THE USE OF GEOPHYSICS IN SUPPORT OF ENVIRONMENTAL JUDGMENTAL SAMPLING STRATEGIES

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Abstract

The determination of appropriate environmental media sampling strategies may often be complicated at sites by 1) poorly documented site ownership and operations history that could have impacted soil and groundwater, and/or 2) the lack of current on-site visual evidence or observations that indicate potential environmental areas of concern. Whether obscured by poor records and facility documentation or the removal of previous site features or surface conditions, the ability to develop a scientifically-based sampling and analysis plan (SAP) based on a valid conceptual site model (CSM) is a fundamental component of effective investigations geared toward risk-based assessment and corrective action. Through the results of two case histories at former commercial and industrial sites, this presentation describes the effective use of geophysical surveys to depict spatial variation in both subsurface materials and chemical impacts. As a result, site-wide characterizations of soil and fill materials are greatly enhanced prior to the development of stratified and targeted sampling plans. Electromagnetics (EM) and 2-D resistivity survey results are shown to reveal historical site operational components and migration pathways indiscernible with typical site characterization techniques. The results presented in this paper vividly demonstrate the advantages site characterization guided by geophysical surveys has over the conventional 'drilling-only' approach in which boring locations are randomly selected.

Introduction

As regulatory efforts have increasingly focused on more accurately quantifying the human-health or ecological risk posed by environmentally-impacted sites, media sampling strategies based on statistically-derived methods have continued to develop. These methods have attempted to identify existing similar, 'homogeneously-averaged' contaminant source areas over a site, and estimate the mean concentrations of contaminants of concern for comparison with established soil screening levels (SSLs) or acceptable regulatory cleanup concentrations (U.S. EPA, 1996; IDEM, 2001). For risk assessment purposes, an individual present on an impacted site in a future scenario is assumed to move randomly across an exposure area over time, spending equivalent amounts of time in each location. This random exposure presumption is the primary reason that statistical hypothesis testing procedures such as the Max test and the Chen method have been used to determine the number of samples required to achieve a certain degree of confidence in the site contaminant characterization.

In the majority of industrial and brownfield-type sites that require assessment, however, historic operational documentation or visual evidence needed to accurately define the size and geometric configuration of these contaminant source areas is often unavailable. As such, conceptual site models (CSMs) used to guide site sampling and analysis plans (SAPs) are fraught with uncertainty, and can lead to risk assessments that do not reflect 'real world' conditions. To minimize unknown or unexpected conditions that may be hidden beneath a site, and to define features such as preferential migratory pathways that can influence the on-site and off-site distribution of contaminants, geophysical surveys when used as a screening tool can be highly beneficial. While others have offered examples of specific geophysical techniques to improve environmental site characterization (*e.g.*, Holt et al., 1998; Holt and Daniels, 2000; Aal et al., 2001), use of multiple geophysical methods to guide site characterization is the subject of this paper.

Technical Approach

Environmental concerns at aged commercial or industrial properties often result from past site operations that have created subsurface disturbances from either the construction of the facility (e.g., floor slabs, foundations, utility lines, subfloor vaults) or the handling of virgin chemical products or wastes (e.g., chemical/liquid storage areas, chemical delivery or conveyance). Generally, these activities have disturbed the shallow soil profile, and have often altered the physical characteristics of the subsoils. The goal of environmental geophysical surveys is to provide a screening characterization of the shallow subsurface, typically the upper 10 feet, using methods which are sensitive to 1) metallic/conductive objects such as reinforced concrete, structural steel, underground storage tanks, utility lines, and metal-bearing fill materials and 2) variations in soil and fill types based on subtle changes in soil moisture, porosity, and chemistry. Identifying areas of similar and dissimilar geophysical properties helps to subdivide the site for stratified sampling strategies, and acts as a guide to near-surface sampling via soil borings or test pits. This sampling, in turn, is used to 'groundtruth' the geophysical data.

The scope of work used for the environmental assessments in the following case histories consists of three geophysical methods, each of which provides differing types of information. ***The first method***, used to locate and characterize metallic objects beneath the surface, is a detailed deep metal detection survey with a *Geonics EM-61*. The *EM-61* is an electromagnetic instrument that is commonly used to locate and characterize concealed metallic objects such as underground storage tanks, steel drums, utilities, metallic debris, and other metallic objects of interest lying in the upper 5 to 10 feet of the subsurface. ***The second method*** is apparent conductivity mapping using a *Geonics EM-31* terrain conductivity meter. The *EM-31* is an electromagnetic instrument that is designed to continuously map the apparent conductivity of subsoils in the upper 10 to 15 feet. It is primarily intended to quantify the apparent conductivity of low conductivity materials such as soils, rock and fill materials. ***The third method***, 2-D resistivity imaging, is one that selectively evaluates the vertical distribution of the materials encountered with the first two methods. An Advanced Geosciences *Sting/Swift 2-D* resistivity imaging system is used for this task. This instrument leads to the creation of modeled, 2-D cross-sections of true resistivity. 2-D resistivity imaging greatly aids in the vertical delineation of soil and fill better than terrain conductivity can do alone.

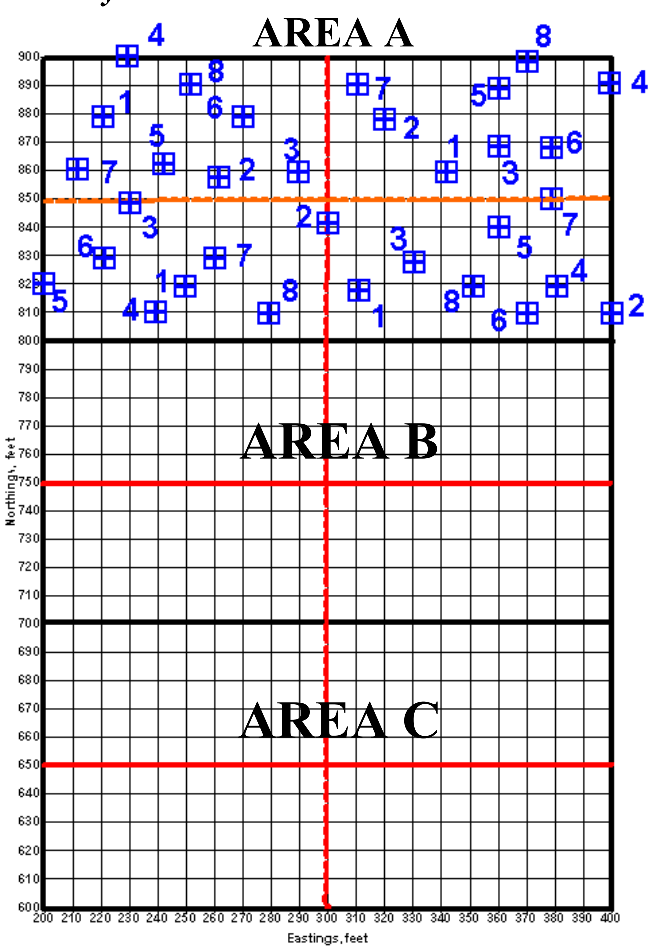
For both the *EM-61* and the *EM-31*, data is typically collected at the ground surface in a nearly continuous fashion along closely spaced parallel lines in a gridded pattern. Both instruments allow for rapid screening of multi-acre sites, particularly when used with global positioning on larger sites.

Based on the EM metal detection and terrain conductivity screening results, the selective acquisition of 2-D resistivity cross-sections can be completed with an *Advanced Geosciences Sting R1* resistivity meter and *Swift* automatic electrode switching system. Apparent electrical resistivity readings are collected along a specified cross-section that is favorably positioned over the EM-61 or EM-31 anomalies of interest. Stainless steel electrodes are driven into the ground at an equal spacing with an anticipated total effective depth of the electrical field penetration of 15 to 20 feet below the ground surface. Once the electrodes are emplaced, the automated data acquisition system is programmed to acquire electrical resistivity readings using standard array configurations designed to image the features of interest. The resulting apparent resistivity data set is subjected to a 2-dimensional inversion analysis that creates a true resistivity model of the earth. The following case histories demonstrate the usefulness of this multi-faceted geophysical survey approach in helping to develop effective stratified and targeted soil sampling strategies.

Case History No. 1 – Urban Brownfield

The first case history is the study of a 1.4 acre, rectangular-shaped, gravel-covered parcel presently being used as a parking lot in a downtown urban environment. Based on review of historical ownership records and Sanborn Fire Insurance Maps, the parcel had been developed since the late 1800s, and was reportedly used for a number of facilities including warehouses, a bar, a restaurant, a baker, and a dentist office. The site structures were reportedly razed during the last decade. Because of the desire to develop the property by an interested purchaser, subsurface exploration including drilling, soil sampling, and material analytical testing was to take place to determine the character of the subsurface materials for evaluating foundation support, excavation costs, and to assess the possible presence of any environmental impacts. However, because of the observed lack of variation in the current surface cover at the site (i.e., crushed stone) and poor historical records, a statistically valid, random sampling strategy requiring a large number of sampling locations would be needed to assure a high degree of confidence in the site characterization (e.g., see Figures 1 and 2). Instead, the prospective site purchaser opted for the use of a screening geophysical survey to develop a more targeted sampling program directed at specific areas of interest.

EM Survey Results



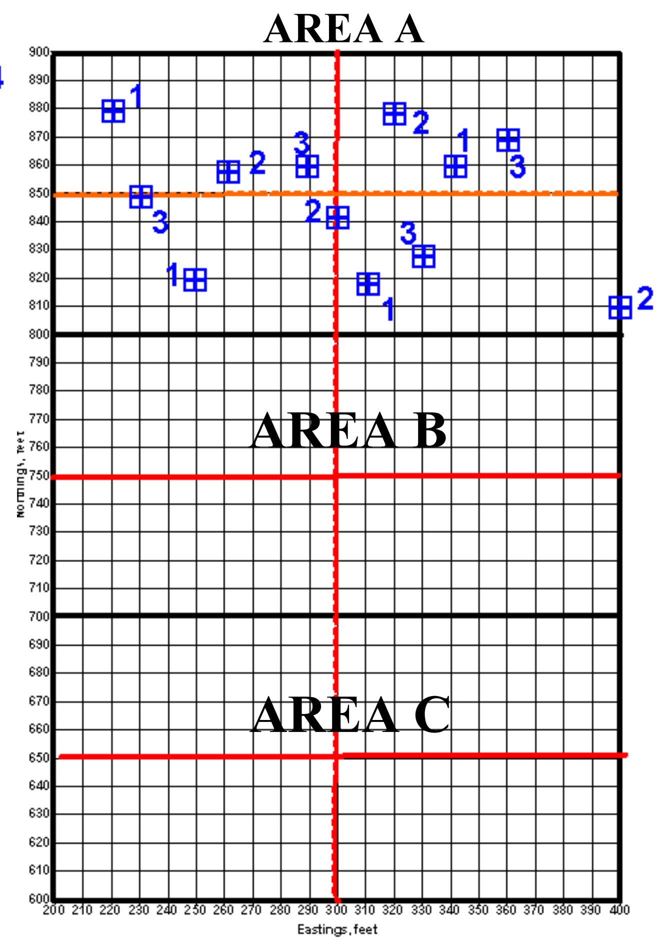
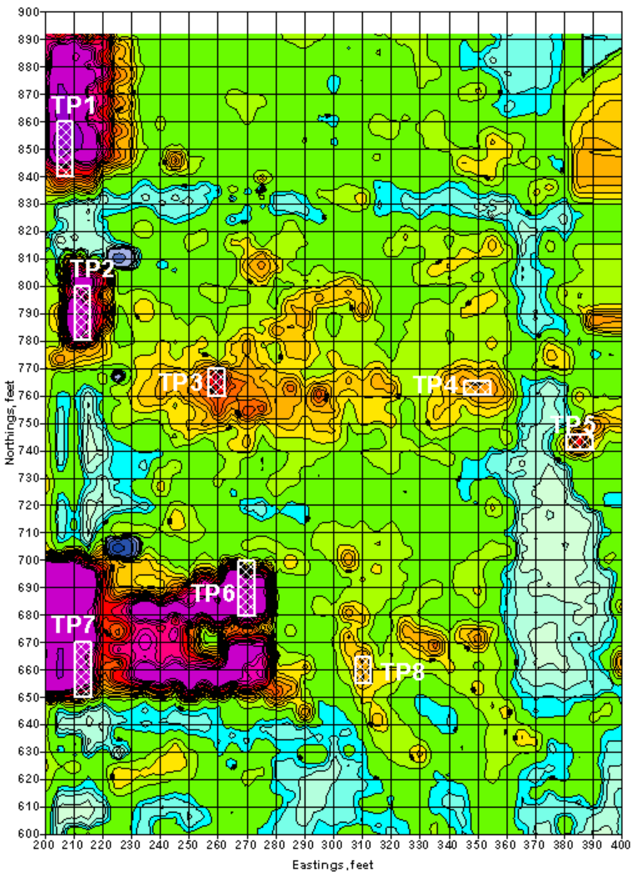


Figure 1, Typical Statistical Sampling Strategy for Nonvolatile Compounds using the Max Test (left) within the 0.5 acre Area A (left), and Figure 2, Typical Statistical Soil Sampling Strategy for Volatile Compounds using the Chen Test within Area A (right).

Figures 3 and 4 depict the results of the EM-61 channel difference and EM31 terrain conductivity surveys, respectively, for the site. For the EM-61 survey (Figure 3), buried metallic objects are likely present in areas where medium to high readings (yellow, orange, and red areas) are observed (magenta indicates locations where reinforced concrete pavement is present), whereas the areas with the uniform light blue and light green colors are relatively free of buried metallic objects. The depth, surface area, and electrical conductivity of buried metallic objects are revealed by the absolute peak intensity of the anomaly, the horizontal gradient, and the anomaly width. As shown in Figure 3, several significant metallic anomalies can be observed along the western border of the site, with smaller, isolated anomalies in the central and southern portions of the site.



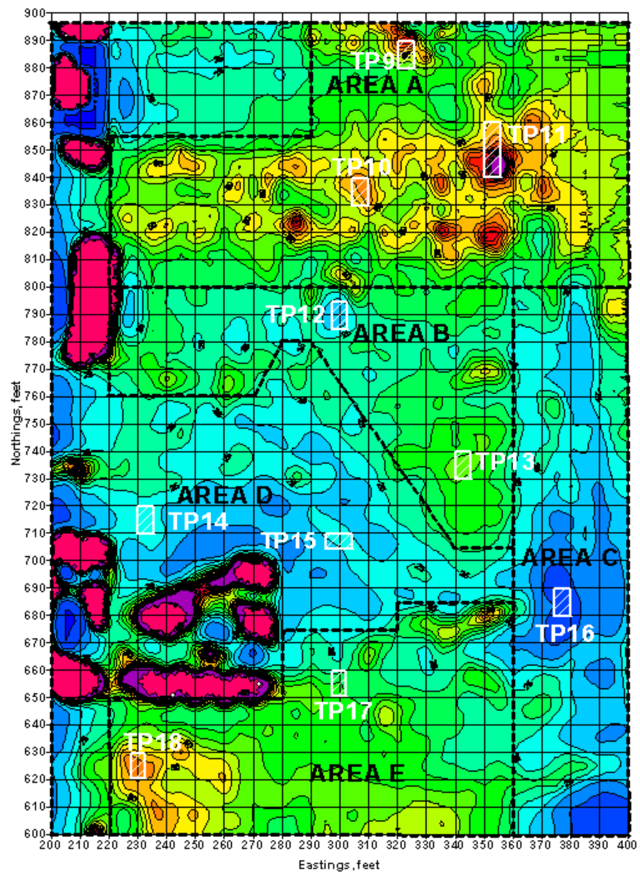


Figure 3, EM61 Channel Difference Map (left) and Figure 4, EM31 Apparent Resistivity Map (right). Data are presented as channel difference signal strength in millivolts for the EM61, and 5 ohm-meters resistivity (vertical dipoles) with a lognormal color scale for the EM31.

The color-filled apparent electrical resistivity map for the study area created from the EM-31 terrain conductivity survey is presented as Figure 4. The primary purpose for utilizing the EM-31 was to map lateral variations in the apparent resistivity of the soil or fill material in the upper 10 to 15 feet of the study area. Variations in the apparent resistivity across the site could potentially reveal a number of concealed features at the site including changes in soil or fill type or thickness due to past industrial development or operations. As shown in Figure 4, distinct areas with similar apparent resistivity characteristics are identifiable. These areas are discussed further below in selecting test pit sampling locations to obtain representative subsurface profiles of the site.

2-D Resistivity Results

One 2-D resistivity cross-section location was chosen to provide an image over the central portion of the site. The resistivity line was oriented in a north-south direction along coordinate 300E near the middle of the site. The results of the 2-D inversion modeling are shown in the cross-section displayed in Figure 5. A low resistivity area from about 690N to 760N is observed to a depth of about 10 to 12 ft. The geometric configuration and resistivity range indicate the potential for some kind of lower resistive soil or fill within a pit or former basement area. Shallower lower resistivity areas are also observed in the upper 5 ft from 760N to about 820N. Resistivity values tend to increase with depth north of 760N, indicating the possibility of relatively shallow natural sands and gravels that are part of the Pleistocene outwash common in this area.

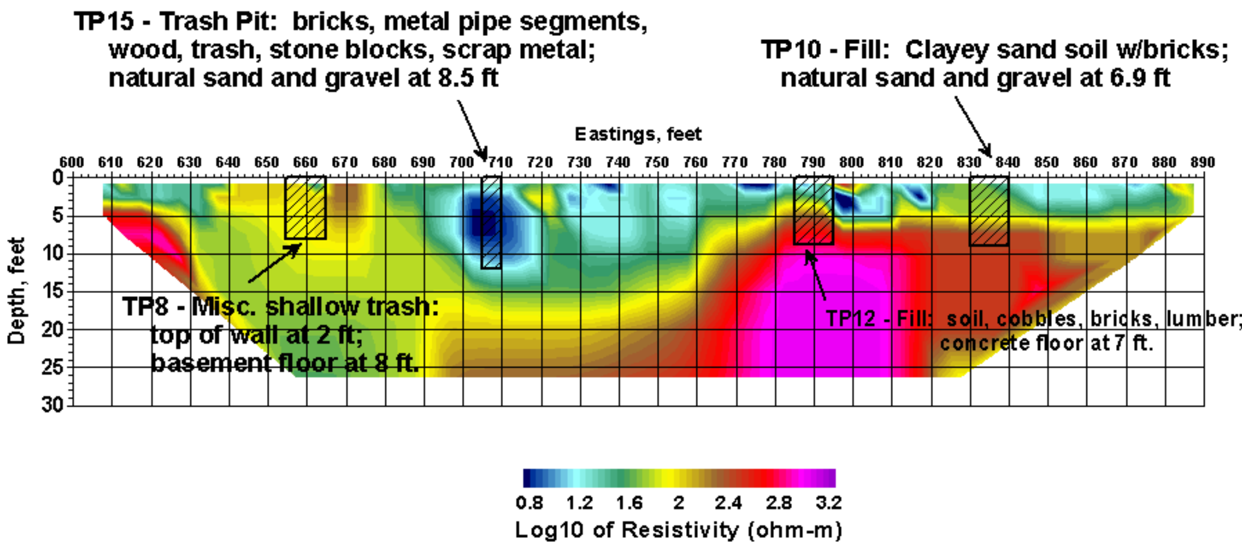


Figure 5. 2-D Electrical Resistivity Cross-Section Along Coordinate *Line 300E*.

Proposed Test Pit Locations

Based on the results of the geophysical survey, eighteen (18) test pit locations were selected for excavation and observation (see Figures 3 and 4). Eight (8) of those locations (TP1 through TP8, shown in Figure 3) were selected to determine the cause of significant metallic anomalies identified at the site. Ten (10) of the proposed test pits (TP9 through TP18, shown in Figure 4) were selected in five areas identified over the site (denoted as *Areas A*, *B*, *C*, *D* and *E*) that exhibited distinct resistivity characteristics. *Area A*, located in the northern part of the site, generally exhibits resistivities greater than 35 ohm-meters, with several smaller anomalous areas greater than 70 ohm-meters distributed within this area. *Area B*, near the center of the site, has intermediate resistivity levels (generally 25 to 35 ohm-meters) relative to the remainder of the site. *Area C*, along the eastern border, and *Area D*, within the south-central to western portions of the site, contain broad, lower resistivity signatures (less than 10 to 25 ohm-meters) relative to other areas. *Area E*, along the southern site border, again has intermediate resistivities (generally 25 to 45 ohm-meters). Within each of these five areas, test pit locations were selected that would be representative of the general character of each area. In addition, three test pit locations (TP12, TP15, and TP17, shown in Figure 4) were located along the 2-D resistivity line to aid in the calibration of material types at the site.

Test Pit Results

In general, the materials encountered in the test pits consisted of fill materials, primarily composed of building and construction debris, overlying natural sand and gravel glacial outwash deposits. The fill materials were of variable thickness over the site, and generally consisted of sandy and clayey soils, concrete slab fragments, bricks, wood, cobbles, with sheet metal, scrap metal and wire mesh noted at selected locations. Based on visual and olfactory observations, chemically-impacted fill materials of concern or asbestos-containing materials were apparently not encountered during these excavations.

In general, the geophysical signatures corresponded reasonably well to the types of materials encountered in the test pit exploration. *Area A* in the northern portion of the side had high concentrations of bricks at very shallow depths, with a concrete floor noted at a 7 ft depth (typically more resistive fill materials). *Area D* contained higher percentages of wet wood debris from former buildings (*i.e.*, more electrically conductive material). *Areas B* and *E* tended to have mixtures of construction debris (brick, wood, cobbles) with a resulting intermediate resistivity character. *Area C* (as determined from test pit TP16) contained a 3 ft thick layer of dark gray and blacked crushed cinders and ash resulting in much lower resistivity due to the higher moisture content and lower pH of wet ash. High intensity EM-61 metallic anomalies (magenta color) were found to be wire-mesh reinforced concrete slabs (TP2, TP6 and TP7) and one steel I-beam reinforced vault that required further evaluation (TP1). The moderate intensity EM-61 metallic anomalies appeared to correspond to smaller, metallic items such as steel pipe sections, sheet metal scraps, baking pans, electric motors and chains (TP3, TP4 and TP5).

Each of the fill material types encountered has a specific level of potential environmental concern, and each is classified as a regulated or unregulated waste type (e.g., clean fill, construction debris, special waste, and hazardous waste) that could require specific waste handling and disposal requirements if the site were developed. The results of the verification test pit excavations together with the geophysical mapping of areas of similar materials indicated that approximately 16,000 to 19,300 cubic yards of materials would require removal from the site to prepare the site for development. Additional analytical testing of selected fill components within each area would further define the waste type classification for proper disposal. Cost estimates were prepared for the prospective purchaser for developing the property that included contractor's excavation costs, material transportation costs, and disposal costs.

Case History No. 2 – Former Industrial Property

A prospective developer desired to construct a building addition over a 3-acre former chemical manufacturing facility that reportedly had had a number of on-site structures, including buildings, chemical storage tanks, and wastewater disposal pits. Operations at the facility had begun in the mid-1940s and were suspended in the mid-1970s, with demolition of all site structures completed by the early 1980s. Since that time, existing development adjacent to this site has continued. The site was subsequently purchased, landscaped, and developed for use as additional parking and ancillary green space for another manufacturer. To initiate the design process for the building foundations of the new addition, six geotechnical engineering borings were drilled in the proposed building footprint (see borings B-1 through B-6 in Figures 6). Glacial outwash sands and gravels were the only materials encountered in all borings to the maximum depths explored (40 ft). However, due to concerns by the developer about the effect that potential, undiscovered environmental impacts could have on the proposed development, it was determined that non-invasive subsurface mapping with geophysical techniques should be conducted in the expansion area and environs to guide additional exploratory trenching and drilling. The area of interest comprised approximately three acres of lawn and parking areas south and west of the southwest corner of an existing building. This geophysical survey area (shown with the surveyed grid system) along with site features is shown on Figures 6 and 7.

Metallic Anomaly Distribution

Figure 6 depicts the combined results of the EM-61 channel difference and EM-31 in-phase surveys denoting areas exhibiting metallic object anomalies. The metallic object anomalies seen on this figure can be divided into two categories. The first category is the "known features" anomalies such as buried utilities and known surface features located at or above the ground surface that were detected by the surveys. The second category is "unexplained" metallic anomalies that do not coincide with any known utility line or apparent surface feature. In general, there was excellent agreement between the site 'as built' utility map (shown on the figure) and most of the "known features" anomalies. Examples of such objects include buried utilities such as a fire protection line, electrical lines and ducts, and storm sewers and aboveground objects such as manhole covers, valves, metal grates, and landscaping items. There did remain, however, a number of "unexplained" metallic anomalies that are unknowns on Figure 6.

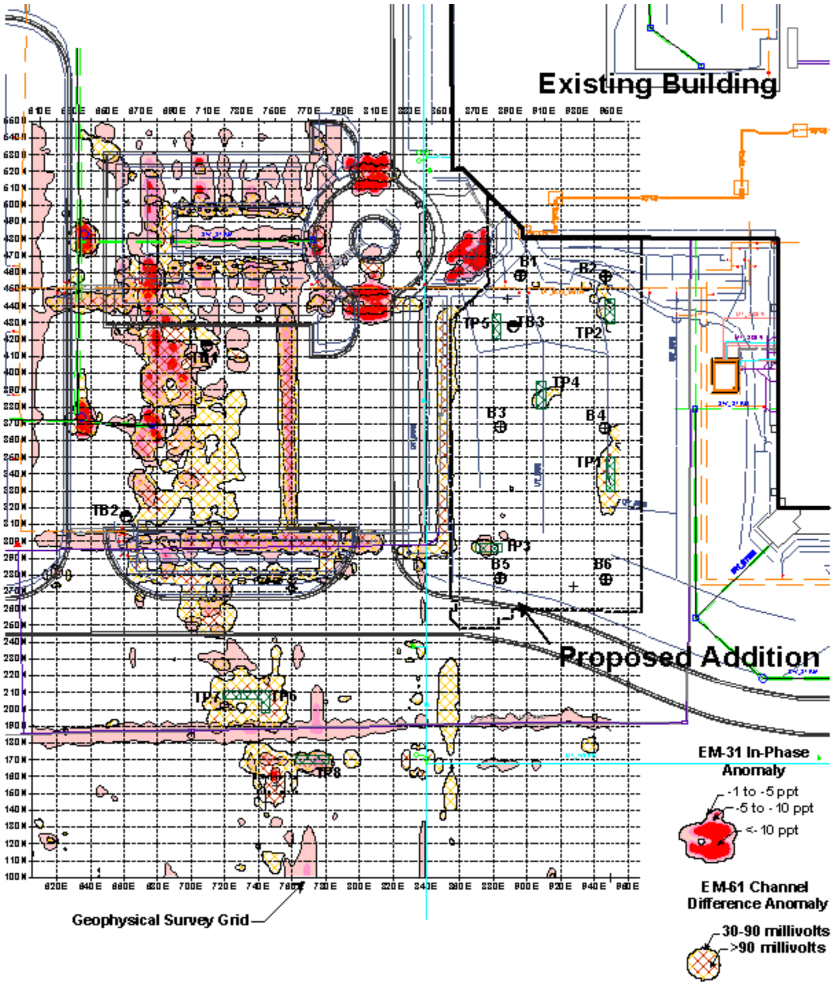


Figure 6. Magnetic Anomalies from EM31/61.

Soil/fill Resistivity Analysis

The variability of the subsurface resistivity was measured by analyzing the EM-31 data. The results of this analysis, with interpreted resistivity anomalies of potential interest, are summarized on Figure 7. It is clear that some of the residual anomalies are partially or completely attributable to the presence of metallic objects. Overall, the broad, "background" resistivity of the soils appears to fall into three discrete regions or "domains" as shown on Figure 7. *Domain I* lies east of approximately grid coordinate line 840E (east of the turn-around drive for the building and also extending south of the road immediately south of the building) and consists of the highest background resistivity within the study area (see uniform light blue area on east side of Figure 7). The resistivity in this area is elevated relative to the rest of the site. This elevated nature within *Domain I* suggests there is a fundamentally different soil/fill type in the eastern portion of the site, much of which coincides with the proposed building addition. Within *Domain I* are a number of high and low resistivity residual anomalies, some of which appear to be related to variations in soil/fill properties and possibly the presence of chemical contaminants which can either elevate or reduce electrical resistivity or reduce electrical resistivity.

The second area of similar resistivity readings, *Domain II,* lies in the western two thirds of the site (shown as the area of light yellow coloration in Figure 7). In this domain, resistivities are intermediate, with several anomalous areas noted in the southern portion of this area.

The third area of similar resistivity character, *Domain III*, is located beneath the parking area west of the existing building, and extending south to the existing building access road (shown as a light red coloration on Figure 7). This area is characterized by anomalously low residual resistivity values. Numerous unexplained metallic objects have also been noted in this area (see Figure 6). Based on limited historical site information, *Domain III* may have been the location of previous seepage pits and production buildings at the former manufacturing facility.

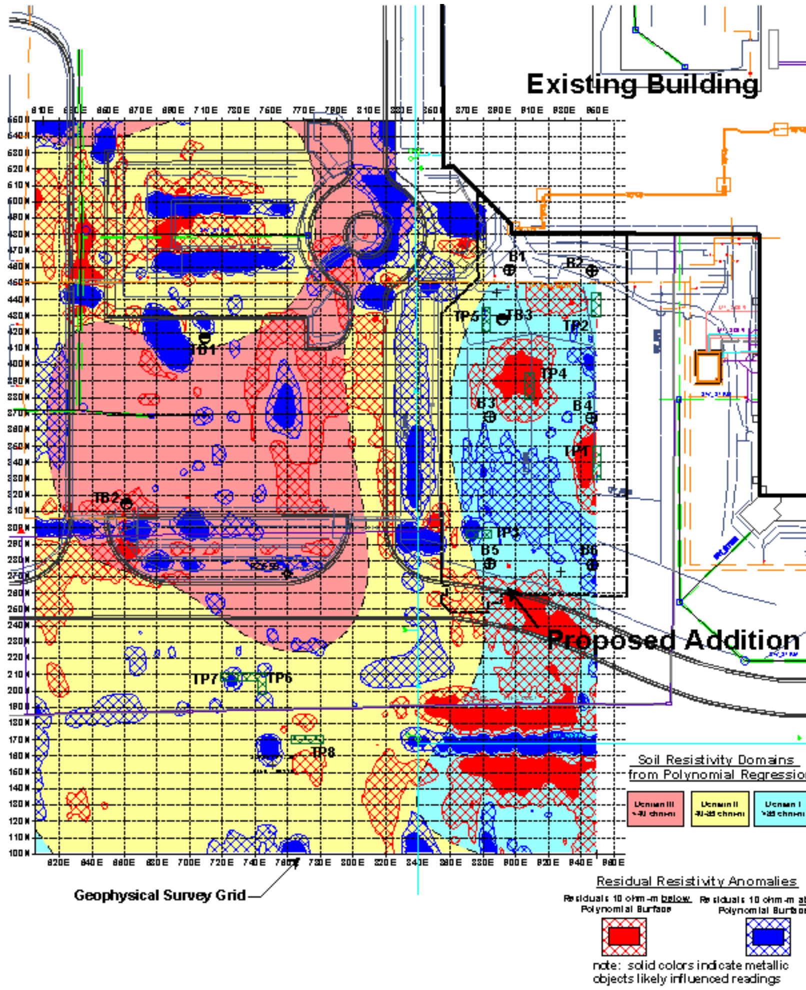


Figure 7. Soil Resistivity Domains with Residual Anomalies from EM31 Quadrature.

Proposed Test Pit Locations

Based on the results of the EM61 and EM31 geophysical surveys, eight (8) test pits (TP1 through TP8) and three soil boring locations (TB1 through TB3) were selected for excavation and observation (see Figures 6). Seven of the eight test pits and the one of the test borings (TB1) were completed to evaluate some of the unexplained metallic anomalies (not shown). Test pit TP4 was located within the footprint of the proposed addition where a negative residual resistivity anomaly appears to be attributable to both metallic debris and other materials.

Within the proposed building footprint, metallic debris including abandoned pipes (likely used for chemical or wastewater conveyance) was disclosed in test pits TP1, TP2 and TP3. The presence of miscellaneous debris within TP4 most likely allowed for a reduced resistivity within this material. Test pit TP5 contained clayey soils that were found to have chemical impacts. Miscellaneous metal pipes and chemically-altered sands were also disclosed in test pits southwest of the building footprint (TP6, TP7 and TP8).

2-D Resistivity Survey

One location for a two-dimensional resistivity cross-section analysis was chosen based on the EM31 electrical resistivity map (see Figure 8). *Line A* was positioned in an effort to cross the areas of highest and lowest resistivity anomalies observed on the site in one cross-section. As shown on the *Line A* cross-section, the line crosses near previous test pits TP4 and TP5. Within test pit TP4 at a depth of 3 ft, mixed debris was encountered. This debris consisted of cinder block, electrical conduit, scrap sheet metal, wood, partially burned plywood, an altered yellow material, a metal pressure gage, and a possible metal storage tank at a depth of 10 ft. As shown in Figure 8, these waste materials appear to show up as low resistivity materials from about 25 to 67 ft along *Line A* at depths ranging from about 4 to 12 ft. Note that this corresponds to a buried "blue and green" area within the cross section. Comparing this cross-section with the resistivity map in Figure 7, it is apparent that much of these low-resistivity materials reside beneath higher resistivity materials closer to the surface.

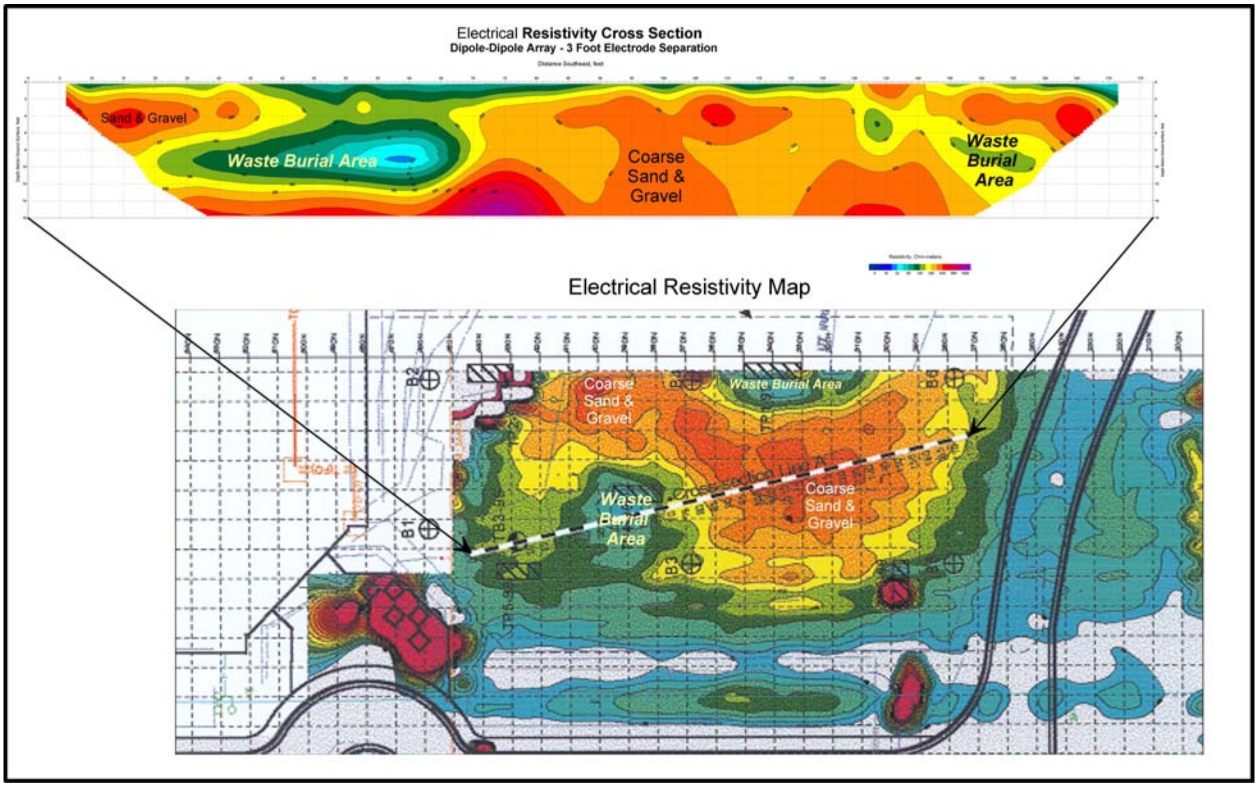


Figure 8. Electrical Resistivity and 2-D Resistivity Cross-Section *Line A*.

Between a distance of about 70 to 130 ft along *Line A*, higher resistivity materials from the ground surface to the maximum depth analyzed by the geophysical instrument (16 ft) were observed. Based on previous observations made during drilling of the six geotechnical borings previously noted, these materials most likely represent natural sand and gravel deposits. A higher resistivity "anomaly" centered at a distance of 75 ft along Line A and at a depth of 12 to 16 ft may be indicative of either an increase in the gravel content of these soils or some unknown feature yet to be disclosed. At distances of about 130 to 160 ft, another lower resistivity region appears at depths of 2 to 12 ft (note the green and yellow region). This region is shallower near a distance of 130 ft along *Line A*, and then appears to dip deeper to the south. This material may be indicative of sandy clay soils observed in test pit TP3 at a depth of 8 to10 ft that exhibited a slight chemical odor.

Observations during construction excavation indicated that chemically-altered yellow sands and gravels were discovered in the areas of lower resistivity from the geophysical surveys (see Figure 8).

Conclusions

Geophysical methods have proven to be valuable screening tools to support the development of site conceptual models and sampling and analysis plans. Armed with knowledge of the likely horizontal and vertical variability of the site surface and subsurface materials prior to the sampling phase of a project, intensive, statistically-based random sampling strategies can be replaced with guided, stratified sampling approaches using targeted or limited random sampling within potential source areas associated with geophysical anomalies. Significant costs savings may be realized in reducing the number of samples required to fully characterize the nature and extent of on-site chemical impacts, and improving the estimated exposure concentrations required in health risk assessments. This improved information can also be used to prepare development construction bid documents and estimates of potential costs for on-site remediation, material handling and off-site disposal of classified wastes. This information is vital to the successful completion of site remediation or brownfield projects where development costs can be significant if site characterization does not adequately address the material types observed during the actual construction process.

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