

In-situ testing methods for groundwater contamination studies

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ABSTRACT: *In-situ* testing where groundwater contamination is either documented or suspected is carried out to provide GeoEnvironmental site characterization. GeoEnvironmental characterization refers to the surficial and subsurficial representation that approximates the actual *in-situ* conditions. Surficial characterization, although often not straightforward, does allow visual appraisal of essentially all of the materials involved. Subsurface characterization, on the other hand, rarely allows even a micro-percentage appraisal. From a statistical significance standpoint, subsurface characterizations for groundwater studies are almost always inadequate and therefore large assumptions based on the best possible information are required.

In-situ testing methods, such as the piezocone penetration test, often provide the best possible information at selected locations for groundwater contamination problems where stratigraphic, geotechnical, hydrogeological and some specific environmental parameters are required on a specific and/or screening basis. The addition of a resistivity module to the basic piezocone has applications for both organic and inorganic contaminants. This paper presents a review of the currently available *in-situ* methodologies for groundwater contamination problems. The methods reviewed include conventional drilling techniques, piezometer cone penetration test technology with resistivity measurements and discrete water sampling systems. The advantages and disadvantages of using each methodology are presented and include comparisons of testing cost, data reliability and regulatory acceptance. Brief case histories are used to demonstrate the preferred technologies. The paper concludes with an overview of current research including recent advances in self-grouting technology for cross-contamination concerns.

1 INTRODUCTION

GeoEnvironmental is a relatively new term in the geoscience field. There are currently several interpretations of meaning for GeoEnvironmental, and the definition used herein is: "the field of study that links geological, geotechnical and environmental engineering and engineering sciences to form an area of interest that includes all physical and environmental concerns within geological media."

Groundwater contamination is an excellent example of an area of interest within the scope of the GeoEnvironmental field. With the basic definition established, GeoEnvironmental subsurface site characterization for groundwater studies can be defined as: "the formulation of the physical, chemical and/or biological information for the site that allows adequate three-dimensional representation for the prevailing subsurface conditions and the engineering requirements of the data."

Modern *in-situ* testing instruments provide the best current technology for developing this three-dimensional representation for many site conditions. This paper presents an overview of the currently available *in-situ* methods for site characterization. *In-situ* testing embodies all of the prevailing field conditions on material behavior whereas laboratory

testing, usually on disturbed samples, attempts to estimate these many factors. The value of a given *in-situ* test is directly related to how much non-quantifiable disturbance is caused during tool insertion; e.g., the degree of data repeatability.

2 GROUNDWATER CONTAMINATION: SITE CHARACTERIZATION STUDIES

As will be shown in the following sections, what makes modern *in-situ* testing methods attractive for groundwater site characterization studies is that, it is accurate, repeatable, and direct results can be obtained in a fast, cost-effective manner. Traditional methods of *in-situ* site characterization, like conventional drilling and sampling, cannot match the speed, accuracy or economy achieved by the tools described in this paper. However, in cemented and fractured sedimentary formations and in compact, thick gravel layers (where penetration tools are restricted) drilling and coring likely have an advantage. Surface geophysical methods are least disruptive, but they lack ground-truthing capability and therefore the results are difficult to interpret.

Modern *in-situ* testing also provides a huge advantage over conventional drilling in that soil

cuttings are not produced. On many contaminated sites, the cost of preparing for, handling and disposing of, these cuttings can be extremely high and tends to limit the amount of necessary subsurface investigation ultimately carried out.

The key items that must be evaluated in order to formulate the subsurface characterization for appropriate groundwater studies are:

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

Therefore, the assessment of any given *in-situ* technique must include an evaluation of whether it will provide the requisite items and how comprehensive and accurate the results provided will be.

3 IN-SITU TESTING

As defined above, *in-situ* testing involves evaluating material properties "in place;" where physical and biochemical stresses are evaluated as is. Conventional drilling and discrete sampling represents a quasi *in-situ* test method although laboratory evaluations are typically required for samples retrieved. However, drilling is included in the definition for this paper to allow a comparison of the current industry standard with the more sophisticated tools and evaluation procedures available. On the other hand, surface geophysical methods have not been included as most of these approaches are in the early stages with respect to assessing environmental parameters.

3.1 Conventional Drilling and Discrete Sampling

The most common manner in which site characterization for groundwater studies is carried out remains to be conventional drilling with discrete sampling. The large experience base and the retrieval of a physical sample are important advantages of the method whereas lack of standards, relatively high cost and questionable sample quality represent the key disadvantages.

Drilling with reasonable, albeit far from continuous, sampling frequency will result in a production rate for a 30 meter (100 ft) hole from 10 to 20 hours and more. The actual production rate will depend upon soil conditions, equipment and the operator quality, the method of sampling used and decontamination and grouting requirements. Although specifying conventional drilling on a meterage basis is never recommended for obvious reasons, we can apply a generic \$150 hourly rate with modest consumable to provide an approximate \$50 to \$100 per meter for this discrete sampling.

Once a sample is obtained, its quality must be assessed. Table 1 presents the steps and sources of error in taking a sample from its *in-situ* condition to the laboratory. Table 1 does not include the errors introduced by the laboratory itself, such as sample disturbance, loss of *in-situ* stresses, and chemical alterations, etc.

TABLE 1 - Steps in groundwater sampling and their related sources of error

	Step	Sources of error
	In-Situ Condition	-----
1.	Establishing a sample location	Improper borehole completion/placement; poor location choice; poor material choice
2.	Sample collection	Sampling mechanism/procedural bias; operator error
3.	Sample retrieval	Sampling mechanism/procedural bias; sample exposure; degassing; oxygenation; cross-contamination
4.	Preservation/storage	Handling/labeling errors; temperature, etc. control
5.	Transportation	Delay; sample loss

Drilling and sampling are therefore shown to be relatively expensive and provide potentially suspect reliability on a non-continuous basis. However, due to its popular use, regulatory acceptance has traditionally been high although recent trends in data quality management and geostatistical evaluations are tending to make it more difficult to convince all regulators that data from drilling and sampling programs are either comprehensive or accurate enough.

3.2 Piezometer Cone Penetration Test

The piezometer cone penetration test (CPTU) is increasingly being used by practicing engineers as an effective means of geotechnical classification. The method provides a fast, economical, and accurate means of delineating soil stratigraphy and determining geotechnical parameters. The cone has a standard 10 cm², 60° conical tip, friction sleeve with an area of 150 cm² and one or more pore pressure sensors. The CPTU measures tip resistance (q_p), friction sleeve stress (f_s) and pore pressure at up to three locations on the cone. All channels are continuously monitored and reported at either typically 25 or 50 mm intervals, thus providing essentially continuous *in-situ* data sampling. There

are extensive relationships available between the various CPTU channels, and combinations thereof, that provide soil behavior type (often equivalent to stratigraphy), geotechnical strength parameters and hydraulic parameters. Temperature (t) and instrument inclination (i) are usually measured simultaneously. In addition, a seismic model of the cone has been developed that allows the measurement of low strain dynamic properties of the soil.

CPTU is generally regarded as the most effective and cost efficient tool for stratigraphic logging of the soils (Robertson et al., 1986). The cone is pushed into the ground at a constant 2 cm per second (or about 1 m per minute) by a hydraulic pushing source; often a drill rig or a specially outfitted cone truck or penetration vehicle. As the cone is advanced, pore pressures are generated around the cone tip and sleeve. The measurement of the excess pore pressures which are generated during penetration, and their subsequent dissipation, provide insight into the soil type and its hydraulic parameters.

The CPTU can and should be specified on a meterage basis. The rigorous ASTM and International standards ensure high repeatability and reliability, thus eliminating traditional concerns such as the speed of testing being inversely related to data quality. Although there are regional variances, CPTU soundings are typically carried out for between \$20 and \$50 per meter for the continuous data and plots provided. Due to its high standard and operator requirements, engineering supervision to the degree required for the conventional drilling is not necessary. Its continuous data, speed, relatively low cost and excellent repeatability are its main advantages. The main disadvantage is the lack of physical samples but for screening assessments, confirmatory investigations or routine monitoring, the requirement for a physical sample is becoming less important as confidence in the method grows. Regulatory acceptance is variable with the knowledge of the regulator being the key discriminator as to the success of approval. The trend, however, is one of acceptance with the provision of at least an occasional confirmatory/collaborative bore-hole; an approach with which we fully concur.

3.3 Resistivity Piezometer Cone Penetration Test

The resistivity piezometer cone penetration test (RCPTU) is a recent modification of the standard piezocone test (CPTU). The ability to measure the resistance to current flow in saturated soils on a continuous basis is extremely valuable due to the large effects that dissolved and free product constituents have on soil resistivity (conductivity).

Table two presents typical values of bulk soil resistivity measurements with the RCPTU and corresponding measurements of pore fluid resistivity. Since conductivity is the reciprocal of resistivity, it is easy to convert according to:

$$\text{Conductivity}[\mu\text{S}/\text{cm}] = 10,000 \div \text{Resistivity}[\Omega\text{-m}] \quad (1)$$

Table 2 also gives corresponding values in units of conductivity due to their popular use in the geochemical field. The results in Table 2 show that the range of resistivity (conductivity) values is very large from about one (10000) to about 7000 Ohm-m ($14 \mu\text{S}/\text{cm}$) and is very sensitive to both soluble salts and low solubility organic contaminants.

Thus, the RCPTU has the advantage of providing continuous resistivity measurements (which directly correlate on a site specific basis with contaminant concentration) in combination with all of the traditional CPTU data. The current electrode separation used by researchers and practitioners varies from about 10mm to over 150 mm providing different depths of lateral penetration. The more advanced tools have several electrode spacings so that both profiling and sounding resistivity tests are carried out simultaneously. Figure 1 shows a schematic representation of one of UBC's RCPTU tools. Campanella and Weemes (1990) provide a complete summary of the RCPTU and its developments.

Therefore, the RCPTU meets all of the key items identified for formulating a subsurface site characterization. The actual quantification of non-background geochemical processes requires site specific calibration if more than "screening" evaluations are intended. This site specific calibration involves accurate pore fluid-gas sampling which is described in the following section. The cost per meter of RCPTU testing programs is essentially the same as for the CPTU with an allowance of an additional 10% for data reduction. Regulatory approval is variable due to the relative newness of the tool but in our experience, once the technology is demonstrated, the acceptance is typically rapid.

3.4 In-Situ Water Sampling

The main goal of any water sampling program is to rapidly and economically collect representative samples of the *in-situ* regime. Conventionally, bailers and pumps are used to obtain samples from drilled or installed wells or piezometer. To obtain high levels of sample integrity with conventional methods, costly and time consuming installations and procedures are typically required.

In recent years there have been significant developments in *in-situ* discrete depth water samplers. These samplers, such as the BAT Enviroprobe and QED Hydropunch II, minimize purging and exposure to the sample, allow for rapid, high quality, representative samples and are easy and economical to use. (Blegen, et. al, 1988, Zemo, et al, 1992)

A key advantage of these discrete depth samplers is that they can be used effectively in screening studies to better delineate contaminant and thus optimize the location(s) of permanent monitoring wells. Regulatory approval of these new *in-situ*

TABLE 2 -- Summary of typical resistivity (conductivity) measurements of bulk soil mixtures and pore fluid(UBC experience)

Material type	Bulk Resistivity $\rho_b, \Omega\text{-m}$	Fluid Resistivity $\rho_f, \Omega\text{-m}$	Bulk Conductivity $\mu\text{S/cm}$	Fluid Conductivity $\mu\text{S/cm}$
Sea water	—	0.2	—	50000
Drinking water	—	>15	—	<665
McDonald Farm clay	1.5	0.3	6700	33300
Laing Bridge site clay	20	7	500	1430
Colebrook site clay	25	18.2	400	550
TC @ 232 Ave clay	8	—	1250	—
Strong Pit clay	35	—	285	—
Kidd 2 site clay	14	12.5	715	800
McDonald Farm site sand	5-20	1.5-6	2000-500	6700-1670
Laing Bridge site sand	5-40	1.5-10	2000-250	6700-1000
Colebrook site sand	70	—	143	—
Strong Pit site sand	115	—	89	—
Kidd 2 site sand	1.5-40	0.5-21	6700-225	20000-475
Typical landfill leachate	1-30	.5-10	10000-330	20000-1000
Mine tailings site sand with acid drainage leachate	1-40	2-27	10000-250	5000-370
Mine tailings site sand without acid drainage	70-100	15-50	145-100	665-200
Industry site-inorganic contaminants in sand	0.5-1.5	0.3-0.5	20000-6500	33000-20000
100% ethylene dichloride (ED)	—	20,400	—	0.5
50% ED/50% water in sand	700	—	14	—
17% ED/83% water in sand	275	—	36	—
Industry site - organic contaminants in sand	125	—	80	—
BC Place Parcel 2, PAHs (coal gas plant)	200-300	—	50-33	—
BC Place Parcel 2 (wood waste)	300-600	—	33-66	—

sampling methods has been widespread and rapid. As use and experience increases, the methods will likely become industry standard for appropriate sites.

Figure 2 shows a schematic sketch of the rapid sampling probe used at UBC which uses the BAT groundwater system (Torstensson, B-A, 1984). This 50 mm diameter probe with a central HDP filter is pushed down the hole previously made by the RCPTU which left a 44 mm diameter hole. The probe is pushed to a specific depth to obtain a pore water sample which is then chemically analyzed to provide site specific correlations of contaminant concentrations with bulk resistivity measurements. The preceding RCPTU sounding provides soil classification information with the use of CPTINT (a cone interpretation program developed at UBC) to indicate the depth where high hydraulic conductivity zones exist so rapid water sampling can be achieved. Soil classification is reliably predicted using either friction ratio or pore pressure ratio.

Current studies with this continually advancing water sampling probe indicate that it takes representative samples of volumes of about 250 ml. A 250 ml sample can often be obtained in less than

10 minutes as long as its position is carefully placed in the coarse zones as indicated by CPTINT soil classification. A complete RCPTU sounding to 30m depth followed by 10 or more water samples (including a purge sample at each depth) can be completed in one working day.

4 CASE EXAMPLES

4.1 Organic Contaminants: Heavy Oils

RCPTU and discrete depth water sampling were used in a research capacity to confirm and augment data obtained through a conventional drilling and sampling program at a contaminated site in the Lower Mainland, B.C. The aim behind the research program was to demonstrate the capabilities and limitations of using this technology as a screening tool on organically contaminated sites.

The field program consisted of 7 RCPTU soundings (3 were used as water sampling holes) located to make optimum use of existing information. Figure 3 shows a typical RCPTU

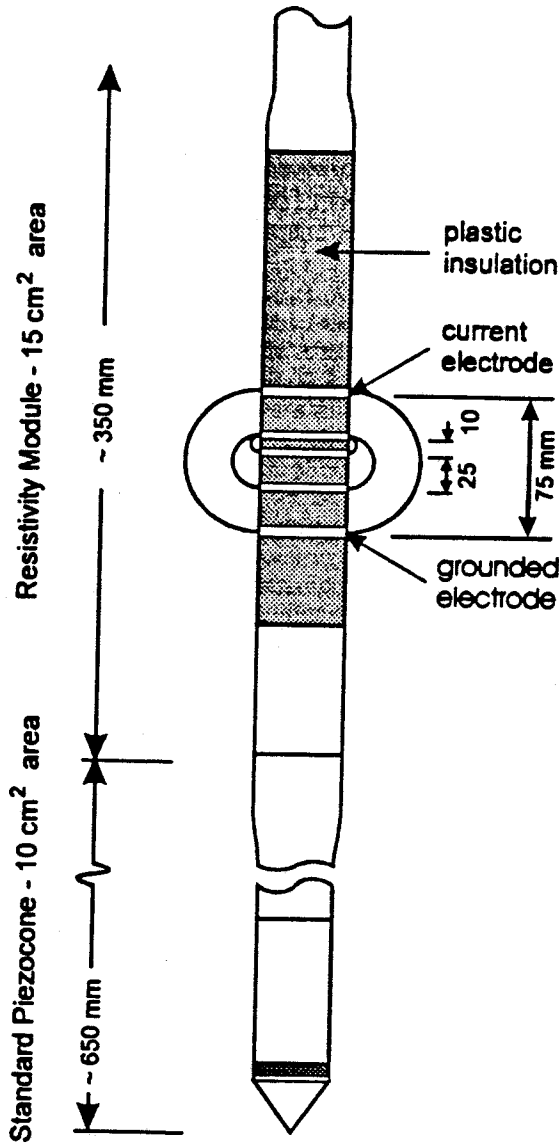


Fig. 1 UBC Resistivity Piezocone (RCPTU)

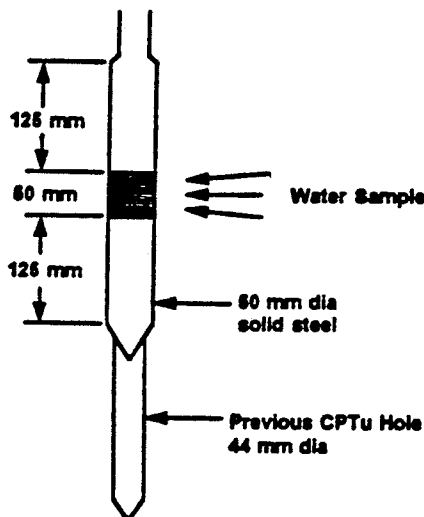


Fig. 2 UBC Modified BAT Pore Water Sampler

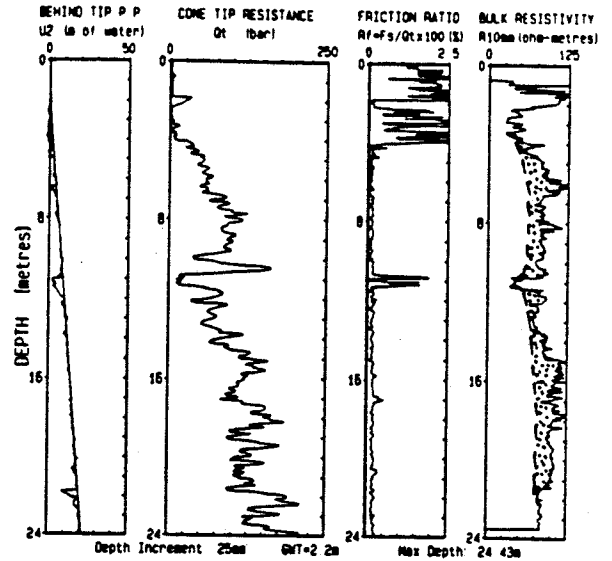


Fig. 3 RCPTU Sounding:
Organic Contamination by Heavy Oils

profile of cone tip resistance, pore pressure, friction ratio and resistivity with depth. Contrasts in bulk resistivity showing elevated values (due to the insulating quality of the organic contaminants) compared to "background" values are indicated by the shaded zones in Fig.3. The changes in bulk resistivity are dominated by pore fluid chemistry which was verified by discrete depth water sampling and lab testing.

4.2 Industrial Inorganic Pollutants - Western Canada

RCPTU and discrete depth water sampling were used to characterize an individual site in Western Canada with respect to the geological, hydrogeological and geochemical setting. The purpose of the investigation was to delineate the plume of inorganic contaminants (sulphates, chlorides, and phosphates) and to speculate on the potential for offsite migration. RCPTU and discrete depth water sampling were chosen for their technical and cost advantages. Geotechnical and hydrogeological parameters (e.g. soil type, relative density, hydraulic conductivity, etc.) were readily obtained from the investigation. Chemical analyses conducted on groundwater samples correlated reasonably well with bulk resistivity contours. A trend between total dissolved solids (TDS) and bulk resistivity was noted to be similar to Ebraheem, et al (1990). In contaminated zones, bulk resistivity varied between 0.5 and 1.5 Ohm-m (20,000 - 6500 $\mu\text{S}/\text{cm}$). Pore fluid resistivities within contaminated zones varied between 0.3 and 0.5 Ohm-m (30,000-20,000 $\mu\text{S}/\text{cm}$). Contaminated zones and their direction and rate of movement were subsequently identified through on-going RCPTU studies.

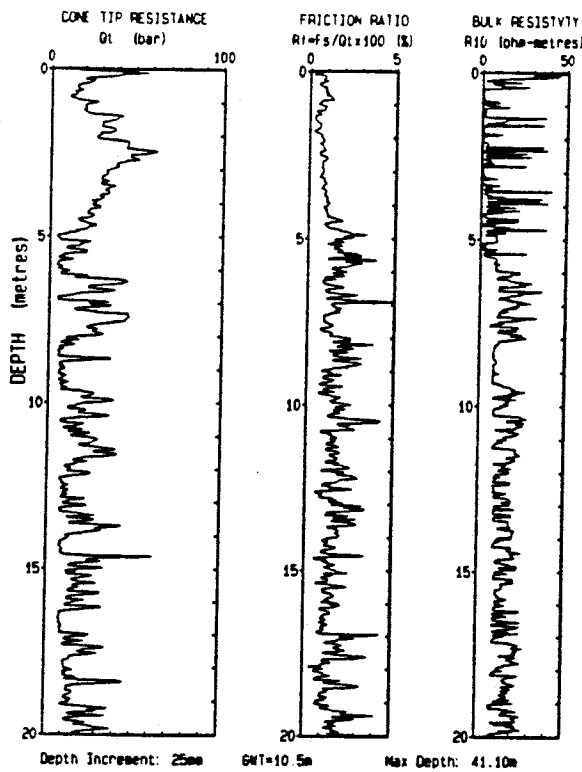


Fig. 4 RCPTU Sounding: Acid Generating Mine Tailings

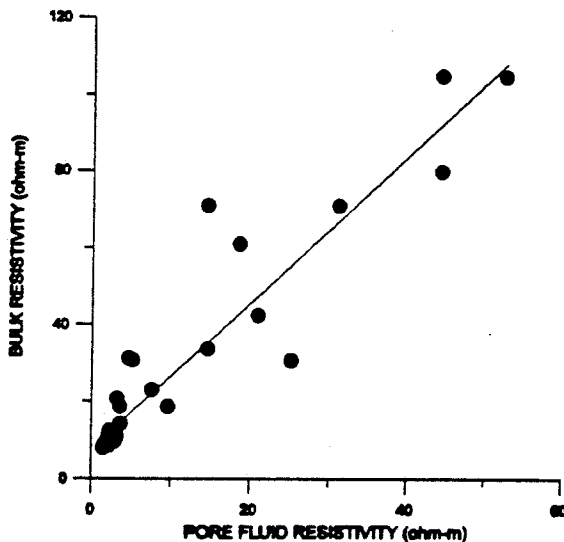


Fig. 5 Bulk versus Fluid Resistivity for Mine Tailings

4.3 Acid Rock Drainage (ARD) in Mine Tailings - Eastern Canada

A field program was conducted at a sulphide tailings impoundment in eastern Canada, at which a well documented case of ARD is occurring. The field program consisted of more than thirty RCPTU soundings with calibrative discrete groundwater sampling using the UBC modified BAT System, previously described, at selected holes.

A typical RCPTU sounding in acid generating tailings is shown below in Fig.4. Note that these tailings below 5 m depth are very mixed and stratified as indicated by the cyclic nature of the cone resistance and friction ratio with depth and are fairly fine and quite loose. However, the soil to 5 m depth is fairly uniform fine sand with little fines as shown by the consistent value of 1% and less for friction ratio.

The extremely low bulk resistivity measurements of less than 1 Ohm-m (or bulk conductivity more than 10,000 $\mu\text{S}/\text{cm}$) are very interesting and suggest that from ground surface to about 5 m in depth there is very high accumulation of ions in solution. This is a zone of high capillary pore water tension in fairly fine sands where saturation levels are high (causing lower resistivity), but, more important, this is a zone of high oxidation which gives rise to sulphate and acid generation which is the main cause for the very low resistivities. Note that from 5 m to well below the water table (10.5 m) the lowest bulk resistivity values are about 10 Ohm-m indicating a dilution of dissolved solids compared to the top 5 m

The results of resistivity logging and pore water sampling at another tailings impoundment are summarized in Fig.5 where bulk resistivity is plotted against fluid resistivity at all depths where discrete water samples were taken. The linear relationship in Fig. 5 gives a ratio of bulk to fluid resistivity (called Formation Factor) of about 2 in these tailings. Resistivity of soil particles is much higher than that of the pore fluid, and therefore it is expected that the bulk resistivity values would be significantly higher than that of the pore water. Typically the Formation Factor for clean quartz sands is between 2 and 5, but can be much lower with the clay minerals and particles with low resistivity surfaces. The agreement between the data in Fig. 5 demonstrate the effectiveness of the RCPTU in identifying zones of lower resistivity and potential groundwater contamination in mine tailings which contain mixed and often conductive fine grains.

Chemical testing has been conducted to determine sulphate and metal levels in the water samples. The results of the sulphate tests are presented in Fig.6 which shows a good correlation between sulphate concentration in mg/l and bulk conductivity in $\mu\text{S}/\text{cm}$. With this average correlation the concentration of sulphates in the pore water can be mapped, three dimensionally, using the bulk resistivity measurements from the rapidly performed RCPTU soundings. This work is ongoing and promising results are indicated.

5 CURRENT RESEARCH

One of our highest research priorities is the development of a grouting and decontamination system for the cone penetrometer. This system must easily and economically grout and seal the cone hole to prevent potential cross contamination from occurring. Conventionally, the hole is grouted after the cone is removed and requires a special grouting

pipe to be pushed back down the cone hole and withdrawn slowly while introducing grout. This procedure takes at least as long as the RCPTU soundings itself and is therefore time consuming and requires extra equipment, thereby increasing the cost substantially. It is therefore desirable to develop a "self"-grouting system.

Figure 7 shows a diagrammatic sketch of a self-grouting system where the CPTU is grouted while it is pushed in and when it is withdrawn. During the penetration, the grout is "sucked" down into the annulus (about 5 mm thick zone) behind the friction reducer. In the case of the resistivity-piezococone, the friction reducer is larger than the resistivity module and behind it, so the grouting does not interfere with the resistivity measurements. When the cone is withdrawn the friction reducer sleeve (which is about 50 to 75 mm long) is sacrificed and left in the ground so that the grout can fill the cone hole while it is withdrawn. Other than the time to premix the bentonite grout, little extra time is required. We use a recirculating Moyno pump and hopper to mix about 75 l of grout which is enough for a 30 m deep penetration.

To facilitate the cleaning and decontamination of the rods, multiple jet high pressure "steam," washed with detergent, all housed in a container fitted with a double rod wiper and under the cone truck. The high temperature wash uses a propane RV heater, a delivery pump and a high pressure washer. A recovery tank is also required so wash water is taken off site. The decontamination system is automatic and remote to the operations in the vehicle, hence requires no addition to the time of testing.

Initial results with this self grouting and decontamination system indicate that the system works efficiently and as expected. It is not clear who should be given credit for this idea for self grouting, but we first heard of it from Dr. Alan Lutenegeger (1992), during his review of various grouting methodologies. We continue to evaluate and improve the performance characteristics of this system.

Other current priorities include the following:

1. To develop improved methods of rapid water sampling for screening studies;
2. To develop new techniques to measure the hydraulic conductivity, K, of coarse soils *in-situ* and to correlate measurements with CPTU parameters to allow RAPID estimate of K vs. depth;
3. To evaluate and develop other geophysical techniques applied to cone penetration technology, such as the induced polarization technique (IP) and ground probing broad band radar (GPR);
4. To evaluate and apply other sensor technology, especially in the vadose zone and in the detection and quantification of 'floaters' and specific DNAPLs and LNAPLs. The recent "explosion" of new developments in the sensor technology is

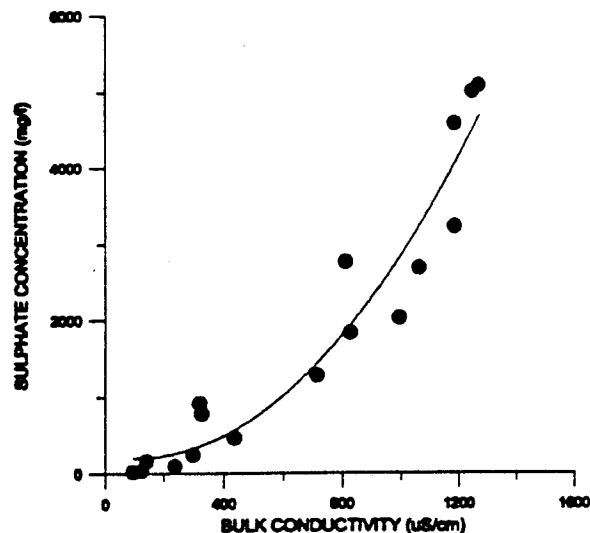


Fig. 6 Sulphate Concentration versus Bulk Conductivity: Mine Tailings

evident when one reviews the proceedings of "Field Screening Methods for Hazardous Wastes and Toxic Chemicals," (1993), which is in two volumes and covers 1,323 pages.

5. The importation, application and use of high density, *in-situ* measurements of contamination levels directly into SQL databases, data worth models and contaminant transport models.

Specific groundwater contamination problems currently under investigation include:

1. Hydrocarbon detection and mapping of DNAPLs and LNAPLs;
 2. Accumulation of nitrates and pesticides due to excessive agricultural activities;
 3. Develop rapid methods of detection, mapping and characterization of metals and sulphates in mine tailings and waste dumps coupled with characterizing acid generation and drainage mechanisms;
- All of our current research thrusts are related and applied to industrial and public needs concerning rapid and economical screening methods to measure groundwater quality.

6 CONCLUSIONS

The use of rapidly deployed logging tool like the Resistivity Piezocone (RCPTU) to identify subsurface stratigraphy and estimate groundwater flow parameters to guide the location for specific depth pore water sampling has been presented and described. The specific depth pore water sampling is also rapidly done with the use of a modified BAT groundwater system. The case histories relating to both organic and inorganic contamination demonstrate the application of the resistivity

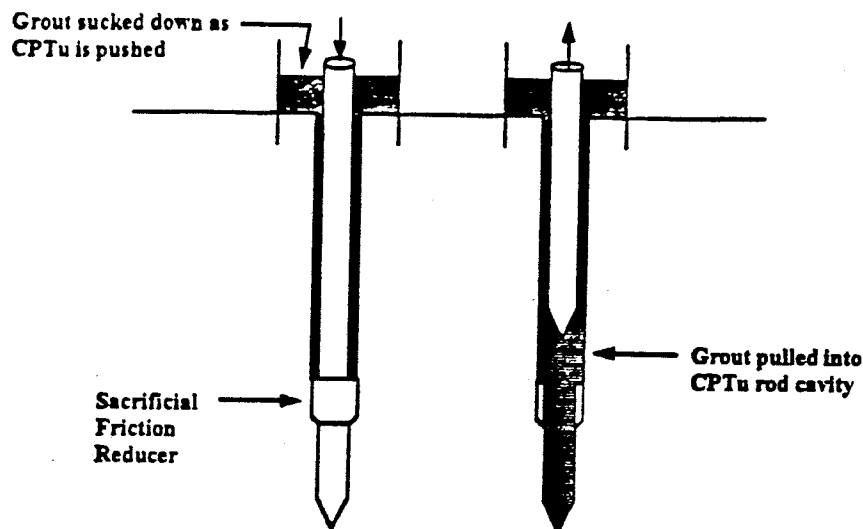


Fig. 7 Simplified Self-Grouting System for a Cone Penetration Sounding

penetration technology to identify levels of contamination. The results clearly show that these methods give a better definition of the lateral and vertical extent of the stratigraphy and contaminant zones than the conventional methods and at substantially lower cost and are especially useful in screening applications.

These *in-situ* testing tools are well past the research and development stage and should be made use of by practicing geoenvironmental engineers for site characterization of soil deposits. As of 1994, there are many cone contractors operating throughout the world who can demonstrate the effectiveness of modern penetration technology even on relatively small projects. Furthermore, the interpretation of piezocone test results can quickly be done by engineers, especially those new to the field, with the aid of user oriented software like CPTINT developed at UBC.

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