Geophysical Imaging Techniques as a Screening Tool

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ABSTRACT

Geophysical studies provide an inverse solution to the resolution of environmental problems, and are analogous to a murder mystery investigation. In a murder investigation, we know a murder occurred, but don't know the cause (i.e., the murderer or weapon). Environmental geophysics then is used to image a site (i.e., the murder scene) and to identify the target (i.e., the murderer and weapon). In this way, geophysical representations of the subsurface provide a fast and inexpensive method for understanding the environmental problems prior to complex and expensive intrusive methods.

Environmental geophysical tools exploit field conditions (passive) or measure induced conditions (active) and collect data in either a profiling or sounding method, with computers producing real-time images. Passive methods include measurements of acoustic, electrical potential, electromagnetic, thermal, radioactivity, gravimetric, and magnetic fields. The last three methods are the most commonly employed environmental methods.

Active or induced methods include acoustic, seismic disturbance, electric induction, and electromagnetic imaging. Seismic reflection is used on a routine basis to image deep in the earth; however, seismic methods can also be used to image the shallow subsurface. Resistivity is a method for profiling the subsurface using electric current. Electromagnetic methods (e.g., time-domain, frequency-domain) use a specific electromagnetic frequency to induce a secondary eddy field and are the most common tools used in environmental geophysical investigations. Ground penetrating radar, a pulsed electromagnetic tool, can provide detailed subsurface profiles.

INTRODUCTION

Environmental geophysical techniques are rapid, cost effective means of preliminary site investigation (Hutchinson and Barta 2003). Various geophysical techniques reveal physical properties of the subsurface that can be used to determine, for example, the hydrogeologic framework, depth to bedrock, extent of groundwater contaminant plumes, locations of voids, faults or fractures, underground utilities, and the presence of buried materials such as waste, and steel drums and tanks (Milson, 1989; Reynolds, 1997).

Geophysical investigations are most effective when used in conjunction with a drilling or boring program, and should not be considered a substitute for these intrusive methods. Environmental geophysics only provides focus and direction for a more cost effective intrusive investigation such as; optimal well or test pit placement, waste recovery or capping, or void avoidance or rehabilitation. Further, recent improvements in the resolution, acquisition and interpretation of geophysical data have lowered the cost and increased the application of environmental geophysics.

Each geophysical method has its advantages and limitations and a more effective geophysical program includes 2 or more techniques to fully understand the site's subsurface conditions. Six surface geophysical methods are commonly used in environmental geophysics. Passive methods include gravity and magnetics; and the active methods include acoustic, electrical imaging, electromagnetic and seismic imaging.

Passive Measurements

Geophysical field measurements consist of measuring existing physical properties of the earth, such as temperature, nuclear-response, acoustic, magnetism, and gravity. Temperature, acoustic and nuclear-response are usually relegated to the health-and-safety side of environmental work and are not discussed herein. The most common geophysical passive field methods include magnetism and gravity.

Magnetism

A magnetometer is an instrument that measures the earth's magnetic field strength in units of gammas or nanoTeslas (1 gamma = 1 nanoTesla). Disturbances in the earth's magnetic field are caused by variations in concentrations of ferromagnetic material (Nettleton, 1976). A buried drum, for example, disturbs the earth's magnetic field and results in a magnetic anomaly. The magnetometer when coupled with a digital global positioning system (DGPS) can be used to generate maps of anomalous areas that can then be interpreted for subsequent intrusive investigations. The three most common magnetometers include the flux-gate, proton-free precession, and alkali optical-absorption. The flux-gate is more commonly used to sweep an area without data-logging capabilities. The proton-free precession magnetometer is a sounding type tool, whereas the alkali optical-absorption, for example the cesium, magnetometer can record in a continuous mode for rapid data collection when coupled with a DGPS.

Magnetometers will find ferromagnetic objects such as underground storage tanks, unexploded ordinance, utilities, and dikes (i.e., groundwater investigations; Hutchinson et al., 2005). These tools are easy to deploy and relatively easily interpreted (Figure 1).

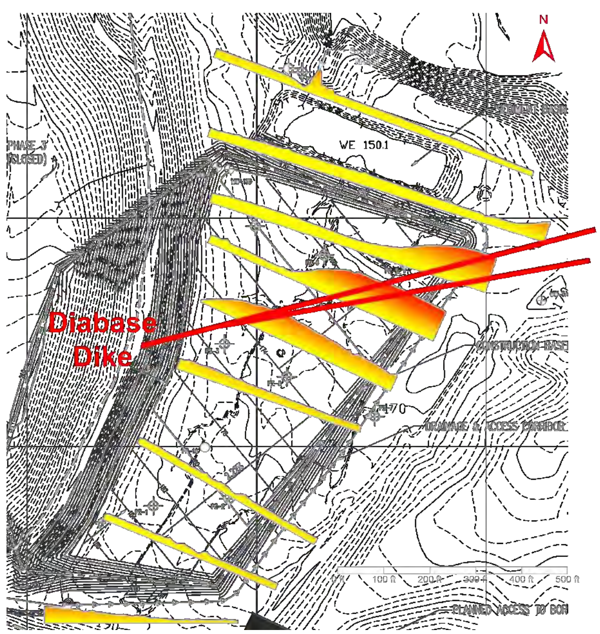

Figure 1 Proton-free precession magnetometer survey for the location of a magnetite-rich igneous (diabase) dike (scale, 100-meter grid; contour interval, 1 meter).

Gravity

A microgravimeter measures the acceleration due to the earth's gravitational field (in milligal = 0.001 cm/sec^2). This method is a sounding type tool and can be slow. Two variables must be solved for interpretation of microgravity data; density contrasts between the underlying materials and depths of the contacts between areas of density contrasts (Carmichael and George, 1977). Further, an accurate vertical and horizontal position for each location is necessary for data processing.

Microgravity measurements are not readily impacted by cultural noise; consequently, microgravity measurements can be collected in heavily populated areas, including buildings. Microgravity has been used for many geologic purposes; however, for the environmental geophysicist, microgravity is used to determine the presence of subsurface voids, to image bedrock topography, and to find the depth of waste (Carmichael and George, 1977; Kick, 1985; Stewart, 1980).

Active (Induced) Measurements

Induced methods include electromagnetic, acoustic, seismic, and electrical resistivity. The advantage to these methods is that the geophysicist controls the source of the response, which provides more flexibility with regard to the application of the tool and in survey deployment (Reynolds 1997).

Electromagnetic (EM) methods consist of transmitting a radio wave and recording the response for the induced (secondary) frequencies or frequencies. The response can be recorded based upon time-window or frequency (McNeil, 1988). The common EM methods include ground (or surface) penetrating radar (GPR, time-domain (TDEM) and frequency-domain (FDEM) terrain conductivity, and very low frequency (VLF).

Ground Penetrating Radar

The ground penetrating radar (GPR) method uses a transmitter that emits pulses of high-frequency (50 mHz to 1.6 gHz) electromagnetic waves into the subsurface (Daniels, 1996). The penetrating electromagnetic waves are scattered at interfaces in the dielectric permittivity, which is an electrical property of the subsurface material that is dependent primarily upon the bulk density, clay concentration, and water content of the subsurface (Anan and Cosway, 1992; Olhoeft, 1986). The electromagnetic energy is reflected back to the surface-receiving antenna and is recorded as a function of travel-time in units of nanoseconds (Daniels, 1996). Presentation is similar to that of seismic profiles.

Depth penetration is severely limited by attenuation and/or absorption of the transmitted radar energy from high clay content, shallow water table or soils with high electrical conductance. Depth of penetration ranges from a few millimeters to 15 meters, depending upon the frequency (Hutchinson et al., 2002). The lower the frequency emitted by the transmitter, the deeper the depth of penetration; however, resolution decreases with frequency.

GPR data can resolve changes in soil horizons, bedrock fractures, water-insoluble contaminants, geological features, man-made buried objects, voids, and hydrogeologic features (Ulriksen, 1982). Data are continuously displayed in real-time as a profile for rapid interpretation, similar to a seismic profile (Figure 2). Three-dimensional surveys can be conducted and time-depth maps can be prepared (Hutchinson, et al., 2002). The time-depth maps can be converted to depth using an appropriate velocity for the predominant ground material (Figure 3).

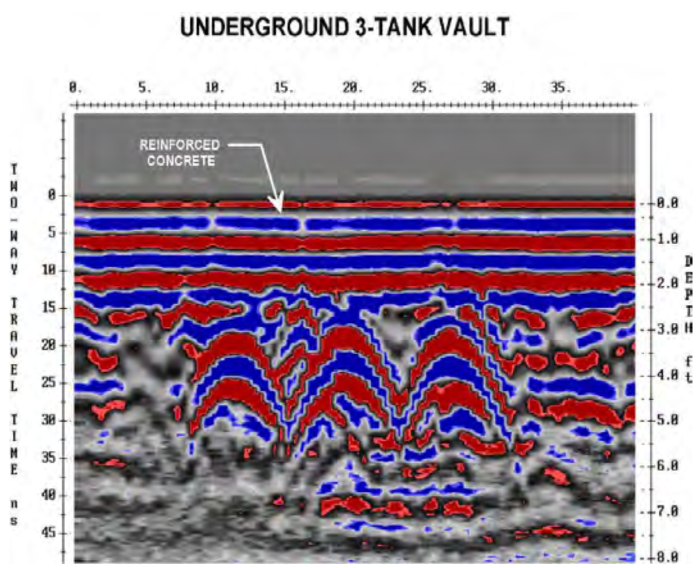

Figure 2 Ground penetrating radar profile of 3 underground storage tanks (horizontal scale in feet).

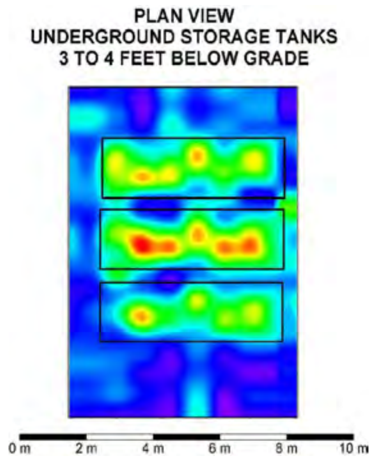

Figure 3 Average amplitude map of 3 underground storage tanks from three-dimensional GPR survey

Time- and Frequency-Domain Electromagnetic Terrain Conductivity

The time- and frequency-domain electromagnetic terrain conductivity methods measure the bulk conductivity (the inverse of resistivity) of the subsurface material beneath the transmitter and receiver coils (McNeil, 1988). FDEM devices measure conductivity as a function of the induced field versus the transmitted field. TDEM methods measure the amplitude of the induced signal as it decays with time. FDEM readings are commonly expressed as millimhos/meter (or milliSiemens/meter); whereas, TDEM readings are expressed as milliVolts. EM methods can detect pipes, utility lines, cables, buried steel drums, trenches, buried waste, and contaminant plumes (Reynolds, 1997). Coupled with a digital global positioning system receiver, EM methods are very fast and effective tools for mapping large areas (Hutchinson and Barta, 2005). Although sensitive to urban noise, such as metal fences, buildings, and powerlines, these tools are some of the best screening tools available to the geophysicist for a quick, inexpensive and reliable overview of a site.

TDEM tools are used to image buried ferrous and non-ferrous metallic objects, including tanks, utilities, and reinforced concrete. TDEM devices can also be used to map stratigraphy in conductive soils and rock where seismic or resistivity methods may not be appropriate. FDEM tools can map waste margins, buried utilities, underground storage tanks, and dissolved-phased plumes. Thickness of waste, to some degree, can also be inferred from terrain conductivity data (Hutchinson and Spieler, 1998;

Hutchinson and Barta, 2000). These two EM methods are some of the most common screening tools available to the environmental geophysicist (Figures 4, 5, and 6).

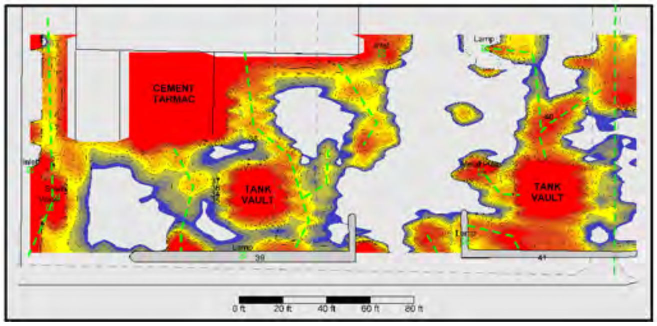

Figure 4 TDEM map of underground storage tank locations (blue to red are low to high milliVolts, respectively).

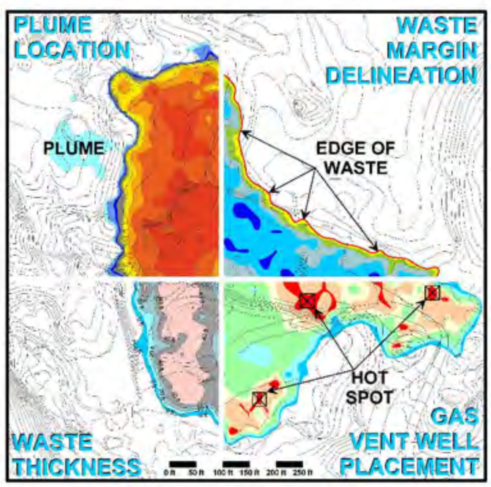

Figure 5 Processed FDEM terrain conductivity data, showing waste margin, inferred depth of waste, waste thickness and areas of gas-generating bacterial activity using various processing algorithms (units as shown or relative).

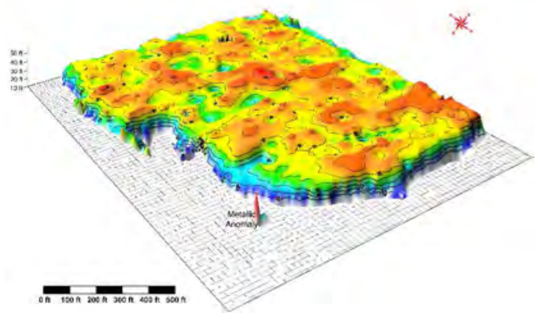

Figure 6 Processed terrain conductivity data, showing an inferred depth of waste.

VLF

Very low frequency transmitters are military-based antennas for navigation that emit radio waves below the short-wave spectrum (3 to 30 kHz). The migrating planar wave front can be disturbed by vertical subsurface anomalies, including fractures, faults and some utilities (Hutchinson and Barta, 2002). The dip-angle reading of the disturbed wave front can be used to map fractures and faults to a depth of 100 meters. Although this tool can be sensitive to cultural features, it is easy to use and interpret (Fraser, 1969). Approximately 3 kilometers (2 miles) of data can be collected in 1 day and when coupled with a DGPS receiver can rapidly locate fractures in bedrock (Figure 7; Hutchinson and Barta, 2002).

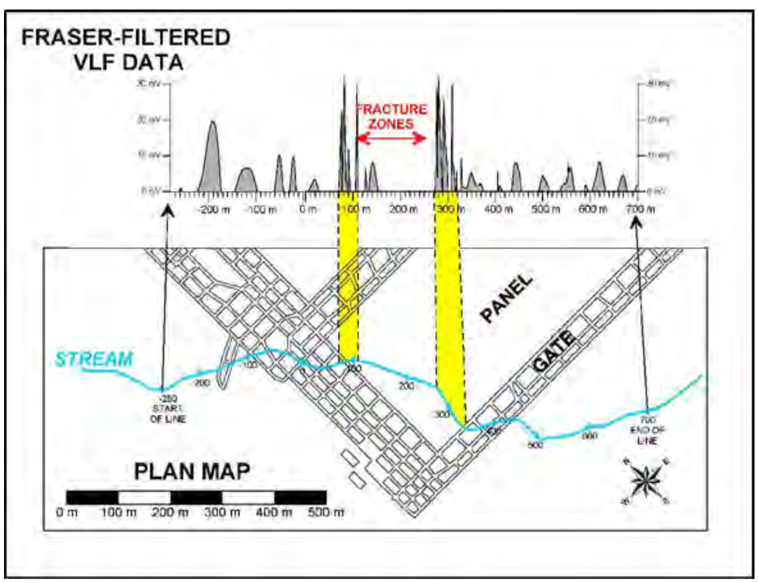

Figure 7 VLF map showing long-wall mining-induced fractures in a stream bank (from Hutchinson and Barta, 2002).

Acoustic

Acoustic instruments include the bathymeter and can include seismic energy; however, seismic methods will be discussed subsequently. Bathymeters transmit a low frequency (acoustic) signal and record the travel time to and from the water bottom. The 2-way travel time from the transmitter to the bottom of the water column and back is converted to a depth based upon the water salinity and temperature (Eden et al., 2001). When coupled with a DGPS receiver, the bathymeter can collect dense data over several hectares per day (Figure 8).

Bathymeters can be very accurate; however, salinity and water temperature are the 2 variables that can impact this tool's ability to map a water bottom accurately. The type of substrate and the turbidity of the water can also adversely impact the interpretation (Eden et al., 2001).

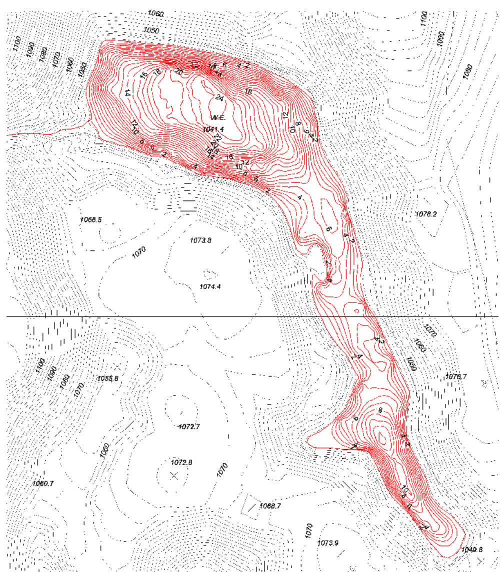

Figure 8 Depth of water (in red) in an abandoned surface-mine lake in Ohio (scale, 1 cm equals 50 meters; contour interval 2 feet).

Seismic

Seismic methods involve bouncing elastic waves (i.e., acoustic) off of subsurface density contrasts (Reynolds, 1987). Reflection seismic techniques record the 2-way travel time of a wave front from the source to receiver (Dobrin, 1976). Refraction seismic methods exploit Snell's Law, which states that the refraction of a wave front is caused by the change in density experienced by a wave when it changes medium (Redpath, 1973). Either of these two methods, when deployed conventionally, requires that data collection occur in a straight line with significant coverage on either side of the target. Modern methods incorporate massive computers and can cost a prohibitive amount of money to conduct. Seismic data collection in the 1920's and 1930's included 1 source and 1 receiver and, due to the lack of computers, collected 1 record per event, more commonly referred to as "single-fold" data. Environmental requirements, through urban environments, for example, have brought "single-fold" or "100%" reflection data back into use (EPA, 2000). Single-fold reflection events are multiply-stacked for cleaner data and then combined into pseudo-seismic lines for conventional processing and interpretation (Figure 9). The single record method can be collected virtually anywhere (i.e., highways, buildings, landfills), since the geophone and seismic source are at the same location (Figure 10).

Seismic methods are very interpretive and processing of the profiles requires extensive knowledge of the processing techniques, the rock/soil layers, and velocity of the materials (Rodrigues 1987). Seismic data are usually ineffective for depths that are shallower than 10 meters (30 feet) and cultural noise (i.e., vibrations) can cause spurious data.

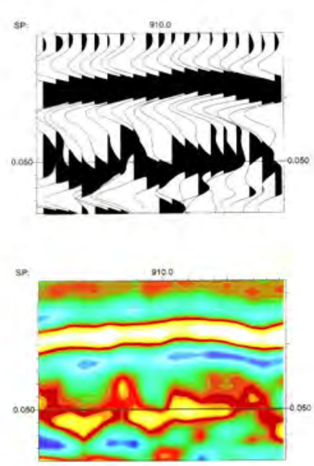

Figure 9 Conventional reflection seismic profile (top) and amplitude profile (bottom) of coal-mine voids (vertical scale in milliseconds; horizontal scale, 3 meters between records).

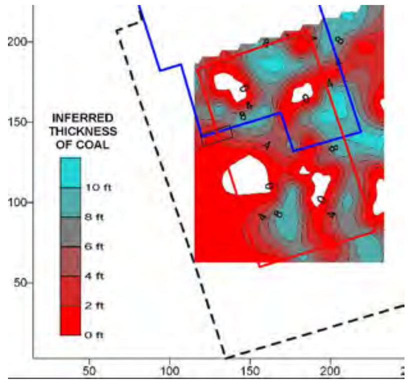

Figure 10 Plan map of interpreted coal thickness in an underground mine (in feet).

Electrical Resistivity

The electrical resistivity or imaging method (EI) is used to map subsurface electrical resistivity structures, such as geologic features and/or physical properties of geological materials (Mooney 1958). The electrical resistivity of a geologic unit is measured in Ohm-meters and is a function of the porosity, permeability, water saturation and the concentration of dissolved solids in pore fluids. EI methods measure the bulk resistivity of the subsurface by injecting current into the ground through surface electrodes.

EI methods, in a continuous vertical electric sounding mode, can provide accurate estimates of depths, thickness and electrical resistivity of subsurface layers (Hutchinson, 2005a and 2005b; Hutchinson and Barta, 2003 and 2004). The disadvantage to resistivity methods is that the survey must be conducted far away from grounded structures, so the survey cannot be collected near metal fences, pipelines, and railroad tracks. Further, most industrial sites have ambient broad-spectrum electrical noise to cause spurious data. The EI method is also one of the more labor-intensive geophysical methods for data collection. Nevertheless, EI methods are easily interpreted by currently available computer processing programs and can be one of the more user-friendly geophysical tools (Loke and Barker, 1996; Loke, 1998).

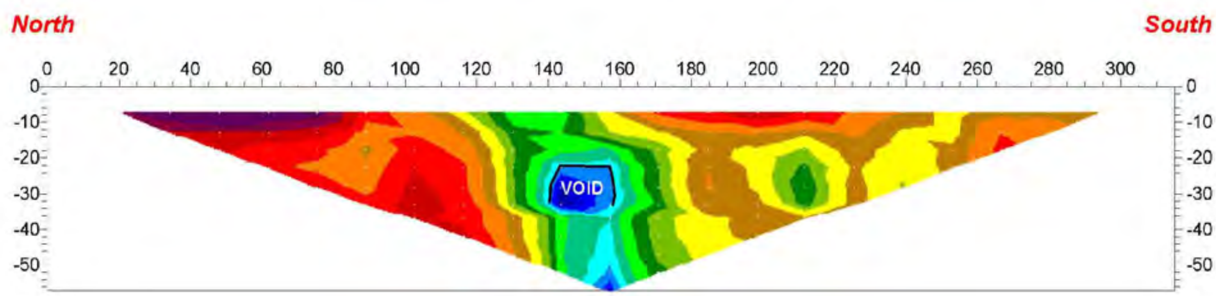

Figure 11 Electrical imaging profile of a karst void (no vertical exaggeration, in feet)

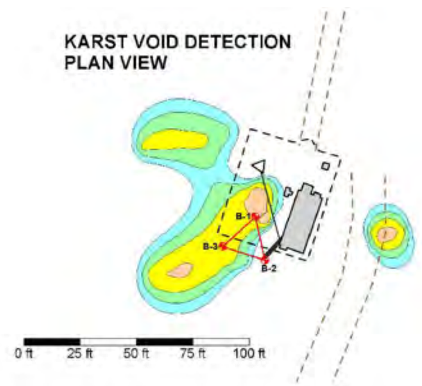

Figure 12 Plan map of karst voids showing depth to top of voids (color scheme; 10 meters [tan] to 25 meters [blue] below grade in 5-meter increments).

CONCLUSION

With the advent of computers, environmental geophysics has moved to the forefront of site investigation tools, since it is inexpensive and rapid, and provides a three-dimensional aspect to the site. The information obtained from a geophysical investigation can be used to determine the subsurface conditions at and near a site. Further, many aspects of a site can be delineated by the application of several geophysical methods and, in general, several methods should be deployed at each site to minimize the limitation inherent in each tool (Table 1).

Passive methods include gravity and magnetic, with the limitation that the geophysicist does not control the input or field conditions. The advantage, however, is that field conditions are always present. Gravity requires detailed topographic control but can be used virtually anywhere for location of voids or depth of bedrock. Magnetometers, though sensitive to cultural noise, are excellent for the location of subsurface metal.

Active or induced methods include EM, acoustic, seismic and EI and these methods offer the geophysicist the opportunity to modify the data collection to the project. The common EM methods include FDEM and TDEM terrain conductivity mapping, VLF profiling, and GPR imaging. Terrain conductivity mapping when coupled with a DGPS receiver can provide a fast method of mapping an area for metal, waste, plumes, underground storage tanks, and utilities. Although EM methods have limited vertical imaging capabilities, their horizontal control when coupled with another geophysical tool can readily provide a three-dimensional image of the site. Ground penetrating radar is a relatively shallow imaging tool, can be very interpretive, and is sensitive to clay and saturated conditions; but, is easily deployed and can provide detailed shallow subsurface conditions. Acoustic or bathymetric surveys are excellent tools for mapping soil/water interfaces and have few limitations. EI data can be impacted by close proximity to grounded objects, for example railroad tracks, fences, power lines, but is very useful for delineating subsurface conditions up to 35 meters below the surface.

Environmental geophysical methods should be deployed at the start of any environmental investigation since most methods are cost effective and easily deployed. Consequently, geophysical investigations provide a fast and inexpensive method for understanding the environmental problems prior to complex and expensive intrusive methods.

BIOGRAPHICAL SKETCH

Peter J. Hutchinson, PhD, PG is president of the Hutchinson Group, Ltd. (THG), a company that specializes in environmental geophysics and has published over 40 papers on environmental geophysics and geology. THG has been in business for 15 years and has completed thousands of environmental geophysical projects since incorporating. THG has an office in Palm Coast, Florida and Murrysville, Pennsylvania.

Table 1

GEOPHYSICAL APPLICATION SUMMARY

	METHOD	DETECTION						DEPTH OF PENETRATION	EASE OF INTERPRETATION	EASE OF DATA COLLECTION	SURVEY COST	IMPACT OF CULTURAL NOISE
		UST	WASTE	UTILITIES	VOIDS	PLUMES	BEDROCK					
Passive	Gravity	0	2	0	5	0	5	5	2	2	2	5
	Magnetics	5	2	5	0	0	1	5	5	4	4	1
Active (Induced)	EM	5	5	5	1	5	3	5	5	5	5	3
	GPR	4	4	5	5	4	5	2	5	4	5	4
	VLF	3	2	4	0	5	3	5	4	4	5	3
	Acoustic	0	0	0	0	0	0	3	5	5	5	4
	Seismic	0	3	0	4	1	5	5	3	3	2	4
	EI	2	5	2	5	5	5	5	5	3	3	4

Where 5 is a strong characteristic or application and 0 is a poor characteristic or weak application.
See text for abbreviations.

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