USE OF THE RESISTIVITY PIEZOCONE FOR THE GEOTECHNICAL AND GEOCHEMICAL EVALUATION OF A TAILINGS IMPOUNDMENT

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ABSTRACT

Recent research efforts by the UBC In-Situ Testing Group (ISTG) have focused on the application of in-situ methods for geotechnical characterization and groundwater quality assessments. This work has led to the development of a resistivity module, which is used in combination with a standard piezocone. This paper presents a summary of a recent evaluation of a large sulphide tailings impoundment in eastern Canada, where a well-documented case of acid rock drainage is occurring. The results of a resistivity piezocone testing program are presented with respect to both geotechnical and environmental issues.

RÉSUMÉ

Les récents efforts de recherche du "groupe d'essai in-situ" se sont concentrés sur l'application de méthodes in-situ pour la caractérisation géotechnique et pour l'évaluation de la qualité des eaux souterraines. Ce travail a amené le developpement d'un module de résistivité, qui est utilisé en combinaison avec un piézocone standard. Cette communication présente le sommaire d'une évaluation récente d'un bassin de rejets de concentrateur de l'est Canadien où se produit un cas de drainage rocheux acide documenté. Les résultats d'une levé de résistivité piézocone sont présentés en rapport avec des questions géotechnique et environementale.

INTRODUCTION

The University of British Columbia's In-Situ Testing Group (UBC ISTG) has been developing and documenting in-situ testing tools for engineering design for over 15 years. The primary geotechnical focus of the first 10 years has been augmented by the fields of hydrogeology and environmental engineering. This expanded focus of work has led to the development of a resistivity module which is used in combination with a standard piezocone. The standard piezocone has proven to be an excellent means of logging stratigraphy for most soils and provides accurate estimates of key physical geotechnical and hydrogeological parameters. 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 resistivity piezocone and presents a summary of a recent resistivity piezocone evaluation at a large sulphide tailings area in eastern Canada. This tailings area consists of several large impoundments, many of which have well-documented cases of sulphide oxidation including ARD. Both geotechnical and geochemical parameter evaluations are discussed. Cost comparisons with conventional investigation methods, also carried out at the site, are included to demonstrate the economic advantages of the resistivity piezocone technology.

EVALUATION OF SULPHIDE TAILINGS IMPOUNDMENTS

Static and transient load stability considerations are usually the primary geotechnical engineering concern with respect to the design, construction, and operation of a tailings impoundment. Recent failures of large tailings dams such as Stava (Berti et al, 1988), Mochikoshi (Marcuson, 1979), and Tyrone (Vick et al, 1985) have caused significant economic and environmental damage as 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.

In addition to geotechnical concerns, tailings impoundments also represent a potential for negative environmental impact. The most significant environmental liability for sulphide tailings is the formation of ARD. ARD is the largest environmental concern currently facing the Canadian mining industry (Filion and Ferguson, 1989). ARD is a term for the high ionic strength, low pH drainage that can result from the oxidation of sulphide minerals in the presence of oxygen and water. Fully developed ARD results in the dissolution of ionic constituents in tailings or native materials which can then be transported to surrounding surficial and groundwater systems. Once in the receiving waters, these ionic loadings can have an adverse effect on water quality and, in extreme cases, cause loss of biological habitat.

Overall, the characterization of sulphide tailings requires evaluation of the:

- stratigraphic profile;
- relative geotechnical properties of each stratigraphic unit;
- hydraulic properties of the aquifer and the aquitard materials; and
- nature of pore fluid-gases present in the materials.

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 the needs stated above. The following section describes the resistivity piezocone technology and how it is deployed for a typical program.

EQUIPMENT AND PROCEDURES

The standard piezocone (CPTU) has a standard (ASTM D-3441) 10 cm^2, 60° conical tip, a 150 cm^2 friction sleeve and pore pressure transducers which allow the CPTU to measure tip resistance (q_c), friction sleeve stress (f_s), and pore pressure response at three locations (typically referred to as U1, U2, and U3). Temperature (t) and inclination (i) are also measured simultaneously as the CPTU is advanced into the ground. All channels are continuously monitored and are typically digitally reported at 25 mm intervals, thus providing essentially continuous in-situ data sampling. Data is acquired in clear format ASCII files which allow the user to carry out straightforward post-investigation analyses with any number of proprietary and commercial piezocone evaluation software packages.

The cone is pushed into the ground at a rate of about one metre per minute as per the ASTM Standard by a hydraulic pushing source, such as a standard drill rig. As the cone is advanced, the forces measured by the tip and friction sleeve will vary with the material properties of the soil being penetrated. Pushing (dynamic) pore pressures are also indicative of material state and type. Dissipation records of excess pore pressures during pauses in penetration can be applied to appropriate cavity expansion theories to yield good estimates of in-situ hydraulic parameters. Robertson and Campanella (1986) provide a comprehensive summary of CPTU interpretation procedures.

The resistivity piezocone (RCPTU) is a relatively recent development in CPTU technology (Campanella and Weemees, 1990). The RCPTU consists of a resistivity module which is added to a standard piezocone. The addition of the resistivity module permits the RCPTU to assess groundwater quality by measuring a near-continuous bulk resistivity log of the soil and pore fluid, in addition to all other standard CPTU measurements. Campanella et al. (1994) give an overview summary of the RCPTU and its perceived application areas.

A schematic of a typical UBC resistivity module is shown in Figure 1. An excitation current at 1000 Hz is supplied to the outer electrodes, and the bulk resistivity of the soil is measured across three pairs of electrodes (10, 25, and 75 mm spacings). The smallest electrode spacing is useful for detection of thin layers of contrasting bulk resistivity, whereas the largest electrode spacing measures an average resistivity over a larger depth and a greater penetration of the electric field into the undisturbed soil.

The UBC ISTG advocates the use of 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 correlations. Such correlations 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. Zemo et al. (1992) summarizes the advantages of combining CPTU and discrete water sampling technologies. 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.

RESISTIVITY PIEZOCONE: APPLICATION TO SULPHIDE TAILINGS 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. For example, Figure 2 shows the relationship between bulk and pore fluid resistivities from the case project described in the next section. The project site has a metallic ore and relatively high iron-sulphide content tailings yet the pore fluid - bulk resistivity relationship is apparent and linear. Scatter about the true linear relationship is mainly due to density variations (changes in porosity) between different data sets and not surface charge effects from the metallic content in the tailings.

The use of resistivity (or conductivity) measurements to delineate zones where ARD is developing or occurring is relatively well documented. For example, Ebraheem et al. (1990) and King and Sartorelli (1991) show how the high ionic loading of both early stage and low pH, fully developed ARD is well defined by surficial geophysics. The main reason the process is detectable is due to the elevated ion concentration which is often dominated by elevated sulphate levels, which occur in the early stages of ARD development even at neutral or basic pH levels. The ability to carry out resistivity soundings and avoid the non-unique solution interpretation of surface geophysics is a large advantage of the RCPTU.

The use of the piezocone for geotechnical characterization of tailings is also well established. Campanella et al. (1984) and Woeller et al. (1989) each demonstrate the use of the piezocone for geotechnical characterization of tailings, with specific case examples. The piezocone is particularly well suited to problems involving stability controlled by thin layers, liquefaction susceptibility assessments and soft foundation conditions. The continuity and repeatability of the piezocone, coupled with the difficulty of undisturbed sampling in cohesionless materials like most tailings, make the tool ideal for geotechnical characterization of sulphide tailings.

CASE EXAMPLE - SULPHIDE TAILINGS AREA, EASTERN CANADA

A sulphide tailings area in eastern Canada, representing several large impoundments, was the subject of a recent characterization program by the UBC ISTG. The overall project included 34 RCPTU soundings, and water sampling. The following briefly describes the use of the data obtained to evaluate the stratigraphic profile, physical parameters, and pore fluid geochemistry. The data collected is being used as part of ongoing assessment programs with respect to geotechnical stability, hydrogeological conditions, and geochemical status.

Stratigraphy

Figure 3 shows a typical RCPTU profile from the program that includes cone tip resistance, sleeve friction, friction ratio, pore pressure, and bulk resistivity measurements. The sounding shown in Figure 3 was at the crest of an impoundment dam. To briefly review the sounding, there is a dense oxidized layer evident from the surface to a depth of approximately 3 m. Below this depth are fine sandy tailings which show a slight fining trend with depth. Based upon the pore pressure and bulk resistivity response, the phreatic surface is estimated to be at a depth of 15 m. The pore pressure profile from 15 to 37 m in the tailings shows interlayered contractive and dilative materials. This signature is consistent with beached tailings that periodically are allowed to establish a dessicated and oxidized layer during the period following deposition and prior to further dam construction. The sounding exited from the tailings at a depth of approximately 37 m into a very stiff silty clay deposit. In this fine-grained native material dynamic pore pressures in excess of 100 m of water pressure were measured, attesting to the very stiff nature, low hydraulic conductivity, and high stress state present in the material.

Physical Parameters

Physical characterization deals mainly with geotechnical and hydrogeological aspects of subsurface materials; i.e. how strong and hydraulically conductive each stratigraphic unit is.

The sulphide tailings exhibited a fairly wide range of strength as evidenced by the ranges in relative density (30%-100%), drained strength (33°-45°) and equivalent SPT-N_1 (7-40 blows/300 mm). This variability can be partially attributed to the dessication and oxidation of successive layers of beached tailings, but there are also inherent differences in the material properties of the tailings (i.e. gradation, mineralogy, etc.) in large impoundments.

The strength variability of hydraulic tailings makes a continuous measurement technology such as the piezocone almost a requirement. Static and transient liquefaction, for example, can occur in thin, loose zones often missed by more conventional discrete depth methods (e.g. SPT).

Hydrogeological parameters were estimated by ceasing penetration at specific depths of interest and allowing the dynamic pore pressures to dissipate to equilibrium values. For evaluating the pathways and rates of influence of sulphide mine wastes, these parameters are essential. Measurable hydraulic gradients were observed at test locations in the different impoundments. An estimate of the hydraulic gradient at an example test location is shown in Figure 4. Excess pore pressure may be defined as the difference between the measured equilibrium pore pressure and the expected piezometric pore pressure based upon estimates of phreatic surface location. Estimates of hydraulic conductivity for the tailings also had a wide range with values from 10^{-5} to 10^{-7} cm/sec, which is representative of the fine-grained nature of the tailings ($\approx$ 40-50% < 74 μm) and which also agree well with the literature values (Vick, 1983).

Pore Fluid Geochemistry

Assessments of the pore fluid geochemistry of the different tailings impoundments were made by comparing the RCPTU bulk resistivity logs and the chemical analyses on discrete groundwater samples. Figure 5 shows one of the relationships developed between bulk conductivity ($resistivity^{-1}$) and pore fluid sulphate concentration. Figure 5 is shown in terms of conductivity, the direct inverse of resistivity, as this relationship plots in a more demonstrative fashion. Sulphate concentration is a key ionic constituent of all stages of sulphide oxidation. The detection of sulphate production 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 5 is global in nature. However, the site-specific relationship was developed within a short-time period and can now be used on this large project for ongoing surveillance of possible oxidation development in tailings areas.

Other ionic constituents also showed some correlation trends, but the overall relationship of total dissolved solids (TDS) versus bulk resistivity was the only other relationship for which the authors feel the RCPTU can currently provide reliable screening information (Ebraheem et al., 1990). However, the pH of the tailings pore water did show a good correlation trend in relation to bulk resistivity. Figure 6 shows the pH-bulk conductivity ($resistivity^{-1}$) relationship developed at the project site. This type of trend has also been documented for similar sites by others (e.g. King and Sartorelli, 1991).

Cost Comparison

Industry experience with CPTU/RCPTU cost comparisons are generally positive. In the authors' experience, the best results with piezocone technology, both logistically and economically, occur when projects are costed on a per-metre basis. Unlike other geotechnical investigations, per-metre specification for piezocone programs will not hamper data quality due to the strict standards governing the test. For the example project described in this paper, when in production mode, completion rates of roughly 80 metres or more per day were experienced. Typical commercial rates for CPTU/RCPTU work cost between $25 and $40 per metre depending upon region and project size. Conversely, a conventional drilling program was carried out at the site during the same time as the RCPTU program. The drilling program consisted of auger drilling with 3 to 5 metre interval SPT samples which 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 drilled hole typically average about $45 per metre. To match the RCPTU, a combined drilling and downhole resistivity program could therefore easily exceed $100/metre, or between 2.5 and 4 times typical commercial piezocone rates..

SUMMARY AND CONCLUSIONS

This paper has briefly introduced a relatively new tool to geotechnical engineering, the resistivity piezocone. The introduction has been coupled with a demonstration of the tools' ability to characterize sulphide mine tailings with respect to both geotechnical and geochemical considerations. The rapid procurement and continuous nature of RCPTU data coupled with the accuracy of measurement and lower cost when compared to conventional methods makes it an ideal characterization tool for sulphide tailings impoundments.

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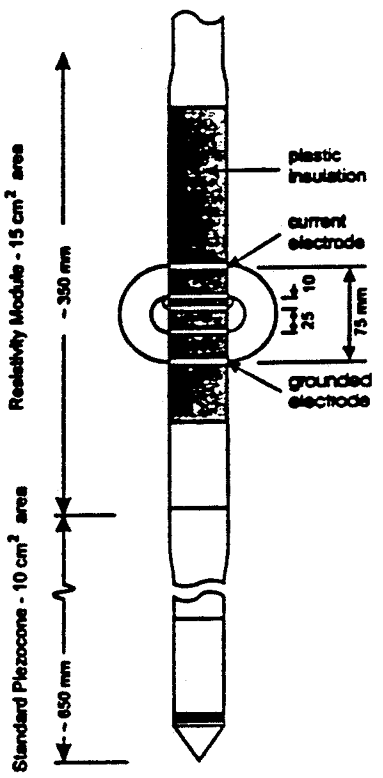

FIGURE 1 - Schematic of UBC Resistivity Piezocone

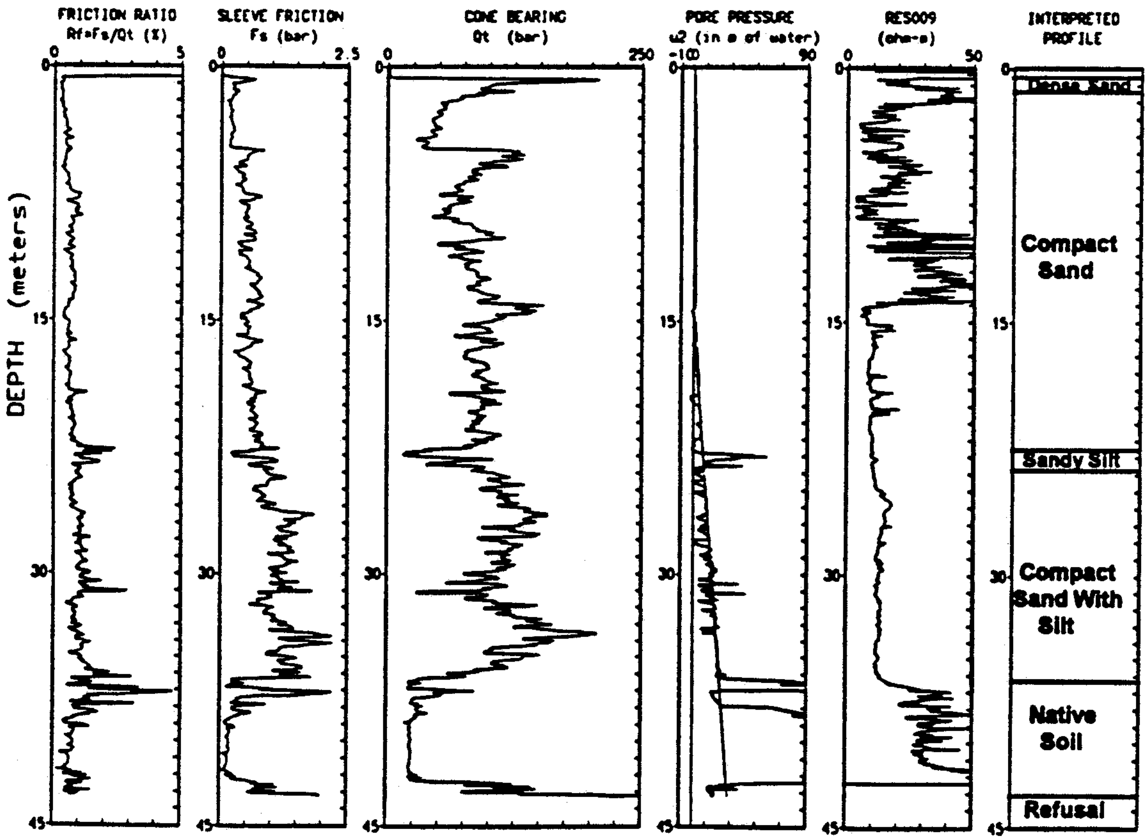

FIGURE 3 - Typical RCPTU Profile

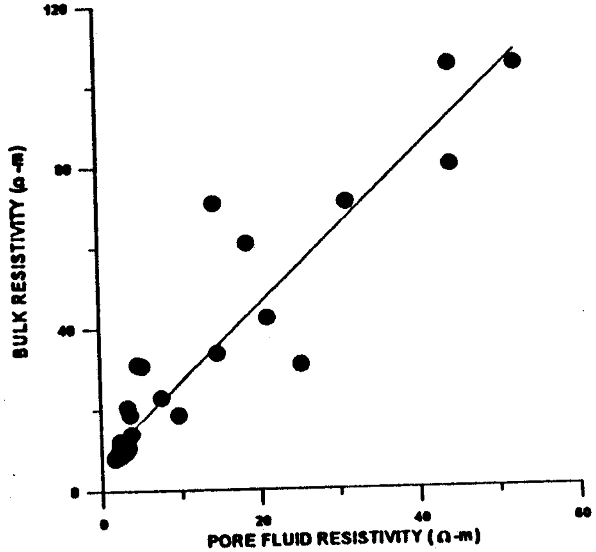

FIGURE 2 - Bulk Resistivity versus Pore Fluid Resistivity

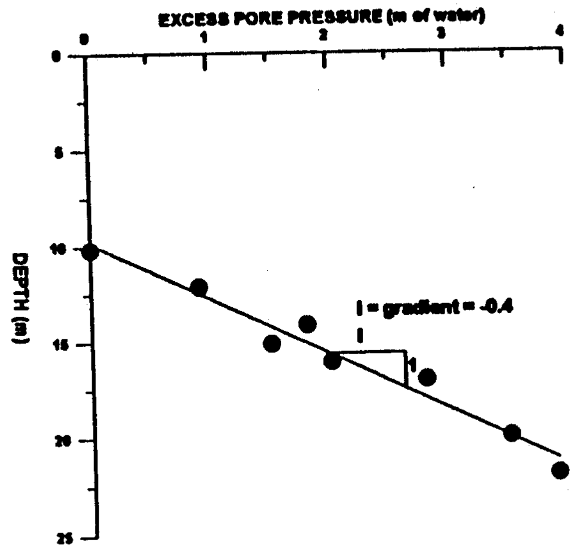

FIGURE 4 - Estimate of Hydraulic Gradient For Typical RCPTU Sounding

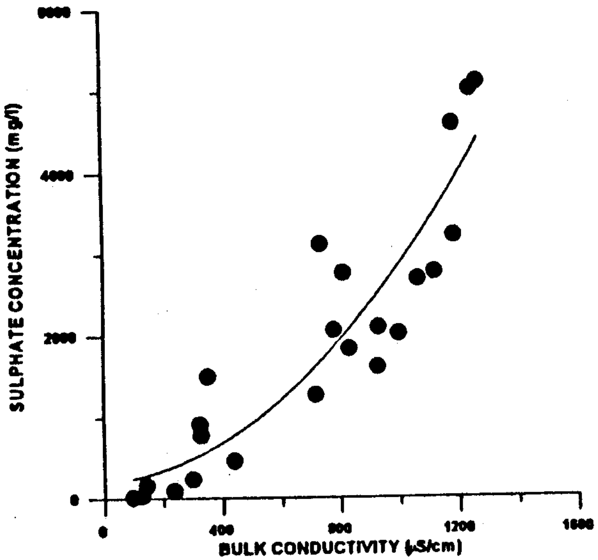

FIGURE 5 - Sulphate Concentration versus Bulk Conductivity (Resistivity)

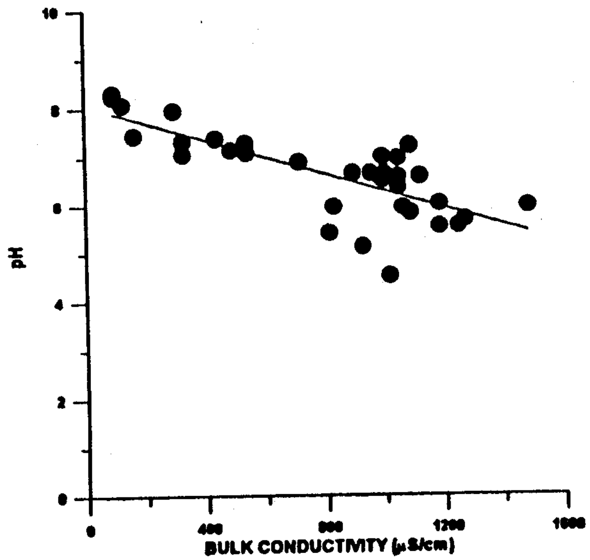

FIGURE 6 - pH versus Bulk Conductivity (Resistivity)