Conductivity mapping to identify vertical and lateral extents of contaminated soils



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ABSTRACT

A combined electromagnetic and electrical imaging survey was undertaken in an effort to map variations in electrical conductivity associated with a pipeline break at a site in central Alberta. Along with a fixed-frequency electromagnetic (FEM) instrument, the relatively new OhmMapper apparent resistivity system was deployed. These tools were used to determine the lateral as well the vertical extent of chloride contaminant resultant from the break. Survey data indicate that, although a single, laterally extensive anomaly was identified using the FEM system, vertical variations in apparent conductivity mapped using the OhmMapper show that there may have been multiple spills in the area. The OhmMapper, has proven to be a fast, easy and cost-effective technique to obtain both lateral and vertical extents of the contaminant, useful information for remediation planning.

RÉSUMÉ

Une étude d'imagerie combinés électromagnétiques et électriques a été entrepris dans le but de cartographier les variations de la conductivité électrique associé à une rupture de pipeline à un endroit dans le centre de l'Alberta. Avec un électromagnétiques à fréquence fixe (FEM) instrument, relativement nouveau système OhmMapper résistivité apparente a été déployé. Ces outils ont été utilisés pour déterminer le latérales ainsi l'étendue verticale de chlorure de contaminants résultant de la rupture. Les données d'enquête indiquent que, même si une seule anomalie vaste latéral a été identifié en utilisant le système FEM, les variations verticales de la conductivité apparente cartographiés à l'aide du spectacle OhmMapper qu'il pourrait y avoir été plusieurs déversements dans la région. Le OhmMapper, s'est avérée être un moyen rapide, technique facile et rentable d'obtenir des degrés vertical et latéral du polluant, les renseignements utiles pour la planification d'assainissement.

1 INTRODUCTION

The survey area is located at a facility in central Alberta and, at the time of the summer survey, was covered mostly with grass and alfalfa. The survey grid covered an area of almost 1 hectare which was relatively flat-lying. Stressed and dead vegetation, along with salt encrustation, over a small area (20 x 25 m2) observed by site personnel prompted investigations at the site. Hand auger data collected prior to the geophysical survey identified coarse sand in the upper 1.5 m of the subsurface and the presence of produced water.

Apparent conductivity data were acquired using a Geonics EM31 Terrain Conductivity Meter. OhmMapper apparent conductivity profiles were collected over 8 survey lines located within the survey area (Figure 1).

Six boreholes were advanced based on the results of the geophysical survey. Subsequent laboratory testing yielded findings consistent with the results of the geophysical survey.

2 METHOD

Given the contrast in electrical resistivity expected between chloride contaminant and host soils, the measurement of apparent conductivity is a common tool used in environmental investigations.

In-situ measurement of apparent resistivity of earth materials is dependent on several factors. In

environmental applications, the most important of these factors is concentration of total dissolved solids (TDS) within the groundwater. Increased concentrations of TDS tend to increase apparent conductivity of the TDS-bearing soils.

Soil type, or, more specifically, grain size, also affects the magnitude of measured apparent conductivity. In general, as the clay content of bulk materials increases, apparent conductivity increases owing to the increased electrical conductivity of the fine grains comprising clay. It is typically the case that apparent conductivities due to the presence of TDS are higher in magnitude than those associated with fine-grained soils.

Electromagnetic (EM) and electrical methods are commonly used to map apparent conductivity variations. EM instrumentation, including the widely used Geonics EM31, EM34-3 and EM38, exploit EM induction laws to obtain measurements of apparent conductivity.

Conventional electrical methods direct current through steel electrodes hammered into the ground. Resultant voltages are then measured across alternate electrode pairs. Systems in use today, such as the IRIS Syscal systems and the AGI Sting, use switch boxes to regulate measurement cycles over quartets of electrodes along linear arrays that can accommodate many tens of electrodes. This approach tends to be time-consuming and labour intensive.



Figure 1: Areal plot of apparent conductivity data over survey area. Solid black lines indicate locations of OhmMapper survey lines while dashed black lines illustrate subsurface pipeline locations. Borehole locations are denoted by white symbols.

Manufactured by Geometrics Inc., the OhmMapper measures apparent resistivity by generating electrical current flow in the subsurface through capacitive coupling. Whereas conventional electrical resistivity systems directly inject current through metal electrodes driven into the ground, the OhmMapper applies a current to the ground using capacitive coupling between its transmitting electrical dipole and the subsurface. The OhmMapper system is illustrated in Figure 2 and consists of a transmitting antenna, one or more receiving antenna(s), a fibre-optic isolator and a data-logging console.

The system functions by imparting current to the subsurface using the soils as the dielectric in a capacitive 'circuit' between the system and the subsurface. Current distribution within the subsurface varies as a function of the electrical resistivity of the subsurface material and voltages generated by the current flow are sensed and recorded by the receiver dipoles. The receiver voltage depends on the transmitter voltage, the lengths of the dipoles, the separation of the transmitter and the receivers, and the resistivity of the subsurface. For any single measurement, receiver voltage is adjusted for the geometry of the transmitter-receiver arrangement and converted to an apparent conductivity by assuming that the subsurface is uniform. The dipole lengths and transmitter-receiver separations can be adjusted to assess apparent conductivities at different depths and with varying vertical resolution.



Figure 2: Towed OhmMapper array.

Whereas conventional electrical resistivity systems require the insertion of multiple electrodes into the ground, the capacitively-coupled OhmMapper is generally towed along the ground surface which gives it many practical advantages over conventional systems. System assembly and data acquisition are simplified and the data collection more rapid than with conventional resistivity systems. The OhmMapper is relatively insensitive to contact resistance problems experienced by conventional systems in the presence of gravels, exposed bedrock and permafrost. Areas that have traditionally been problematic for conventional systems, such as roads, asphalt walkways and frozen or wellcompacted near-surface sediments, can be surveyed with the OhmMapper. As well, rough terrain that contributes to the high labour intensity of the conventional resistivity systems (e.g. heavy tree cover, thick snow, steep inclines) can be surveyed with greater ease, provided there are cleared survey lines.

Electromagnetic (EM) methods are also commonly used in environmental investigations. These systems are useful for delineating the lateral extent of high conductivities associated with contaminants. However, observed values of apparent conductivity are bulk values that reflect all of the material within the sphere of influence of the system. For example, using an EM31 in vertical dipole mode at ground surface will yield an effective depth of exploration of 6 metres. Measured apparent conductivities will thus have contributions from all of the material between the ground surface and 6 metres below surface, reducing its capacity to clearly resolve the depth extent of particular anomalies. This is a very useful parameter for remediation planning.

As with any geophysical method, the measurement of apparent conductivity is susceptible to limitations. As exploration depth is increased, vertical resolution decreases. A significant limitation of the OhmMapper system is its relative inability to penetrate electrically conductive media to great depth. The nominal depth of exploration of the system is 20 metres but this is crucially dependent on array geometry and subsurface conditions (i.e. material conductivity, temperature, pore volume and fluid). In a situation where the target is beyond the depth capability of the OhmMapper, conventional (i.e. galvanic-coupling) electrical resistivity methods are required.

Direct comparison of OhmMapper data with conventional electrical resistivity imaging data collected at a separate site (Figure 3) shows little variation between the two. Similar lateral and vertical extents of the primary anomaly near the surface have been mapped using each method.



Figure 3: Direct comparison of conventional electrical resistivity technique (top) and OhmMapper (bottom). Modelled resistivity is relatively low at the red end of the colour spectrum and high in the blue zone. This example is taken from an environmental survey during which the OhmMapper was used to map the presence of conductive contaminant. Note that the cross-sections are not presented at the same scale but that the anomaly of interest exhibits similar lateral and vertical extents (Chidlaw and Henderson, 2009).

3 RESULTS

Site stratigraphy consists of sands overlying clays. The EM31 data were collected in vertical co-planar mode yielding an approximate depth of exploration on the order of 6 metres below ground surface. The data (Figure 1) show that there is a highly conductive area (approximately 200 mS/m peak magnitude) at the centre of the survey area. Slightly higher apparent conductivities have been recorded to the west and northwest of the central localised anomaly and may be an indication of contaminant migration or may be due to the presence of buried pipelines in this area.

Background apparent conductivities are low, corresponding to the clean coarse-grained sands comprising the near-surface soils.

The EM31 gives a reasonable indication of the lateral extent of the contaminated zone, i.e. relatively highly conductive zone. Problems with the EM31 include extremely limited depth resolution (begging the questions how thick is the contaminant? how deep to the base of it? to the top of it?) Also, in the presence of underground lines (pipelines or utilities), the data are compromised; in this case does the contaminant extend to the north or is the local conductivity high in this area due solely to the underground lines?

OhmMapper acquired along eight (8) north-south survey lines in an effort to more clearly resolve the depth extent of the contaminated area. Data are presented in Figure 4, progressing from west (topmost cross-section) to east (bottom cross-section).



Figure 4: Modeled apparent conductivity along each of the eight (8) survey lines. Results of laboratory EC measurements are included for comparison on Lines 3 through

There is very good agreement between the EM31 apparent conductivity data and the OhmMapper apparent conductivity model. Lines 1 and 2 exhibit a layer-like apparent conductivity high that extends along much of the cross-sections. The character of the anomaly changes at Line 3, becoming more bulb-like. The moderately conductive material extending to the north (right) of the anomaly is likely related to the basal clay unit identified at the site. The slightly higher apparent conductivities observed on Lines 7 and 8 may indicate a potential contaminant pathway or the presence of clean clays.

Based on the change in character of the anomaly from Line 2 to Line 3, the geophysical data show that there are, in fact, two separate anomalies. The anomaly observed on Lines 1 and 2 likely corresponds to contaminant associated with a break in an adjacent pipeline whereas the anomaly detailed on the remaining survey lines corresponds to the recent pipeline break that initiated the remediation process.

Results of laboratory electrical conductivity (EC) measurements conducted on samples taken from boreholes 102, 103 and 104 have been incorporated into the cross-sections along Lines 3, 4 and 5 for comparison and indicate that there is remarkable agreement between the two data sets. EC measurements on samples from the remaining bore holes, i.e. 101, 105 and 106 were relatively low.

These results allowed the environmental remediation contractor to reduce its estimate of impacted volume of soil from 1800 m^3 to 1500 m^3 .

The geophysical data indicate that the high-TDS material has migrated through the surficial sands and into the basal clay unit. During the reclamation process, the surficial sands were stripped and salvaged for reuse since the apparent conductivity data showed them to be uncontaminated. The environmental remediation consultants were able to save their client about \$80,000 in reclamation costs based in large part on the results of the geophysical survey.

Furthermore, variations in apparent conductivity associated with soil type can be used in developing a subsequent drilling programme by helping to determine the type of drill rig necessary and the depths to which to drill.

4 DISCUSSION AND CONCLUSION

Results of the geophysical survey show that the OhmMapper has successfully identified the presence of conductive materials associated with a pipeline break and has resolved their depth extent.

The survey has highlighted some clear advantages that the OhmMapper has over more conventional electrical resistivity systems and electromagnetic methods. The most readily apparent of these is the time required to complete the survey. The entire geophysical survey was conducted over one field day. It is estimated that at least 2 days would be required to acquire data along these lines with a conventional electrical resistivity system.

Resolution of depth extent is a decided advantage over electromagnetic methods, which offer lateral resolution but poorly resolve vertical variations in subsurface conductivity. Depth resolution allowed the environmental consultants to tailor a reclamation program that preserved the uncontaminated near-surface sands and resulted in a cost-savings to their client on the order of \$80, 000.

The OhmMapper is not without limitations. In very conductive environments, the signal penetration of the OhmMapper can be so severely reduced as to render the system ineffective, depending on the intended target. While increased apparent conductivities associated with elevated total dissolved solids (TDS) concentrations are mapped with relative ease by the OhmMapper, if TDS concentrations are low, the OhmMapper may not have the resolving capability required for the site, particularly if other, relatively conductive media, such as clays and silts are present in abundance. Similarly, the OhmMapper cannot be used to map or even detect hydrocarbon contamination.

Therefore, it is always advisable to ground-truth the data through a drilling and sampling programme which can be developed and/or streamlined using the geophysical data at the outset of the reclamation process.

The OhmMapper has an effective depth of investigation on the order of 10 to 20 metres. It is, thus, not suited to cases where depth of interest exceeds this range. If contaminant is expected to extend beyond the depth capability of the OhmMapper, other geophysical methods such as a conventional, galvanically-coupled, electrical imaging survey, would be recommended.

Collecting data over a systematic grid enables them to be presented as a pseudo-three-dimensional block model. This is advantageous because it facilitates lateral and vertical delineation of the contaminated zone, allowing volume estimates to be made and, subsequently, more customised reclamation programs to be developed.

REFERENCES

- Chidlaw, T. and Henderson, J. 2009. Resistivity Mapping at Salt Impacted Sites: A New Look at an Old Method, Canadian Land Reclamation Association Annual General Meeting and Conference, Calgary, Alberta, Canada.
- Chidlaw, T. and Morrissey, J. 2010. Resistivity Mapping at Salt Impacted Sites: Application of the OhmMapper, Canadian Land Reclamation Association Annual General Meeting and Conference, Calgary, Alberta, Canada.