The Use of In-Situ Testing for the Characterization of Sulphide Mine Tailings

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ABSTRACT

Mine tailings storage facilities are often massive structures. It is not uncommon for these facilities to have in excess of 100 x 10^6 tonnes of retained solids. There are several cases of base metal mines where the total amount of impounded tailings is in the order of 1 billion tonnes. For the most part, the larger tailings facilities are associated with mining sulphide ores. Consequently, there is potential for many of these facilities to have sulphide oxidation processes that can lead to an undesirable metal-leachate condition.

Characterizing sulphide tailings facilities to assess, among other things, the potential for impact to ground or surface waters, is an essential component of managing these facilities during their operational, care/maintenance and closure phases. Traditional grab and/or drilling field sampling followed by laboratory testing can provide insight to general trends. However, lack of statistical significance and the inherent inhomogeneity of tailings impoundments are two of the reasons representative sampling is not economically or practically feasible with these traditional methods.

In-situ testing, using sophisticated yet robust penetration tools, offers an alternative to traditional methods. Screening characterization of large areas can be carried out in reasonable time at a reasonable cost using these penetration tools. For example, recent advances in in-situ testing, mainly with respect to resistivity piezocone and discrete-depth (BAT) water sampling technologies, have greatly improved the manner in which the geochemical characterizations of sulphide mine tailings can be achieved. The piezocone test has long been established by the worldwide geotechnical community as the premier stratigraphic logging tool for most soil conditions and is ideal for mine tailings. Besides stratigraphic information, the piezocone also provides accurate estimates of key geotechnical parameters and yields extensive information on the physical groundwater regime.

In recent years, additions to the piezocone have included a resistivity module, which can be modified to include induced-polarization measurements. Used in conjunction with one another, resistivity piezocone soundings and a discrete-depth pore fluid for site specific chemical correlations make an impressive and economic methodology of carrying out screening geochemical and geotechnical evaluations of sulphide mine tailings sites.

Keywords: sulphide tailings, in-situ testing, piezocone, resistivity, geophysics, water sampling, and hydrogeology

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. Hydrogeological parameters assessed include accurate location of the phreatic surface, determination of in-situ gradients, and estimates of hydraulic conductivity.

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. The addition of the resistivity module permits assessment of groundwater quality by measuring the bulk soil resistivity without imparting extra costs or time to a standard sounding.

Mine tailings are an ideal material for the utilization of the piezocone technology. Some mine tailings, particularly from large volume sulphide ore operations, pose a significant potential environmental impact due to processes such as acid rock drainage (ARD). Additionally, there are inherent geotechnical stability considerations in large tailings impoundment structures as many of these are hydraulically constructed entirely with tailings. There is a significant challenge in adequately characterizing these impoundments for both their geotechnical and geochemical nature. Consequently, the potential to use a single characterization tool in at least a screening fashion is extremely attractive. The resistivity piezocone represents an accurate, time-effective, and economic tool for the geotechnical and preliminary geochemical characterization of sulphide tailings. In comparison to conventional characterization methods, the enhanced accuracy of the piezocone technology typically comes at 1/4 to 1/2 the cost on a per-metre basis.

This paper introduces the salient advances in piezocone technology resulting from a recently completed cooperative industry-government-University research program. These advances allow piezocone technology to be a key geochemical screening tool for sulphide mine tailings. BAT water sampling technology will also be introduced as the manner by which accurate and defensible calibration of resistivity piezocone values to laboratory analyzed geochemical quantities can be made. A brief case study is presented to demonstrate a typical application of these in-situ tools in a tailings characterization project.

EVALUATION OF SULPHIDE TAILINGS IMPOUNDMENTS

Tailings impoundments often pose geotechnical engineering concerns, which require adequate characterization during their design, construction, and operation phases. Recent failures of large tailings dams such as Stava, Mochikoshi, Tyrone, Merriespruit and Omai have caused significant economic loss well as occasional human injury and loss of life. The magnitude of these failures only serves to underscore the importance of adequate geotechnical characterizations of all tailings impoundments.

However, “catastrophic” geotechnical failure is not necessary to create the potential for negative environmental impact from sulphide tailings impoundments. For example, the initiation of ARD can represent a significant environmental liability from otherwise competent tailings storage facilities. ARD, which is becoming a “catch-all” term for many related geochemical phenomena, is the high ionic strength, often-suppressed pH, drainage that can result from the oxidation of sulphide minerals in the presence of oxygen and water. Fully developed ARD can result in the dissolution of heavy metal ionic constituents in the tailings themselves or in adjacent native soil/rock materials, which can then be transported, to surrounding surficial and groundwater systems. Once in the receiving waters, the elevated ionic loading can have an adverse effect on water quality and, in extreme cases, cause loss of biological habitat.

Consequently, both potential geotechnical and geochemical “instability” issues require characterization when assessing the potential liability a given sulphide tailings impoundment may present to the owners of that facility. From this dual perspective, the characterization of sulphide tailings requires evaluation of:

- stratigraphic variance within the tailings;
- tailings mineralogy;
- relative geotechnical properties of each discernible stratigraphic unit;
- the hydraulic properties of both aquifer and the aquitard zones in the tailings; and
- the nature of pore fluid-gases present in each unit.

The results of site investigations should permit adequate three-dimensional representation of prevailing site conditions. Because of the large size of most tailings impoundments and areal size of potentially affected adjacent native deposits, statistically significant characterization is not logistically or economically feasible. The use of continuous logging tools that are both highly repeatable and able to provide a suite of requisite information is almost essential if meaningful characterization is to be carried out at a reasonable cost.

The resistivity piezocone is a continuous logging tool that meets all of the needs stated above, save a mineralogical evaluation. The following section describes the resistivity piezocone technology and how it is deployed for a typical program.

RESISTIVITY CONE PIEZOMETER 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 CPT, 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. Rigorous ASTM and International standards control both dimensions and rate of penetration. Figure 1 shows the basic concept of carrying out a modern CPT sounding.

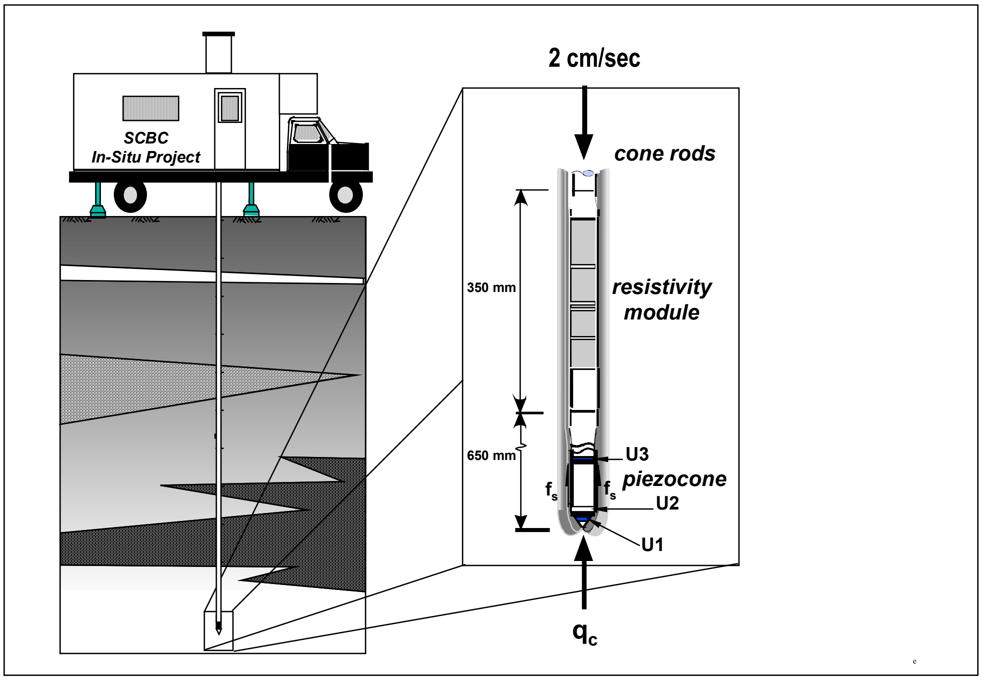

Figure 1 - CPT Concept

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). All channels are continuously monitored and typically digitized at 25 mm intervals.

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 a 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.

Excess pore pressure measurements also provide valuable hydrogeological insight. When penetration ceases, e.g. after a 1-metre rod push, excess pore pressures generated during cone penetration start to dissipate. The rate of dissipation is dependent upon the coefficient of consolidation, which, in turn, is dependent upon layer compressibility and hydraulic conductivity. Estimates of the hydraulic conductivity 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.

The resistivity piezocone (RCPTU) is a relatively recent development at the University of British Columbia (UBC) (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. Davies and Campanella (1995) give a summary of the RCPTU and its perceived application areas. The schematic concept of a CPT sounding in Figure 1 also shows a typical RCPTU arrangement.

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.

Values of bulk resistivity can be readily compared with those of bulk conductivity, a more common geochemical measures, since conductivity is the reciprocal of resistivity:

$$\textbf{Conductivity}(\mu\textbf{S/cm}) = \textbf{10,000} \div [\textbf{Resistivity(Ohm-m)}] \qquad \textbf{(1)}$$

For mine tailings, depending upon saturation and oxidation processes, the range of resistivity (conductivity) values is very large from about 0.01 (1000000) to about 1000 Ohm-m (10 µS/cm).

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 correlation with RCPTU bulk resistivity values is most commonly site-specific in nature, although sulphate anions and divalent iron have shown remarkable global correlation in our experience to date.

DISCRETE DEPTH WATER SAMPLING

The “BAT” System

A modification of the commercially available *BAT* System (named after the inventor, Bengt Arne Torstensson, 1984) is recommended for obtaining in-situ pore fluid samples. The original system consists of a sampling tip that is accessed through sterile evacuated glass sample tubes and a double-ended hypodermic needle set-up. The tube sampler is lowered either by cable or electrical wire depending upon whether a pore fluid sample is taken with or without a pressure test being carried out. The modifications made at UBC include using a stainless steel sampling carrier of approximately 120 ml volume and replacing the hypodermic needle system with Swagelock fittings. This latter modification allows much more accurate and feasible sampling in higher TDS environments as experienced, for example, during water sampling in metallic mine tailings. The equipment is hydraulically pushed with the same equipment used for cone penetration testing. The modified BAT sampling tip consists of a probe slightly larger in diameter than the resistivity module (50 mm versus 37 to 44 mm). This sampling tip can be pushed on its own or down the same alignment as the smaller diameter CPTU sounding. Standard AWL casing rods work well for the BAT system.

A schematic of a typical modified BAT system is shown in Figure 2. The US-EPA and other high conformance requirement groups have adopted BAT technology as appropriate and preferred for many environmental characterization applications. The attraction of no drill cuttings and the repeatability of the data are cited as the key reasons for this preference. BAT technology has been scrutinized by many investigators and has met with widespread acceptance (e.g. Zemo et al., 1992).

After BAT water samples are retrieved to the ground surface, preliminary chemical tests should be conducted on-site and then the sample can be stored for further laboratory analyses. Field measurements should, at a minimum, include conductivity, temperature, and pH. Once enough sampling is carried out at a specific depth, the BAT probe is then pushed to the next depth and the procedure repeated. There is no limit to the number of samples that can be taken at one location.

BAT Hydraulic Conductivity Measuring System

Recent studies at UBC (Wilson, 1996) have made use of the Modified BAT with quick connect fittings to perform out-flow hydraulic conductivity, K, tests. The analytical solution was verified in comparison testing where the BAT tip is made to function as an out-flow slug test. Not only were the results identical but also laboratory tests in 5 m high water columns showed that the current limiting highest K of the measuring system with 50 mm long filter section and 3/8 inch valves was 0.0001 m/s (or a medium sand). An important finding in this study showed clearly that an in-flow K test in the field often gave incorrect and misleading K values which were usually more than an order of magnitude too low due to fines migrating and plugging the filter. Thus, water sampling (in-flow) cannot be used to also give K of the soil.

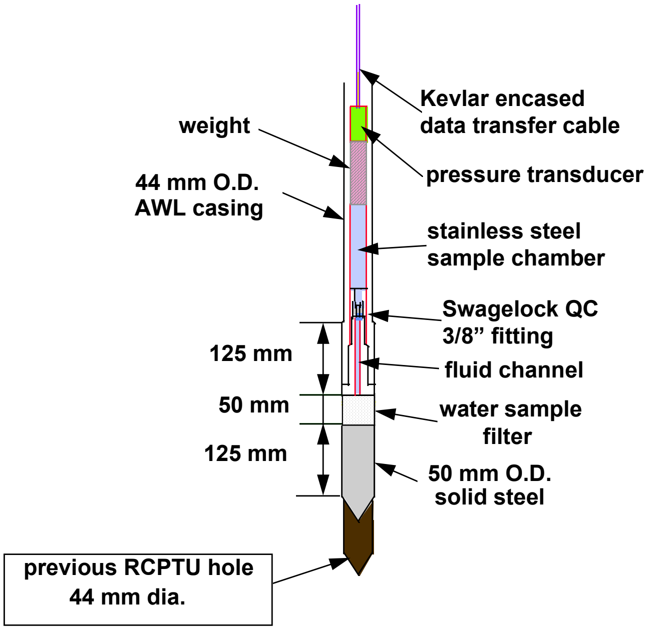

Figure 2 - Schematic of the Modified BAT Discrete-Depth Pore Fluid Sampler

The measurement of high speed pore pressure dissipation when CPTU penetration is stopped is also used to estimate the time for 50% dissipation, which can be 1 sec. or less, from which the hydraulic conductivity can be calculated. However, the equation constant needed to calculate K is directly calibrated using the out-flow K-BAT determination at the same locations. Only a few K-BAT determinations are usually needed at a given study site.

IN-SITU TESTING RESEARCH PROJECT

December 1996 saw a 30-month, cooperative Governmental-Industry-University applied research project come to a close. This project included assessing a suite of in-situ tests on a variety of sulphide tailings materials. The project was truly a cooperative effort. Placer Dome Inc. provided the principle investigator. Placer and Cominco Ltd. provided more than 50% of the hard funding (and almost 75% of overall funding) and the research sites used. The Science Council of British Columbia provided project guidance and roughly 45% of the hard funding. The In-Situ Testing Group at the University of British Columbia provided equipment, expertise and graduate researchers. Klohn-Crippen Consultants Ltd. provided engineering expertise, the project manager (in-kind), some hard funding and project accounting.

The project resulted in a total of 8 “field-trips” of between 3 and 16 days at four sites:

- the Sullivan tailings complex in Kimberley, B.C. (three trips);
- the Endako tailings impoundments near Fraser Lake, B.C. (two trips);
- the Gibraltar Mine tailings impoundment near Williams Lake, B.C. (two trips); and
- the Trail smelter site in Trail, B.C.

The latter site involved assessment of arsenic storage sites and natural ground conditions. The coarse-grained nature of the natural ground at the Trail site resulted in little success with the piezocone technology at that site. The Sullivan tailings include pyrrhotite-rich materials, which have undergone extensive oxidation process and have ARD related phenomena. The Endako and Gibraltar ore-bodies have sulphide materials but at much lower concentrations than at Sullivan giving the research program a good range of “typical” mine tailings.

In addition to the field trips to the mine sites, local (Vancouver) field trials involving roughly 30 days were carried out to test new equipment developments and equipment modifications resulting from the research project.

EXAMPLE DATA FROM RESEARCH PROJECT

One of the objectives of the research project was to determine whether the RCPTU could be used to assess sulphide oxidization processes in tailings. The use of surface resistivity (or conductivity) measurements to delineate zones within sulphide mine wastes where oxidation processes are developing or have occurred is relatively well documented. For example, King and Sartorelli (1991) have shown 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 was noted as a potentially significant advantage of the RCPTU.

At three sulphide tailings impoundments in Western Canada, the RCPTU and BAT water sampling tools were used together to compare their ability to characterize the tailings with respect to more conventional techniques. A total of more than 90 RCPTU soundings totaling nearly 2,500 metres were carried out. These soundings were augmented by over 60 discrete-depth water samples and subsequent laboratory geochemical evaluation.

Figure 3 shows a typical RCPTU sounding from one of the tailings areas. Stratigraphic interpretation and geotechnical parameter selection were carried out for each sounding using routine piezocone techniques and are not discussed herein. As can be seen by the example in Figure 3, the stratified nature of the hydraulically placed tailings is easily discernible with the piezocone.

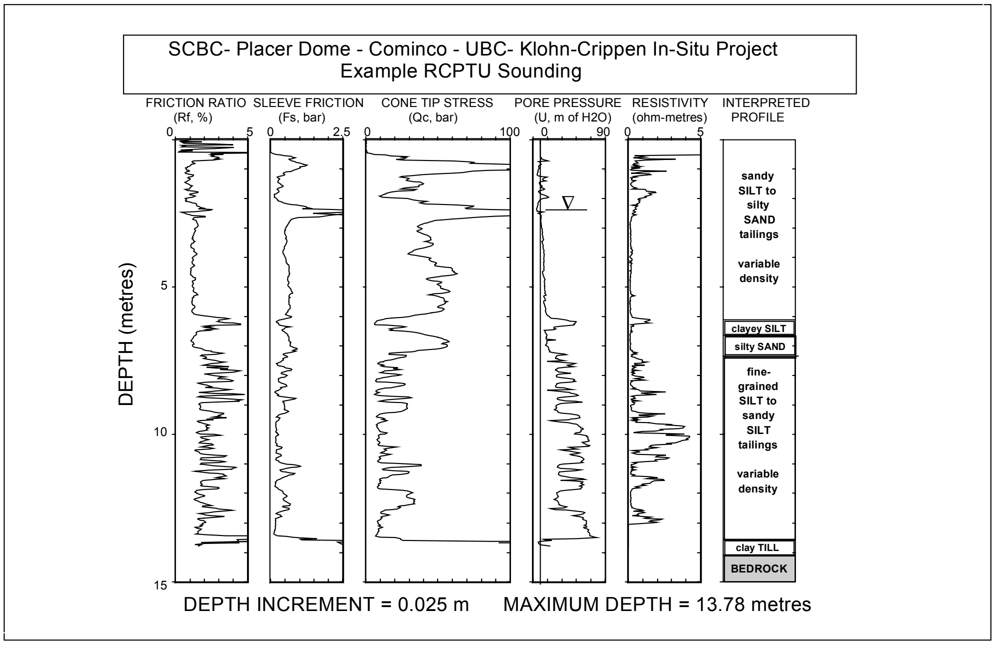

Figure 3. Example RCPTU Profile from Research Project

Using Figure 3 specifically, the bulk resistivity values shown range from 0.2 to 5 ohm-m below the water table; these values are indicative of heavy ionic loading. A particularly heavy ionic loading was evident from 2.7 to 6.1 metres. Figure 4 shows the characterization image for the tailings area of Figure 3. The composite image from the RCPTU was developed using the bulk resistivity value every 0.5 metres. The composite presentation format allows spatial identification of an above-background ionic plume, which can then result in optimized sampling and/or monitoring locations being identified. Previous conventional drilling and sampling at this example site had poorly defined the plume and entirely missed the overall flow direction; all at a cost substantially in excess of the commercially equivalent RCPTU program.

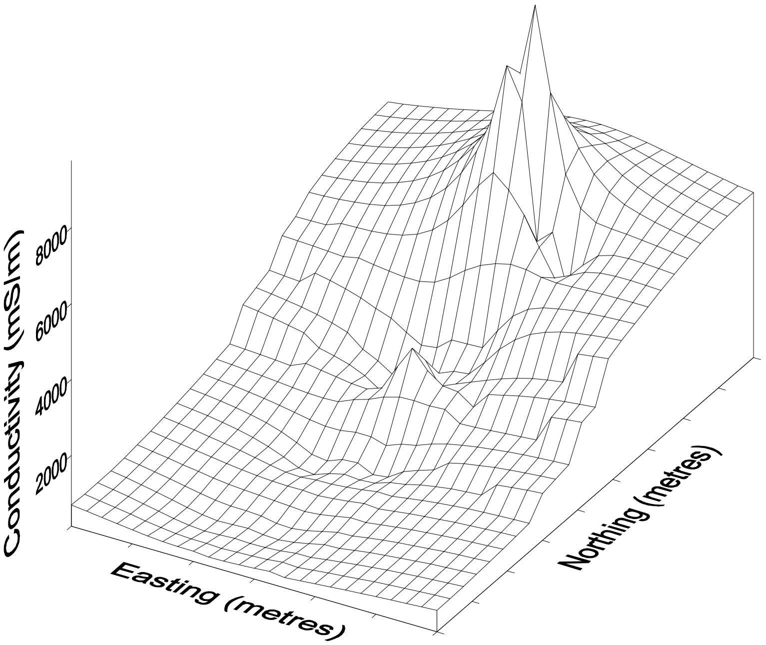

Figure 4. RCPTU Bulk Conductivity Values at 5-metre depth from Tailings Area

An additional key finding from the research program was the extremely complimentary fashion in which the surface geophysical tools (e.g. Geonics EM-31™) and the RCPTU soundings operated. For a fraction of the cost of traditional investigation methods, the project's experience showed combined surface and RCPTU geophysical surveys *in addition to* the continuous geotechnical and hydrogeological information obtained at each sounding location via the standard piezocone information provide a very comprehensive geoenvironmental site characterization.

As described above, the RCPTU provides the user with essentially continuous measurements of standard piezocone data as well as the bulk resistivity of the soil-pore water system. Most soil solids have a considerably lower specific conductance than ionic strength water, and consequently the pore fluid chemistry tends to dominate the bulk resistivity response.

As noted above, other researchers (e.g. Ebraheem et al., 1990; King and Sartorelli, 1991) have shown how the high ionic loading of both early stage and low pH, fully developed ARD is well defined by surficial geophysics. The main reason the process is detectable is due to the elevated ion concentration, which is often dominated by elevated sulphate levels that occur in the early stages of ARD development even at neutral or basic pH levels.

Figure 5 shows typical data from the sulphide tailings impoundment used in compiling Figures 3 and 4. The pH versus bulk conductivity trend is not strong, although a trend is certainly apparent.

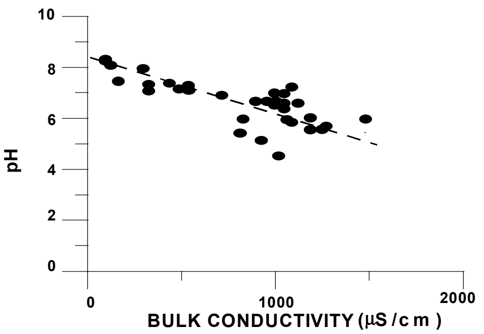

Figure 5 - Bulk Conductivity Versus pH for Sulphide Tailings Impoundment

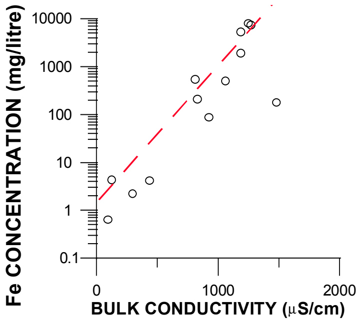

Figure 6 - Iron Concentration versus Bulk Conductivity for Sulphide Tailings Impoundment

Figure 6 shows a stronger trend from the same site for iron concentration versus bulk conductivity. In the case of Figure 6, it could be argued that a relatively good, albeit likely site-specific, trend exists between iron concentration (per pore water testing) and bulk conductivity.

During the research project, assessment of pore fluid geochemistry for the different tailings impoundments was made by comparing the RCPTU bulk resistivity logs and the chemical analyses on discrete groundwater samples. Figure 6 demonstrates one such typical relationship. In general, the relationships tend to be quite site-specific. However, Figure 7 shows the relationships developed between bulk conductivity (resistivity^{-1}) and pore fluid sulphate concentration, which may be somewhat different.

Sulphate is a key ionic constituent of all stages of sulphide oxidation. The detection of sulphate within sulphide tailings prior to the onset of significant ARD contamination is feasible with the RCPTU, which makes it a good screening tool for planning remediation and/or reclamation strategies. The authors do not contend that the sulphate-bulk resistivity relationship shown in Figure 7 is extensively global in nature. However, excellent site-specific relationships can be developed within a short time period and they can then be used for ongoing surveillance of possible oxidation development in tailings areas. As far as global applicability, there is this potential as shown by the strength of the correlation with several different sites.

One initially curious aspect of Figure 7 is its bi-linear distribution. The sulphate anion tends to dominate the TDS initially in the ARD process and thus the bulk resistivity/conductivity response. As the process advances and more ions begin to make up the TDS, the importance of the sulphate anion to the overall total diminishes thus causing a damping effect to the relationship between sulphate anion and bulk resistivity/conductivity.

COST COMPARISON WITH TRADITIONAL CHARACTERIZATION METHODS

Industry experience comparing the cost of the in-situ tests described with conventional site characterization tools is generally positive. In the authors' experience, the best results with piezocone technology, both logistically and economically, occur when characterization projects are cost- and production-controlled on a per-metre basis. Unlike other site investigation methodologies, per-metre specification for piezocone programs will not hamper data quality due to the strict standards governing the test. Typical commercial rates for piezocone work are between $25 and $40 per metre depending upon region and project size.

During the research project, the daily rates of progress when in “production mode” were roughly 80 metres or more. With the comprehensive geochemical and geotechnical information provided by this method in addition to the stratigraphic profile, traditional drilling and sampling would require at least twice the time to complete the same amount of work. An in-situ research/investigation program carried out in conjunction with Canada’s MEND initiative provided at site-specific example of such differences in cost. At the site (INCO’s Copper Cliff tailings area), a conventional drilling program was carried out to parallel an RCPTU/BAT program. The “traditional” site investigation program consisted of auger drilling with 3 to 5 metre interval Standard Penetration Test (SPT) samples. The drilling averaged approximately 30 metres per day at roughly $50 per metre. This drilling did not provide near the continuous data of the RCPTU let alone match its accuracy and repeatability. Downhole resistivity soundings within a drill hole typically averaged about $45 per metre. From this isolated example, a combined drilling and downhole resistivity program could therefore easily exceed $100/metre, or between 2.5 and 4 times typical commercial piezocone rates.

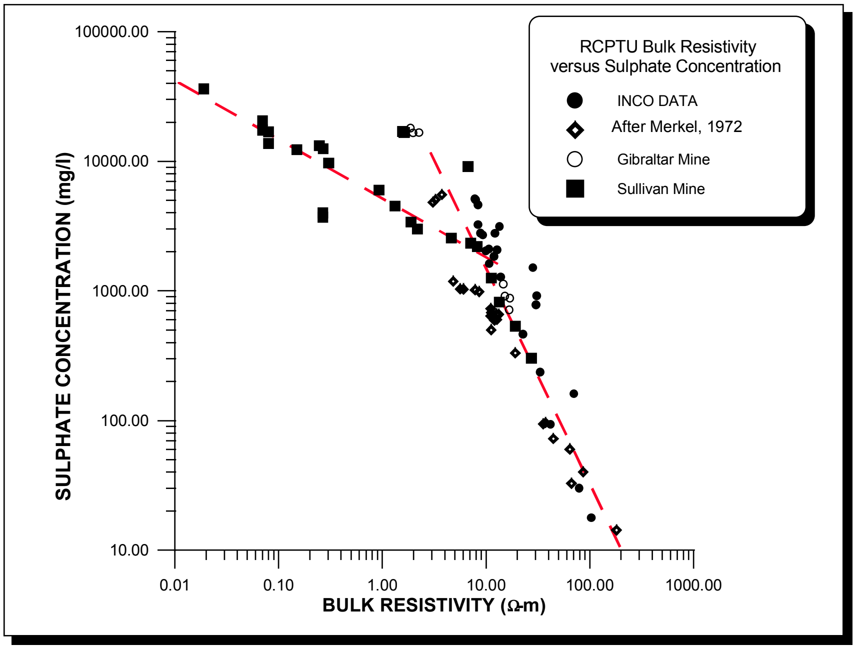

Figure 7 - Bulk Resistivity versus Sulphate Concentration for Sulphide Tailings

SUMMARY COMMENTS

The best manner to characterize sulphide tailings is to use the RCPTU in combination with discrete pore fluid-gas sampling. Comparisons between bulk resistivity logs and specific chemical properties of discrete pore fluid-gas samples can permit the formation of site-specific correlation. Such correlation can improve the interpretation of any future RCPTU soundings at the site which makes the technology attractive for monitoring water quality changes over time, thus reducing the need for expensive discrete pore fluid-gas sampling installations. The RCPTU is well suited for long-term monitoring of groundwater quality at sulphide tailings impoundments, where contamination due to ARD can take place over tens of years.

To provide the reader new to the technology with a concise summary, Table 2 presents a synopsis of piezocone technology from a commercial standpoint with respect to most soil characterization issues including sulphide tailings.

Table 2 - Rating Piezocone Technology for the Characterization of Most Soils

Characterization Issue	RCPTU/BAT Water Sampler
Stratigraphic Interpretation	A
Static/Dynamic Geotechnical Parameters	
• Strength	A
• Modulus	A
• Liquefaction Susceptibility	A
Hydrogeological Parameters	
• Hydraulic Conductivity	A
• Hydraulic Gradients	A
• Geochemical Gradients	B
Information from Bulk Conductivity/Resistivity	
• Total Dissolved Solids	A
• Specific Ion Detection	C-B
• Sulphate Anion Concentration	B-A
• LNAPL Detection (**)	B
• DNAPL Detection (**)	A
Pore Fluid Geochemistry(*)	
• Total Dissolved Solids	A
• Specific Ion Discrimination	A
• LNAPL Discrimination (**)	A
• DNAPL Discrimination (**)	B

(*) with post-testing laboratory analyses
(**) not discussed in this paper, organic contaminants are insulators and result in very high bulk resistivities

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

The rapid screening ability of the in-situ technology as a complement to surface geophysics is extremely effective as a characterization tool for sulphide tailings impoundments. Site specific correlations with, for example, sulphate concentration can be readily established with the technology and then used to further evaluate the overall rate and nature of upstream tailings oxidation. The results are then best used in optimizing the location of future permanent monitoring well installations.

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