In-situ testing for geo-environmental site characterization: A mine tailings example

Identification géotechnique et environmentale d'un site par essais en place: cas de stériles miniers

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ABSTRACT: Proper environmental site characterization is not limited to an evaluation of water chemistry; it involves assessing the stratigraphic, geotechnical, hydrogeological and geochemical nature of the site in a manner which best represents actual in-situ conditions. In-situ testing methods offer the best available technology to achieve this representative characterization for many site conditions including, especially, all mine tailings. The key in-situ tools available for this characterization are the piezocone, resistivity piezocone and the BAT water sampling system.

RÉSUMÉ: La caracteization des sites environnementales n'est pas limitée par des chimiques dans l'eau; l'evaluation du stratigraphi etqualités an milieu géotechnic, hydrogeotlogic et géochimique d'un site en maniè qui reprèsente les conditions "ini-situ" est nécessaire. Des méthodes "in-situ" utilisé es se presentent la technologic la plus avancée à réaliser cette characterization représentatif por plusieurs des conditions du site. Les utils les plus importants pour cette characterization sont la piezocone, le "resistivity piezocone" et le BAT système pour la prélèvement de l'eau.

1 INTRODUCTION

Environmental site characterization refers to the surficial and subsurficial representation of the site that approximates actual in-situ conditions. This representation is typically developed by both surface and subsurface characterization. The United States Environmental Protection Agency (US EPA, 1989) note the following site specific requirements for environmental site characterization:

- stratigraphy;
- water-level data;
- hydraulic conductivity;
- chemical distribution and source(s)/receptor(s) for potential or existing contaminants.

Several of these requirements can be met accurately and economically with available in-situ testing methods.

For example, in-situ testing methods such as the resistivity piezocone provide an excellent representation of actual in-situ conditions at selected locations. Stratigraphic, strength, hydrogeological and specific geochemical parameters are provided on a specific and/or screening basis. The use of in-situ testing can often lead to the best possible representation which tends to make the large assumptions required in an overall environmental characterization effort as accurate and defensible as possible.

This paper presents a very brief review of selected in-situ test methods for geo-environmental site characterization, a mine tailings case example and recent developments and experience in the UBC In-situ testing group. The methods include the piezometer cone penetration test (or piezocone), the resistivity piezocone and the BAT water sampling and in-situ hydraulic conductivity measuring systems.

2 ENVIRONMENTAL SITE CHARACTERIZATION

Geo-environmental is a relatively new term to the geoscience/geotechnical engineering field. There are several interpretations of what an environmental site characterization program constitutes. As both the authors and the projected audience of this paper are primarily of geotechnical or geoscience background, the recommended definition is:

> "The field of study that links geological, geotechnical and environmental engineering, and the corresponding sciences, to form an area of interest that includes all environmental concerns within natural or processed geological media."

Detection and assessment of groundwater contamination and its approximate transport velocity is an excellent example of an area of interest within the scope of environmental site characterization.

3 IN-SITU TESTING

3.1 *Piezocone*

The piezometer cone penetration test (CPTU) involves pushing into the ground a 60° apex and typically 35.7 mm diameter (10 cm^2 area) piezocone on the end of a series of rods of the same or lesser diameter as the piezocone. The pushing is carried out at a constant rate of 2 cm/sec, or roughly a metre per minute. Pushing is achieved by hydraulic force supplied typically by either a drill-rig or a specially outfitted cone pushing vehicle. Most any drill-rig with a minimum pushing capacity of 5 tonnes and a hydraulic ram stroke of 1.5 metres or more can be used to successfully push cones in most soils. Davies and Campanella (1995) list typical pushing capabilities for clay and sand soils.

The 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 (referred to as U1, U2, and U3 respectively). Most correlations and direct calculations assume measurement at the U2 location. Temperature (T) and inclination (I) are also measured simultaneously as the piezocone is advanced into the ground. All channels are continuously monitored and typically digitized at 25 or 50 mm intervals. Campanella and Robertson (1988) outline the piezocone's main advantages, limitations, and standard testing and recommended interpretation procedures.

3.2 *Resistivity Piezocone*

The resistivity piezocone (RCPTU) provides the ability to measure the resistance to current flow in the ground on a

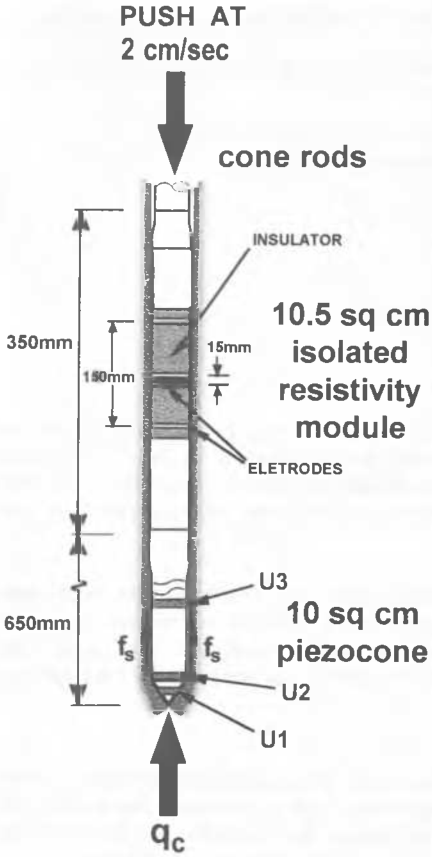

FIGURE 1 - Piezocone with electronically isolated resistivity module (RCPTU)

continuous basis. This ability 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 an overview summary of the RCPTU and its perceived application areas.

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 either from 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 detailed chemical analyses. Of considerable practical value is the fact that the measured resistivity is almost totally governed by the pore fluid chemistry and the pore volume. In other words, soil mineralogy has a limited affect in most circumstances.

A schematic of a resistivity piezocone is shown in Figure 1. 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 lateral penetration of the electric field into the undisturbed soil. Davies and Campanella (1995) note that the depth of penetration from this type of logging device is roughly twice the electrode spacing.

3.3 *BAT Water Sampling 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

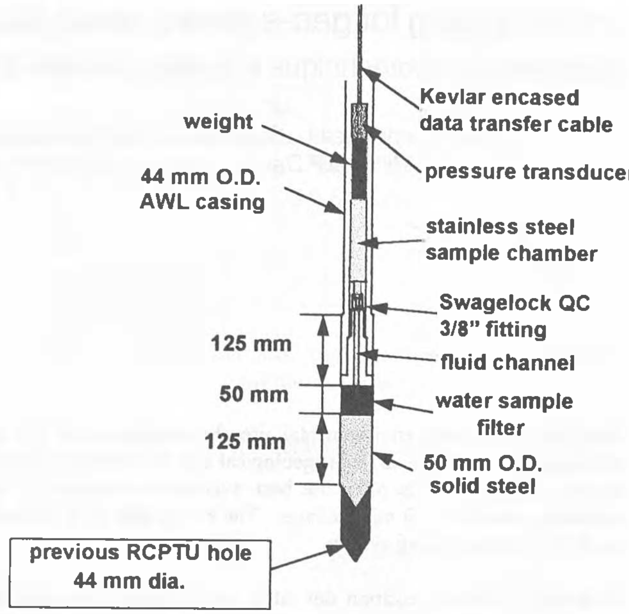

FIGURE 2 -UBC-Modified BAT discrete depth water sampler

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.

3.4 *BAT hydraulic conductivity measuring system*

Recent studies at the University of British Columbia (UBC) (Wilson, 1996) have made use of the UBC-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 laboratory tests in 5

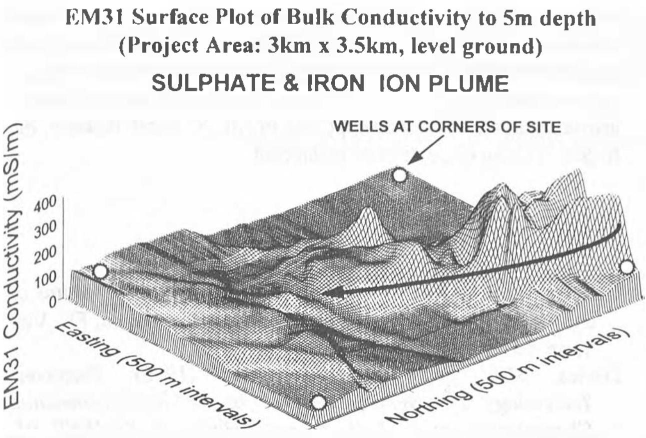

FIGURE 3 - EM31 Surface plot of effective bulk conductivity in sulphide mine tailings to a depth of 5 m

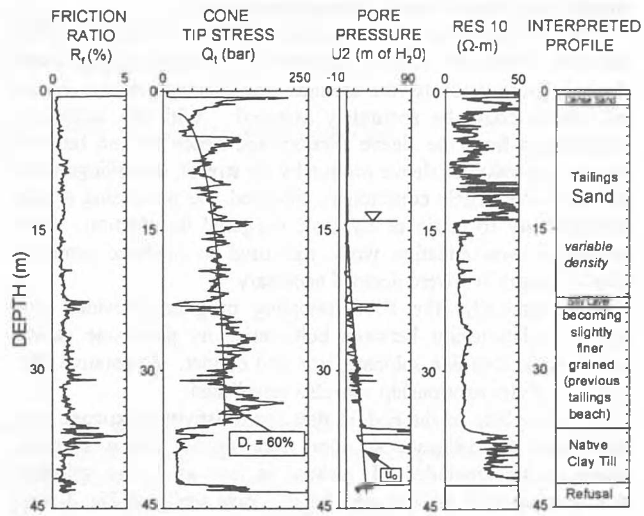

FIGURE 4 - Typical resistivity piezocone sounding profile from base-metal mine tailings

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) could not be used to also give K of the soil.

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.

4 USE OF IN-SITU TESTING IN ENVIRONMENTAL SITE CHARACTERIZATION

As summarized by Davies and Campanella (1995), the resistivity piezocone can be used to evaluate the following environmental/geotechnical parameters:

- soil stratigraphy;
- soil density;
- undrained shear strength;
- hydraulic conductivity;
- in-situ hydraulic gradients;
- drained strength; and relative geochemical nature

The geochemical nature comes from evaluation of the continuous bulk resistivity signature from the resistivity piezocone compared with chemical analyses on samples obtained from the BAT sampling system.

Table 1 presents a small sampling of typical RCPTU bulk soil resistivity measurement values and corresponding measurements of pore fluid resistivity.

The relationship between total dissolved solids (TDS) and bulk resistivity is global and linear. Specific ion correlations with RCPTU bulk resistivity values are most commonly site-specific in nature although sulphate anions and divalent iron have shown remarkable global correlation in our experience to date.

5 MINE TAILINGS EXAMPLE CASE HISTORY

As noted previously, a wide range of environmental characterization projects are amenable to the in-situ technology summarized herein. To demonstrate a specific application, the characterization of a base-metal mine tailings impoundment in Western Canada is briefly introduced.

Table 1 - Summary of typical resistivity measurements of bulk soil mixtures and pore fluid (saturated mixtures only) (adapted from Davies and Campanella, 1995)

Material type	Bulk Resistivity ρ_b, Ω-m	Fluid Resistivity ρ_f, Ω-m
Deltaic sands with saltwater intrusion	2	0.5
Drinking water from sand	>50	>15
Typical landfill leachate	1-30	.5-10
Mine tailings site (base metal) with oxidized sulphide leachate	0.01-20	.005-15
Mine tailings site (base metal) without oxidized sulphide leachate	20-100	15-50
Arsenic contaminated sand and gravel	1-10	.5-4
Industry site-inorganic contaminants in sand	0.5-1.5	0.3-0.5
Industrial site - creosote contaminated silts and sands	200-1000	75-450
Industrial site - wood waste in clayey silts	300-600	80-200

The site, which is relatively flat and consisting of tailings from a sulphide ore-body, had several geotechnical, hydrogeological and geochemical concerns. The resistivity piezocone and BAT sampling technology were selected for characterizing the site for the specific concerns.

Because of the very large extent of the site, a portable surface geophysical tool called a ground conductivity meter (GEONICS™ EM31) was used to obtain a preliminary estimate of the location of high ionic groundwaters and plumes. A single person walks the site with the meter collecting digital data every 2 m in a fixed grid spacing. Figure 3 shows the effective conductivity to a depth of about 5 m in an area 3km by 3.5km, which was walked in one day. The higher the apparent conductivity, the higher the ion concentration in the groundwater and the lower the bulk resistivity. In this case the existing observation wells could not identify the plume of its direction of movement.

Figure 4 shows a typical resistivity piezocone sounding from the site. From the continuous record of tip bearing stress and dynamic pore pressure, the strength and drainage characteristics of tailings could be accurately assessed. With the additional information from the sleeve friction, and hence friction ratio (a percentage value of sleeve friction by tip stress), the tailings were shown to be largely contractant, silt-sized and possessing a high susceptibility to static or dynamic triggered liquefaction. This strength characterization work was used to optimize remedial works (berm) that were deemed necessary.

Geochemically, the BAT sampling program provided site specific relationships between bulk resistivity piezocone values and specific ions like sulphate, iron and copper. A tentative pH-bulk resistivity relationship was also established.

With the help of the EM-31 data the resistivity piezocone was also used to delineate an ionic rich plume whose sampled characteristics included pH values as low as 1 and sulphate concentrations to 60,000 mg/l (ppm). Plots similar to Fig. 3 were used to show a three-dimensional representation of bulk resistivity piezocone values, converted to conductivity units, from 17 soundings, but only using the data at one depth. Plots were chosen for 0.5 metre depth intervals for the project to delineate the plume. The delineation from the resistivity piezocone allowed the future optimal spatial placement of regulatory required monitoring wells; both in plan and to accurately locate discrete well screens with depth.

6 CONCLUSIONS

Recent environmental characterization projects by UBC using the tools described include:

- DNAPL and dissolved creosote contaminated site in B.C.;
- sulphide mine tailings impoundments in Ontario;
- mine tailings geotechnical and groundwater evaluations at several mines in B.C;
- arsenic contaminated sands and gravels in B.C.;
- salt-water intrusion to a fresh-water aquifer in B.C.; and
- regional hydrogeological evaluation in major aquifers in B.C.

Other recent activities include combining the presented in-situ tools with surface geophysical techniques to provide enhanced site information.

Commercially available resistivity piezocone work is readily available in Canada for roughly \$25 to \$30 Cdn per metre in most instances. Many environmental characterization projects are carried out each year in materials well-suited to the technology presented in this paper and it is recommended that more of these projects choose what is likely the best available technology *and* the most economic for those paying the bills.

This paper has briefly summarized the main in-situ tools available for geo-environmental site characterization. The piezocone is used as a screening tool to determine stratigraphy and estimate strength and stability parameters. In addition, for groundwater studies, the resistivity piezocone is used to identify and indicate the hydraulic (equilibrium water pressure, gradients and K) and chemical characteristics (contaminant plume delineation) of the groundwater in coarse soils where contaminants are mobile and water sampling is fastest. The BAT is used to take water samples, measure K and therefore, to validate correlations. The resistivity piezocone and BAT sampling technology are establishing themselves as the premier tools where ground conditions are appropriate.

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