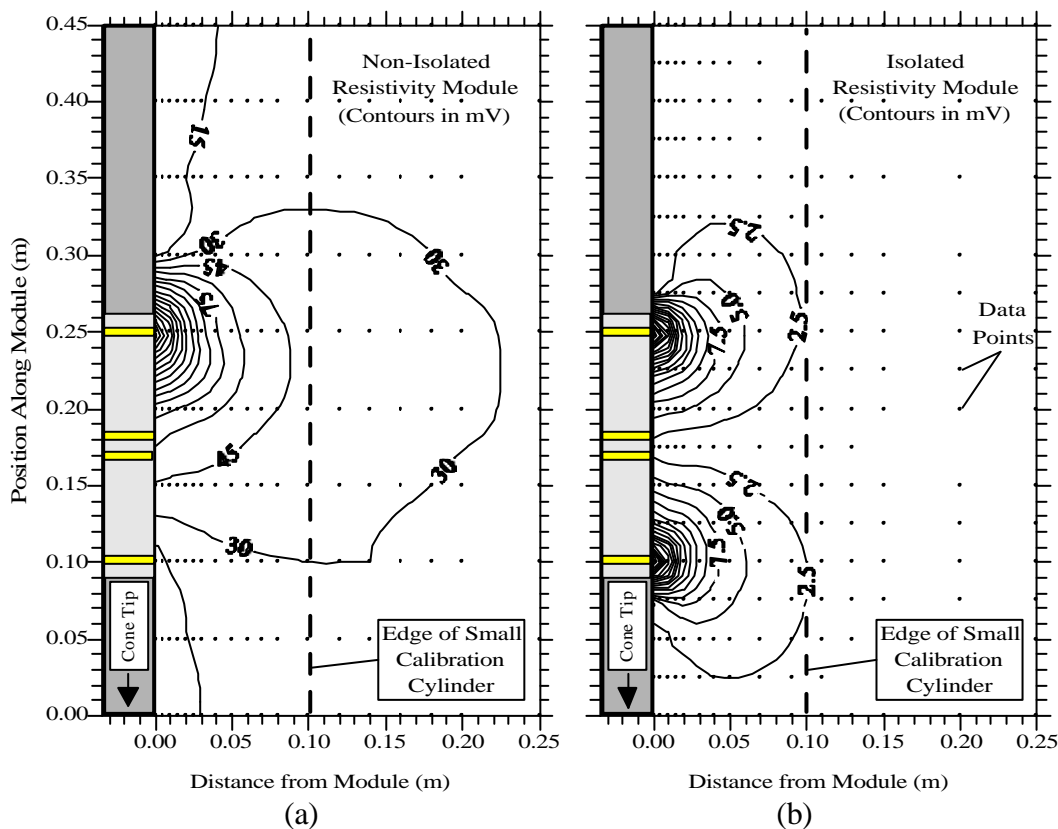


Figure 6. Electric potentials measured in salt-water tub around the UBC (a) Non-Isolated and (b) Isolated resistivity modules.

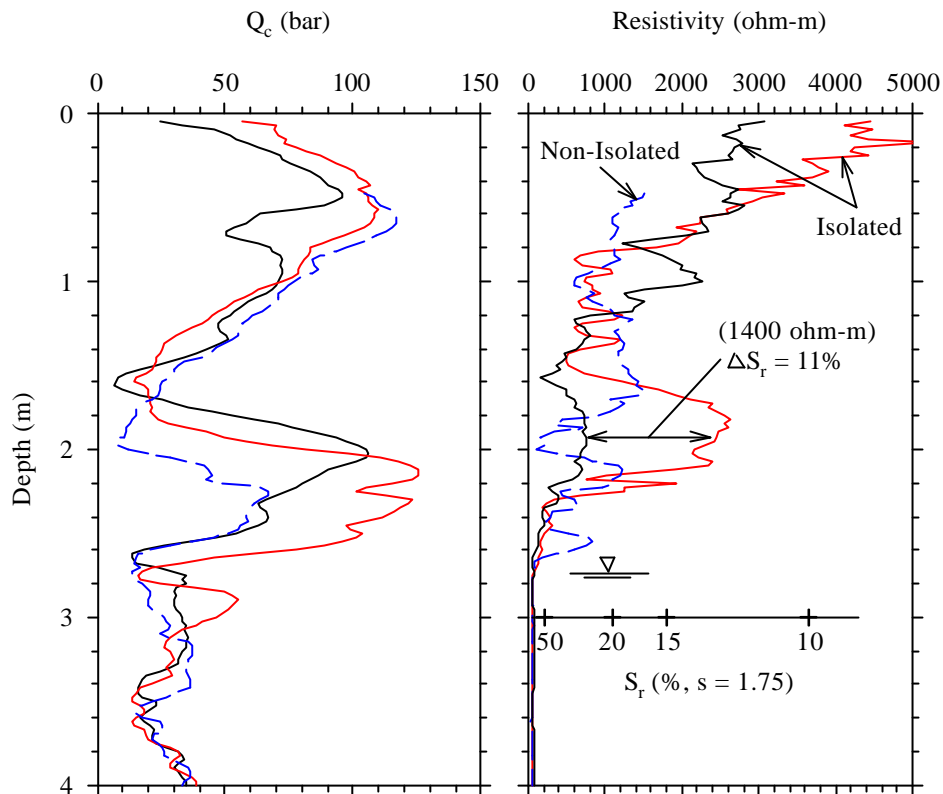


Figure 7. RCPTU tip resistance and resistivity measured during three soundings in unsaturated soil.

for the non-isolated module (45 versus 25 mV). Accordingly, the cylinder calibration trend for the non-isolated module in Figure 2 is distinct from the tub calibration trend but the isolated module calibration is not affected by the small size of the cylinder.

The type of results shown in Figure 6 could be combined with computer modeling predictions or calibration chamber measurements of the magnitude and distribution of volumetric strain around a piezocone to complete the theoretical approach. Alternatively, Belloti et. al. (1994) developed a self-boring electrical resistivity probe (SBEPT) for sands to eliminate soil disturbance considerations. Though the SBEPT does not yield the standard piezocone results and is likely much slower, empirical comparison of SBEPT and RCPTU resistivity values in a range of soil types and densities could be used to quantify and correct RCPTU data for the effect of plastic strain.

### 3.3 Monitoring Degree of Soil Saturation

The significant effect of degree of saturation on measured bulk resistivity was described in Section 3. This effect is clear in Figure 4 where the groundwater table identified from U2 data is confirmed by the resistivity profile. Figure 7 shows ( $q_c$ ) and resistivity data from three closely spaced soundings at a UBC research site. The ( $q_c$ ) data show that the variability within the site is low. The two isolated module resistivity profiles follow similar trends but magnitudes are quite different between 1.6 and 2.2 meters depth. For comparison purposes a degree of saturation scale is plotted at 3 meters depth assuming an ( $s$ ) value of 1.75 (published values range from 1 to 2.5). The scale shows that the 1400 ohm-m difference between two isolated module soundings at 2 meters depth likely represents a small (11%) change in degree of saturation. The non-isolated resistivity data is of similar magnitude but shows different trends at some depths. This may be the result of variability between the sounding locations or

the fact that the resistivity measurements are derived from different volumes of soil (e.g. the non-isolated data will be less sensitive to thin layers).

Unfortunately, it is not possible to disregard porosity above the groundwater table in the manner that degree of saturation may be ignored when monitoring porosity below the groundwater table. To account for this additional variable, some researchers are measuring dielectric constant as well as resistivity to provide input data for the Universal (Topp's) equation to estimate soil moisture (Rose et. al., 1998)

#### 4 CONCLUSIONS

The RCPTU has already proven to be a useful tool for environmental screening, confirmation of interpreted stratigraphy and locating groundwater tables. It has been shown that each of these three applications utilize one of the three input parameters of Archie's law. It is the opinion of the authors that the factors hindering more quantitative analyses of resistivity data are no more severe than those encountered while interpreting CPTU data. Preliminary study results were presented to illustrate the manner in which researchers at UBC and elsewhere have been approaching quantitative RCPTU interpretation problems related to estimating specific ion concentration, density (porosity) and degree of saturation.

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