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GEOENVIRONMENTAL CHARACTERIZATION OF MINE TAILINGS USING PIEZOCONE TECHNOLOGY AND SURFACE ELECTROMAGNETIC GEOPHYSICS

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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 conductivity.

The addition of a resistivity module to the piezocone (RCPTU) brings a tool to the industry that provides geoenvironmental characterization which is accurate, rapid, and economical. for most natural and man-made soil deposits. However, in a consulting engineering environment, new techniques that allow for more expedient yet accurate site characterization are constantly sought. One such new technique, the use of non-invasive and portable electromagnetic instruments such as the Geonics™ EM31 as screening tools to guide more thorough investigations (RCPTU, soil sampling, monitoring wells) shows promise and is the focus of this study.

Two large sulphide tailings impoundments in Western Canada were sites for comparing the ability of the RCPTU and EM31 to geoenvironmentally characterize the tailings. Given the layered geometry of mine tailings, a forward modeling of the RCPTU conductivity, to yield a predicted EM31 value, is possible. A consistent correlation between the predicted and obtained data would support and promote the use of the EM31 as a viable tool for use where an invasive investigation is not possible, cost effective, or where conductive zones need to be targeted for RCPTU investigation.

PIEZOMETER CONE PENETRATION TEST

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/s, or roughly a metre per minute (Figure 1). 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 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 may deflect and damage rods and cones, 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. .

The standard piezocone measures tip resistance (q_c) friction sleeve stress (f_s), and pore pressure response as well as temperature(t) and inclination(i). All channels are continuously monitored and typically digitized at 25 mm intervals. Campanella and Robertson (1988) outline the piezocone's main advantages, limitations, and standard testing and interpretation procedures.

Stratigraphic logging with the piezocone is one of its primary uses in site investigation work. As the cone is advanced, the forces measured behind 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 centimetres. Further details on CPTU interpretation and commercial rates are covered in Davies and Campanella (1995).

RESISTIVITY PIEZOCONE

The resistivity piezocone (RCPTU) is a 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 added behind a standard piezocone. Campanella et al. (1993) give an overview summary of the RCPTU and its perceived application areas. Davies and Campanella (1995) provide further detail on the theory behind the RCPTU and how the RCPTU can be used for geoenvironmental characterization projects.

The most recent UBC resistivity piezocone is illustrated schematically in Figure 1. 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 greater lateral penetration of the electric field into the undisturbed soil. Both the excitation and measurement/amplification circuitry is totally isolated from the piezocone electronics.

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 a 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, still in the developmental stages, is the inclusion of circuitry which allows a low frequency square-wave input signal to be pulsed on and off so that the induced polarization effect can be observed.

A summary of some typical resistivity (conductivity) measurements of bulk soil mixtures and pore fluid is given in Davies and Campanella (1995). Figure 2 shows a typical RCPTU sounding from a sulphide mine 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 2, the stratified nature of the hydraulically placed tailings is easily discernible with the piezocone.

ELECTROMAGNETIC TECHNIQUES

Based upon the projected audience of this paper, it is assumed that the reader is familiar with the standard use of the EM31 instrument. While only the aspects of the EM31 relevant to this study will be mentioned here, the reader is referred to technical note TN-6, "Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers" (Geonics™) for a more complete description including the theory, instrumentation, survey techniques and interpretation with respect to the EM31 and EM34 instruments.

Figure 3 illustrates a transmitter coil T_x energized with an audio frequency and placed on the surface of the earth and a receiver coil R_x located a distance, s, away. For the EM31, s is fixed at 3.66 metres and the operating frequency is 9.8 kHz. Figure 3 shows the EM31 in the vertical dipole mode. Small currents in the ground are induced by the time-varying magnetic field produced from the alternating current in the transmitter coil. A secondary magnetic field, H_s, is generated by these small currents. The primary field, H_p, and the secondary field are detected by the receiver coil.

The secondary magnetic field is generally a complicated function of the intercoil spacing, s, the operating frequency, f, and the ground conductivity, σ. However, when the Low Induction Number(LIN) assumption is satisfied, i.e.;

$$\omega << \frac{2}{\mu_0 \sigma s^2} \qquad (3)$$

where $\omega = 2\pi f$
f = operating frequency (Hz)
μ_0 = permeability of free space
= $4\pi * 10^{-7}$ H/m
σ = ground conductivity (mho/m)
s = intercoil spacing (m)

then H_s is a straightforward function of these variables. The accuracy of the EM31 is contingent upon the LIN constraints being satisfied. For the Geonics™ EM31 instrument in the vertical mode, this equates to the ground conductivity, σ, being much less than 1900 mmho/m. The EM31 conductivity is governed by the relationship given in equation 4.

$$\frac{H_s}{H_p} \cong \frac{i\omega\mu_0\sigma s^2}{4} \qquad (4)$$

where $i = \sqrt{-1}$

Thus, the apparent conductivity, σ_a, is given by;

$$\sigma_a = \frac{4}{\omega \mu_0 s^2}\left(\frac{H_s}{H_p}\right) \qquad (5)$$

In a homogeneous or horizontally stratified earth, induced current flow from the EM31 occurs in a horizontal direction. As well, the instrument has been designed to prevent any magnetic coupling between current loops. The depth of penetration (or exploration depth) is, under these constraints, governed only by the intercoil spacing. The relative response function $\phi(z)$, where z = depth/spacing, for both vertical and horizontal dipoles is shown in Figure 4(a). The response function $\phi(z)$ describes the relative contribution to the secondary magnetic field arising from a thin layer at any depth. It is interesting to note that the near-surface soil contributes little to the apparent conductivity, whereas at $0.4z$ the soil's conductivity has a maximum contribution to the secondary magnetic field.

A more useful relationship, however, is the relative contribution to the secondary magnetic field from all material *below* any depth. This "cumulative" response is given by;

$$R_v(z) = \int_z^{\infty} \phi_v(z)dz \qquad (6)$$

where
$R_v(z)$ = cumulative response versus depth for vertical dipole mode
z = depth/coil spacing, i.e. normalized depth

An easier method of calculating $R_v(z)$, however, is possible with the same relationship in following form:

$$R_v(z) = \frac{1}{(4z^2 + 1)^{1/2}} \qquad (7)$$

The resulting $R_v(z)$ curve is shown in Figure 4(b).

Equations 6 and 7 only provide expressions for the vertical dipole mode; the coil orientation used for the surveys completed for this study and those most common in single-mode surveys. Expressions for $R_H(z)$ (cumulative response for horizontal dipole mode) can be found in Geonics™, TN-6.

PREDICTING EM RESPONSE USING RCPTU DATA

A method of predicting the EM31 response given a horizontally layered earth of known strata thicknesses and conductivities is shown by a three-layer example in Figure 5. RCPTU data provide conductivity values for each successive 2.5 cm thickness of stratum. As mine tailings sites are known to be largely horizontally stratified, they provide ideal scenarios for testing the predicted electromagnetic response and the value recorded with the electromagnetic instrument.

Figure 6 shows a typical RCPTU conductivity plot together with the relative response function, $\phi_v(z)$ and the cumulative response function, $R_v(z)$. The conductivity data of Figure 6 provides over 600 discrete layers for the forward calculation. In all surveys carried out for this study, the EM31 instrument was held at hip height (0.9 m) to facilitate efficient data collection. As $R_v(z)$ (equation 7) is based on the transmitter and receiver coils being at ground level, a position 0.9 m above the actual ground surface is treated as "$z = 0$" for the purposes of modeling RCPTU data. While the exact conductivity of the air is not known, we know air must have a conductivity somewhere between zero and the first perceptible non-zero value recorded by the RCPTU probe as it is pushed into the ground. A sensitivity analysis was carried out by observing the discrepancy between the predicted EM31 response achieved by setting air conductivity at zero and the predicted response obtained by setting air conductivity as the first value recorded by the resistivity cone. The difference in predicted responses did not exceed 1%. We therefore decided that our calculated responses are not significantly affected by the limited knowledge of the air's conductivity.

Factors which were determined to influence the calculated or predicted EM31 response include: the water table location, the final depth at which resistivity is recorded in an RCPTU hole, and the actual conductivity of the soil's pore fluid. As shown with the relative response curve in Figure 6 and discussed in the previous section, the EM31's maximum response is derived from layers near a depth of 1.5 m. If the water table's position is above this level, the predicted response will be markedly higher than if the water table were located much below 1.5 m. The conductivity log in Figure 6 would, therefore, predict a value reflecting a strong influence from the unsaturated zone's low conductivity values. While no holes shallower than 4 m were used in this study, the final depth influences the magnitude of relative contribution assigned to the final conductivity value. The conductivity log in Figure 6 is for a relatively deep hole, whose predicted EM31 value will not be significantly influenced by the final depth's conductivity. A hole terminating nearer to 4 metres depth will predict a value more affected by the final step conductivity. Finally, the presence, nature and location of any contaminants in the pore fluid greatly affects the fluid conductivity. Assuming a constant water table, a highly conductive sulfate-rich fluid-saturated soil would have a higher predicted EM31 value than a soil saturated with a low ionic strength fluid.

Predicted EM31 response calculations were carried out for data collected from two mine sites over two years. Figure 7 illustrates the calculated (predicted) EM31 response data in relation to the actual EM31 values recorded. All data points on this plot represent locations where an RCPTU hole was completed in the same location as an EM31 data point was recorded. The solid line on this chart represents the relationship shown by Geonics™ (see TN-6, Geonics™) for measured EM31 conductivity versus true bulk conductivity (i.e. assuming a homogeneous half-space). The line loses its linearity at bulk conductivities greater than approximately 80 mmho/m as the LIN assumption (equation 3) begins to break down. Above 80 mmho/m, the EM31 has not been properly calibrated to read true ground conductivity. As a result, the high predicted EM31 conductivity's are not able to accurately provide conductivity responses from the EM31 in its current configuration. Beyond the intended linear range for the tool, a more complex predictive methodology is required.

We have found empirically, however, that the EM31 can still be used as a qualitative tool at high conductivity values. In a localized area of a tailings site at Mine A of approximate dimensions 3000m x 3500m several RCPTU holes and EM31 lines were completed. Nine of the resistivity piezocone locations coincided with EM31 information. The data from these nine soundings, included in Figure 7, may be compared using 3-D surface contouring as shown in Figure 8. The apparent peak and trough visible in both plots at the same locations show good agreement between the modeled(predicted) and obtained EM response. The difference in scale between the two plots reflect the inability of the EM31, at high ground conductivity's, to show an accurate conductivity response. However, use of EM31 data to locate relative highs and lows in conductivity appears to remain valid at conductivity's beyond those in which the EM31 is made to work. Perhaps, with the escalating focus on waste management and contaminated soil remediation, the demand for accurate EM31 measurements will be sufficient enough to, with the same depth of penetration as the EM31, encourage the creation of an instrument calibrated in a range of, say, 100 to 1000 mmho/m. In the meantime, further quantitative understanding of the non-linear response of the EM31, a tool already available which has the depth of penetration required, is recommended.

DISCUSSION

The implications of the relationship observed between downhole resistivity/conductivity information measured with the RCPTU and EM31 response data are promising. Indeed, RCPTU investigations preceded by a rapid EM31 survey appears to be a satisfactory marriage of a geophysical tool and an invasive instrument that will more effectively and economically carry out a geoenvironmental site characterization. Figure 9 clearly illustrates this point. RCPTU holes 01, 02 and 03 were carried out prior to the EM31 survey. After plotting and interpreting the EM31 survey data, hole RCPTU15 was pushed. Fluid conductivities, from the RCPTU logs, appear to be lower in hole 15 than in 01, 02 and 03.

The increasing popularity of the EM31 ensures its continued use in the future. The results of this study provide a quantitative reassurance of the relative accuracy of the EM31 values being recorded.

ACKNOWLEDGMENTS

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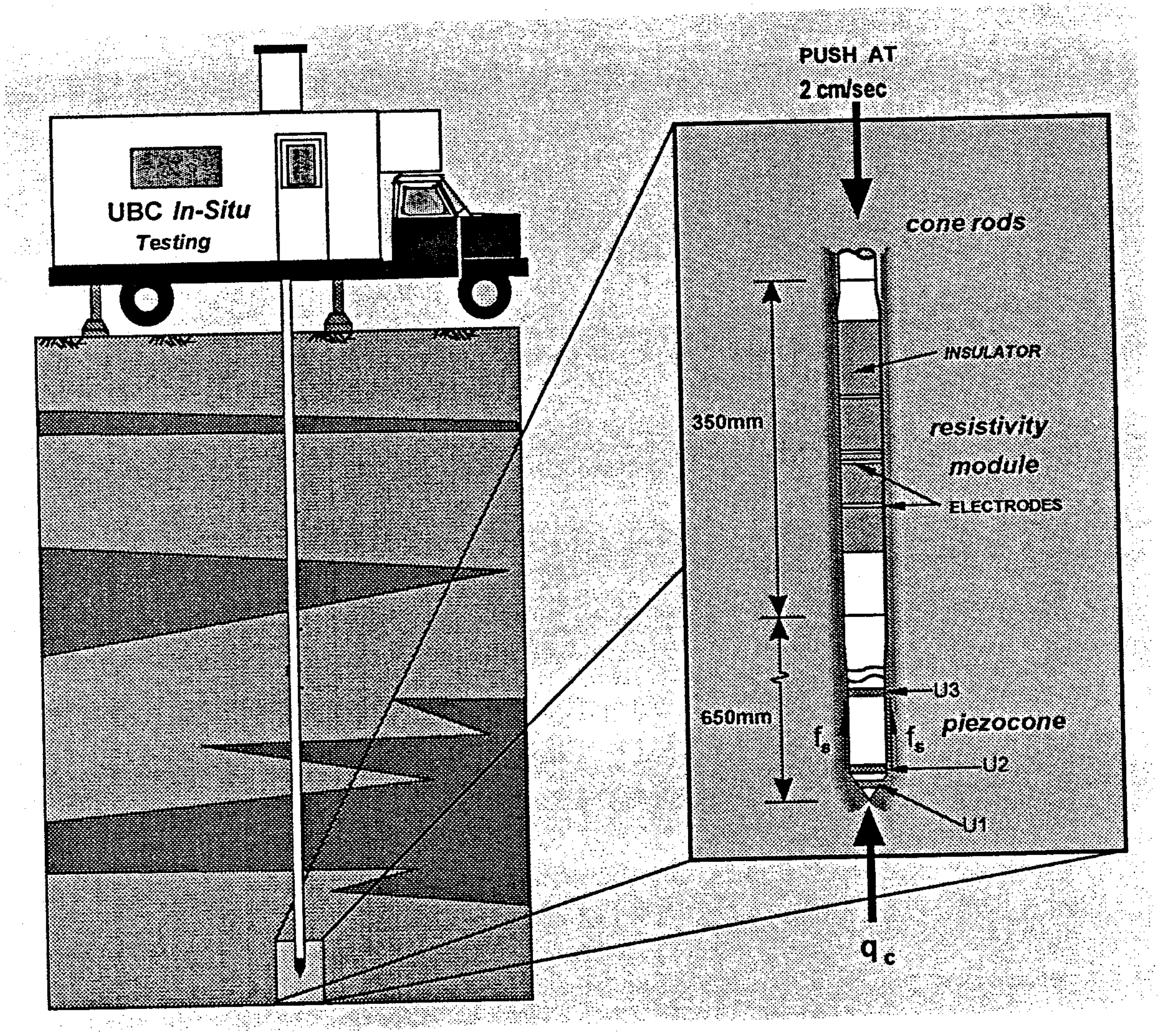


Fig. 1 UBC Cone Truck and Resistivity Piezocone.

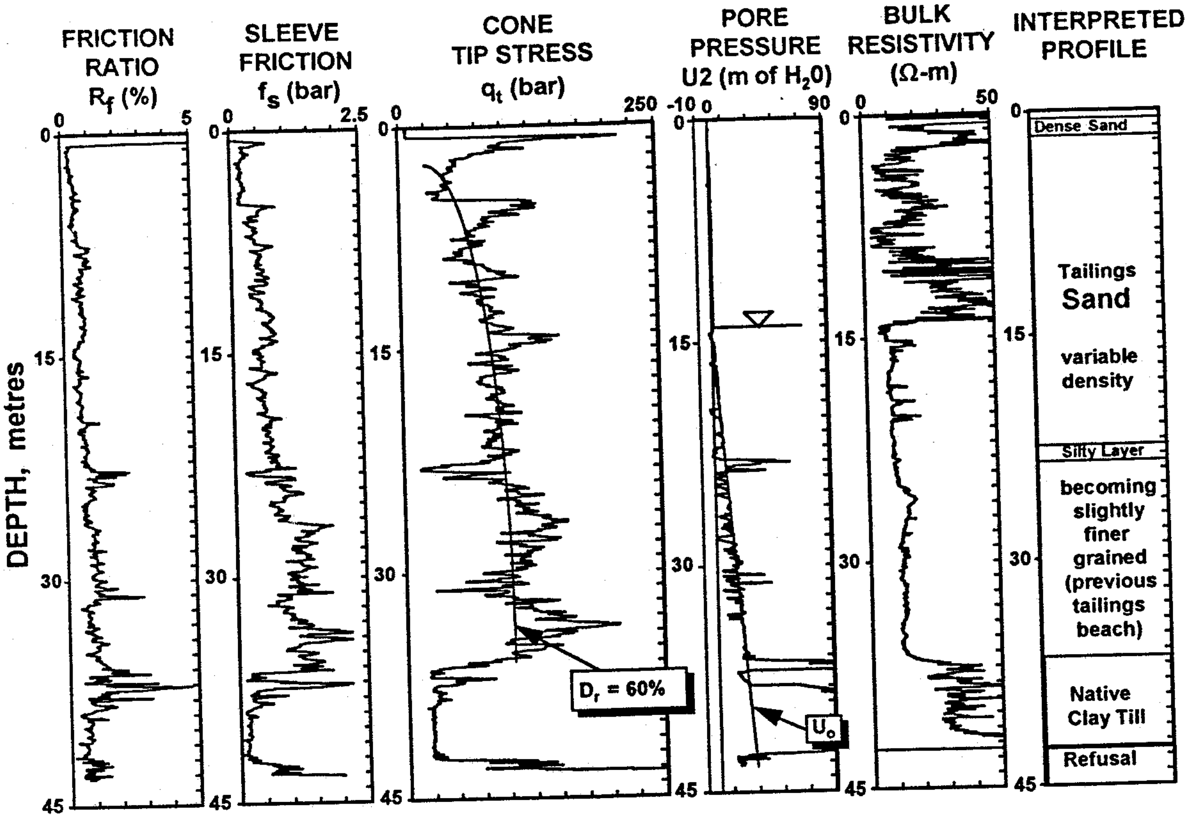


Fig. 2 Typical RCPTU Sounding profile from a tailings area.

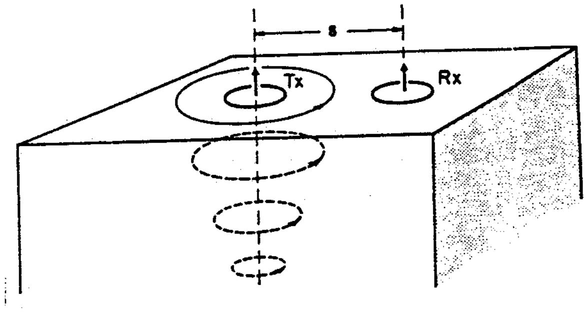


Fig. 3 Induced Current Flow (homogeneous halfspace), after Geonics TN-6.

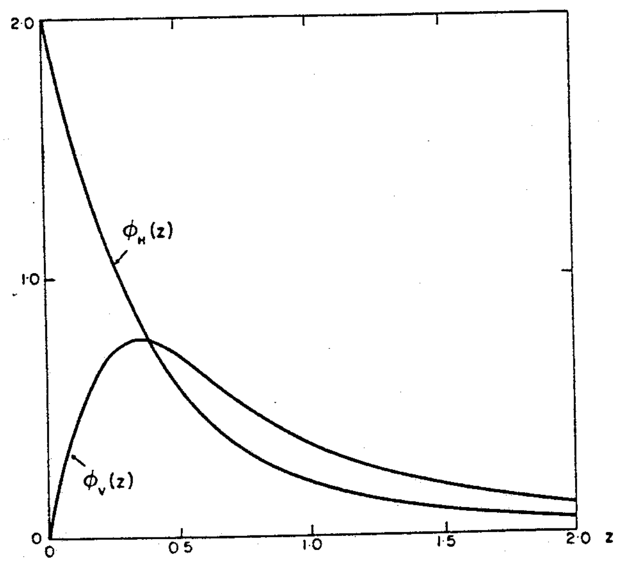


Fig.4a Relative responses for vertical and horizontal dipoles (After Geonics, TN-6).

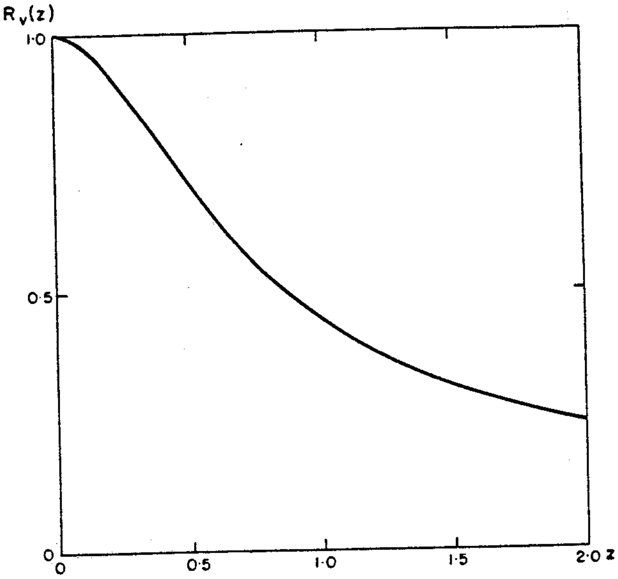
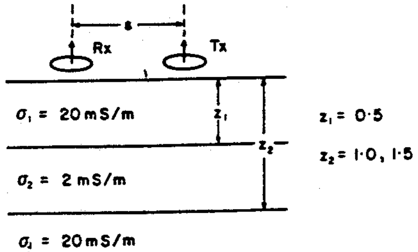


Fig. 4b Cumulative response versus depth for vertical dipoles (After Geonics, TN-6).



$$\sigma_0 = \sigma_1 [1 - R(z_1)] + \sigma_2 [R(z_1) - R(z_2)] + \sigma_3 R(z_2)$$

$$z_2 = 1{\cdot}0, \quad \sigma_0 = 20[1 - 0{\cdot}70] + 2[0{\cdot}70 - 0{\cdot}44] + 20 \times 0{\cdot}44 = 15{\cdot}3 \text{ mmho/m}$$

$$z_2 = 1{\cdot}5, \quad \sigma_0 = 20[1 - 0{\cdot}70] + 2[0{\cdot}70 - 0{\cdot}32] + 20 \times 0{\cdot}32 = 13{\cdot}2 \text{ mmho/m}$$

Fig. 5 Calculation of response to three layer earth-center layer thickness varying (Geonics, TN-6).

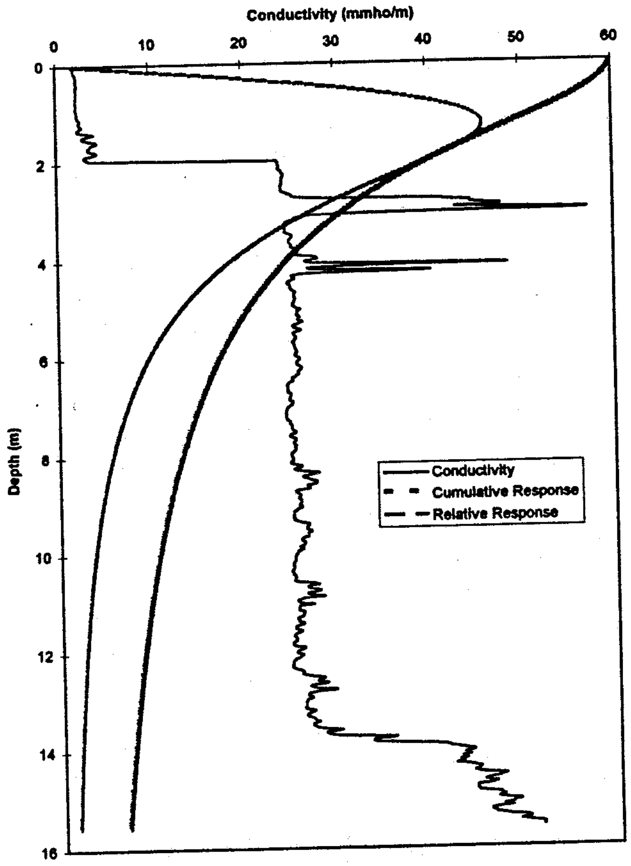


Fig. 6 RCPTU conductivity log with cumulative and relative response curves.

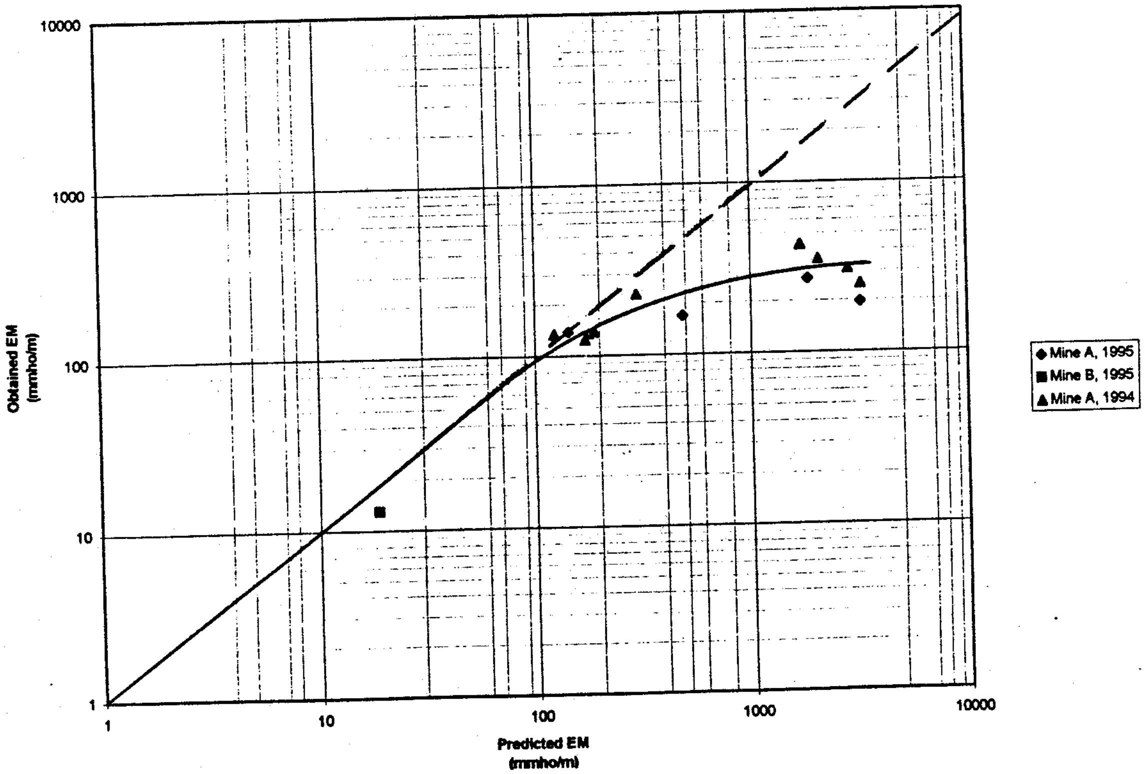


Fig. 7 Measured vs. predicted EM31 response data.

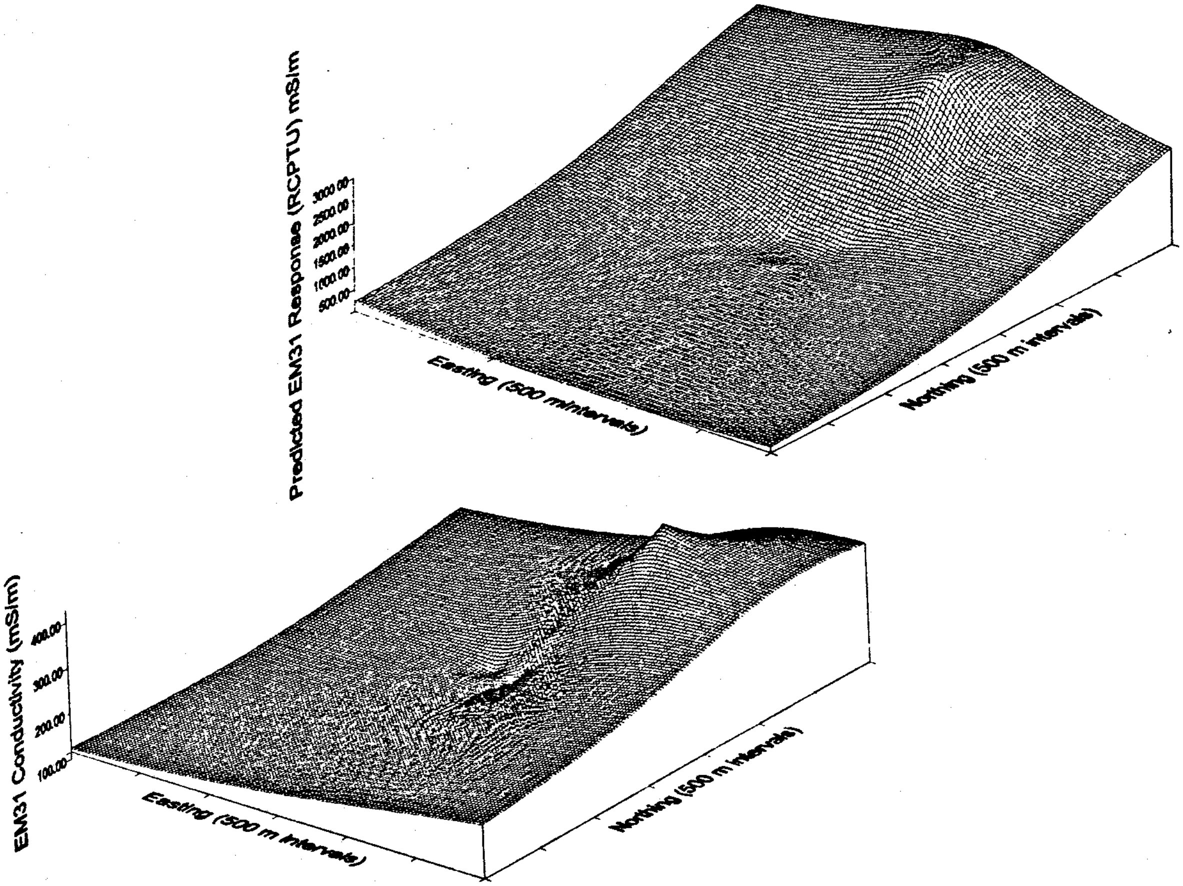


Fig. 8 Surface plots of measured response (EM31) and predicted from RCPTU data at Mine A tailings.

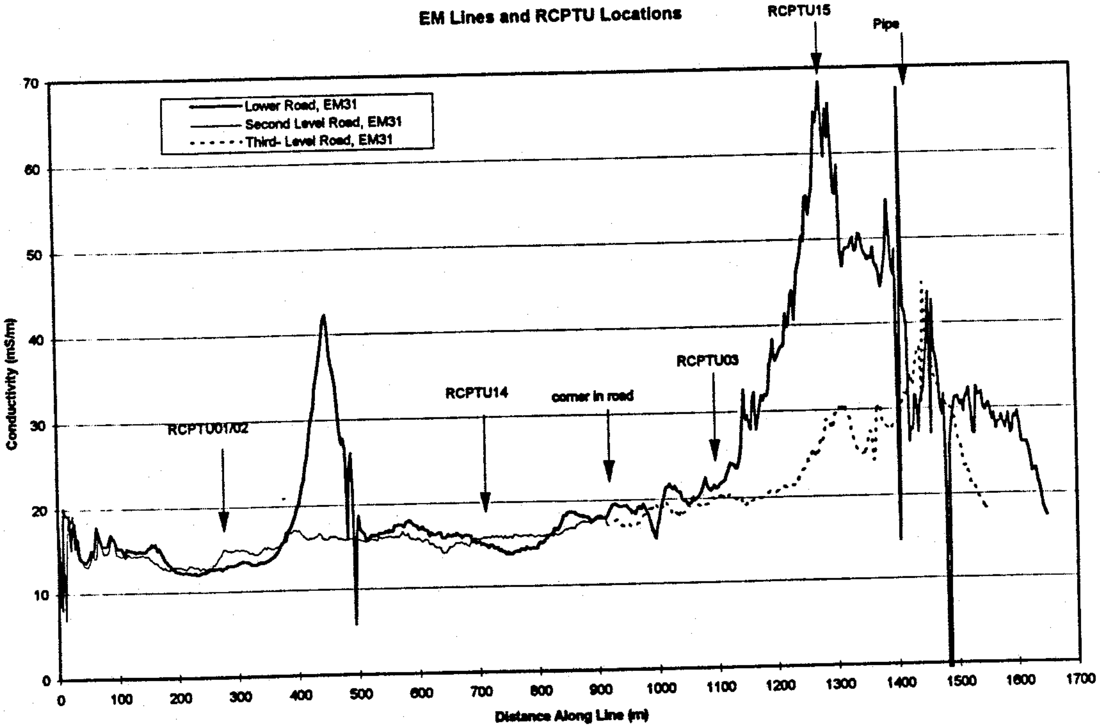


Fig. 9 RCPTU locations and EM lines recorded on successive benches of tailings dam.