

Specific Depth Cone Resistivity Measurements to Determine Soil Engineering Properties

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ABSTRACT

The University of British Columbia (UBC) began performing piezocone penetration tests (CPTU) with electrical resistivity measurements (RCPTU) in 1989. Since then, RCPTU research at UBC has focused on obtaining geo-environmental parameters such as fluid resistivity and soil engineering properties such as porosity and degree of saturation from measurements of bulk soil electrical resistivity using the empirical relationship proposed by Archie (1942). Within this framework, the paper illustrates and discusses important design and calibration issues for resistivity modules such as the use of isolated circuitry to achieve linear calibrations over large ranges of resistivity. The suitability of RCPTU measurements for determination of geo-environmental and geotechnical parameters are assessed using typical ranges of soil and groundwater properties and methods of isolating individual factors for study are discussed. Illustrative examples of RCPTU research efforts including the environmental characterization of mine tailings, delineation of saline water intrusions in fresh water aquifers and the quality control of geotechnical ground densification are presented throughout the text. It is shown that groundwater temperature and hence ion mobility is not significantly altered by frictional heat generated during piezocone penetration and that ratio-based approaches to monitoring soil porosity can be used to eliminate the requirement for extensive groundwater sampling programs. Lastly, it is shown that RCPTU measurements above the water table can only be made using resistivity modules that are stable over a large range of resistivities and that such measurements are the most difficult to interpret because of grain surface conduction effects and generally unknown fluid resistivities.

Introduction

UBC began performing piezocone tests (CPTU) with specific depth electrical resistivity measurements (RCPTU) in 1989. Since then, the RCPTU has proven to be a practical 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 the porosity of saturated soil.

Recent research efforts at UBC confirm that there is excellent potential 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 important aspects of resistivity module design.

The Resistivity Piezocone Penetration Test (RCPTU)

RCPTU equipment at UBC consists of a resistivity module mounted behind a piezocone. The two units are pushed vertically into the ground at the standard CPTU rate of 2 cm/s (Fig. 1). Standard piezocone 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, and their combinations such as the friction ratio ($R_f = (f_s/q_c) \times 100\%$), are very effective for delineating site stratigraphy.

The UBC resistivity module consists of two pairs of brass ring electrodes spaced at 150 and 15 mm around a common midpoint, encased in insulating plastic. The outer electrodes establish a 1000 Hz excitation current of 0.025, 0.25 or 2.5 mA. The magnitude of the excitation current is controlled by the operator during the sounding. The output signal from the module is proportional to the root mean square (RMS) voltage required to establish the selected current. Linear calibration factors are developed by immersing the module in water baths of known resistivities and measuring the module output. The inner electrodes passively measure the electric 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 $2 \times 2 \times 1.5$ meter plastic tub and a 0.25 metre diameter cylindrical plastic container. The modules, referred to as isolated and non-isolated, differ in their electronic design. To illustrate the differ-

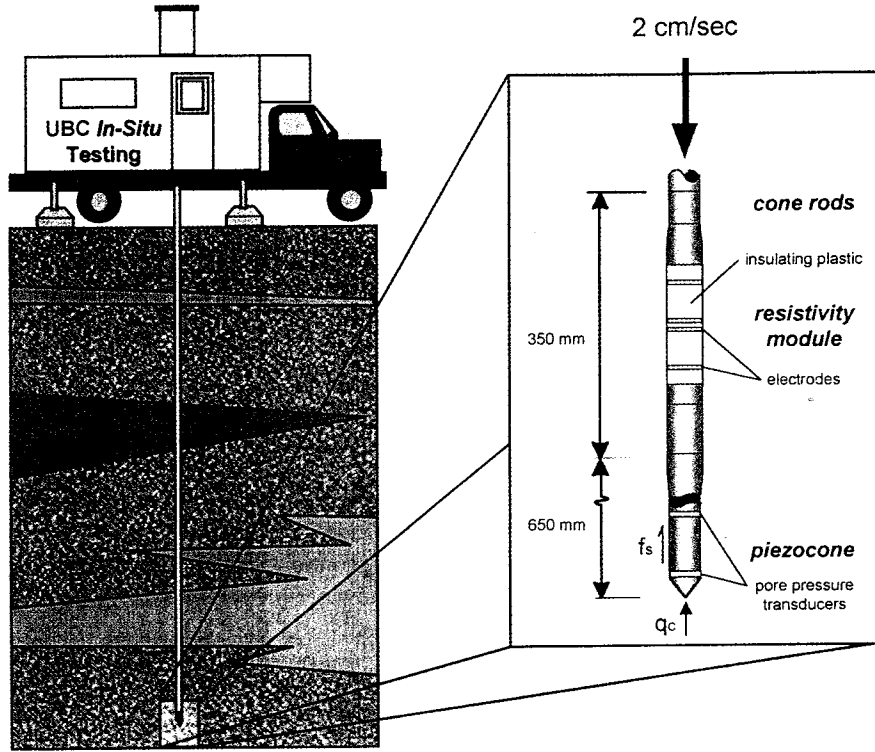


Figure 1. The UBC In-Situ Testing Group (ISTG) truck and resistivity piezocone.

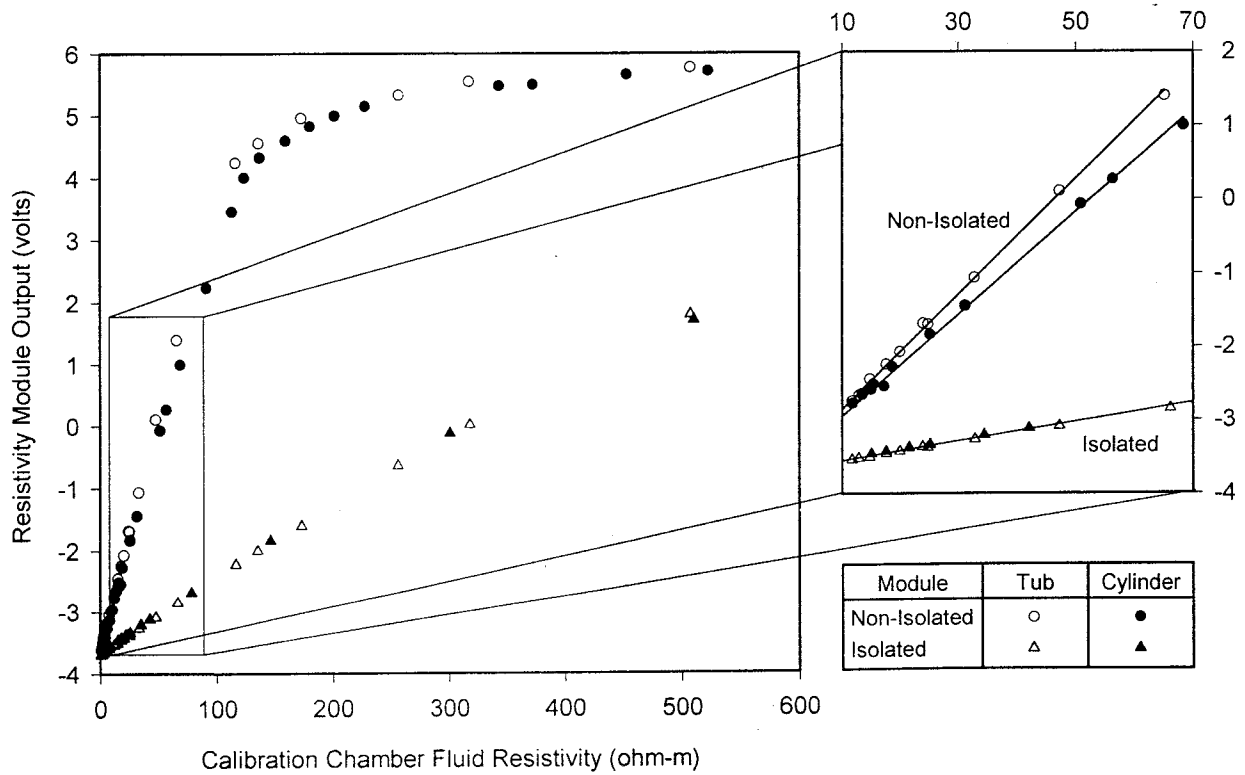


Figure 2. Typical tub and cylinder calibration results for isolated and non-isolated modules.

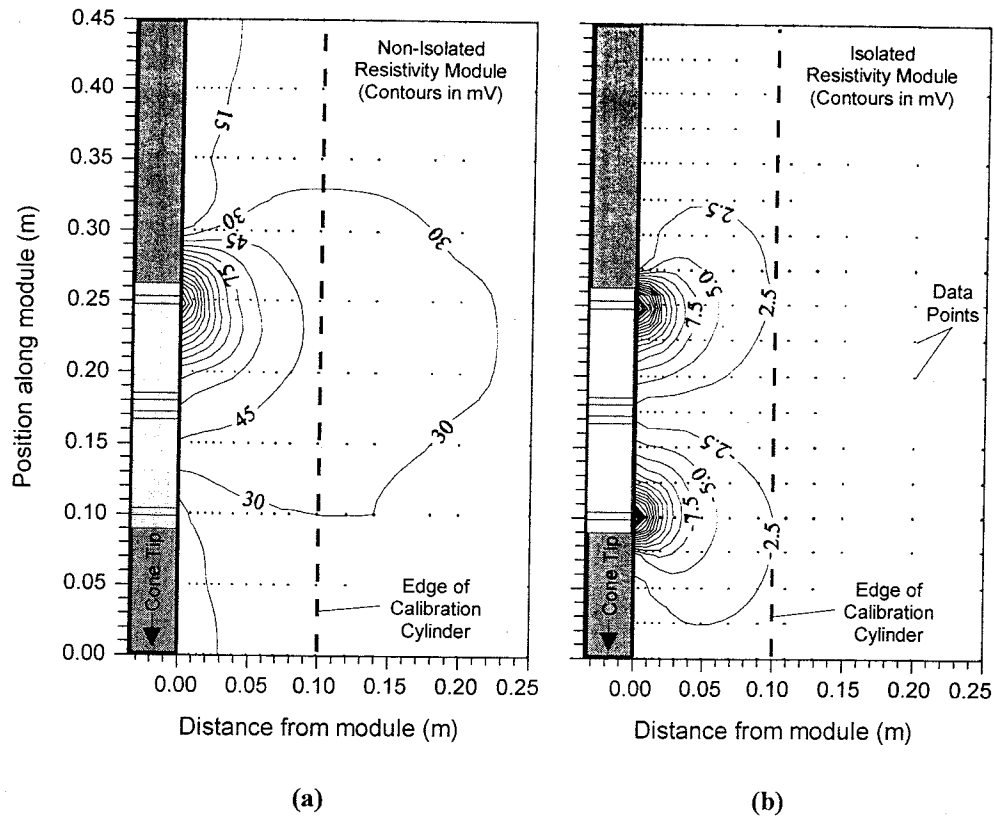


Figure 3. Electric potentials measured in salt-water tub around the UBC (a) non-isolated and (b) isolated resistivity modules.

ence between the two modules, the electric potential was measured at points on a grid pattern around the modules while they were immersed in the large water-filled tub normally used for calibrations. The contoured results for the two modules are shown in Fig. 3. Note that the flow lines of current run at 90 degrees to the equipotential lines shown. The two contour plots are quite different in appearance and the background potentials (*i.e.*, the potentials measured in the tub at greater than 1 m from the modules) also differ, at 25 and 1.5 mV for the non-isolated and isolated modules, respectively. The equipotential lines around the non-isolated module reveal that significant amounts of electrical current are lost to the steel drill rods while the current is largely limited to flowing between the two outer electrodes of the isolated module.

The isolated module electrodes have both an independent excitation and neutral as well as isolation amplifiers, so there are essentially no electrical losses to the steel cone rods. This effect is independent of media conductivity and thus the isolated module calibration curves tend to be linear over a very wide range of resistivity. The non-isolated electrodes have one electrode grounded to the steel cone rods and there are appreciable electrical losses around the insulating plastic jacket to the steel cone rod. These losses vary with media conductivity and, as a result, the

calibration curves tend to be slightly non-linear and effective over a narrower range of resistivity. For the 0.25 mA excitation calibration shown in Fig. 2 the isolated circuitry was linear from 1 to 500 ohm-m while the non-isolated was linear from 1 to 100 ohm-m.

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 for the non-isolated module (45 versus 25 mV). Accordingly, the cylinder and tub calibration trends for the non-isolated module in Fig. 2 are distinct while those for the isolated module can be represented by a single line. These results provide qualitative guidance on the size of chamber required to calibrate the modules and insight into the volume of soil that contributes to the resistivity measurements in the field.

Applications of Bulk Soil Resistivity Measurements

Archie (1942) identified the pore fluid resistivity (ρ_f), soil porosity (n):

$$n = \frac{\text{void volume}}{\text{total volume}} \quad (1)$$

and degree of saturation (S_s):

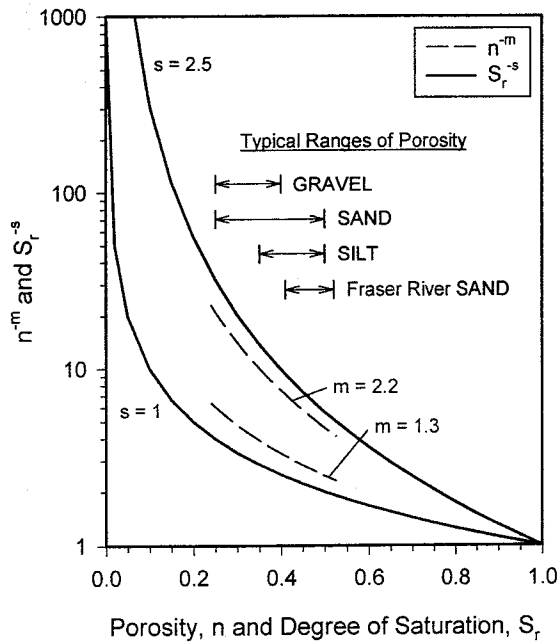


Figure 4. Sensitivity of Archie's Law to variations of porosity and degree of saturation.

$$S_r = \frac{\text{fluid volume}}{\text{void volume}} \quad (2)$$

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

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

where (a), (m) and (s) are constants for a given soil that must be determined experimentally. Early RCPTU work at UBC focused on geo-environmental screening applications using bulk resistivity to assess groundwater quality in saturated soil below the groundwater table. Under those conditions, changes in bulk resistivity are dominated by changes in pore fluid resistivity. The anticipated sensitivity of (ρ_b) to variations of (n) and (S_r) can be assessed by considering the practical ranges of the parameters (n^{-m}) and (S_r^{-s}) in Archie's Law. Published values of (m) and (s) range from 1.3 to 2.2 and 1.0 to 2.5, respectively (Archie, 1942; Dunlap *et al.*, 1949). Figure 4 shows that the range of (S_r^{-s}) is many times larger than that of (n^{-m}), despite the fact that the exponents (m) and (s) are similar in magnitude. This occurs because (S_r) can range from zero to one for any soil while (n) typically only ranges between 0.25 and 0.5. Thus, one might expect RCPTU measurements to be more useful for soil saturation studies than soil density studies.

Monitoring groundwater quality, soil porosity or degree of saturation using RCPTU data requires assumptions

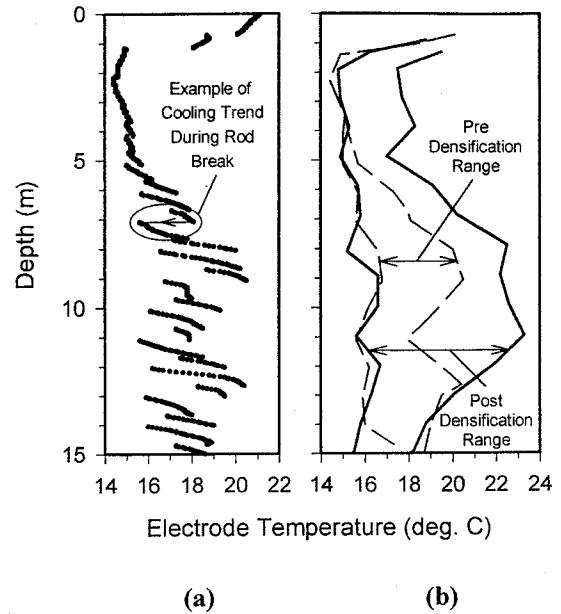


Figure 5. Resistivity module electrode temperatures (a) pre-densification (b) pre and post densification temperature ranges from a ground densification site.

about the parameters that are not being monitored as well as variables such as clay particle surface conductivity that are not explicitly considered in Eq. (3). The following sections describe some of the assumptions and preliminary results of recent research into these types of monitoring.

Monitoring Groundwater Resistivity

Groundwater resistivity is a function of ion mobility and concentration. For groundwater quality screening applications, the engineer is interested in the latter. The following sections illustrate that ion mobility, which is a function of groundwater temperature, is not a critical consideration and that the RCPTU can be a valuable tool for monitoring the concentration of specific ions.

Ion mobility. Figure 5a shows the recorded 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 one meter rod was pushed and decreased while additional rods were being added to the rod string. Figure 5b shows the range of temperatures recorded before and after densification at the same site. The post densification temperature range is larger and higher, presumably due to higher frictional forces acting on the module following densification, but the low ends of the two ranges are roughly equivalent. This suggests that the time required to add a rod to the drill string is sufficient for the electrode to cool to the local ground temperature.

The resistivity of salt-water decreases at roughly 2.5% per degree of temperature increase between 0°C and

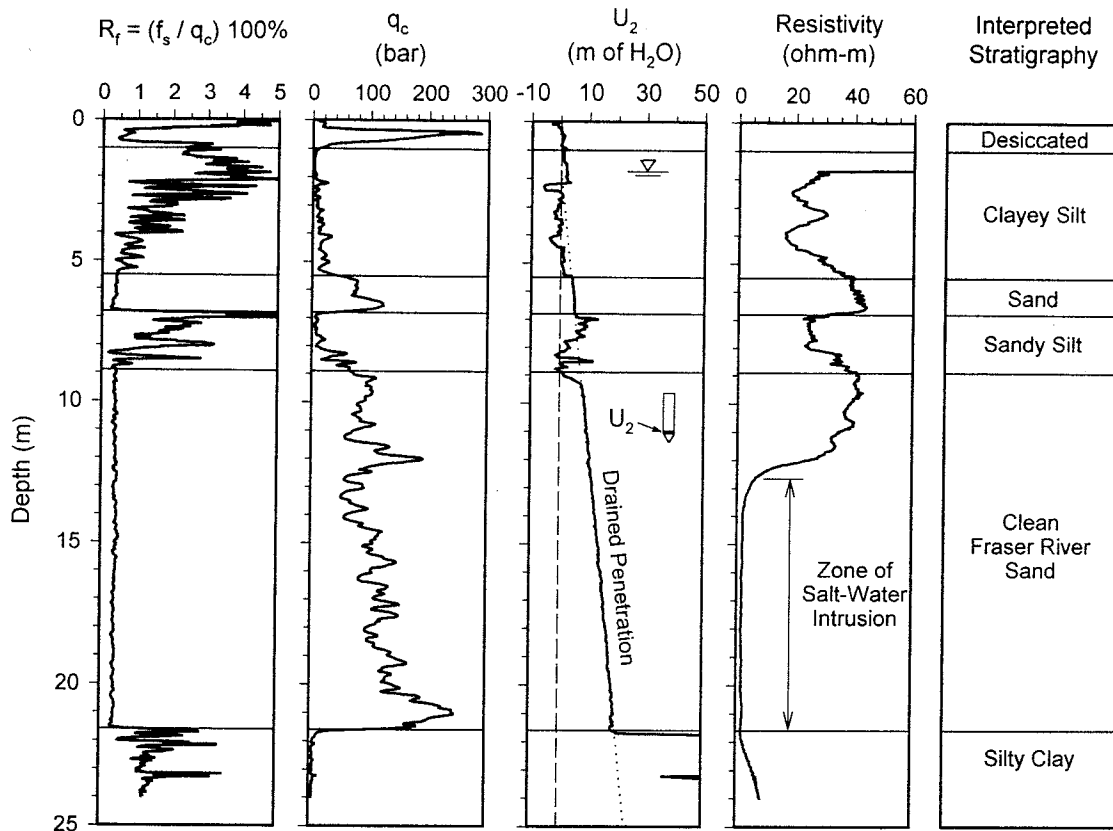


Figure 6. RCPTU profile showing salt-water intrusion (after: Campanella et al., 1998).

25°C. Despite the significant amount of electrode cooling which occurred during rod breaks (up to 7°C in Fig. 5b), UBC experience 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 understood 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 for most applications.

Ion concentration. Figure 6 presents RCPTU data from a well-characterized site on the Fraser River delta near Vancouver, Canada. Horizontal lines in the (R_r), (q_c) and (U_2) plots distinguish 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 variations of resistivity in Fig. 6 can largely be attributed to changes in pore fluid resistivity with minor

effects due to porosity variations and clay particle surface conduction effects (Campanella and Weemee, 1990). There is a significant decrease in resistivity between 13 and 21.5 meters depth within an otherwise uniform layer of Fraser River sand. This anomaly has been attributed to the intrusion of a salt-water wedge along the base of the Fraser River sand aquifer (Campanella et al., 1998). The existence of the wedge has been confirmed by discrete depth water sampling. Using the RCPTU to quickly locate such major changes in fluid resistivity increases the efficiency of environmental groundwater sampling programs.

The range of applications for RCPTU data can be extended beyond simple screening by development of local ion-specific correlations, provided certain criteria are met. For example, Campanella et al. (1998) developed an empirical correlation between sulfate concentration and bulk resistivity for saturated mine tailings. In that case, the effects of porosity variations on measured resistivity were negligible compared to the effect of sulfate concentration, but this may not be true for all ion-specific correlations. Ion-specific correlations are also limited by 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.

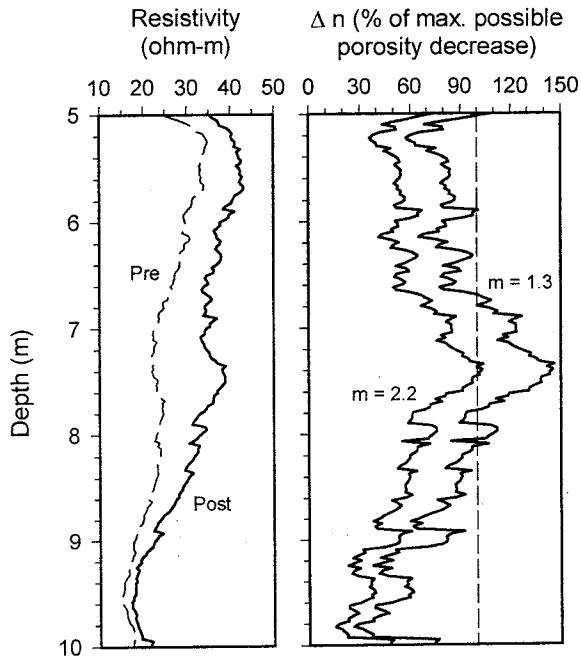


Figure 7. Pre and post densification resistivity data and calculated porosity decrease from a densification site (after: Daniel *et al.*, 1999).

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 assumed values of the soil constants (a) and (m). Groundwater sampling is usually time-consuming work, however, making ratio-based approaches, for which fluid resistivity measurements are not required, the most practical porosity related application. Two ratio-based approaches and the important issue of soil disturbance are discussed in the following sections.

Ratio-based approaches. 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 (Campanella and Kokan, 1992). The ratio of the two values eliminates groundwater considerations because the fluid resistivity is a constant.

Daniel *et al.* (1999) describe the application of a similar ratio-based approach at a vibro-replacement ground densification site. Rather than using resistivity measurements from two electrode spacings, the ratio of post to pre

densification porosity (n'/n) is estimated from the corresponding ratio of bulk resistivity using the formula:

$$\frac{n'}{n} = \left(\frac{\rho_b'}{\rho_b} \right)^{-1/m} \quad (4)$$

Equation (4) is derived by assuming that the soil is saturated and the fluid resistivity is constant between soundings. The latter assumption was validated at a similar densification site using a specific depth water-sampling tool. The range of (n'/n) is limited by the range of (n) for the soil under consideration (*e.g.*, Fig. 4). Consider Fraser River sand, which has maximum and minimum porosities of 0.52 and 0.41, as determined through laboratory testing. The corresponding range of (n'/n) is 0.78 to 1.0. The results of the densification effort are better illustrated by assuming that the sand was initially in its loosest possible state ($n = 0.52$) and plotting the decrease in porosity as a percentage of the maximum possible decrease. Figure 7 shows the pre and post densification resistivity data and the estimated decrease in porosity from a five meter depth interval of Fraser River sand. Curves have been calculated assuming (m) values of 1.3 and 2.2. The plot suggests that the porosity has been reduced, on average, by either 50% or 80% of the maximum possible densification, depending on which value of (m) is used. The 6.5 to 8.0 meter depth interval within which the ($m = 1.3$) curve is greater than 100% may indicate that the correct value of (m) is closer to 2.2, but could also result from fluid resistivity variations (pre and post densification fluid resistivity were not measured at this site).

Effect of soil disturbance. While soil disturbance around the piezocone is the basis of the approach described by Campanella and Kokan (1992), Daniel *et al.* (1999) 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 known to increase following ground densification by the vibro-replacement method (the method employed at the sites tested). Hence, it is difficult to isolate the variable of soil density.

Assessment of the effect of soil disturbance on RCPTU data can be approached empirically or theoretically. Bellotti *et al.* (1994) developed a self-boring electrical resistivity probe (SBEPT) for sands to effectively eliminate soil disturbance considerations. Though the SBEPT does not yield the standard piezocone results and is much slower operationally, comparison of SBEPT and RCPTU resistivity values for a range of soil types and densities could be used to empirically quantify the effect of soil disturbance on RCPTU data. Alternatively, a theoretical approach might utilize measurements of the electric field around a resistivity module embedded in a saturated soil medium (similar

to Fig. 3). Computer modeling could then be used to back-calculate the magnitude and distribution of volumetric strain around the resistivity module.

Monitoring Degree of Soil Saturation

The degree of saturation has a very large effect on measured bulk resistivity, particularly for low values of (S_r), as shown in Fig. 4. This effect is obvious in Fig. 6 where the groundwater table identified from (U_2) data is readily confirmed by the resistivity profile. Figure 8 shows (q_c) and resistivity data from two closely spaced soundings at a UBC research site. The two profiles were recorded using the isolated module because of its superior, linear calibration at high resistivity. The (q_c) data show that the variability within the site is low. The two resistivity profiles follow similar trends but have significant discrepancies at some depths (e.g., 1.6 to 2.2 meters). 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 1,700 ohm-m difference between the two soundings at 1.9 meters depth likely represents a small ($\approx 13\%$) change in degree of saturation.

Unfortunately, while the effect of porosity variations on (ρ_b) will be much less significant than the degree of saturation in partially saturated soils, it is likely not negligible. In addition, the contributions of grain conductivity and clay particle surface conductivity become increasingly important as the degree of saturation decreases (Frohlich and Parke, 1989). Finally, it is very difficult to retrieve groundwater samples from the unsaturated zone and significant variations of fluid resistivity may exist. To account for these additional variables, 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).

Conclusions

The RCPTU has proven to be a practical and valuable tool for environmental screening and locating groundwater tables. Well-designed and carefully calibrated resistivity modules are of critical importance if RCPTU data are to be used for more involved applications such as monitoring the concentrations of specific ions, measuring porosity and measuring degree of saturation. UBC experience indicates that resistivity modules that incorporate isolated circuitry tend to be superior to non-isolated modules because the calibration factors are linear over larger ranges of resistivity. Measurements of the electric fields around the modules indicates that the resistivity values recorded using non-isolated resistivity modules are derived from a larger volume of soil and require larger chambers for calibration. Fluid resistivity is the dominant factor controlling bulk resistivity.

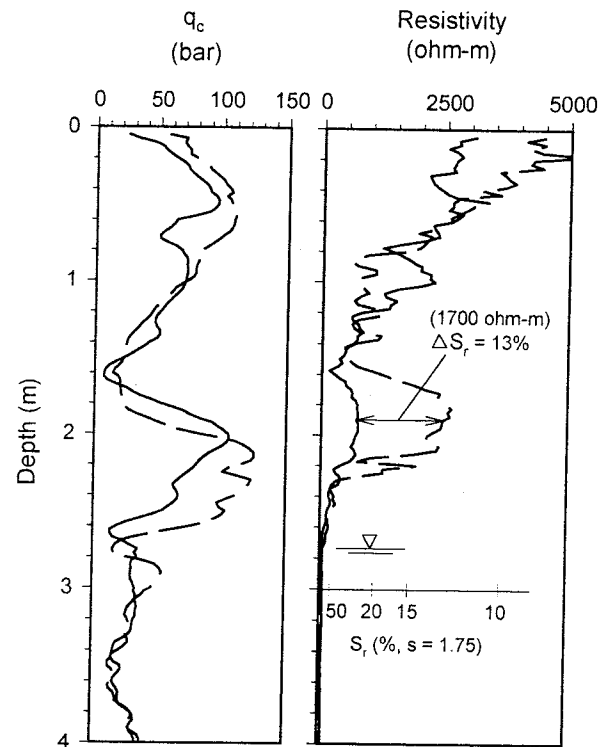


Figure 8. Two RCPTU tip resistance and resistivity profiles from an unsaturated site.

Fluid resistivity is a function of both ion mobility and ion concentration. Ion mobility is a function of groundwater temperature and data presented herein indicates that piezocone penetration does not significantly affect groundwater temperature. The use of RCPTU data to monitor porosity or degree of saturation requires specific assumptions about the other factors that affect bulk resistivity. Ratio-based approaches are useful when monitoring porosity of saturated soils because fluid resistivities can often be assumed to be constant at a given depth. RCPTU equipment must be stable and calibrated over a large range of resistivities for use in unsaturated soils as minor changes in degree of saturation cause large changes in bulk resistivity. The reliability of degree of saturation estimates from RCPTU data (as presented herein) decrease with degree of saturation because clay particle surface conduction and grain conduction effects, which are not explicitly accounted for by Archie's Law, begin to contribute significantly to the total conductivity of the soil and because groundwater resistivity becomes very difficult to measure.

Acknowledgments

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Geopacific Consultants Ltd. arranged access to the densification site. Technicians Scott Jackson and Harald Schrempp build and maintain the equipment.

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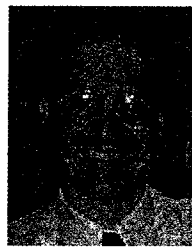
Chris R. Daniel completed an undergraduate program in Geological Engineering and his M.A.Sc. in Civil Engineering at the University of British Columbia (UBC), Canada in the years 1997 and 2000, respectively. He has been involved in the research of *in-situ* soil testing methods at UBC since

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