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The Application of In-Situ Technology in Reclamation and Decommissioning Plans For Tailings Impoundments

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ABSTRACT

Prior to the decommissioning and reclamation of tailings impoundments it is critical to adequately characterize the geotechnical, hydrogeological, and geochemical nature of tailings. Important advances in the capability of in-situ testing for characterizing tailings impoundments have included the development of the resistivity piezocone and improved water sampling technologies. The standard piezocone is an excellent means of logging stratigraphy for most soils and also gives accurate estimates of key physical and hydrogeological parameters. The resistivity piezocone includes a geophysical module, which resides directly behind the standard piezocone during testing, which permits assessment of groundwater quality through the measurement of the bulk resistivity of the soil and the pore water. In addition, recently developed in-situ discrete groundwater sampling systems can be used to augment the bulk resistivity measurements and facilitate site-specific correlations with selected water quality parameters.

This paper presents an overview of the resistivity piezocone and improved water sampling technologies and provides a summary of field testing programs carried out at large sulphide tailings impoundments at three Canadian mines. Test results are presented with respect to environmental and geotechnical aspects of sulphide tailings characterization.

1.0 INTRODUCTION

Two important advances in the capabilities for in-situ characterization of tailings impoundments have been the development of the resistivity piezocone and improved water sampling technologies. These tools permit accurate, rapid and cost-effective investigation of subsurface stratigraphy and provide measurements and estimates of important geotechnical, hydrogeological, and environmental parameters.

Mine tailings, consisting of sand to clay-sized material, are highly amenable to in-situ push-in technology. There are inherent geotechnical stability considerations in the construction of large impoundment structures for tailings storage as many of these are hydraulically constructed entirely or largely with tailings. In addition, some mine tailings, particularly from large volume sulphide ore operations, pose a significant environmental impact due to processes such as acid rock drainage (ARD). There is a significant challenge in adequately characterizing these impoundments for both their geotechnical and geochemical nature. Consequently, the potential to use a single tool in at least a screening fashion is highly attractive.

This paper presents an overview of the resistivity piezocone and improved water sampling technologies and provides a summary of field testing programs carried out at three Canadian mines. The results of the in-situ testing programs are presented with respect to the assessment of sulphide oxidation processes, and the development of correlations between bulk resistivity and specific ionic constituents in the pore water of tailings and native materials. In addition, geotechnical and hydrogeological issues having a direct impact on decommissioning and reclamation strategies for tailings impoundments are also examined.

2.0 EQUIPMENT AND PROCEDURES

2.1 Piezocone (CPT)

The piezometer cone penetration test (CPT) represents a repeatable means of delineating soil stratigraphy and determining geotechnical parameters. The piezocone has a standard (ASTM D-3441) 10 cm^2 60° conical tip and a 150 cm^2 friction sleeve. The cone is designed with an equal end area friction sleeve and a tip end area ratio of 0.85. A pore pressure filter is typically located either directly behind the cone tip or on the face of the cone tip. The filter is made of porous plastic and is 5.0 mm thick. Typically the pore pressure elements are saturated in glycerin under vacuum pressure prior to the field program. Figure 1 shows a schematic of a standard piezocone.

The cone is capable of measuring the following independent parameters: tip resistance, (q_c); sleeve friction, (f_s); dynamic pore pressure, (Ut); temperature, (T); and cone inclination, (i). All channels are continuously monitored and are typically digitally reported at 5 cm intervals, thus providing essentially continuous in-situ data sampling. The data is printed simultaneously on a printer during penetration and stored on a computer diskette for future reference.

The cone is pushed into the ground at a constant rate of about 1 metre/minute by a hydraulic pushing source; often a drill rig or a specially outfitted enclosed vehicle. An example of a cone penetration test rig is shown in Figure 2.

There are extensive empirical correlations available between the various cone parameters, and combinations thereof, that provide soil behavior type. Figure 3 shows one such classification scheme (Robertson et al., 1986) in which an estimate of soil type is made using cone bearing (q_t) and the friction ratio, FR, defined as (f_s/q_t) x 100%. The use of q_t, which is q_c corrected for in-situ water pressures, is only significant for materials with low tip resistance. Stratigraphic interpretation is typically automated with PC-based software programs, but can be carried out for selected depths by the experienced user at a quick glance. For example, in the case of a clean sand the cone bearing will be approximately greater than 40 bars (where 1 bar = 100 kPa) and the friction ratio will be less than 0.5%-1%. As the proportion of fines and plastic characteristics increases, generally the bearing decreases and the friction ratio increases. Values of friction ratio greater than 2% are generally representative of a silty and/or clayey material, whereas values greater than 5 % indicate organic content.

Excess pore pressure measurements also provide valuable insight into the hydraulic parameters of the penetrated soil. Excess pore pressures are defined as the difference between the measured pore pressure and the hydrostatic pore pressure. When penetration ceases, e.g. after a 1m rod push, any excess pore pressures generated during cone penetration will start to dissipate. The rate of dissipation is dependent upon the coefficient of consolidation which, in turn, is dependent upon the compressibility and hydraulic conductivity of the soil.

2.2 Resistivity Piezocone (RCPT)

The resistivity piezocone (RCPT) is a relatively recent development in CPT technology (Weemees, 1990). The RCPT consists of a resistivity module which resides behind a standard piezocone. The addition of the resistivity module permits the RCPT to assess groundwater quality by measuring a near-continuous bulk resistivity log of the soil and pore water in addition to all other standard cone measurements.

A schematic of a typical resistivity piezocone is shown in Figure 4. The RCPT works on the principle that the measured voltage drop across the electrodes in the soil, at a given excitation current, is proportional to the electrical resistivity of the soil. The stainless steel resistivty electrodes are 15 mm wide and are set 75 mm apart. Delrin, a plastic, is used as the insulator separating the electrodes. The probe operates by applying by applying a sinusoidal 1000 Hz current across the electrodes. From the resultant potential difference between the electrodes a resistance is determined. The current is regulated by a downhole microprocessor that adjusts the current when the resistivty changes to ensure a linear response to the soil.

Resistance is not a fundamental property but a function of the modules geometry (electrode spacing and diameter). To convert from resistance to resistivity, which is a material property, a lab calibration is necessary. The resistivity module is calibrated in a water tank. Solutions of known resistivity are prepared in the tank, and the resistance across the electrodes is measured. On the basis of the calibration it is observed that resistivity is linearly related to resistance. It is necessary to assume that the calibration factor, when the cone is advanced through soil, will not vary considerably from that determined in a homogeneous isotropic medium. The bulk resistivity of the soil is largely influenced by the resistivity of the pore fluid, which in turn is a measure of the groundwater chemical composition.

2.3 In-Situ Water Sampling

The main goal of any water sampling program should be 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 piezometers. 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 groundwater sampler (Torstensson, 1984) and QED Hydropunch (Edge and Cordry, 1989) allow for rapid, high quality, representative samples and are easy and economical to use.

The BAT groundwater sampling system was used to collect pore water samples for the case examples presented later in this paper. The BAT 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 by cable or electrical wire depending upon whether or not a pressure test is being carried out. Typically the first sample at each test depth is purged, and then the required volume of sample is collected. The equipment is hydraulically pushed with the same equipment used for cone penetration testing.

3.0 APPLICATION OF IN-SITU TESTING TO SULPHIDE TAILINGS CHARACTERIZATION

The use of the piezocone for geotechnical characterization of tailings is 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, makes the tool ideal for geotechnical characterization of tailings. Additionally, pore pressure measurements can be used to identify the groundwater flow regime, which is required for seepage analysis of the mine waste.

The use of resistivty (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 surface geophysics. The main reason the process is detectable is due to the elevated dissolved solids concentration. The ability to carry out resistivity soundings, thus avoiding the non-unique solution interpretation of surface geophysics, is a large advantage of the RCPT.

In-situ water sampling can significantly enhance the application of the RCPT. RCPT logs can be used to target potential areas of contamination and identify permeable soil strata, which facilitates cost-effective pore water sampling. After pore water samples have been collected, comparisons between bulk resistivity logs and specific chemical properties of the samples can permit the formation of site-specific correlations. Such correlations can improve the interpretation of any future RCPT soundings at the site, which makes the technology attractive for monitoring water quality changes over time, thus reducing the need for more expensive discrete pore water sampling technologies. The RCPT 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.

4.0 CASE EXAMPLES

The following section contains data from in-situ site investigations at large sulphide tailings impoundments at three Canadian mines. The sites are not specifically named due to confidentiality restrictions.

4.1 Example RCPT Sounding in Sulphide Tailings

Figures 5a through 5c illustrate field data collected during an RCPT sounding at the crest of a sulphide tailings impoundment and some of the parameters determined from the sounding. Figure 5a is a graphical representation of the RCPT data, known as a coneplot. To briefly review the sounding there is 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. The pore pressure profile from 15 - 37 m shows interlayered contractive and dilative materials. This signature is consistent with beached tailings that periodically are allowed to establish a desiccated 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.

Hydrogeological parameters were estimated by ceasing penetration at specific depths of interest and allowing the excess pore pressures to dissipate to equilibrium values. Based upon the pore pressure dissipations the phreatic surface is estimated to be at a depth of 15 m. The hydraulic conductivity for the tailings ranged from 10^{-5} to 10^{-6} cm/s, which is representative of the fine grained nature of the tailings (~40-50% < 74 μm). The hydraulic conductivity of the native silty clay material was estimated to be 10^{-7} cm/s, which is in agreement with the material type. Additionally, as shown in Figure 5b, a downward gradient in the tailings of approximately 0.4 was estimated from the pore pressure dissipation data. For evaluating the pathways and rates of influence of sulphide mine wastes these hydrogeological parameters are essential.

It is interesting to note that some lower resistivity values do exist above the phreatic surface. The moisture retention capabilities of tailings is well-documented (Vick, 1983) and it is clear that the unsaturated tailings in this area have a high degree of saturation and that the pore fluid present has elevated levels of ionic constituents. Figure 5c, which is a plot of bulk resistivity versus sulphate concentration, provides further evidence of significant ionic loading in the unsaturated zone. The very high sulphate concentrations above the phreatic surface are due to extensive oxidation of sulphide minerals. Below the phreatic surface, the bulk resistivity values were quite constant at approximately 10 Ω-m, and this was in good agreement with sulphate concentrations which also remained relatively constant. The resistivity values in the native materials rose sharply to values of approximately 40 Ω-*m,* indicating that no significant ionic loading above expected background values exist in these materials.

4.2 Geochemical Characterization

Assessments of the pore water geochemistry of the tailings impoundments were made by comparing the RCPT bulk resistivity logs and the chemical analyses on discrete groundwater samples. The groundwater samples were obtained using the BAT system and by sampling permanent piezometer installations. Figure 6 shows a relationship developed between bulk resistivity and pore fluid sulphate concentration for soundings at all sites. 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 possible with the RCPT, making it a good screening tool for planning remediation and/or reclamation strategies.

Other ionic constituents also showed some correlation trends. Figure 7 is a plot of pH of tailings pore water versus bulk conductivity (resistivity^{-1}). A linear trend is evident and is in agreement with the type of trend documented for similar sites by others (e.g. King and Sartorelli, 1991). Figures 8a and 8b show RCPT conductivity values versus pore water concentrations of iron and magnesium respectively. The purpose of these of these comparisons is not to show specific correlations between RCPT conductivity measurements and metal concentrations, but rather to discern generalized trends. Both of the metals increase in concentration with increasing bulk conductivity, and this is likely due to ARD processes.

5.0 CONCLUSION

The decommissioning and reclamation of tailings impoundments requires adequate understanding of subsurface conditions. The resistivity piezocone represents a rapid, cost-effective means of accurately characterizing sulphide tailings with respect to geotechnical and environmental considerations. In addition, discrete groundwater sampling can be used to augment RCPT data to provide site-specific correlations with pore water chemistry. Test data from field investigation programs at three Canadian mines demonstrated the application and capabilities of the in-situ tools.

REFERENCES

Campanella, R.G., P.K. Robertson, E.J. Klohn, and D.G. Gillespie (1984). Piezometer-Friction Cone Investigation at a Tailings Dam, Canadian Geotechnical Journal, Volume21, Numbers, pp. 551-562.

Ebraheem, A.M., M.W. Hamburger, E.R. Bayless, and N.C. Krothe (1990). A Study of Acid Mine Drainage Using Earth Resistivity Measurements. Groundwater, Vol 28, No. 3, pp. 361-368.

Edge, R.W. and K. Cordry (1989). The Hydropunch: An In Situ Sampling Tool For Collecting Groundwater From Unconsolidated Sediments. Groundwater Monitoring Review, Vol. 9, No. 3, pp. 177-183.

King, A. and A.N. Sartorelli (1991). Mapping Acidified Groundwater Using Surficial Geophysical Methods. Proceedings of second international conference on the abatement of acidic drainage, Montreal, September, 1991, V3, pp. 451-487.

Merkel, R.H. (1972). The Use of Resistivity Techniques to Delineate Acid Mine Drainage in Groundwater. Ground Water, V.10, No. 5, pp. 38-42.

Robertson, P.K. and R.G. Campanella (1986). Guidelines For Use, Interpretation And Application of the CPT And CPTU. University of British Columbia Soil Mechanics Series No. 105, University of British Columbia, Vancouver, B.C.

Torstensson, B.A. (1984). A New System For Groundwater Monitoring. Groundwater Monitoring Review, Vol. 4, No. 4, pp. 131-138.

Vick, S.G. (1983). Planning, Design, and Analysis of Tailings Dams. Bi-Tech Publishers Ltd. Vancouver, B.C., pp. 369 (2nd edition, 1990).

Weemees, I.A. (1990). Development of a Resistivity Cone for Groundwater Contamination Studies. M.A.Sc. thesis, Department of Civil Engineering, University of British Columbia, Vancouver, B.C.

Woeller, D.J., M.P. Davies, and P.K. Robertson (1989). Use of Recent Cone Penetration Test Technology in Evaluating Geotechnical Properties of Mine Waste, in Proceedings 1989 Vancouver Geotechnical Society Symposium - Geotechnical Aspects of Tailings Disposal and Acid Mine Drainage.

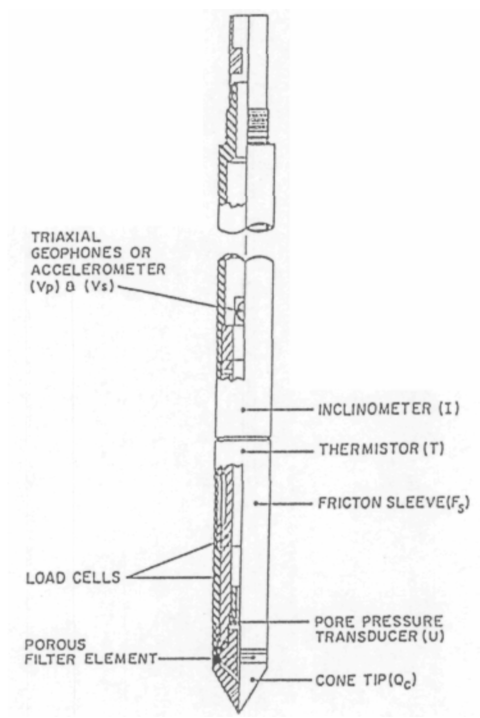
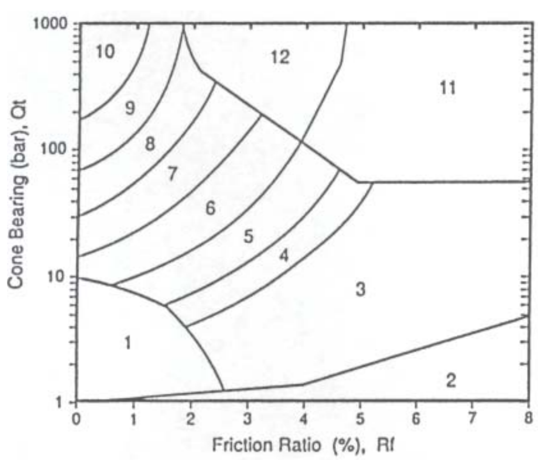


Figure 1 - Standard Piezocone

Figure 2 - Track-Mounted Cone Penetration Testing Unit



Zone	Q_t/N	Soil Behaviour Type
1	2	sensitive line grained
2	1	organic material
3	1	clay
4	1.5	silly clay to clay
5	2	clayey silt to silly clay
6	2.5	sandy silt to clayey silt
7	3	silty sand to sandy silt
8	4	sand to silty sand
9	5	sand
10	6	gravelly sand to sand
11	1	very still line grained *
12	2	sand to clayey sand '

* overconsolidated or cemented

Figure 3 - Classification of Soil Behavior Types From CRT Data
(After Robertson et al., 1986)

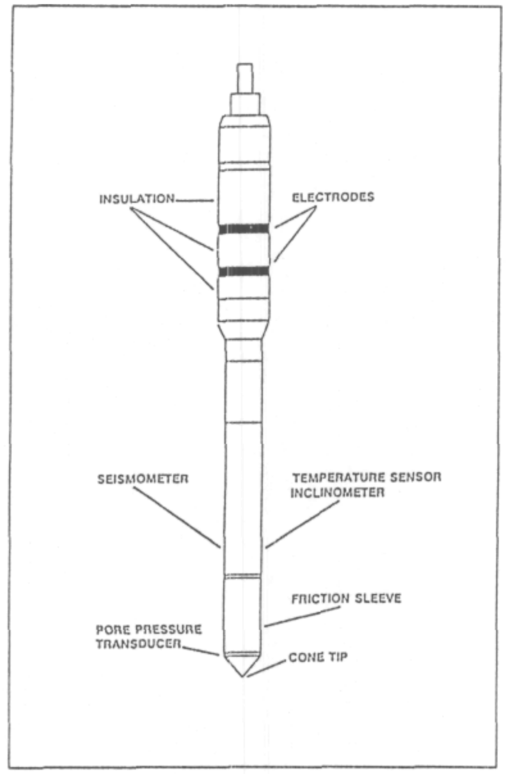


Figure 4 - Resistivity Piezocone

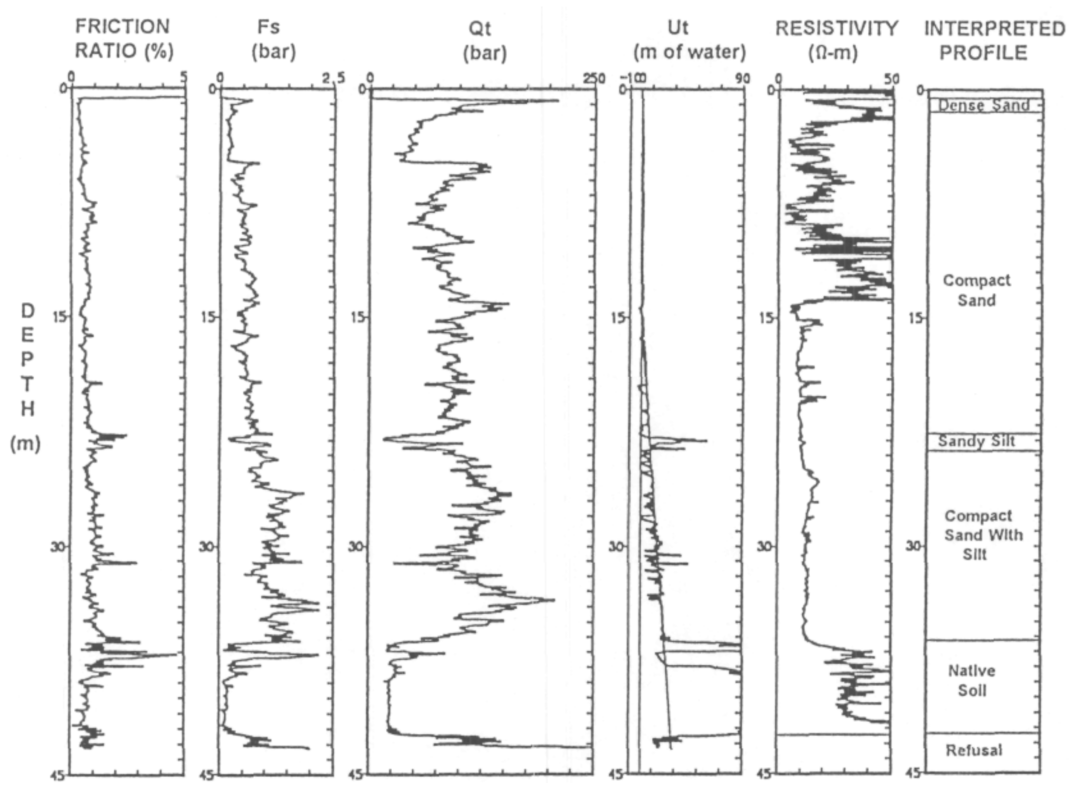


Figure 5a - Example RCPT Profile

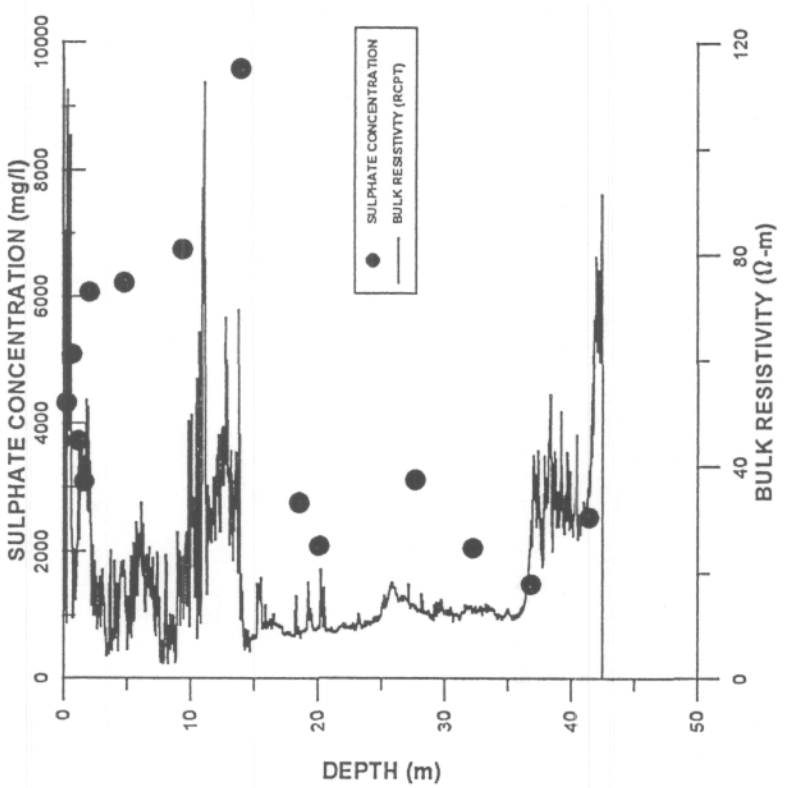


Figure 5c - Sulphate Concentration versus Bulk Resistivity For Example RCPT Sounding

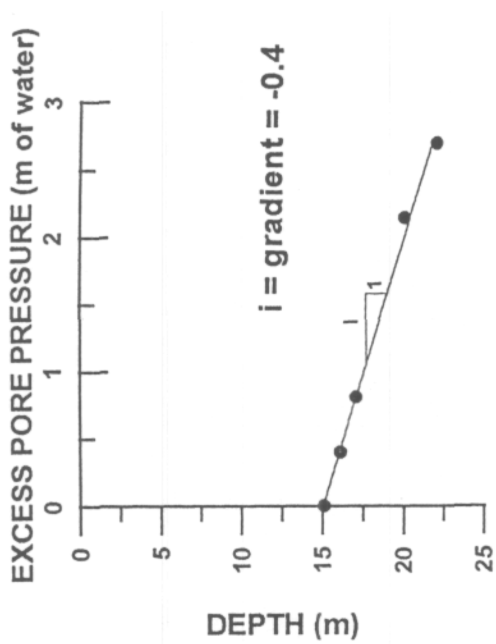


Figure 5b - Estimate of Hydraulic Gradient For Example RCPT Sounding

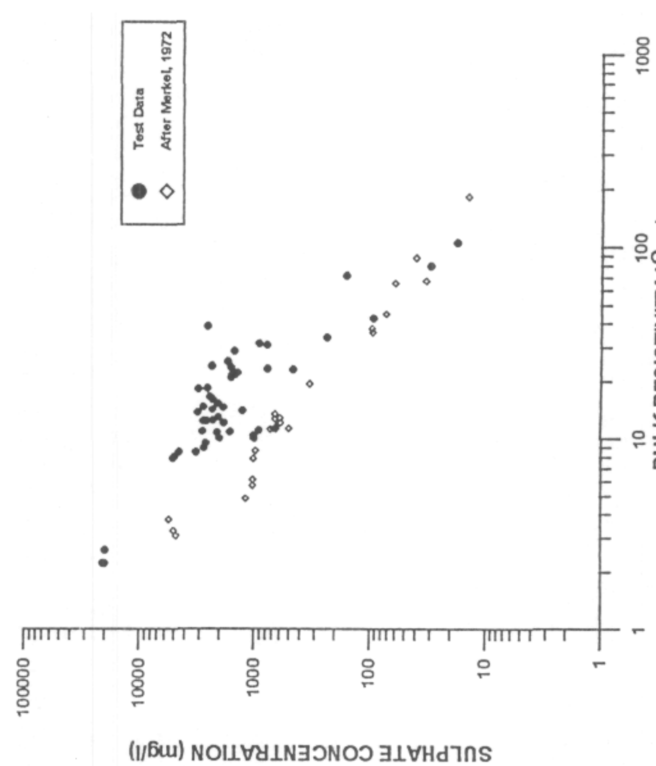


Figure 6 - Sulphate Concentration versus Bulk Resistivity

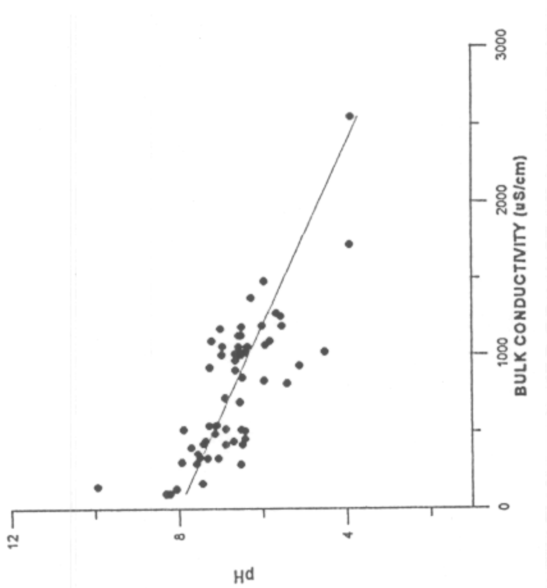


Figure 7 - pH versus Bulk Conductivity

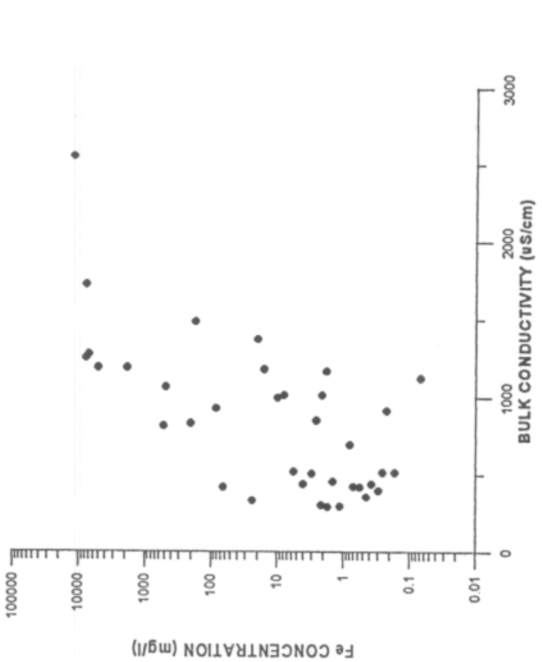


Figure 8a - Fe Concentration versus Bulk Conductivity

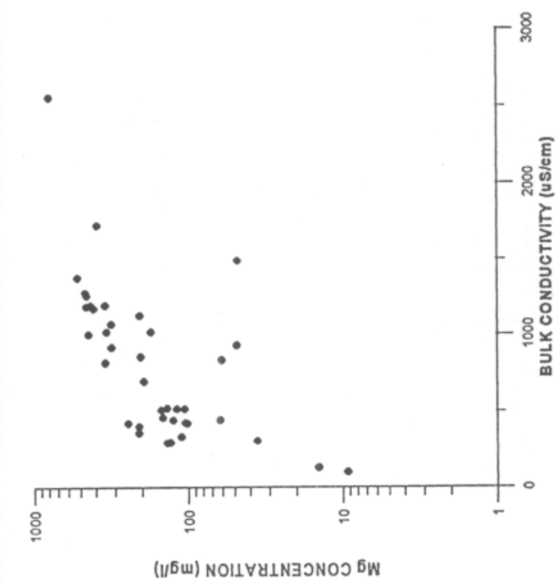


Figure 8b - Mg Concentration versus Bulk Conductivity

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