GEOPHYSICAL CHARACTERIZATION OF BROWNFIELD SITES FOR BETTER DEVELOPMENT EVALUATION AND CONSTRUCTION PLANNING

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Abstract

Subsurface characterization using standard drilling methods does not provide the level of detail necessary to accurately evaluate the true distribution of unexpected 'surprises' that often lurk beneath the ground surface at many brownfield sites. These 'surprises', which may come in the form of chemically-impacted soils, solid or hazardous wastes, debris or fill materials, and old structure foundations, can result in construction worker health and safety issues, difficult excavation conditions, and off-site waste disposal requirements. The end result: project delays, cost overruns and, in some cases, the termination of the project. This paper presents two case histories demonstrating the effective use of geophysical surveys in urban brownfield development. These surveys were shown to significantly aid the interpretation of actual site conditions, guide the development of appropriate contingency plans for handling 'expected' conditions, and provide more accurate estimates of actual development costs. Electromagnetic (EM) screening methods coupled with 2-D resistivity profiling are highlighted as a useful means of directing additional site sampling in areas of similar geophysical characteristics.

Introduction

Over the past ten years, there has been an increased awareness across the United States of the need to bring back abandoned commercial or industrial properties into productive use. Often called 'brownfield' properties, these sites have either real or perceived environmental impacts that may hinder their development. The first step in the evaluation of such sites is to perform phased investigations to determine the potential for environmental impacts and how those might affect the cost, schedule and liability associated with the future development. Contrary to other real estate transactions that occur, redevelopment of a property often involves significant regrading or excavation that will expose unknown site features previously buried. In order to minimize the 'unexpected' nature of such features, it is important that appropriate site investigations take place to aid the identification of past features of concern requiring further consideration during the planning process. While others have offered examples of specific geophysical techniques to improve brownfield site characterization (*e.g.*, Holt et al., 1998; Holt and Daniels, 2000; Aal et al., 2001), the use of a multi-faceted geophysical methodology to help in this endeavor is the subject of this paper.

Technical Approach

Features of environmental concern at older commercial or industrial properties are often the result of former site operations that have created 'disturbances' from 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). These activities have, in some way, altered the natural material properties and have disturbed the upper site material profile. Therefore, the goal of a brownfield geophysical survey is to provide a screening characterization of the shallow subsurface, typically the upper 10 to 15 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 across the site. Determining the variation in the subsurface materials by identifying areas of similar and dissimilar properties helps to direct the appropriate location of future near-surface sampling, soil borings or test pits to confirm these material types.

The scope of work used for the brownfields assessments in the following case histories consists of a multi-faceted geophysical survey approach conducted with three types of geophysical methods. ***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*** to be employed 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 optimally tuned to quantify the apparent conductivity of low conductivity materials such as soils, rock and fill materials. ***The third method*** used is the selective evaluation of the depth and/or thickness of the materials encountered using an Advanced Geosciences *Sting/Swift 2-D* resistivity imaging system. This instrument leads to the creation of modeled 2-D cross-sections using inversion modeling software (*e.g.*, RES2DINV), showing variations of resistivity corresponding to the types of buried soils and materials. In addition, 2-D resistivity aids in the vertical delineation of specific material types better than terrain conductivity alone.

For both the *EM61* and the *EM31*, data is typically collected in a nearly continuous fashion along closely spaced parallel lines, typically five to ten feet apart. Survey control can either be accomplished with a staked grid, or by using global positioning, although in the both cases presented here a staked grid was used. The *EM61* makes a measurement approximately every 0.63 feet as it is triggered by an odometer located on one of the instrument's wheels. The operator simply walks in a straight line while the *EM61* collects data as the rotating wheel triggers the instrument. The *EM31*, however, does not contact the ground and instead collects data based on time, rather than distance. An internal clock within the instrument collects data at a constant rate, 0.4 seconds per reading in this case, and the operator must carry the instrument in a straight line at a relatively constant pace. Positional control is maintained by pressing a trigger and imbedding a fiducial marker in the data at known intervals. Both instruments allow for rapid screening of multi-acre sites, particularly when used with global positioning on larger sites.

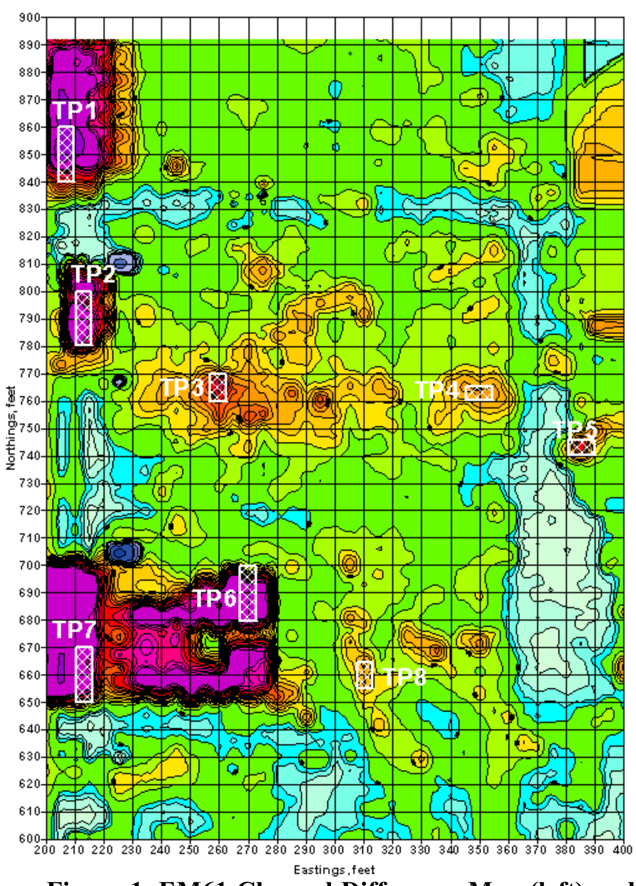
Depending on the EM metal detection and terrain conductivity screening results, the selective acquisition of 2-D resistivity cross-sections can be completed with an *Advanced Geosciences Sting R1* resistivity meter and *Swift* automatic electrode switching system. Apparent electrical resistivity readings are collected along a specified cross-section, with a varying number of stainless steel electrodes driven into the ground at an equal spacing of three feet 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 a standard dipole-dipole array. This array configuration is chosen because it is most sensitive to lateral changes in electrical resistivity, and might better detect changes in subsurface material type. Once the initial dipole-dipole array is acquired, additional electrodes are moved down-line to increase the line length where necessary. The resulting apparent resistivity data set is subsequently downloaded to a laptop computer for inversion analysis. The following case histories demonstrate the use of this approach in helping to characterization brownfield sites.

Case History No. 1 - Sampling Strategy Guidance

The first case history is the study of a 1.4 acre, 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 lack of variation in the current surficial cover materials at the site (i.e., crushed stone), the purchaser of the property desired a higher level of guidance to the subsurface characterization program than the typical ‘random sampling’ soil boring approach so that a more accurate portrayal of materials could be achieved.

EM Survey Results

Figures 1 and 2 depict the results of the EM61 channel difference and EM31 terrain conductivity surveys, respectively. For the EM61 survey (Figure 1), 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 green color are relatively free of buried metallic objects. The depth, surface area, and electrical conductivity



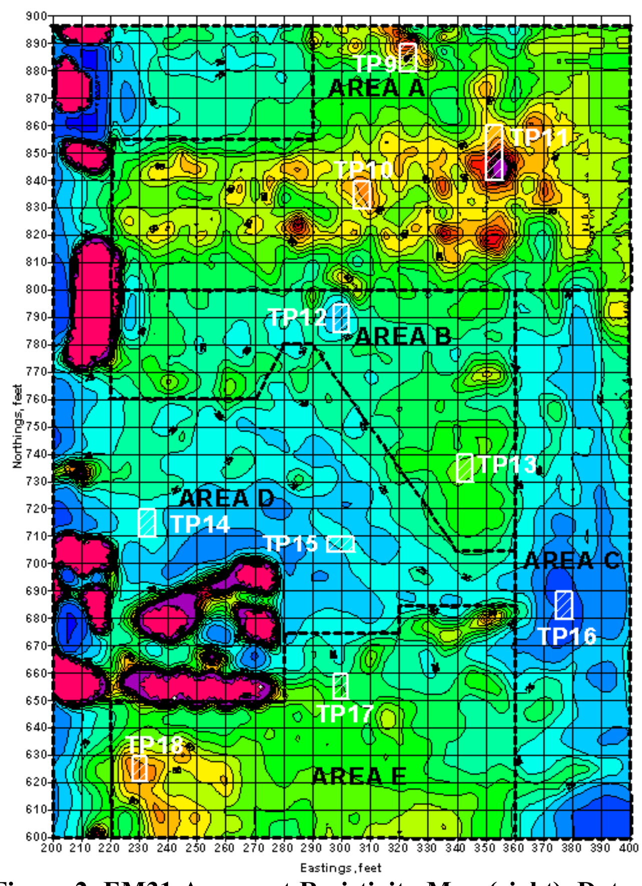


Figure 1, EM61 Channel Difference Map (left) and Figure 2, EM31 Apparent Resistivity Map (right). Data are presented as channel difference signal strength in millivolts for the EM61, and 5 ohm-meters resistivity (vertical dipoles) with a lognormal color scale for the EM31.

of buried metallic objects are revealed by the absolute peak intensity of the anomaly, the horizontal gradient, and the anomaly width. In general, very high peak readings (red to magenta, i.e., greater than 300 to 1000's of millivolts) combined with peak horizontal gradients greater than 100 to 200 millivolts per foot generally indicate the presence of relatively shallow objects (*i.e.*, depths of one foot or less). Conversely, peak readings of 300 millivolts or less (from orange to yellow to green coloration) with peak horizontal gradients on the order of 30 millivolts per foot or less generally indicate less massive and/or more deeply buried objects. In general, the same type of object buried at progressively greater depths will produce broader and less intense anomalies with depth. As shown in Figure 1, 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.

The color-filled apparent electrical resistivity map for the study area from the EM31 terrain conductivity survey (vertical dipoles) is presented as Figure 2. Note that the EM31 conductivity data were converted to apparent resistivity. The primary purpose for utilizing the EM31 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 2, distinct areas with similar apparent resistivity characteristics are identifiable. These areas are discussed further below in selecting test pit 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 north-south along coordinate 300E near the middle of the site. In this case 30 electrodes were used to collect a dipole-dipole array. The apparent resistivity data were processed with RES2DINV written by M.H. Loke. The results of the 2-D inversion modeling are shown in the cross-section displayed in Figure 3. As shown in the cross-section, 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

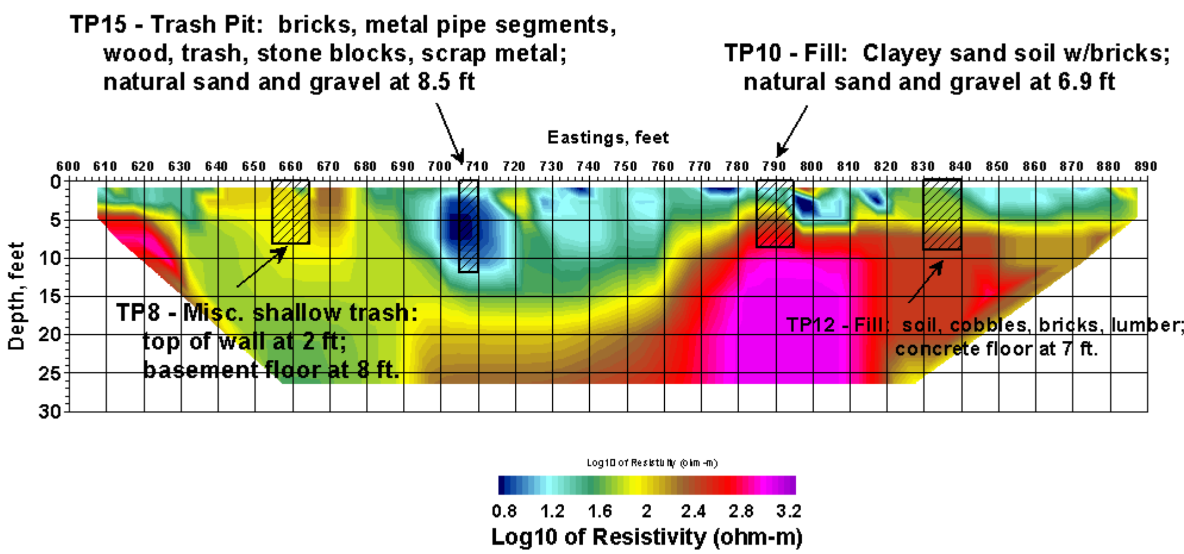


Figure 3. 2-D Electrical Resistivity Cross-Section Along Coordinate Line 300E.

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.

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 1 and 2). Eight (8) of those locations (TP1 through TP8, shown in Figure 1) 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 2) 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 2) were located along the 2-D resistivity line in order 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 EM61 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 EM61 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).

Development Costs

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 requires specific waste handling and disposal requirements during the excavation process. Development costs are often directly related to the waste type generated during excavation and the ease of excavation and segregation. This is especially significant if each of the waste types must be handled in a distinctly differing manner.

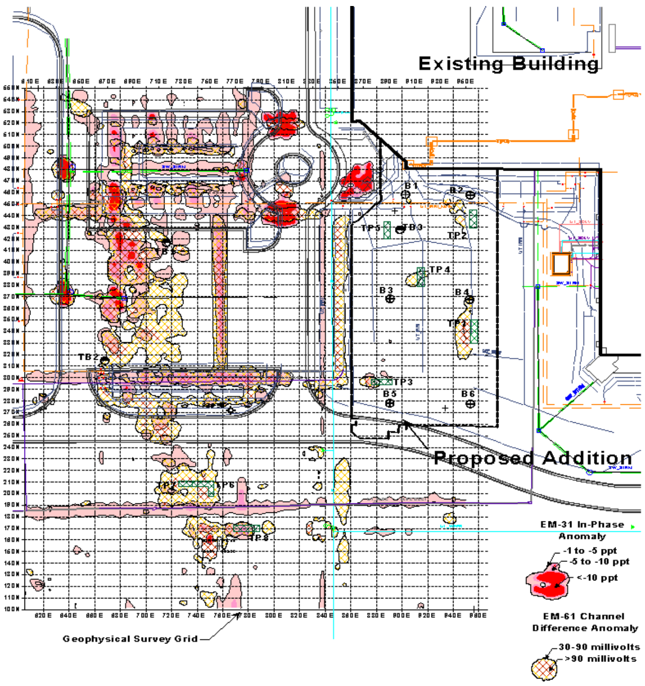
Cost estimates were prepared for developing the property that included contractor's excavation costs, material off-site transportation costs, and disposal costs for 1) clean fill, 2) building debris, and 3) contaminated fill. The results of the verification test pit excavations together with the geophysical 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, at a cost range of $525,000 to $970,000. Additional analytical testing of selected fill components within each area would further define the waste type classification for proper disposal. Based on these estimates, the future owner was ultimately able to negotiate a final purchase agreement on the property that took into account these contingencies, and provided bid specification documents for selecting a contractor to perform the work.

Case History No. 2 – Bid Specification and Construction Guidance

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 4 and 5). 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 4 and 5.

Metallic Anomaly Distribution

Figure 4 depicts the combined results of the EM61 channel difference and EM31 in-phase (vertical dipole, north-south orientation) surveys denoting areas exhibiting metallic object anomalies. Interpretation of EM61 anomalies is as previously described. For the EM31 in-phase component, interpretation is also relatively straightforward, although the anomalous signature of buried metallic objects is generally more complex than for the EM61. Metallic objects that are smaller than the intercoil spacing of the EM31 (3.7 meters) will produce an anomalous response consisting of a negative trough bounded by positive peaks on either side. Background readings will generally be near zero parts per thousand. For deeply buried and/or objects which exceed the intercoil spacing of the EM31, anomalies will generally consist of a singular positive peak.



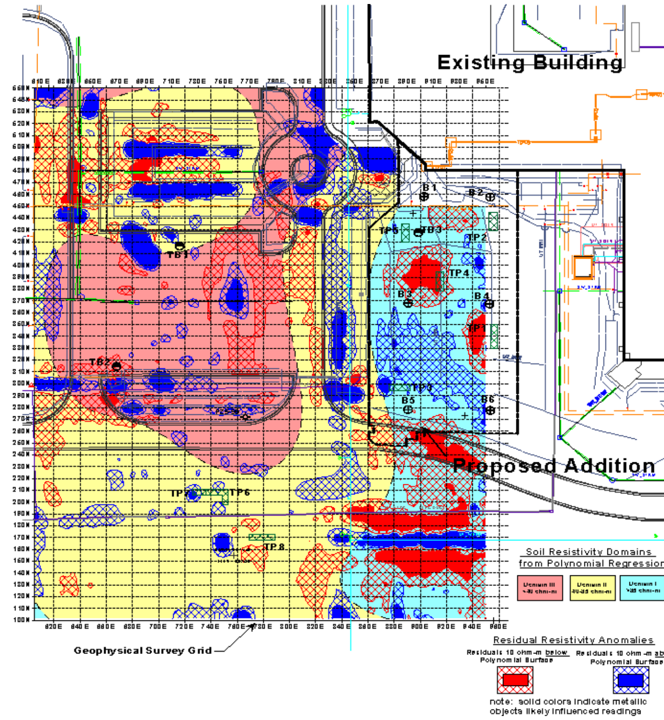


Figure 4, Metallic Anomalies from EM61/EM31 in-phase (left), and Figure 5, Resistivity Anomalies from EM31 Quadrature (right).

On Figure 4, the metallic object anomalies 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 4.

Soil/fill Resistivity Analysis

The variability of the soil/fill conductivity/resistivity was measured by analyzing the EM-31 quadrature component (vertical dipole, north-south orientation), converted to apparent resistivity. The results of this analysis, with interpreted resistivity anomalies of potential interest, are summarized on Figure 5. This figure is the result of quantitatively decomposing the resistivity into distinct spatial patterns denoting variations over both larger-scale (on the order of hundreds of feet) regions, which would be more indicative of broad changes in material type or thickness, and smaller-scale variations (on the order of a few feet to tens of feet) indicative of anomalous subregion areas. The technique used in Figure 5 was to mathematically fit a polynomial surface to the resistivity data using regression analysis. The fitted surface would then "approximately" represent the broad, large-scale trends presumably of a natural, geologic origin. Subsequent subtraction of the fitted polynomial surface from the original resistivity data results in discrete, residual anomalies of anthropomorphic origin and of potential environmental interest. Some of these smaller-scale anomalies may reflect activities from previous historical development and operation of the site that have locally altered the physical or chemical condition of the subsurface. This could include such activities as soil excavation and backfilling, building demolition, chemical spills, fuel dispensing, or waste or wastewater disposal (*e.g.*, seepage pits or lagoons).

The process of polynomial regression analysis was completed using Surfer Version 7.0 and was begun with a third-order polynomial equation approximation of the data set since the data were clearly more complex than lower-order surfaces. Progressively higher-order polynomial fits were completed until the residual was minimized. A sixth-order polynomial provided the best overall fit to the data set.

The residual anomalies resulting from subtracting the sixth-order surface are shown in Figure 5**.** Both positive and negative resistivity anomalies are present across the site. It is clear that some of the residual anomalies are partially or completely attributable to the presence of metallic objects. Careful consideration of the metallic anomalies shown in Figure 4 should coincide with review of Figure 5. Overall, the broad, "background" resistivity of the soils appears to fall into three discrete regions or "domains" as shown on Figure 5. *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 5). The resistivity in this area is elevated relative to the rest of the site, and the boundary of this area has been selected at the approximate inflection point at 85 ohm-meters resistivity. 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 such as mineralogy, moisture content, presence or absence of foreign objects, and possibly the presence of chemical contaminants which elevate electrical resistivity (e.g., generally organic compounds) or reduce electrical resistivity (e.g., generally inorganic chemicals such as acids, bases, and salts).

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 5). In this domain, resistivities are relatively uniform, and range between about 40 to 85 ohm-meters. Several anomalous areas are noted in the southern portion of this area, and these anomalies are generally negative (i.e., below background levels).

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 5). This area is characterized by anomalously low residual resistivity values (generally less than 40 ohm-meters). Numerous unexplained metallic objects have also been noted in this area (see Figure 4). Based on historical site information, *Domain III* may have been the location of previous seepage pits and production buildings at the former manufacturing facility. Past discharges into these pits of ionically-conductive materials could, in part, explain the low resistivity character of these areas (as well as the effects of numerous metallic objects).

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 4 and 5). Seven of the eight test pits and the one of the test borings (TB1) were completed to evaluate some of the unexplained metallic anomalies. 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 (see below for further discussion) 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).

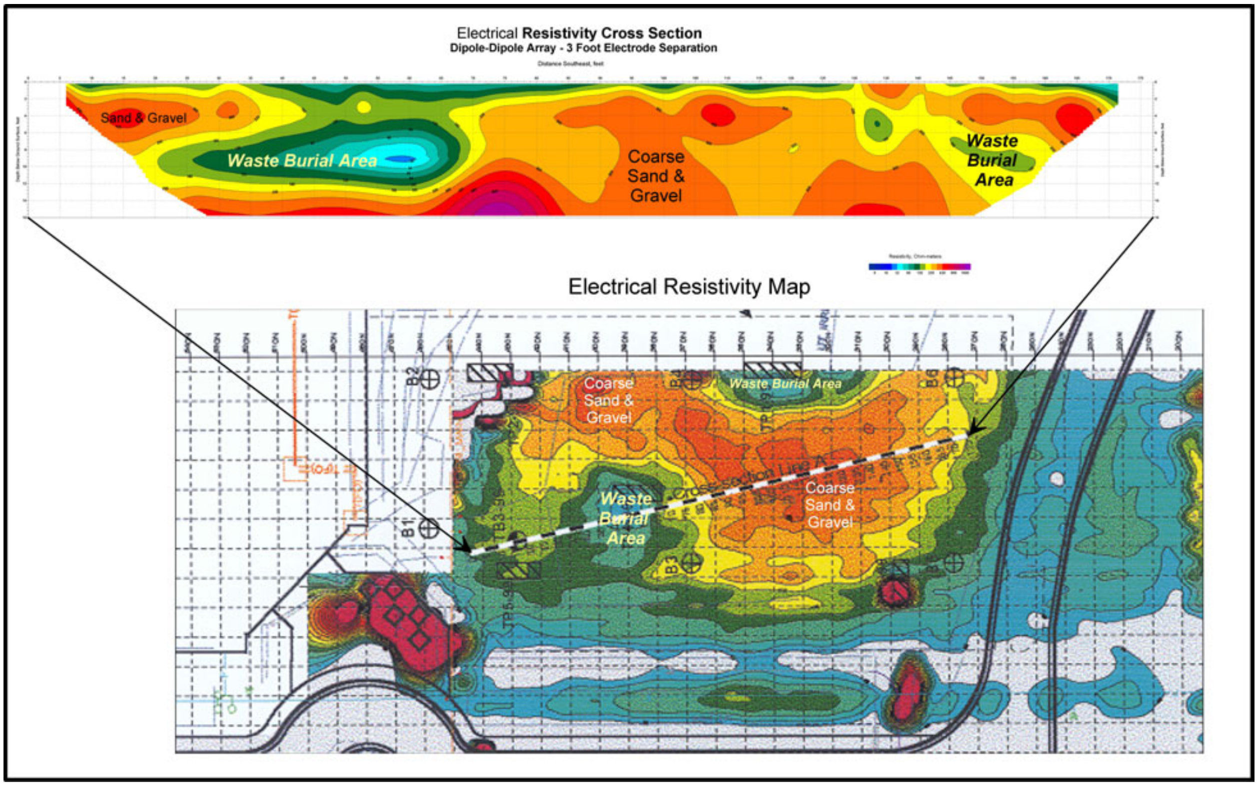


Figure 6. Electrical Resistivity and 2-D Resistivity Cross-Section *Line A*.

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 6). *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. The final total resistivity line length was 177 ft. A dipole-dipole array was used, and the data were inverted using RES2DINV. 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 6, 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 6, it is apparent that much of these low-resistivity materials reside beneath higher resistivity materials closer to the surface.

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 to 10 ft that exhibited a slight chemical odor.

Construction Planning and Oversight

The results of the geophysical survey were used to prepare the excavation contractor bid specifications for the project. An estimate of approximately 30 percent of the volume of the excavation required for the building basement would require special health and safety monitoring and handling procedures for off-site waste disposal. Predictions for the cost of removal of special wastes were originally estimated to be on the order of about $1,000,000. After the geophysical surveys, this estimate was revised to be on the order of $550,000. Observations during construction excavation indicated that chemically altered sands and gravels were discovered in the areas of lower resistivity from the geophysical surveys (see Figure 6). Final removal numbers for these wastes were within five percent of this revised bid. In addition, during the excavation for the new building, adequate health and safety and air monitoring considerations were planned and in place via an approved health and safety plan. This planning allowed for the completion of the excavation without delays or significant incident. Finally, post-excavation geophysical surveys (EM) were completed prior to building foundation construction to assure the developer that all environmental areas of concern were completely removed.

Conclusions

Geophysical surveys should be considered for every major brownfield redevelopment project in which the likelihood of past environmental impacts is possible. The approach outlined in this paper allows for the rapid characterization of subsurface materials that can help to guide site investigations through the advancement of soil borings or test pits. Anomalous areas as defined by the results of the surveys can be sampled to determine the presence of any environmental impacts, and allow for the calibration of various site materials to the geophysical signatures observed. These results can then be used to prepare construction bid documents and estimate potential costs for on-site material handling and off-site disposal of classified wastes. Health and safety concerns associated with various materials can be addressed prior to the initiation of the development, helping to minimize construction slowdowns and the request for change orders due to unanticipated conditions. This information is vital to the successful completion of 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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