Geophysical Applications for Oil Sand Mine Tailings Management

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ABSTRACT
The proper management of tailings facilities plays a major role in the planning, development, operation and abandonment of a mine. Geophysical techniques can be applied throughout a mine's life cycle to assist in siting, constructing and monitoring of tailings dumps and ponds. Through three short case studies, this presentation will demonstrate some of the concerns associated with oil sand mine tailings, and the information that geophysical surveys can provide.

RÉSUMÉ
Une gestion adéquate des bassins de résidus joue un role majeur dans la planification, le développement, l'opération et l'abandon d'une mine. Diverses techniques géophysiques peuvent être appliquées au cours du cycle de vie d'une mine, que ce soit au moment de l'implantation de la mine, lors de sa construction et même à titre de surveillance environnementale des zones de décharges des résidus et des bassins eux-mêmes. À l'aide de trois courts scénarios, quelques problèmes associés aux bassins de résidus résultant de l'exploitation des sables bitumineux seront présentés ainsi que les renseignements que peuvent fournir les sondages géophysiques sur ces préoccupations.

1 INTRODUCTION

The oil sands deposits of the Athabasca region in northeast Alberta represent one of the largest hydrocarbon reserves in the world. The deposits are typically defined by two extraction processes; steam assisted gravity drainage (SAGD) for deeper deposits, and open pit mining recovery for shallower deposits. Open pit extraction activities require large tailings facilities to store mine tailings until proper reclamation is feasible. Tailings facilities are typically in excess of 10 km^2 and require a vast amount of planning prior to construction and operation. Once operational, the tailings facilities require regular monitoring and must adhere to stringent federal and provincial regulations.

Geophysical techniques can be applied throughout a mine's life cycle to assist in siting, constructing and monitoring tailings dumps and ponds.

2 SITING AND CONSTRUCTION

A detailed understanding of the geology underlying a proposed tailings facility must be obtained prior to construction. A number of the existing and proposed tailings facilities in the Athabasca region are underlain by large Pleistocene channels. Tailings facilities are often built on these large alluvial deposits as a result of mine economics, land availability and regulations limiting ore sterilization (Stephens et al. 2006).

These channels pose crucial design and operational challenges and must be delineated to overcome these challenges. Geophysical techniques can assist with this objective, and provide an efficient method of obtaining site-specific and regional geological trends in a relatively short time frame.

2.1 Pleistocene Channel Mapping

The first case study involves mapping a Pleistocene channel within the area of a proposed tailings facility. The geophysical investigation was undertaken at Suncor Energy's South Tailings Pond (STP) in 2005.

The objective of the study was to delineate sand and gravel deposits associated with a buried Pleistocene channel using the electrical resistivity tomography (ERT) method. Previous geophysical surveys in the Fort McMurray area have demonstrated that ERT can effectively delineate the differing electrical properties of a resistive incised channel and a surrounding conductive medium such as clay till or shale. An understanding of the geologic properties is necessary to properly model the hydrogeologic processes and geotechnical properties under the proposed STP structure.

2.2 Electrical Resistivity Tomography (ERT) Background

ERT is a technique for mapping the distribution of subsurface electrical resistivity in a cross-sectional format. Data are collected through a linear Wenner electrode array coupled to a DC resistivity transmitter/receiver and an electronic switching box. A known direct current (DC) moves into the subsurface from one electrode to another electrode a fixed distance away. Two potential electrodes measure the potential drop, or the force required for the current to overcome the resistance of the subsurface (Figure 1). Given that the current injected into the subsurface is known, resistance can be calculated using Ohm's Law, as in equation 1.

$$I = V/R \qquad [1]$$

An apparent resistivity can then be calculated based on the geometry of the current and potential electrodes. By changing the geometry of the electrodes, resistivity values for various depths can be calculated along a single two-dimensional (2-D) section.

Upon completion of the data acquisition, recorded data are downloaded to a computer for processing. The entire dataset is then inverted using a 2-D finite difference, smooth inversion routine. The final product is a 2-D geoelectrical cross section plotting true resistivity (in ohm-m) versus true depth.

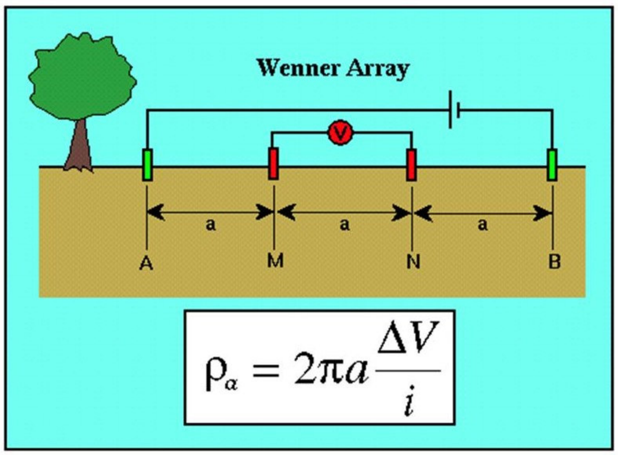

Figure 1. The basic theory for resistivity surveys using a Wenner array.

Resistivity values of matrix lithology usually are higher for coarser grained materials (sands and gravels) and lower for finer grained materials. The addition of small amounts of fines to a generally coarse-grained unit (such as clay-rich sand) can alter the resistivity of the unit, making it electrically more conductive. Conversely, unsaturated channels or the presence of oil sand can elevate resistivity values.

2.3 ERT Survey Results

ERT data at the STP location were collected using a Wenner array with a minimum electrode spacing of 5 m, providing an effective depth of investigation of approximately 60 m below ground surface (bgs). Thirteen ERT lines were surveyed during the field program for a total length of approximately 45 kilometres (km). Figure 2 illustrates the location of the ERT lines, as well as the proposed toe of the dyke of the STP. ERT lines were strategically placed to optimise the dataset in relation to the orientation of the proposed STP footprint.

In the absence of an incised channel, the site geology consists of a thin organic layer on top of the overburden material (clay/sandy tills with areas of surficial and/or interbedded gravels) over Clearwater shale. A buried sand/gravel channel incised into this conductive medium offers an excellent target for resistivity methods.

Typically, clay till and shale materials were quite conductive, being in the 10 to 30 ohm-m range. The coarse-grained channel was markedly more resistive, depending on fines content and/or water saturation and pore water chemistry. Resistivity values ranged from 70 to 90 ohm-m for water saturated clean sand/gravel, with resistivity values decreasing with elevated fines content or ion concentrations in the pore fluids. The resistivity value of a bitumen saturated or unsaturated, clean sand/gravel section of the channel exceeded 300 ohm-m at some locations.

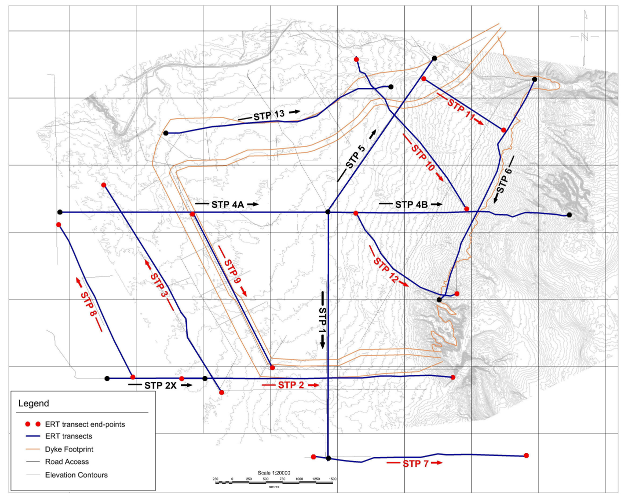

Figure 2. Base map illustrating ERT lines and proposed perimeter of STP.

The ERT program was very effective in mapping the extents of the Pleistocene channel system at the STP site, both laterally and in depth (Figure 3). Correlation of the ERT results with available borehole logs was excellent. The channels appear to have a deeper, coarse-grained thalweg section approximately 35 to 40 mbgs. Corresponding resistivity values within the thalweg are typically 100 ohm-m to 150 ohm-m, but have been observed to be greater than 300 ohm-m in certain areas. The deep scour section (thalweg) is usually flanked on one or both sides by a sand/gravel layer, (15 to 25 m thick) adjacent to the thalweg that ultimately pinches out. Resistivity values within the flanks are generally 40 to 60 ohm-m.

Resistivity values vary within the channels, both along the strike and perpendicular to the strike direction of the channel systems. These changes are most likely related to variations in grain size, groundwater saturation/chemistry, and clay content. Analysis of the regional trends of the datasets clearly delineates two continuous sand/gravel channel systems trending through the survey area, running from the south and the east.

In addition to imaging the channel extents, the geophysical data provide other important information including overburden thickness, the identification of surficial sand/gravel units, the location of areas of channel breaching, and the internal properties and western extents of a significant deposit of granular material.

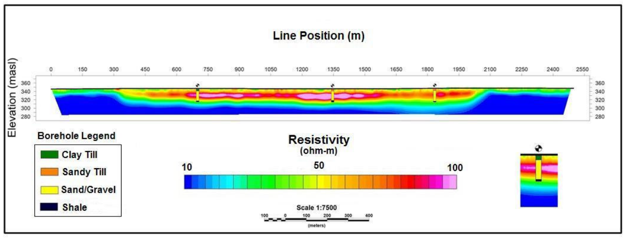

Figure 3. ERT section displaying lateral and depth extents of buried channel.

Follow-up geotechnical drilling confirmed the geophysical results. The ERT survey results were used to guide the geotechnical investigation, thus reducing the cost of the program by decreasing the number of required boreholes to delineate the Pleistocene channel.

3 TAILINGS POND MONITORING

The oil sands refinement process results in the generation of large volumes of tailings. Tailings have both liquid and solid components and are composed of water, sand/clay and residual hydrocarbons. The tailings are of varying grain size where coarser tailings are typically used as dyke construction material for tailings facilities. The thickened tails and thin fine tails runoff are contained.

Determination of the engineering properties of the consolidating tailings requires a continuous determination of the excess pore pressure profile in conjunction with an extensive sampling program. A potential alternative approach is the use of geophysical techniques. When using these techniques, multiple measurements can be made without undue disturbance of the sediments, and different tools can provide a range of parameters, including density, that can be obtained as continuous profiles through the tailings.

3.1 Geophysical Logging

In order to determine if geophysical methods could be used to determine the necessary properties to the necessary accuracy, a side-by-side sampling and geophysical program was conducted within a tailings facility in the Fort McMurray region. The successful development of geophysical methods in determining the properties of sediments could result in a valuable procedure for evaluating the state of non-segregating tails placed into mined pit areas.

The specific objective of the logging program was to gather high resolution density data within the tailings facility. The data were to be used for stress calculations. Information on additional physical properties of secondary importance was also gathered. A number of geophysical instruments, including compensated density, neutron, 4-pi density, induction conductivity, natural gamma, fluid conductivity, and temperature, were used to obtain the required information.

3.2 Logging Methods

The principle behind density logging is the detection of Compton-scattered gamma rays that originate from a small radioactive source housed in the probe. The intensity of the radiation reflected back to the detectors is primarily a function of the bulk density of the media in which the gamma rays are introduced and scattered. Because boreholes are not perfectly smooth, compensation is necessary to correct for the condition in which the tool is not perfectly flush with the borehole wall. When calibrated correctly, compensated measurements can be accurate to within 1% of the true bulk density. In this case study, no compensation was required as the geophysical probes were being lowered directly into the tailings and not down a borehole.

3.3 Results

Geophysical logging data were collected from a barge at four locations of the tailings facility. Logging probes were lowered from the barge directly into the tailings. Due to the nature of tailings settling ponds, a 10 kg weight was attached to the logging tools to ensure maximum penetration of the probes into the tailings (Photo 1).


Photo 1. Geophysical logging setup on barge at tailings pond facility.

The geophysical results indicate that the tailings are overlain by approximately 9.5 to 10.5 m of water. The sediment at the four survey locations ranged from 3 to 5 m thick. The geophysical log data show increasing density of the sediment with depth (Figure 4). The bottom 50 to 75 cm of sediment generally shows a dramatic increase in density. However, especially with the radiation measuring tools, the sensors may be ‘sensing’ the hard pond bottom.

The results show that there is an overall positive correlation of the density logs and sample analysis (Figure 5). However, due to the statistical nature of the radiation measurements and the difficulty with measuring in the same locations for repeatability purposes, the correlation was not deemed accurate enough to be useful. In other words, physical samples of the tailings were deemed to be more reliable than the density logs obtained from the geophysical logging program. That being said, the one major advantage of the geophysical logs is the ability to obtain continuous data points throughout the tailings column.

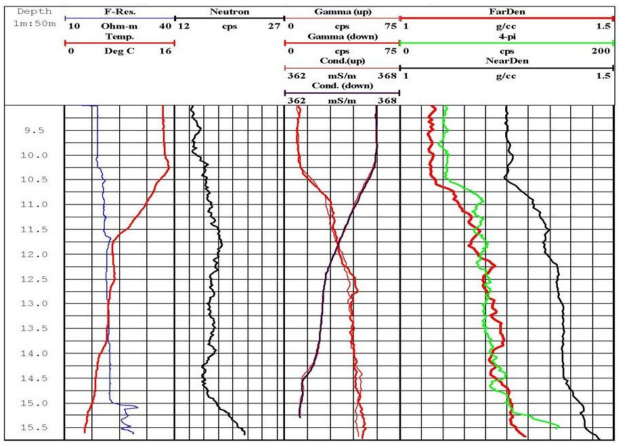

Figure 4. Results for one of the geophysical logging runs.

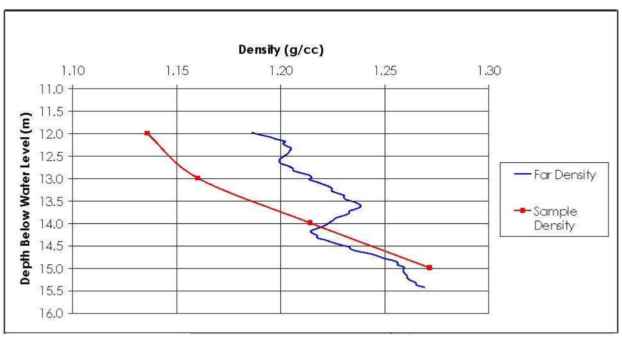

Figure 5. Graph illustrating density versus depth of geophysical density log and grab sample.

Other geophysical logs were useful and provide supporting information concerning the sediment. Specifically, a strong correlation exists between the far density and natural gamma logs, as evident in Figure 4. Despite not proving entirely successful for the objectives of this study, the geophysical logs were deemed useful and should be considered for future tailings pond monitoring investigations.

4 TAILINGS STORAGE MONITORING

Part of the tailings reclamation process is to separate water and hydrocarbons from the sand. Clean sands are then returned to the land and monitored for potential environmental impacts. To achieve this objective, sand tailings are distributed over large areas engineered to remove water, fine particles, and any organic and inorganic constituents from the tailings.

A determination of how the tailings dyke materials are changing over time is critical for reclamation and tailings management. From the reclamation aspect, a determination of groundwater and salt leachate movement will govern the ecosystem health and long-term feasibility of the reclamation efforts, as well as identify vegetation areas that may be affected by soil chemistry changes. A detailed understanding of the internal dynamics of the tailings dyke will allow tailings and geotechnical engineers to determine if the dyke is behaving as designed. The information and insight gained can help in future dyke design.

4.1 Background

The objective of this study was to image the lateral and depth extents of elevated conductivities of soil and groundwater that have elevated salt concentration from the tailings sand pore fluid. Due to high chloride concentrations within the tailings material, salinity impact within the root zone may result in vegetation being affected. A terrain conductivity survey was designed to map the lateral extents of salinity impact, while an ERT survey was utilised to delineate the tailings sand leachate at depth.

The Geonics EM38 terrain conductivity meter is a portable electromagnetic survey instruments that can be used to collect terrain conductivity data over relatively large areas in a short period of time. Terrain conductivity is defined as the bulk electrical conductivity of the subsurface. It is a measure of the combined electrical conductivity of the soil matrix and pore fluids.

Terrain conductivity instruments use the principles of electromagnetic induction to measure the conductivity of the soil. A transmitter coil induces an alternating electrical current to flow in subsurface conductors. A receiver coil measures the strength of the magnetic field caused by the induced alternating current (secondary field), as well as the magnetic field from the transmitter (primary field). Of the combined fields measured by the receiver, the component that is 90 degree out-of-phase (quadrature) with the primary field is recorded by the EM38. Under a limited range of conditions, the quadrature component is directly proportional to the conductivity of the soil.

Generally, the depth of investigation of an electromagnetic (EM) device is a function of the transmitter/receiver inter-coil spacing and the dipole (or coil) orientation. The EM38, with an inter-coil spacing of 1 m, has a maximum depth of investigation of approximately 1.5 m in the vertical dipole mode with a peak response from a depth of 0.5 m.

Electromagnetic (EM38) data were collected over an area of approximately 360 hectares to determine the lateral extent of any potential inorganic impact within the tailings storage area. The EM38 data were then analysed to strategically place the locations of ERT surveys to determine leachate migration in cross-section.

4.2 Results

The geology at the site consists of a thin organic layer on top of tailings sand. Conductivity values within a clean soil or sand deposit are typically 10 to 20 mS/m, with an increase in soil moisture and/or soil salinity altering the geoelectric properties. The conductivity values of a saline water saturated section of the tailings dyke, as illustrated in the areas of linear drainage waterways, typically exceed 75 mS/m (Figure 6).

Engineered drainage swales were imaged in both the vertical and horizontal dipole EM38 datasets as anomalies of elevated terrain conductivity values (>75 mS/m). Discrete anomalies of elevated terrain conductivities not attributed to known swales, areas of soil placement or natural watercourses may be associated with tailings water impact. This could occur from surface runoff, capillary action, evaporation, or a combination of these and other processes.

ERT data were collected using a Wenner array with an electrode spacing of 1 m, providing an effective depth of investigation of approximately 12 mbgs. ERT lines were surveyed on the slopes of the perimeter of the tailings sand storage facility in areas of elevated terrain conductivity in the EM38 dataset.

The ERT response is divided into two distinguishable layers, with the exception of the immediate proximity of the drainage waterways (Figure 7). Sloped areas with some vegetation have a significantly lower conductivity response, in the range of 10 to 20 mS/m. This is most likely due to the presence of dry soil and/or dry tailings sand with a vegetative cover.

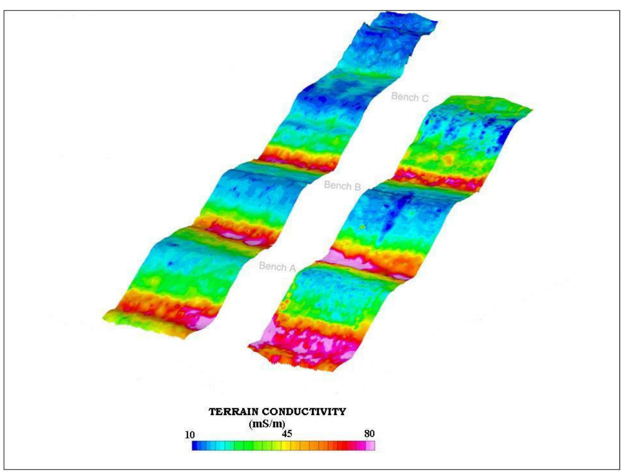

Figure 6. EM38 results over tailings storage area. Engineered drainage swales are highlighted by elevated terrain conductivity (lower topography).

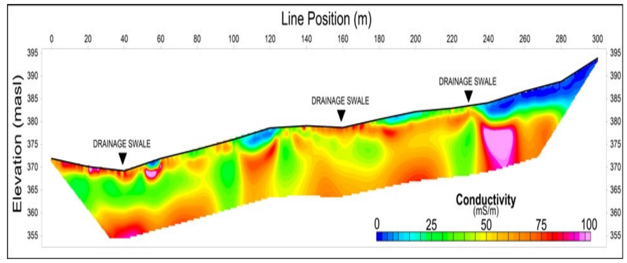

Figure 7. ERT results over tailings storage area.

The lower horizon of the ERT cross-sections has a significantly higher conductivity response ranging between 40 and 100 mS/m. This horizon is non-homogeneous with zones greater than 100 mS/m surrounded by material ranging from 40 to100 mS/m. The contact between the lower and upper horizon may be the groundwater surface. Within the lower zone, the areas of extremely elevated conductivity values may be the result of increased salinity from tailings leachate. Furthermore, pockets in the upper zone possibly unsaturated, displaying slightly elevated conductivity values may be the result of localized soil moisture highs and/or increases in salt concentration from tailings leachate.

As expected, zones of elevated conductivity were identified by the ERT survey in areas of the drainage swales. These zones typically extend from surface to a depth of approximately 2 mbgs and correlate with the lateral extents identified by the EM38 dataset.

Overall, the geophysical investigation was successful in mapping the lateral and depth extents of soil and groundwater that have elevated salt concentration from the tailings sand pore fluid.

5 CONCLUSIONS

Tailings facilities associated with the Athabasca oil sands in northeast Alberta pose a number of engineering and environmental challenges. The proper management of these tailings facilities is vital to the life cycle of a mine. Geophysical techniques can be applied to aid in managing these challenges, from Pleistocene channel mapping, to tailings pond settling characteristics, to reclaiming tailings sands.

REFERENCES

Stephens, B., Langton, C., and Bowron, M. 2006. Design of Tailings Dams on Large Pleistocene Channel Deposits. A Case Study – Suncor’s South Tailings Pond, 2006 Canadian Dam Association Annual Conference, Quebec City, Canada.