Triad Issue Paper: Using Geophysical Tools to Develop the Conceptual Site Model December 2008

PURPOSE AND AUDIENCE

This technology bulletin explains how hazardous-waste site professionals can use geophysical tools to provide information about subsurface conditions to create a more representative conceptual site model (CSM). The CSM is a tool for gaining a synergistic understanding of the site, improve cost effectiveness, and improve decision-making within the Triad approach. Geophysical tools can be applied to create more robust CSMs with more complete data sets that result in a more representative and accurate depiction of the site characteristics at Brownfields and other hazardous waste sites.

1. GEOPHYSICS AND THE TRIAD APPROACH

The Triad approach (www.triadcentral.org) blends traditional analytical laboratory data (using strict data quality assurances) with rapid turnaround field methods to streamline the site assessment and cleanup process without sacrificing overall data quality. Geophysical tools may fit into the Triad approach as a "rapid" turnaround field method that has value throughout the site characterization process—from initial scoping though monitoring of remedial processes, and post-remediation monitoring. Relatively low-cost geophysical surveys can streamline the site assessment process and lead to higher "information value" by providing a more complete data-set. Other available field methods include, but are not limited to, direct push technologies, X-ray fluorescence, field-portable gas chromatography, and immunoassay kits.

The use of applied geophysics for subsurface investigation dates back to the mid-19th century. By the early- to mid-20th century, geophysics became the primary method for mining and petroleum exploration. Over the past several decades, geophysics has increasingly been adopted for environmental site-management and decision-making. Today, environmental site professionals are realizing the full benefits of characterizing sites using geophysical tools during all phases of site investigation.

Geophysical tools use non-invasive or invasive investigative techniques for measuring and interpreting material physical properties to determine subsurface conditions. The investigative tools can be as simple as a metal detection sweep; or as comprehensive as full site digital data collection of thousands of georeferenced data points collected with global positioning system (GPS) survey equipment, and integrated into what geologists may call a (site-specific, near-surface) Common Earth Model (CEM) or Shared Earth Model. The CEM can be a key piece of the CSM. The CEM is a quantitative subsurface model depicting all known data, which is continuously

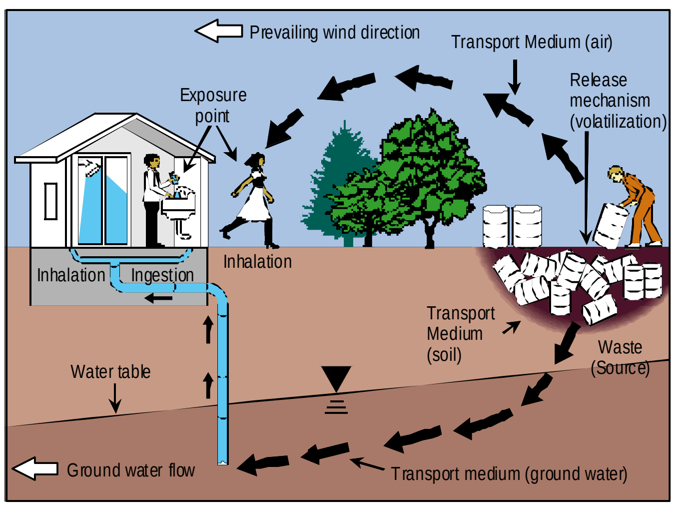

Figure 1: A Simplified Conceptual Site Model. Site investigation and CSM design assess the viability of exposure pathways from contaminant release points to human and environmental receptors. Shown here are potential exposure concerns from transport mechanisms including air, soil, and groundwater, which may lead to contaminant concerns with indoor air and drinking water. The usefulness of a CSM is in generating consensus and assisting with site-closure decisions by depicting a model representative of all data known about a site.

edited and refined as the collection of new field data proceeds.

The CSM is a central element of the Triad approach and any successful site cleanup. The CSM presents all of the relevant data collected at the site, and is not limited to the product the geologist may deliver as a "CEM." There is no prescribed format for the CSM. Information may be presented in various graphical or textual formats with more than one possible representation for a given site, where each component represents a different facet of the site characteristics. For example, Figure 1 depicts a simplified graphical CSM that shows contamination sources, pathways, and receptors. A more complex CSM representing the "final" synthesis of data collection at a site is shown in Figure 2. Each of these CSMs represents different site characteristics and levels of complexity; however, each one is valuable in communicating information about the site.

The CSM provides an interpretation tool, acts as a communication device, identifies gaps where more information is needed, and can be a tool to direct future work (Crumbling 2001). All stakeholders involved in the site, including technical staff and private citizens, reference the CSM for a clear understanding of site conditions and dynamics. The CSM is updated as the project team processes site data and the understanding of site conditions evolve. Updating the CSM continuously is a means of maximizing value obtained through data collection efforts. Site professionals use geophysical survey data to direct invasive sampling efforts and contribute to the CSM by providing information about subsurface conditions and through the sampling strategy.

Often the geophysicist is not the person responsible for overall CSM development and maintenance and, therefore, communication between the geophysicist conducting surveys and the CSM developer is crucial. Without clear communication, the CSM, and all of its dependent stakeholders, will not benefit from the added value of geophysical tools.

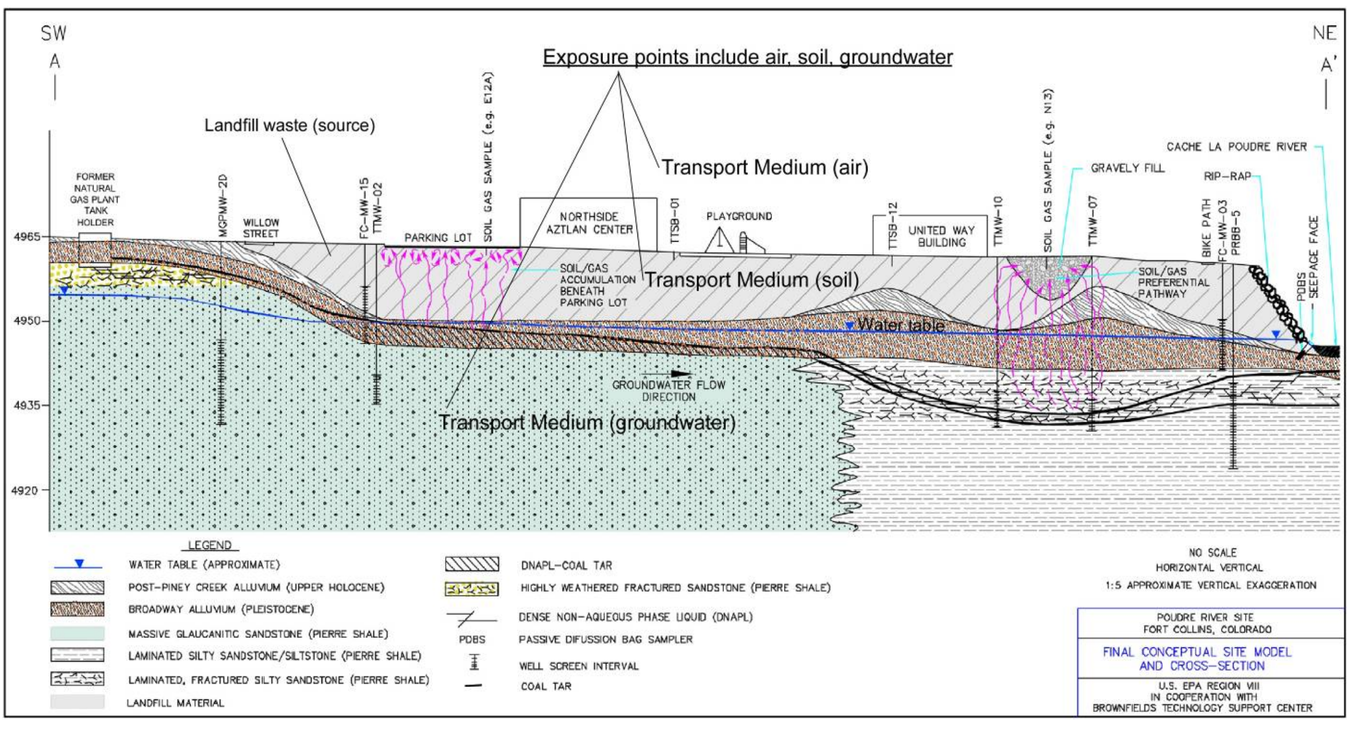

Figure 2: Poudre River Case Study Conceptual Site Model Cross-Section. Electromagnetic and resistivity geophysical surveys were used in conjunction with site characterization tools to map subsurface conditions across the site; including definition of the bedrock surface and identification of the presence or absence of preferential pathways such as bedrock fractures, subsurface channels in alluvium, and underground pipelines. Geophysical data aids the preparation of a more robust CSM. The updated CSM is then used to make decisions about characterization strategy and sampling design, and to assess site concerns related to human health and environmental cleanup.

2. GEOPHYSICS WITHIN A COLLABORATIVE DATA MANAGEMENT PROGRAM

The Triad approach minimizes sampling and analytical uncertainty by leveraging the strengths of each type of analysis in the CSM toolbox. Collaborative data management is a central part of this goal. In order to maximize project cost-effectiveness and efficiency, less expensive field methods are coupled with high-precision analytical methods. Multiple lines of evidence may be developed, with the field methods efficiently covering large spatial areas, and the highly precise analytical methods confirming the results. To understand and manage the relationship between these two data sources, data are classified into operational groups: (1) data for rapid initial CSM development, and (2) data to manage analytical uncertainty. Geophysical data can be used to guide sampling (drilling, etc.), and as a layer of subsurface information in the CSM that can help classify information into the proper risk context for decision-making. Other sampling methods are used to ground-truth the CSM geophysical survey data. Furthermore, the use of geophysics in CSM development may be broken down into two distinct types of uses: (1) as an <u>initial characterization tool</u> for getting a basic understanding of site's physical characteristics, or as a continuation of this use, and (2) as a <u>tool to gain a synergistic understanding</u> of the site. Each of these uses is discussed in detail in the following sections. No matter the application, the fundamental goal of using geophysical tools in CSM development is to obtain the most information from available site resources and direct sampling to maximize coverage and cost-effectiveness. A synergistic understanding may lead to using collaborative strategies throughout the cleanup, monitoring, and closure process; so it is important to think of using geophysics beyond the "assessment" phase of site cleanup.

2.1 Initial Characterizations Using Geophysics

Using geophysical tools during an initial characterization is an intuitive process offering rapid insight to subsurface physical properties. When used in this capacity, often only limited amounts of data have already been collected onsite. Data are usually collected in one or two field mobilizations, and geophysical data add detail to the overall CSM. The goal of the initial characterization may be defining site geology (highly porous and permeable channels, fractures, clay layers, etc.), locating buried objects (drums, underground storage tanks, etc), or mapping utilities. The results present a framework around which the CSM is constructed, or identify gaps or uncertainties in the initial CSM that must then be addressed.

2.2 A Synergistic Approach Using Geophysics

In many initial characterizations, the goal of the geophysical survey is achieved when a target is identified and site investigation can proceed to invasive sampling methods. This scope of work is appropriate at some sites, and no further geophysical investigations may be warranted. For example, a site assessment using geophysics may uncover locations where drums are buried and excavation can proceed accordingly. However, in other cases, an initial geophysical survey may only be the first step in a broader geophysical investigation for continual CSM refinement.

This CSM-building approach requires a broader scope of work. Rather than using geophysical methods in the one-time contribution described above, geophysical tools should be used in conjunction with sampling to strategically collect samples, compare analytical data with geophysical results, and repeat the process as necessary. At sites where monitoring wells are used for sampling, an example of this iterative approach may be to: (1) carry out an initial characterization to identify well placement locations, (2) compare sample analytical data, borehole geophysical data, and well log information to initial geophysical data, and (3) place additional monitoring wells based on the collaborative data sets and any additional characterization surveys necessary.

This approach produces a more complete picture of the site by leveraging the data from each step of the process. Because data are ground-truthed through collaborative analysis, the features observed in the geophysical data set may be attributed to subsurface properties with a higher level of confidence. A result can be increased confidence in the characterization of a contaminant plume or preferential flow pathway. The collaborative analysis may identify additional areas of concern and the iterative process takes over each time resulting in a better understanding of the geophysical data and how it relates to characteristics at that particular site.

2.3 Real-time Analysis and a Dynamic Work Strategy

In accordance with the Triad's incorporation of dynamic work strategies, survey design must be flexible to accommodate data results as they become available. Data are often available from geophysical surveys before the processing and modeling that follows a field mobilization effort. Efforts should be made to use these data products to direct and adapt the ongoing geophysical survey. However, generally speaking, geophysical methods are not truly "real-time" field screening techniques. Most methods require complex processing routines and strict scrutiny for a reliable, final interpretation. Data reviewed in the field are useful for providing a rough-cut idea of the final results and generally should not be taken as a final product. Whenever possible, data should be ground-truthed to verify any modeling or interpretation before preparing the final product. For example, data from resistivity profiling that require inversion can be considered in the field by processing data immediately after collection on a field computer. Although the models generated during field data processing may not be of high enough confidence to include in a final report, these data often provide sufficient information to immediately direct additional field surveys without the expense of an additional field mobilization.

2.4 Cost

Projects that follow the Triad approach have demonstrated an overall project cost savings of up to fifty percent over traditional management approaches (Crumbling et al 2001). The dynamic and continually evolving CSM created through the use of geophysical tools contributes significantly to this savings through improved site characterization that results in a more effective remediation and/or management plan. Although overall project costs are significantly decreased with the creation of an accurate CSM, the initial costs of site investigation may be higher than traditional approaches, potentially creating an administrative hurdle when initiating a geophysical investigation for CSM development. It is important to remember that investing in CSM development using the most appropriate geophysical tools will pay off by providing a clearer understanding of the site dynamics and result in an improved, cost-effective, site-specific assessment or remedy designed.

The actual cost of a geophysical investigation varies with the type and scale of the survey being conducted. Instrument specifics, terrain, labor requirements, size of survey, grid spacing, and other elements will all contribute to survey costs. Standard equipment rental prices can vary from less than $100 per day to over $250 per day, but these estimates do not include other mobilization and data interpretation costs and generally do not include the necessary processing software, which may be costly for some instruments. In most instances, a contractor is used to provide geophysical services and expertise. One day of work from a contractor using standard geophysical equipment may start at around $1,500 and may rise significantly depending upon survey specifics. These costs may be comparable to one day of drilling; however, the benefits of a drilling program supported by geophysical services may far outweigh the value of data from drilling alone by both guiding the drilling operation and potentially minimizing the number of required borings.

3. CHOOSING THE RIGHT TOOLS

The sections below provide environmental site professionals with a general understanding of different geophysical methods and the basics for carrying out a survey. A knowledgeable and experienced geophysicist should always conduct each step of a geophysical survey, from planning to interpretation, and should contribute to the Systematic Project Planning (SPP) concept using a dynamic work strategy approach.

While geophysics offers great promise in overall project cost savings and improved data coverage, poor planning and communication will result in wasted money or data that contribute little value to achieving overall objectives. Planning for a successful survey requires a working knowledge of various methods and a clear understanding of project objectives by all stakeholders.

Even though geophysics may be used in the earliest stages of the CSM development, choosing the appropriate tools to use at a site requires some understanding of the physical properties of the site that are expected to affect geophysical measurements. For example, ground penetrating radar (GPR) is often employed in an attempt to locate buried drums; however, this method is not suitable for use in many clayey soils that exhibit a high cation exchange capacity (CEC), because the CEC of the clay quickly attenuates the radar signal. Another common problem is buried electrical utilities. An electrical geophysical method may be the perfect tool for a specific problem, but electrical utilities may preclude its use at a site depending on the survey objectives and survey geometry. There is no "one-size-fits-all" approach for geophysical investigations, and each site will inevitably have a scientifically-based, site-specific work plan. The level of knowledge of site characteristics needed before conducting a geophysical survey will vary with the investigation's goals and the scale of the project.

No matter what tools are chosen, the most comprehensive data sets are born through the integration of several methods (Haeni et al 2001, Shapiro et al 1999). This geophysical "toolbox" approach reflects an understanding that a number of physical properties affect the data collected and the inherent heterogeneity of the subsurface can be better managed by a multi-method approach. Each data set, affected by different physical properties, can be compared and interpreted collaboratively. In addition, if one method fails to detect the target of interest, another method, already planned for use at the site, may provide detection.

4. COMMON GEOPHYSICAL METHODS

Geophysical methods involve a response to some physical property of the subsurface. In most environmental investigations, the main purpose of applying geophysical methods is to delineate some subsurface structure or other discreet target. To be able to resolve a target, there must be a sufficient physical contrast between the target and the surrounding matrix to cause a response in the measured signal. Table 1 (page 10) provides an overview of common surface geophysical methods applied to environmental problems.

Different methods rely on different physical properties. For the purposes of this document, the geophysical methods have been broken down into broad categories to provide an overview of the types of methods in use at environmental sites: magnetometry and gravity methods, electrical methods, electromagnetic methods, seismic methods, and borehole methods; all of which are discussed in the following subsections. These broad categories each encompass several specific methods. Methods such as magnetic resonance sounding and induced polarization, which are not yet in common practice in the environmental field, are omitted from the discussion. References containing detailed information on any method including theory, field operation, and data interpretation are provided below.

Regardless of the method, geophysical data are being integrated more often with digital positioning methods, such as differential GPS or robotic total station (RTS). This approach increases the overall positioning accuracy of the data and provides georeferenced data (that is, field data for which spatial coordinates are known) that can be overlaid with other site data, enhancing the quality of the overall CSM.

4.1 Magnetometry and Gravity Methods

Magnetometry and gravity methods measure small-scale variations in a larger field that is constantly changing with position and time. Both methods can take measurements using handheld instruments or, for large area surveys, an airborne 1-dimensional profile line. The two methods may be used to complement each other and facilitate interpretation.

In gravity surveying, a gravimeter is used to measure the strength of a gravitational field. After applying a series of corrections to account for latitude, elevation, terrain, etc., any anomalies (that is, a geophysical reading considered a deviation from normal data) present that are the result of subsurface density

Additional Resources

Books/Publications:
ASTM D6429-99, Milsom 1996, Reynolds 1997, Sharma 1997, Telford 1990, U.S. EPA 1991

Internet sites:

- U.S. Geological Survey, Office of Ground Water, Branch of Geophysics (http://water.usgs.gov/ogw/bgas/)
- U.S. Geological Survey, Toxic Substances Hydrology Program, Geophysical Characterization (http://toxics.usgs.gov/topics/geophysics.html)
- U.S. Environmental Protection Agency, Field-Based Geophysical Technologies Online Seminar (http://www.clu-in.org/conf/tio/geophysical_121201/)
- U.S. Environmental Protection Agency, Region 5, Field Services Section (http://www.epa.gov/region5superfund/sfdfss/htm/geophy.html)
- U.S. Army Corps of Engineers, EM1110-1-1802, Geophysical Exploration for Engineering and Environmental Investigation (http://140.194.76.129/publications/eng-manuals/em1110-1-1802/)
- Natural Resources Canada, Borehole Geophysics and Petrophysics (http://gsc.nrcan.gc.ca/borehole/index_e.php)

variations are recorded. Any subsurface target that creates a sufficient density contrast with the matrix (for example, unconsolidated sediments, voids, or rock) can be detected. Gravity surveying requires precise field instrumentation, a precise geographic location system (with elevation), and a detailed processing routine.

Magnetic surveys are more common in the environmental field than gravity surveys. Iron objects and magnetic minerals cause local variations in the earth's magnetic field. Magnetic surveys are often used to locate buried ferrous metal drums and underground storage tanks. The two common magnetic surveying measurement techniques are total field magnetometry (TFM) and gradient magnetometry. TFM uses one sensor and helps locate near surface objects and detect local trends due to larger scale geologic features and changes in soil magnetic susceptibility that may also be of interest to the site investigation. Gradient magnetometry measures the difference in the total magnetic field between two sensors separated by a small vertical or horizontal distance. Gradient magnetometry emphases near surface anomalies and does not require corrections for diurnal variations (variations due to solar activity) since both sensors are equally affected. TFM does require a correction for diurnal variation, but this correction is simplified with the use of modern digital data collection and software, and it does not add significantly to the field time. Magnetic surveys will not directly respond to non-ferrous metal or non-metallic objects, such as non-metal drums and composite tanks, or to container contents and spillage. Magnetometer and gravity data are most often presented in the form of plan view contour and/or color filled maps showing lateral changes in response.

4.2 Electrical Methods

Electrical geophysical methods measure the distribution of electrical resistance in the subsurface by applying direct current (DC) to the ground using, for example, two electrodes (current sources) and measuring the potential difference (voltage) between a second pair of electrodes (current receptors). The resistance data may be inverted to produce conductivity estimates. Multiple voltages can be measured at once using several pairs of source and receptor electrodes. Electrical methods such as direct current (DC) resistivity have become popular in environmental surveys as field resistivity systems have become more user-friendly and computing advances have made processing steps easier. Investigations to detect contaminant plumes, fluid-filled bedrock fractures, or landfill boundaries and voids, all lend themselves to the resistivity method if a sufficient resistivity contrast exists. Furthermore, resistivity surveys can be used periodically during a site remediation process to monitor changes in the subsurface electrical properties because of plume or contaminant attenuation. Field data must be processed to create a model of resistivity distribution in order to approximate the true resistivity of the measured subsurface.

The earliest resistivity surveys were conducted as soundings or profiles, and inverted into 1-dimension. Improvements in computing capabilities and advances in field equipment have increased the ease of performing more complex, 2- and even 3-dimensional imaging surveys. For these surveys, a multi-electrode system is typically used to collect a series of sounding data over a profile line or lines. Field acquired (apparent resistivity) data are inverted in 2- (or 3-) dimensions to produce a subsurface model. The final product may be as simple as a 2-dimensional profile, called an "earth section" or a "pseudo-section," to a full 3-dimensional image contoured to illustrate vertical and horizontal changes in subsurface resistivity. A multi-channel system can be used to collect near-continuous data and the system can be deployed as a towed survey on either land or water.

Electrical resistivity tomography (ERT) is a cross-borehole or surface to borehole application that produces a tomogram (an image constructed from ER data at the site) of subsurface resistivity. ERT surveys have been used for monitoring subsurface conditions that are expected to change over time. Electrodes are temporarily or permanently placed in boreholes and data are automatically collected using a surface multi-electrode system. ERT surveys produce a 2- or 3-dimensional model, often performed repeatedly over time as part of a monitoring investigation.

4.3 Electromagnetic Methods

The methods in the electromagnetic (EM) category are perhaps the most varied and diverse. EM induction (EMI) and ground penetrating radar (GPR) both fall within this category, although their methods of operation are quite different. EMI methods operate by inducing an EM pulse (referred to as an 'EM field') into the subsurface and measuring the secondary field generated by conductive and/or magnetic media or objects in order to map the distribution of these magnetic materials in the subsurface. Conversely, GPR relies on the propagation of EM waves in the subsurface and records reflections off subsurface structures and/or objects due to the contrast in electrical properties of these structures and objects.

EMI data are depicted commonly as factors of frequency (in milliVolts), depth (in feet or meters) or time between current induction and reception (in milliseconds). Methods may use a local, active source of induced EM energy (for example, terrain conductivity, time domain EM) or a remote source of induced EM energy (for example, very low frequency [VLF]). If an active source is used, an EMI instrument consists of a transmitter and receiver coil. A VLF unit only requires a receiver. With an active source, the transmitter coil produces a magnetic field that induces an EM pulse into the ground. If there are subsurface conductive materials, this primary EM wave generates a secondary wave that the instrument measures at the receiver coil. The fundamental principle of electromagnetic induction is the measurement of the change in impedance (the ratio of the electrical field to the magnetic-field strength) between the transmitting and receiving of coils above the earth after the EM energy passes through subsurface conditions with various electromagnetic properties. The strength and direction of the fields is used to determine the conductive nature of subsurface materials. Examples of these conductive media include subsurface soils and ferrous and non-ferrous metals.

EMI surveys have been used to map plumes and locate metal (ferrous and non-ferrous) objects such as drums, tanks, and utilities (Figure 3). EMI surveys are often the chosen method when the goal of a survey is to locate a buried anthropogenic object. Surveys by hand-held instruments (Figure 4), borehole surveys, and airborne surveys are all common applications. Some instruments have a fixed-coil spacing (giving it a fixed maximum investigation depth, unless variable frequencies are used), while others have adjustable coil spacing so the operator may change the depth of exploration. Instruments have trade-offs. A fixed-coil instrument, for example, may require fewer operators in the field and may be more rapid in data collection.

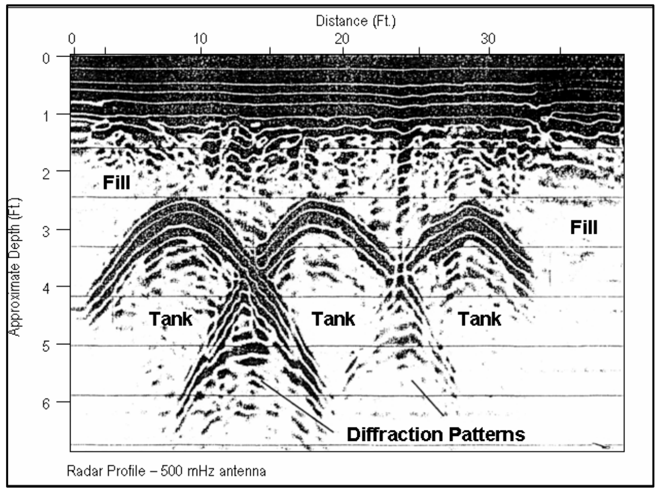

Figure 3: GPR survey of underground storage tanks. GPR produces an underground cross-sectional, two-dimensional image of the soils and subsurface features. GPR provides a high resolution, cross-sectional image of the shallow subsurface. A good example of geophysical tools, GPR works by sending a short pulse of electromagnetic energy into the subsurface. When this pulse strikes an interface between layers of material with different electrical properties, part of the wave reflects back, and the remaining energy continues to the next interface. Depth measurements to interfaces are determined from travel time of the reflected pulse and the velocity of the radar signal. GPR works well to detect fiberglass tanks or tanks beneath highly cluttered sites or building floors.

One advantage of the EMI system over resistivity systems is that direct contact with the ground is not required. EMI data is most often presented as a plan view contour and/or color filled maps showing lateral changes in response.

GPR transmits EM waves, or pulses, into the subsurface and records the reflections of these pulses off subsurface structures that have contrasting electrical properties. The amount of EM energy reflected back to the surface at an interface is determined by the material's ability to transmit an electric field (relative electric permittivity) between the two layers and the electrical conductivity of a layer. Therefore, only targets that have dielectric properties that contrast with surrounding media will be detectable using GPR. Dielectric materials are non-conductive, but can sustain an electric field; so "dielectric" relates to a layer's ability to transmit electric energy by induction and not conduction. Thus, EM waves are quickly attenuated by conductive media such as fine silts and clays with high cation exchange capacity, thereby greatly reducing exploration depth under these conditions. However, GPR is often used to detect areas of high conductivity in this way, such as a biodegrading petroleum plume. As seen in Figure 5, the final product is similar to that produced by seismic reflection. The amount of data processing necessary before final interpretation depends upon the complexity of data and subsurface conditions.

Best penetration using GPR is achieved in dry sandy soils or massive dry materials such as granite, limestone, and concrete. GPR provides the greatest resolution of currently available surface geophysical methods and is a method for detecting buried plastic containers. GPR has been used in environmental field work to locate buried objects such as drums, tanks, and utilities; although for these purposes EMI is often better suited, faster, and less expensive for initial or reconnaissance surveys. GPR has also been used to map or identify subsurface stratigraphy, disturbed zones, or conductive or resistive groundwater plumes.

Specialized GPR systems can also be used to collect borehole radar data either between two boreholes (radar tomography) or in a single borehole (reflection). Borehole radar can be used in polyvinylchloride (PVC) cased or open holes and can locate fractures or other targets that do not physically intersect the borehole. GPR data is most often

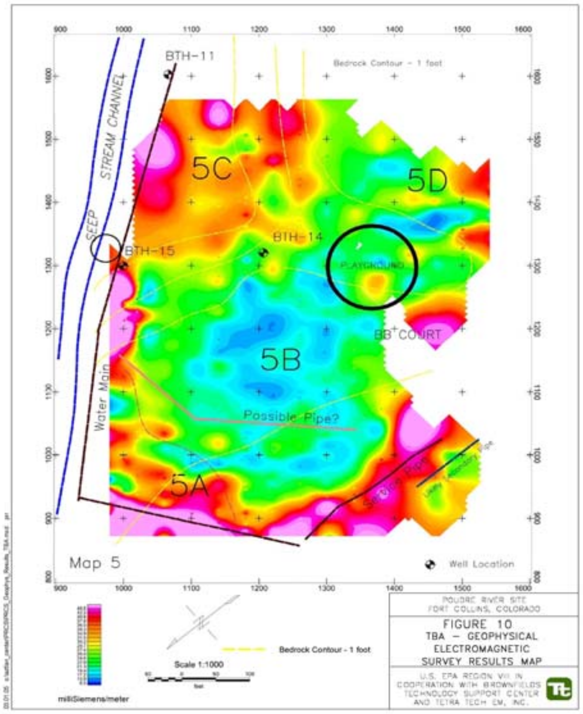

Figure 4: EMI survey results at the Poudre River site Case Study. Higher conductivity readings (shown in red) indicate denser subsurface lithology, influenced by bedrock topography and locations of subsurface metal objects. In general, the lower apparent conductivity materials are located at the northwest (lower left) half of the site. The range of conductivities here would suggest loose fill, sand, and other porous materials (such as landfill debris). The higher conductivity areas of the east and northeast (upper left) portion of the site nearer the buildings suggest engineering fill and fine-grained soil such as clay or clay-like silts. Data and interpretations from this survey were added to the CSM to produce the updated cross-section (Figure 2).The black circle indicates the boundary of a playground.

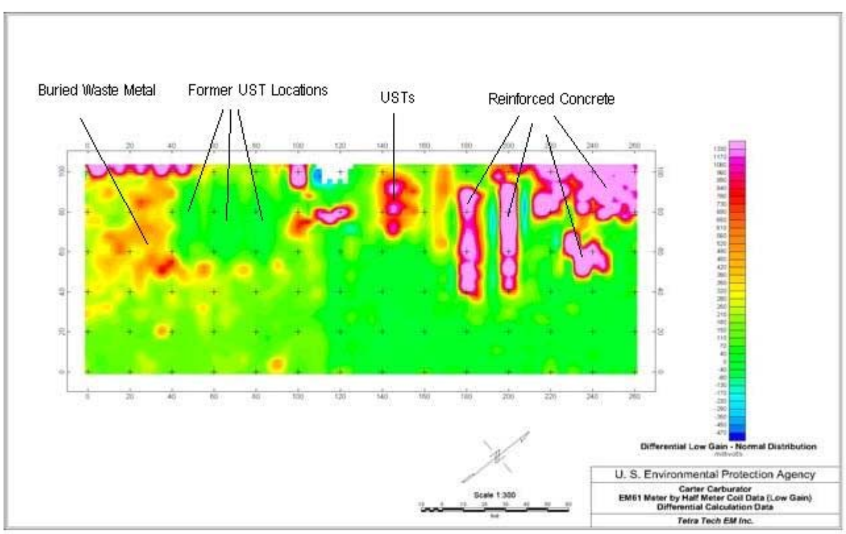

Figure 5: Electromagnetic (EM) Induction Time Domain Metal Detection Survey Showing Multiple Targets. EM systems can be used for near-surface environmental investigations, including detection of buried structures such as building foundations, as well as for the detection of highly conductive metallic objects like steel drums, tanks, large metallic utilities and other nondescript buried iron metallic objects.

presented in the form of profiles or cross sections similar to seismic reflection surveys (see Section 4.4 below) but can also be presented as 3-dimensional images and plan view depth or time slices showing lateral trends in instrument response.

4.4 Seismic Methods

Seismic refraction and seismic reflection are used in CSM development primarily to determine depth to bedrock, to determine depth to water table, and to map subsurface stratigraphy. Advances in equipment and automated processing have led to the increasingly common use of seismic reflection methods in both terrestrial and marine settings. Both methods transmit a seismic wave into the subsurface and measure the refraction of the wave off subsurface layers (seismic refraction method) or the reflection of the wave off these layers (seismic reflection method). These refractions and reflections are caused by either the seismic velocity contrasts in the subsurface (Figure 6) or the acoustic impedance of the subsurface stratigraphy. The contrasts can be caused by material contrasts as well as by the presence or lack of subsurface fluids, such as groundwater or contaminants. Refraction surveys can provide information about depth to bedrock and other subsurface layers such as the water saturated zone. Minimal data processing is needed for seismic refraction surveys. However, more detailed information about subsurface structure and stratigraphy can be obtained from seismic reflection surveys, which require significant data processing before final interpretation. The equipment used for each type of survey may be similar, but setup and acquisition time may be quite different. Final results may be presented as a profile of the subsurface or a contour map indicating depth to some layer, such as the bedrock surface.

4.5 Borehole Methods

Borehole geophysical methods are used to obtain subsurface information such as lithology, well construction, fracture orientation, or vertical groundwater flow. The combined use of borehole and surface methods described earlier at a site often yields the most complete geophysical data set possible through all phases of an investigation or remediation. Some borehole methods are discussed above in their respective method categories. Other standard borehole methods are presented in Table 2 (Page 12). Table 2 is not a comprehensive list of all methods; rather, it represents some of the more common methods used in the development of a CSM.

USGS field-scale examples of using borehole radar to monitor remediation:

- Vegetable Oil Biostimulation
  http://pubs.usgs.gov/sir/2006/5199/pdf/SIR2006-5199.pdf
- Steam-enhanced Remediation
  http://pubs.usgs.gov/sir/2006/5191/SIR2006-5191.pdf

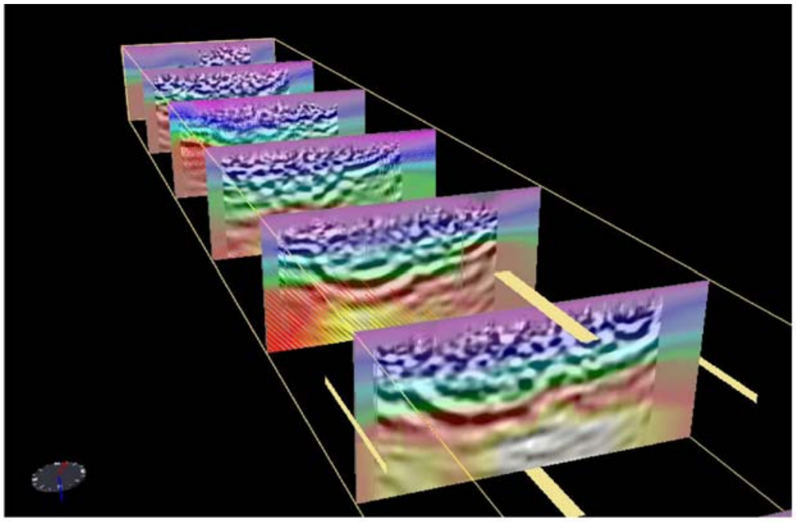

Figure 6: Seismic Velocity Subsurface Model. The top of each of the six cross-sections indicates ground surface with increasing depth on the y-axis. Each cross-section represents a parallel seismic 'slice' through the subsurface investigation area. The varied topography and presence or absence of interpreted geologic horizons indicate possible pathways for contaminants. For example, identification of subsurface channel morphology is clearly delineated in this vertical cross-section seismic velocity model. Spacing between sections is 8.75m. Violet represents seismic wave travel times at ~200 meters per second (m/s) and red at ~1000 m/s. In addition, shallow subsurface seismic models can be used to isolate lithology surfaces, the thickness of lithologic units, and even the competency of a unit at limiting vertical groundwater and contaminant migration.

Table 1: Common surface geophysical methods applied to environmental problems

Category	Operation	Common Methods	Typical Application	Typical Final Product
Magnetometry (See Section 4.1)	Measures the total magnetic field intensity that changes or is disturbed by subsurface features of contrasting magnetic properties. Typical units of measure: nanoTesla (nT), or nanoTesla/meter (nT/m) for gradient. Some environmental geophysics users prefer gammas and gammas/meter. Sensing technologies vary and will determine speed of operation. Range of detection increases with size of buried anomalies.	Total Field Magnetometry (uses one sensor – and base station recommended)	Locating buried ferrous metal objects such as MEC, drums, tanks, utilities landfills, waste pits, and foundations. Requires corrections to diurnal changes.	Color contoured or color filled plan view maps showing characteristic magnetic intensity responses from targets of interest (anomalies) in contrasting colors to background (ambient) responses. Data profiles along survey lines may also be produced, showing response curves that can be compared to standard models. Product may also indicate the amount of mass present (i.e., how much contamination, mappable by magnetic methods, is below ground). Other methods cannot provide this information.
		Gradient Magnetometry (uses two sensors)	Locating buried ferrous metal objects such as tanks, drums, utilities, MEC*, landfills, waste pits, and foundations. When used in combination with EM methods, can help delineate metal by ferrous and non-ferrous.	
Gravity (See Section 4.1)	Measures total attraction of the earth's gravity field that changes over subsurface media of contrasting density. Units of measure: Milligals (mgals) or Microgals (ugals).	Gravimetry	Mapping subsurface structural features such as voids and sinkholes.	
		Microgravimetry	Mapping subsurface structural features such as voids and sinkholes.	
Electrical Resistivity (See Section 4.2)	Electrical current is applied to the ground by a series of surface electrodes and the potential field (voltage) is measured at the surface between another set of electrodes. Electrode position, applied current, and the measured electric field are used to calculate resistivity. Unit of measure: Ohm-meter	Direct Current (DC) Resistivity	Mapping subsurface structural features and stratigraphy; identifying disturbed zones, significantly conductive or resistive groundwater plumes, and depth to groundwater and bedrock.	2D cross sections showing lateral and vertical changes in resistivity of subsurface features along a single survey line. The cross sections are mathematically derived from raw data pseudo sections and must be interpreted in light of available geologic information. 3D models can be derived from several cross sections.
Electromagnetics (See Section 4.3)	Measures the ratio of the transmitted electric and magnetic fields compared to received (induced) electric and magnetic fields from subsurface media. This ratio is converted into a relative response and conductivity, or resistivity. Units: milliVolts, milliSiemens per meter (mS/m) Range of detection (frequency domain) dependent on coil spacing. Range of detection limited to about 10-15 feet max. Best in sands; poorest in clays. Not recommended to operate two EM instruments at same time because they will interfere.	Frequency Domain Terrain Conductivity	Mapping lateral changes in soil, ground conductivity, contaminant plumes (only if significant thickness and difference exists between background conditions), and both geologic and anthropogenic features. Also useful in locating buried metal objects, such as drums, tanks, landfills, waste pits, foundations, and utilities. Averages large bulk area within range of transmitter and receiver.	Contour maps similar to magnetic data.
		Time Domain Metal Detection	Locating ferrous and nonferrous metal objects such as tanks, drums, utilities, MEC, landfills, waste pits, and foundations. Measures area directly under coils—which allows operator to detect shape of anomaly (i.e., for a tank, operator can detect lateral extents of tank).	
	Measures radar (electromagnetic) travel time, which is converted into velocity contrasts in subsurface media. Units of measure: Travel time/wave velocity in nanoseconds and nanoseconds per meter (ns/m) Often must test-run area to determine depth of penetration. Signals may not penetrate past first metallic objects.	Ground Penetrating Radar	Mapping subsurface structural features and stratigraphy; identifying disturbed zones, conductive or resistive groundwater plumes, and depth to groundwater and bedrock. Secondary application in locating buried objects such as MEC, drums, tanks, landfills, waste pits, foundations, and utilities. May be good at determining if buried objects have rounded or flat surface.	Profiles or cross sections similar to seismic records. Several GPR lines can be used to create 2D plan view and full 3D displays.

Category	Operation	Common Methods	Typical Application	Typical Final Product
Seismic (See Section 4.4)	Measures seismic energy travel time that is converted into velocity contrasts in subsurface medium. Units of measure: Travel time/wave velocity in milliseconds and milliseconds per meter (ms/m). Range of detection determined by geology and type of sound source to generate energy.	Seismic Refraction	Mapping subsurface stratigraphy in bedrock, low velocity unconsolidated materials and structural features such as voids and sinkholes. Particularly useful for finding depth to bedrock and groundwater.	Travel time curves in which 2D and 3D models are created.
		Seismic Reflection	Mapping subsurface bedrock stratigraphy and fine geologic structural features such as voids and sinkholes.	Seismic cross sections showing reflectors from rock interfaces in alternating black and white lines or shades of color. Several cross sections can be used to create a 3D model.

*MEC = Munitions and explosives of concern   Some information for this table derived from Hoover et al, 1996.

Table 2: Common borehole geophysical methods

Method	Casing Status/Type Required for Operation	Operation	Typical application
Optical Televiewer (OTV)	open borehole, PVC or metal casing,	Oriented 360˚ digital photo of borehole wall. Some optical units only show video view of hole (not orientated).	Fracture/void zones, orientation of fractures, orientation of strata, lithology, well construction, casing condition, screen condition or elevation location. Requires clear fluids for camera to view through.
Acoustic Televiewer (ATV)	open borehole	Oriented 360˚ acoustic image of borehole wall	Open fracture zones, orientation of open fractures, orientation of strata, well construction. Does not require clear fluids, can work in holes filled with mud.
EM Induction Logging	open borehole or PVC casing	Records the electrical conductivity or resistivity of the rocks and water surrounding the borehole.	Significantly conductive or non-conductive contaminants that contrast substantially from background, fracture zones, lithology (clay layers). Locate steel centralizers outside PVC casing (Caution: centralizers could be interpreted as clay or conductive interval).
Gamma Logging	open borehole, PVC or metal casing,	Records natural gamma radiation emission from formation.	Lithology (clay layers)
Normal/Lateral Resistivity (electric logs)	open borehole	Uses variably spaced electrodes to measure resistivity of borehole and materials surrounding a borehole. Logs are affected by bed thickness, borehole diameter, and borehole fluid.	Resistivity of borehole conditions, surrounding rock, and surrounding water
Caliper / Acoustic Caliper	open borehole	Mechanical arms / acoustic waves measure variation in borehole diameter.	Fracture zones, lithology changes, well construction casing joints, voids, changes in casing diameter
Heat Pulse Flow Meter (HPFM)	open borehole or screened	Measures vertical flow of water by tracking the movement of a pulse of heated water.	Transmissive zones, vertical groundwater flow
Colloidal Borescope (lateral flow meter)	open borehole or screened	Measures naturally occurring particles in groundwater moving through a well's screened interval. Observes flow at the pore scale, measure velocities ranging from 0 to 25 mm/sec.	Groundwater velocity, direction, capture zones, particle size, tidal influences
Cross-hole/Tomography	various	Measures physical properties of subsurface media between two or more boreholes. Commonly EMI, resistivity, and seismic methods are used.	Lithology, fracture zones, and conductive contamination
Spontaneous Potential	open borehole	Records potentials or voltages developed between the borehole fluid and the surrounding rock and fluids.	Lithology, water quality

5. CASE STUDIES

Increasingly, traditional geophysical techniques have found new and innovative uses at hazardous waste sites. Geophysical techniques have been used for decades in other industries, principally the petroleum and mining industries, for their ability to describe geological structures deep within the earth's crust. This proven track record has been applied to subsurface characterization at hazardous waste sites. Examples of how geophysical surveys have been used to improve CSMs are described in the following case studies.

Poudre River: EPA issued a Targeted Brownfields Assessment (TBA) grant in 2003 to evaluate the potential for official landfill closure to support the planned expansion of a recreation center built on the former landfill. Geophysical techniques were used at the Poudre River site to support the CSM and to establish a connection between potential landfill source areas and coal tar contamination found in a nearby river. A geophysical subcontractor conducted high-resolution resistivity (HRR) and GPR geophysical surveys to better define the bedrock surface and to identify the presence or absence of preferential pathways such as bedrock fractures, subsurface channels in alluvium, or underground pipelines. The survey was conducted prior to drilling and sampling mobilization to allow time for geophysical data evaluation, CSM refinement, and subsequent refining of the sampling strategy.

The use of geophysical techniques at the Poudre River Site provided a relatively inexpensive approach for addressing the project team's presumptions about the distribution of geologic features, such as preferential pathways at the site, and allowed the development of a more accurate CSM. Collaborative data analysis and a synergistic site approach were used to create a detailed soil and groundwater CSM based on geophysical and site sampling data.

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UConn Landfill: The U.S. Geological Survey, Office of Ground Water, Branch of Geophysics, conducted an intensive investigation to characterize groundwater contamination in fractured bedrock at the University of Connecticut Landfill. The investigation was undertaken as part of a collaborative effort with state and federal regulators, private consulting firms, and the public. A suite of surface and borehole geophysical techniques were used in conjunction with hydraulic and sampling methods to interpret data in an integrated and iterative process. The development of a groundwater CSM was a main goal of the investigation.

Surface geophysical methods (including several resistivity methods, EM induction, and seismic methods) were successfully used to identify fractures, to define the dominant fracture orientation, and to locate potential leachate plumes. Based on results from surface geophysical analysis, several boreholes were drilled and logged with multiple borehole geophysical methods including conventional methods. Borehole geophysical logging successfully differentiated high and low conductivity areas, which were attributed to lithologic changes and those caused by fluid-filled fractures. Further surface geophysical surveys coupled with hydraulic and chemical data interpretation helped to define the extent of the conductive contaminant plume and to produce an accurate CSM. The investigation occurred in stages, with the first comprehensive round of geophysical analysis, including surface methods, drilling, and borehole methods, completed in six months. The full scale, integrated geophysical investigation occurred over several years, continually refining the groundwater CSM.

Collaborative data analysis and a synergistic site approach were used to create a detailed groundwater CSM based on geophysical and hydraulic data.

Johnson, C.D., Dawson, C.B., Belaval, M., and Lane, J.W., Jr., 2002, *An integrated surface-geophysical investigation of the University of Connecticut landfill, Storrs, Connecticut—2000*: U.S. Geological Survey, Water Resources Investigations Report 02-4008, 39 p.

Johnson, C.D., Joesten, P.K., and Mondazzi, R.A., 2005, *Integrated borehole-geophysical and hydraulic investigation of the fractured-rock aquifer near the University of Connecticut landfill, Storrs, Connecticut—2000 to 2001*: U.S. Geological Survey Water-Resources Investigations Report 03-4125, 133 p.

Brunswick Naval Air Station: In order to refine a CSM for the Brunswick Naval Air Station in Brunswick, ME, the site contractor employed a suite of surface geophysical tools to map the bedrock surface, identify fracture zones, and to map the continuity and extent of key stratigraphic horizons. The contamination is attributed to past solvent disposal and is known to extend deep into an aquifer. Existing data from boreholes and cone penetrometer studies were integrated with geophysical data from seismic refraction and reflection, GPR, and resistivity to produce an integrated database and construct a 2-dimensional grid model.

A total of 28 geophysical survey lines using the above methods were carried out during the study. Data sets were processed individually and merged for conceptual modeling purposes. Each geophysical technique contributed to achieving the goals of the survey. GPR data were used primarily for modeling stratigraphy and depth to bedrock. Resistivity profiles aided in locating fractures and, to a lesser degree, identified depth to bedrock and stratigraphy. Seismic methods provided information on depth to bedrock and possible fracture locations. Final results were presented in integrated models showing depth to bedrock, fractures, and major stratigraphic units.

The entire geophysical investigation took approximately 3½ months to complete, including geophysical data collection and compiling and integrating almost ten years of previous site data from various consulting firms. A new extraction well was sited based on the improved CSM.

Creosote Investigation Using EM Methods: The U.S. EPA Region 5 and the Department of Geological Sciences at Ohio State University used EM induction and GPR to investigate creosote contamination at the former Baker Wood Creosoting Company industrial site in Ohio. Data compiled from the geophysical investigation were used to design an efficient, comprehensive, and cost-effective remediation plan. The study went beyond standard application of these methods by successfully detecting high levels of organic contamination that produced a resistive response, rather than the typical inorganic, electrically conductive plumes usually detected by EM methods.

Although clay-rich deposits are typical of the site geology, GPR still provided valuable sub-surface information. GPR data were collected in a cross-pole configuration (transmitter and receiver arranged orthogonal to each other) to improve the signal to noise ratio. GPR penetration was sufficient to detect back-filled trenches and a creosote-filled vault beneath a foundation. EM data were used to map the extent and depth of creosote compounds.

Contamination predictions based on the geophysical data were validated through sampling analytical methods.

Through integration of geophysics, an accurate delineation of site contamination was completed with as little invasive sampling as possible. In addition, locating previously unknown buried waste pits prevented possible future contamination.

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