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Standard Guide for Selecting Surface Geophysical Methods[1]

This standard is issued under the fixed designation D 6429; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers the selection of surface geophysical methods, as commonly applied to geologic, geotechnical, hydrologic, and environmental investigations (hereafter referred to as site characterization), as well as forensic and archaeological applications. This guide does not describe the specific procedures for conducting geophysical surveys. Individual guides are being developed for each surface geophysical method.

1.2 Surface geophysical methods yield direct and indirect measurements of the physical properties of soil and rock and pore fluids, as well as buried objects.

1.3 The geophysical methods presented in this guide are regularly used and have been proven effective for hydrologic, geologic, geotechnical, and hazardous waste site assessments.

1.4 This guide provides an overview of applications for which surface geophysical methods are appropriate. It does not address the details of the theory underlying specific methods, field procedures, or interpretation of the data. Numerous references are included for that purpose and are considered an essential part of this guide. It is recommended that the user of this guide be familiar with the references cited **(1-20)**[2] and with Guides D 420, D 5730, D 5753, D 5777, D 6235, and D 6285, as well as Practices D 5088, D 5608, and Test Method G 57.

1.5 To obtain detailed information on specific geophysical methods, ASTM standards, other publications, and references cited in this guide, should be consulted.

1.6 The success of a geophysical survey is dependent upon many factors. One of the most important factors is the competence of the person(s) responsible for planning, carrying out the survey, and interpreting the data. An understanding of the method's theory, field procedures, and interpretation along with an understanding of the site geology, is necessary to successfully complete a survey. Personnel not having specialized training or experience should be cautious about using geophysical methods and should solicit assistance from qualified practitioners.

1.7 The values stated in SI units are to be regarded as the guide. The values given in parentheses are for information only.

1.8 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

1.9 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 420 Guide to Site Characterization for Engineering, Design, and Construction Purposes[3]

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[3]

D 4428/D 4428M Test Methods for Crosshole Seismic Testing[3]

D 5088 Practice for Decontamination of Field Equipment Used at Nonradioactive Waste Sites[3]

D 5608 Practice for Decontamination of Field Equipment Used at Low Level Radioactive Waste Sites[3]

D 5730 Guide to Site Characterization for Environmental Purposes with Emphasis on Soil, Rock, the Vadose Zone and Ground Water[3]

D 5753 Guide for Planning and Conducting Borehole Geophysical Logging[3]

D 5777 Guide for Using the Seismic Refraction Method for Subsurface Investigation[3]

D 6235 Practice for Expedited Site Characterization of

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[1] This guide is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.01 on Surface and Subsurface Characterization.

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[2] The boldface numbers given in parentheses refer to a list of references at the end of this standard.

[3] *Annual Book of ASTM Standards,* Vol 04.08.

Vadose Zone and Ground Water Contamination at Hazardous Waste Contaminated Sites[4]

D 6285 Guide for Locating Abandoned Wells[4]

G 57 Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method[5]

3. Terminology

3.1 *Definitions*—Definitions shall be in accordance with the terms and symbols given in Terminology D 653. Also see Ref **(1)** for specific geophysical terms and definitions.

4. Summary of Guide

4.1 This guide applies to surface geophysical techniques that are commonly used in site characterization, as well as forensic and archaeological applications.

4.2 The selection of preferred geophysical methods for a number of common applications is summarized in Table 1. The table is followed by brief descriptions of each application.

4.3 A brief description of each geophysical method along with some of the field considerations and limitations also are provided.

4.4 It is recommended that personnel consult appropriate references on each of the methods, applications, and their interpretations. All geophysical measurements should be carried out by knowledgeable professionals who have experience and training in theory and application of the method, and the interpretation of the data resulting from the use of the specific method.

5. Significance and Use

5.1 This guide applies to commonly used surface geophysical methods for those applications listed in Table 1. The rating system used in Table 1 is based upon the ability of each method to produce results under average field conditions when compared to other methods applied to the same application. An "A" rating implies a preferred method and a "B" rating implies an alternate method. There may be a single method or multiple methods that can be applied with equal success. There may also be a method or methods that will be successful technically at a lower cost. The final selection must be made considering site specific conditions and project objectives; therefore, it is critical to have an experienced professional make the final decision as to the method(s) selected.

5.1.1 Benson **(2)** provides one of the earlier guides to the application of geophysics to environmental problems.

5.1.2 Ward **(3)** is a three-volume compendium that deals with geophysical methods applied to geotechnical and environmental problems.

5.1.3 Olhoeft **(4)** provides an expert system for helping select geophysical methods to be used at hazardous waste sites.

5.1.4 EPA **(5)** provides an excellent literature review of the theory and use of geophysical methods for use at contaminated sites.

TABLE 1 Selection of Geophysical Methods for Common Applications[A,B]

	Geophysical Methods											
	Seismic		Electrical		Electromagnetic							
Applications	Refraction (6.1)	Reflection (6.2)	DC Resistivity (6.3)	SP (6.4)	Frequency Domain (6.5)	Time Domain (6.6)	VLF (6.7)	Pipe/Cable Locator (6.8)	Metal Detectors (6.9)	Ground Penetrating Radar (6.10)	Magnetics (6.11)	Gravity (6.12)
Natural Geologic and Hydrologic Conditions												
Soil/unconsolidated layers	A	B	A		B	A	B			A		
Rock layers	B	A	B			B				B		
Depth to bedrock	A	A	B		B	B	B			A		B
Depth to water table	A	A	B		B	B	B			A		
Fractures and fault zones	B	B	B		A	B	A			B	B	B
Voids and sinkholes	B	B	B		B	B				A		A
Soil and rock properties	A		A		B							
Dam and lagoon leakage			B	A	B					B		
Inorganic Contaminants												
Landfill leachate			A		A	A	B			B		
Saltwater intrusion			A		A	A	B			B		
Soil salinity			A		A							
Organic Contaminants												
Light, nonaqueous phase liquids			B		B	B				B		
Dissolved phase[C]												
Dense, nonaqueous phase liquids[C]												
Manmade Buried Objects												
Utilities					B			A	B	A		
Drums and USTs					A			A	A	A	A	
UXO									A	B	A	
Abandoned wells					B			B	B		A	
Landfill and trench boundaries	B		B		A	B				A		
Forensics			B		A			B	B	A	B	
Archaeological features	B	B	B		A					A	A	B

[A] "A" implies primary choice of method.

[B] "B" implies secondary choice or alternate method.

[C] Also see natural geologic and hydrologic conditions to characterize contaminant pathways.

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[4] *Annual Book of ASTM Standards*, Vol 04.09.

[5] *Annual Book of ASTM Standards*, Vol 03.02.

5.2 *An Introduction to Geophysical Measurements*:

5.2.1 A primary factor affecting the accuracy of geotechnical or environmental site characterization efforts is the number of sample points or borings. Insufficient spatial sampling to adequately characterize the conditions at a site can result if the number of samples is too small. Interpolation between these sample points may be difficult and may lead to an inaccurate site characterization. Benson **(2)** provides an assessment of the probability of target detection using only borings.

5.2.2 Surface and borehole geophysical measurements generally can be made relatively quickly, are minimally intrusive, and enable interpolation between known points of control. Continuous data acquisition can be obtained with certain geophysical methods at speeds up to several km/h. In some cases, total site coverage is economically possible. Because of the greater sample density, the use of geophysical methods can be used to define background (ambient) conditions and detect anomalous conditions resulting in a more accurate site characterization than using borings alone.

5.2.3 Geophysical measurements provide a means of mapping lateral and vertical variations of one or more physical properties or monitoring temporal changes in conditions, or both.

5.3 A contrast must be present for geophysical measurements to be successful.

5.3.1 Geophysical methods measure the physical, electrical, or chemical properties of soil, rock, and pore fluids. To detect an anomaly, a soil to rock contact, the presence of inorganic contaminants, or a buried drum, there must be a contrast in the property being measured, for example, the target to be detected or geologic feature to be defined must have properties significantly different from "background" conditions.

5.3.2 For example, the interface between fresh water and saltwater in an aquifer can be detected by the differences in electrical properties of the pore fluids. The contact between soil and unweathered bedrock can be detected by the differences in acoustic velocity of the materials. In some cases, the differences in measured physical properties may be too small for anomaly detection by geophysical methods.

5.3.3 Because physical properties of soil and rock vary widely, some by many orders of magnitude, one or more of these properties usually will correspond to a geologic discontinuity; therefore, boundaries determined by the geophysical methods will usually coincide with geological boundaries, and a cross-section produced from the geophysical data may resemble a geological cross-section, although the two are not necessarily identical.

5.4 Geophysical methods commonly are used for the following reasons:

5.4.1 Mapping natural hydrogeologic conditions;

5.4.2 Detecting and mapping contaminant plumes; and,

5.4.3 Locating and mapping buried objects.

5.5 Geophysical methods should be used in the following instances:

5.5.1 Surface geophysical methods can and should be used early in a site characterization program to aid in identifying background conditions, as well as anomalous conditions so that boring and sampling points can be located to be representative of site conditions and to investigate anomalies. Geophysical methods also can be used later in the site characterization program after an initial study is completed to confirm and improve the site characterization findings and provide fill-in data between other measurements.

5.5.2 The level of success of a geophysical survey is improved if the survey objectives are well defined. In some cases, the objective may be refined as the survey uncovers new or unknown data about the site conditions. The flexibility to change or add to the technical approach should be built into the program to account for changes in interpretation of site conditions as a site investigation progresses.

5.6 *Profiling and Sounding Measurements*:

5.6.1 Profiling by stations or by continuous measurements provides a means of assessing lateral changes in subsurface conditions.

5.6.2 Soundings provide a means of assessing depth and thickness of geologic layers or other targets. Most surface geophysical sounding measurements can resolve three and possibly four layers.

5.7 *Ease of Use and Interpretation of Data*:

5.7.1 The theory of applied geophysics is quantitative, however, in application, geophysical methods often yield interpretations that are qualitative.

5.7.2 Some geophysical methods provide data from which a preliminary interpretation can be made in the field, for example, ground penetrating radar (GPR), frequency domain electromagnetic profiling, direct current (DC) resistivity profiling, magnetic profiling, and metal detector profiling. A map of GPR anomalies or a contour map of the EM (electromagnetic), resistivity, magnetic or metal detector data often can be created in the field.

5.7.3 Some methods, (for example, time domain electromagnetics and DC resistivity soundings, seismic refraction, seismic reflection, and gravity), require that the data be processed before any quantitative interpretation can be done.

5.7.4 Any preliminary interpretation of field data should be treated with caution. Such preliminary analysis should be confirmed by correlation with other information from known points of control, such as borings or outcrops. Such preliminary analysis is subject to change after data processing and is performed mostly as a means of quality control (QC).

5.7.5 It is the interpretation and integration of all site data that results in useful information for site characterization. The conversion of raw data to useful information is a value-added process that experienced professionals achieve by careful analysis. Such analysis must be conducted by a competent professional to ensure that the interpretation is consistent with geologic and hydrologic conditions.

5.8 *Discussion of Applications*:

5.8.1 *Natural Geologic and Hydrologic Conditions*:

5.8.1.1 *Soil/Unconsolidated Layers*—This application includes determining the depth to, thickness of, and areal extent of unconsolidated layers. These layers may be discontinuous or include lenses of various materials. These layers can be detected because of differences in their physical properties as compared to adjacent materials.

5.8.1.2 *Rock Layers*—This application includes determining the contact between different rock layers, for example, limestone over granite or sandstone over shale, discontinuous bedding planes, and unconformities and the thicknesses of these layers. Several geophysical methods can be used to delineate rock layers depending on the physical properties and the depths and thicknesses of the layers.

5.8.1.3 *Depth to Bedrock*—This application includes determining depth to the top of competent rock covered by unconsolidated overburden. The choice of geophysical method depends on whether there is a physical property contrast between the rock and the overlying material. In areas where the top of rock is weathered or highly fractured, top of rock may be difficult to determine. Highly irregular rock surfaces may present additional problems.

5.8.1.4 *Depth to Water Table*—This application includes determining the depth at which a subsurface unit is fully saturated. The water table (top of the saturated zone) can be detected because of the changes in physical properties that are caused by saturated conditions. The ability to detect the water table may depend on the geologic unit in which it occurs. Seismic methods can be used to detect the water table in most unconsolidated materials; electrical, electromagnetic, or GPR methods may be used to detect the water table in either consolidated or unconsolidated materials.

5.8.1.5 *Fractures and Fault Zones*—This application includes the location and characterization of joints, fractures, and faults. These features range from individual joints and fracture zones to larger regional structural features. Joints, fractures and fault zones may be dry, fluid-filled or filled with clays or weathered rock. The detectability of these features increases with the size of the feature and with the presence of distinctive pore fluids or conductive fill material.

5.8.1.6 *Voids and Sinkholes*—This application includes karst features, such as weathered depressions in rock, open, water-filled, or sediment-filled sinkholes, and cavities or larger cave systems. In many cases, the target of concern may be beyond the effective resolution or depth range of some or all of the surface geophysical methods; however, deep cavities often show signs of their presence in the near surface and may be interpreted using shallow geophysical data. The ability to detect a given size cavity decreases with increasing depth for all surface geophysical methods.

5.8.1.7 *Soil and Rock Properties*—This application refers to the measurement of the physical properties of soil and rock, for example, elastic, plastic, and electrical. The choice of the geophysical method selected will be determined by the specific property to be measured. ASTM standards pertinent to those properties should be consulted. For example, rippability and acoustic velocities of rock are discussed in Guide D 5777, the dynamic modulus measured between boreholes in Test Methods D 4428/D 4428M, soil resistivity in Test Method G 57, and density, porosity measurements and seismic velocity measurements in boreholes in Guide D 5753.

5.8.1.8 *Dam and Lagoon Leakage*—This application refers to the detection and mapping of fluids leaking along preferential flow pathways from a dam or lagoon. The application of surface geophysical methods to detect leakage is contingent upon the presence of localized flow or difference in conductivity.

5.8.2 *Inorganic Contaminants*:

5.8.2.1 *Landfill Leachate*—This application includes all types of waste disposal sites in which the primary leachate is likely to be inorganic and electrically conductive. This includes municipal landfill sites, hazardous waste sites, and mine tailings. Inorganic contaminants can be detected using electrical or electromagnetic geophysical methods.

5.8.2.2 *Saltwater Intrusion*—Saltwater intrusion refers to movement of saline water into fresh water aquifers, and although this is primarily a coastal problem, it can occur naturally in inland aquifers or by man-made contamination, for example, brine ponds. Saline water is highly conductive and can be detected by DC resistivity and electromagnetic methods. The lateral boundary of the saltwater/fresh water interface can be mapped and the depth of the saline water estimated.

5.8.2.3 *Soil Salinity*—Soil salinity is a condition in which salt concentrations within soils have reached levels affecting the growth and yields of crops. DC resistivity and electromagnetic conductivity measurements provide means for measuring the soil salinity over a large area and at various depths.

5.9 *Organic Contaminants*:

5.9.1 *Light, Nonaqueous Phase Liquids (LNAPL)*—This application includes petroleum products present as discrete, measurable contaminants with concentrations greater than their solubility in water. The contaminants are lighter than water and “float” on the surface of an unconfined aquifer in porous media. The geometry of their occurrence in fractured soil or rock is more complex and less well defined. LNAPL dissolves into water and acts as a source of dissolved contaminant plumes (see dissolved organic contaminants). LNAPL can be detected in some cases because its electrical properties are different from those of ground water; it depresses the ground water surface if present in sufficient quantities; and, it can alter the capillary properties of soil.

5.9.2 *Dense, Nonaqueous Phase Liquids (DNAPL)*:

5.9.2.1 This application includes chlorinated organic solvents and other contaminants that are present as a discrete, measurable contaminant phase with concentrations greater than their solubility in water. The contaminants are denser than water and “sink” below the water table. The distribution of DNAPL in the subsurface is complex and is controlled by gravity and the capillary properties of subsurface materials, rather than by ground water flow direction. DNAPL dissolves into water and acts as a source of dissolved contaminant plumes (see dissolved organic contaminants). Moreover,“ residual” DNAPL (immobile contaminant left behind during migration) also can act as a source of dissolved organic contamination. Residual concentrations of DNAPL do not significantly alter the properties measured by most geophysical methods.

5.9.2.2 Some DNAPLs have dielectric properties that may allow their detection using GPR if temporal measurements are made before the DNAPL is introduced to compare with properties that exist after the DNAPL is present; thus, GPR may be useful to monitor the movement of DNAPL during remediation.

5.9.2.3 The geophysical methods listed in Table 1 under natural geologic and hydrologic conditions are appropriate to characterize the hydrogeology of a site; therefore, an attempt can be made to predict DNAPL occurrence and distribution based upon an understanding of site geology.

5.9.3 *Dissolved Phase*:

5.9.3.1 This application includes fuels, solvents, and other organic contaminants dissolved in ground water. Sources can be leaks and spills of LNAPL or DNAPL or can be leaks and spills of such small volume that the contaminant is dissolved as it reaches ground water.

5.9.3.2 Dissolved organic contaminants are of regulatory concern at very low concentrations (parts per billion) in ground water. The properties of the dissolved organic plumes that can be measured by most geophysical methods are not sufficiently different from those of ambient ground water to be detectable. Some organic contaminants, such as alcohol, are highly soluble, and are not detectable even at high concentrations.

5.9.3.3 When sources of dissolved organic contaminants have been identified, geophysical methods can be used to characterize the hydrogeology of a site so that pathways for migration of dissolved plumes can be identified. The appropriate methods are discussed in the sections of this guide that pertain to geologic and hydrologic conditions.

5.9.4 *Man-Made Buried Objects*:

5.9.4.1 *Utilities*—This application includes a very wide range of targets including pipes, cables, and utilities. Fortunately, most utilities are buried near the ground surface, making them relatively easy targets to detect. The geophysical method selected will depend on the material of which the pipes or utilities are made (ferrous or nonferrous metals or nonmetallic materials). Nonmetallic utilities, that is, concrete or plastic, can sometimes be detected with GPR.

5.9.4.2 *Underground Storage Tanks and Drums*—This application includes underground storage tanks (UST) and drums. Since most underground storage tanks are large (more than 2000 L (500 gal)), buried shallow, and often made of steel, they are relatively easy to detect. If the tank is made of non-metallic material (for example, concrete or fiberglass), it is more difficult to detect. Drums of various sizes (typically 4 to 200 L (1 to 55 gal)) are manufactured from either non-metallic or metallic materials. While groups of drums may be detected, a single 200-L (55-gal) drum and smaller drums are more difficult to locate.

5.9.4.3 *Unexploded Ordnance (UXO)*—This application includes a wide range of materials that were designed to explode, such as bombs, mines, and antipersonnel weapons. UXO occur in a variety of sizes from a few centimeters to meters and are made of a wide variety of metals and other materials. Shape, size, depth, composition and orientation of the UXO can limit detectability.

5.9.4.4 *Abandoned Wells*—This application includes abandoned wells that may be uncased or cased with steel, PVC, or concrete. Abandoned wells can be detected by various methods depending upon construction, associated surface pits and other facilities, leaking fluids, and the method of abandonment. Guide D 6285 provides a discussion of geophysical and other methods to locate abandoned wells.

5.9.4.5 *Landfill and Trench Boundaries*—This application includes landfills, pits, and trenches. Those that contain buried metallic materials can be detected because of the presence of the metal. Boundaries of trenches and pits can sometimes be detected by changes in electrical conductivity, disturbance of subsurface layers, or the presence of fill material. Determining the depth to the bottom of a landfill or trench is much more difficult than defining the lateral boundaries.

5.9.4.6 *Forensics*—This application includes buried bodies and a variety of metallic and nonmetallic objects. These objects can sometimes be detected directly or may be detected indirectly by disturbed soil conditions.

5.9.4.7 *Archaeological Features*—This application includes a wide range of targets, including stone foundations, walls, roads, fire pits, caves, and graves, as well as metallic and nonmetallic objects. These targets and objects can sometimes be detected directly or may be detected indirectly by changes in soil conditions.

6. Discussion of the Geophysical Methods

6.1 *Seismic Refraction*:

6.1.1 *Introduction*—Seismic refraction measurements are made by measuring the travel time of direct and refracted acoustic waves as they travel from the surface through one layer to another and back to the surface where their arrival times are recorded. The travel time is a function of the seismic or acoustic velocity and the geometry of subsurface layers of soil and rock.

6.1.2 *Applications*—The primary application for seismic refraction is for determination of depth and thickness of geologic layers, for example, depth to bedrock and water table, and to delineate geologic structure. Velocity measurements are a measure of the material properties and can be used as an aid in assessing rock quality and rippability of rock. If compressional P-wave and shear S-wave velocities are measured, in situ elastic moduli of soil and rock can be determined.

6.1.3 *Depth*—Typical depths of measurements are less than 30 m (100 ft), but measurements can be made to much greater depths, if necessary. Shallow measurements may be made using the energy of a sledgehammer or a shotgun source while deeper measurements will require larger mechanical energy sources and possibly explosives.

6.1.4 *Ease of Use*—Seismic refraction measurements are labor intensive. Refraction measurements require that the geophones and the energy source be in contact with the ground. Extensive cable handling and moving of the source is required. The resulting data must be analyzed before a quantitative interpretation can be made. The travel time of the P-wave arrivals are picked and then a time distance plot is drawn from which depths and velocities are determined. A variety of interpretive methods can be used ranging from the simple time intercept method to delay time, ray tracing, and the generalized reciprocal method. Each interpretive method requires specific data acquisition in the field. The results of seismic refraction data commonly are displayed as interpreted depth cross-sections or as contour maps of stratigraphic layers.

6.1.5 *Resolution*—Vertical resolution requires that a layer have a thickness that is a substantial fraction of the depth to its upper surface. Seismic refraction measurements can typically resolve three to four layers. Lateral resolution is a function of geophone spacing, typically 2 to 6 m or more (5 to 20 ft). Large spacings between source and geophones are used for deeper measurements.

6.1.6 *Limitations*—Measurements are sensitive to acoustic noise and vibrations. Seismic velocity of layers must increase with depth. The method will not detect thin layers. A source to geophone distance of up to three to five times the desired depth of investigation is needed.

6.1.7 *References*—Haeni **(14)** provides an excellent introduction to the method with case histories. Guide D 5777 is the standard guide for the use of this method.

6.2 *Seismic Reflection*:

6.2.1 *Introduction*—The seismic reflection technique measures the two way travel time of seismic waves from the ground surface downward to a geologic contact at which part of the seismic energy is reflected back to geophones at the surface. Reflections occur when there is a contrast in material density or velocity, or both, between two layers.

6.2.2 *Applications*—The primary application for the seismic reflection method is to identify and determine the depth and thickness of geologic layers. The top of bedrock may be mapped along with overlying layers. The method also can be used to locate and characterize geologic structure.

6.2.3 *Depth*—Reflection measurements detect layers from about 15 to 300 m (50 to 1000 ft) deep. Shallow measurements often can be made using a sledge hammer, shotgun, or rifle as seismic sources. Larger mechanical sources or explosives may be required for deeper explorations or in highly attenuative material.

6.2.4 *Ease of Use*—Seismic reflection measurements are relatively difficult to make and are labor intensive. Reflection measurements require that the geophones and the energy source be in contact with the ground. Extensive cable handling and moving of the source is required. Two different approaches to data acquisition are used, the common offset method and the common depth point (CDP) method. The CDP method has become more common for use with modern seismographs. The resulting field data must be processed prior to quantitative interpretation.

6.2.5 *Resolution*—Vertical resolution is proportional to the frequency of the seismic energy that can be generated and propagated. Resolution may be as good as 1 m with frequencies of 500 Hz. The optimum conditions for shallow reflection surveys are saturated fine-grained soils that enable higher frequency energy to be coupled with the ground. Lateral resolution is a function of geophone spacing, which is commonly 0.3 to 3 m (1 to 10 ft). The reflection method provides a high resolution cross section of soil or rock layers along a profile line. Although two-dimensional reflection surveys are common, three-dimensional reflection surveys also can be conducted.

6.2.6 *Limitations*—Measurements are sensitive to acoustic noise and vibrations. The distance between the source and the farthest geophone usually is 1 to 2 times the desired depth of investigation, much less than that required for refraction measurements.

6.2.7 *References*—Steeples and Miller **(15)** provide an introduction to the reflection method with emphasis on the common depth point method. Pullan and Hunter **(16)** provide a case history using the common offset method.

6.3 *DC Resistivity*:

6.3.1 *Introduction*—DC resistivity measurements are made by injecting a DC current into the ground through two current electrodes and measuring the resulting voltage at the surface between two potential electrodes. This method measures bulk electrical resistivity that is a function of the soil and rock matrix, percentage of fluid saturation, and the conductivity of pore fluids.

6.3.2 *Applications*—Resistivity measurements can be made as soundings to determine depth and thickness of geologic layers, or as profiles to locate lateral changes in geologic conditions, detecting and mapping inorganic contaminant plumes, and locating buried wastes. Sounding measurements are made by incrementally increasing the spacing between electrodes to make a sequence of measurements at increasing depths. Soundings generally are applicable to defining geologic layers where the geology is laterally homogeneous and layers are flat or gently dipping. Profile measurements are made with a fixed electrode spacing. Profiling is used to locate and map areas of significant lateral variations in resistivity at a given depth, for example, a conductive inorganic contaminant plume.

6.3.3 *Depth*—The depth of measurements is related primarily to electrode spacing and the electrical properties of the subsurface. Measurements can be made to depths of a few hundred meters or more. There is no theoretical limit to the depth of investigation if sufficient space is available to lay out the electrode array and sufficient energy is injected into the ground.

6.3.4 *Ease of Use*—Resistivity measurements are relatively slow and labor intensive since the method requires ground contact. This is achieved by driving metal electrodes into the ground and deploying connecting cables. Measurements are made on a station by station basis. Measurements also can be made by placing a grid of electrodes in the ground and making measurements between various electrodes to achieve different electrode spacings and geometries (as in azimuthal surveys). Profile data can be plotted as apparent resistivity versus distance along a profile line with little if any processing. Sounding data must be processed to obtain depth, thickness, and resistivity of layers. Processing can be done by curve matching or by using forward and inverse modeling. Results of grid surveys are modeled to provide an image of the subsurface.

6.3.5 *Resolution*—Lateral resolution is a function of electrode spacing, as well as, the spacing between station measurements. Resistivity soundings typically can resolve three to four layers.

6.3.6 *Limitations*—Measurements are susceptible, but less so than EM measurements, to interference from nearby metal pipes, cables, or fences. The spacing between electrodes must extend three to five times the depth of interest, which results in long electrode spreads and cables. Finding sufficient accessible space can sometimes be a problem. Obtaining a good connection with the ground can sometimes be a problem in areas with high resistivity soils.

6.3.7 *References*—Ward **(11)** provides an introduction to the method and Zohdy **(12)** provides an introduction and applications of the method.

6.4 *Spontaneous Potential (SP)*:

6.4.1 *Introduction*—The spontaneous, or self, potential (SP) method measures the natural voltage that exists at the ground surface. Measurements are made between two nonpolarizing electrodes, usually copper-copper sulfate cells, in contact with the ground. Usually one electrode is fixed as a reference electrode and measurements are made with the second roving electrode. SP voltages are produced by two different sources, as a result of the electrochemical differences between soils, rock, pore fluids, or minerals and their oxidation or reduction state, as well as by the electrokinetic effect of the presence of flowing water, sometimes called streaming potential. Voltages produced can be as great as a few 100 millivolts, but are more commonly a few tens of millivolts.

6.4.2 *Applications*—The primary application for SP measurements is assessing seepage from dams and embankments. Environmental and engineering applications of the self-potential method have been investigations of subsurface water movement. These include landslide investigations, location of faults, location and study of drainage structures, location of shafts, tunnels and sinkholes, and the mapping of coal mine fires. Time series SP measurements also can be made to monitor changes in seepage. It is possible that SP can be used to map geochemical variations associated with contaminant plumes.

6.4.3 *Depth*—SP is a potential field technique, so source parameters cannot be changed to vary the depth of investigation. The size, depth, orientation, and magnitude of subsurface targets all affect the magnitude of the detected SP anomaly. Depth of investigation is usually less than 30 m (100 ft).

6.4.4 *Ease of Use*—SP measurements are made on a station to station basis and are relatively easy to make; however, the electrodes must be in good electrical contact with the ground. Results can be plotted as profiles or contoured and often can be used with little processing. Corrections are applied to improve the signal to noise ratio and geometric curve matching and analytical models may be used for analysis; however, interpretation of self-potential data is often qualitative, using the anomalies observed in profile data or contour patterns to identify seepage flow paths or other sources.

6.4.5 *Resolution*—Lateral resolution is a function of station spacing.

6.4.6 *Limitations*—Measurements are susceptible to interference from natural earth currents, soil conditions, topographic effects and from stray earth currents, cathodic protection currents, and cultural features.

6.4.7 *References*—Corwin **(13)** provides an introduction and overview to the method.

6.5 *Frequency Domain Electromagnetics (FDEM)*:

6.5.1 *Introduction*—Frequency domain electromagnetics (sometimes called EM or terrain conductivity) measures the electrical conductivity of the subsurface using the magnitude and phase of the secondary field resulting from induced electromagnetic currents. Electrical conductivity is a function of the electrical properties of the soil and rock matrix, percentage of fluid saturation, and the conductivity of pore fluids.

6.5.2 *Applications*—FDEM measurements are used for profiling to detect and map lateral changes in geologic and hydrogeologic conditions. The method also is applicable to detecting and mapping inorganic (and sometimes organic) contaminant plumes and can be used for locating and mapping buried wastes, metal drums and tanks, and metal utilities. The method also can be used to obtain sounding data for a limited number of layers.

6.5.3 *Depth*—Depth of measurement is a function of the spacing between transmitter and receiver coil and coil orientation. Various instruments provide measurements from 0.75 to 60 m (2.5 to 200 ft) deep. Some instruments can be used with two coil orientations, coil axis vertical (vertical dipole) or coil axis horizontal (horizontal dipole). The vertical dipole provides greater depth of measurement compared to the horizontal dipole with the same coil separation.

6.5.4 *Ease of Use*—EM measurements are relatively easy to make and are not intrusive. The instruments may be carried by hand or in a vehicle at speeds from 0.8 to 8 kph (0.5 to 5 mph) or more. Field EM data can be plotted as a profile line or contoured. The data can sometimes be interpreted without any data processing.

6.5.5 *Resolution*—Frequency domain electromagnetics can provide excellent lateral resolution particularly when continuous measurements are used. Lateral resolution is determined by the spacing between the transmitter and receiver coils and station spacing between measurements. Frequency domain EM methods have limited depth sounding capabilities. By using several intercoil spacings and both horizontal and vertical dipole configurations, interpretations of two or three contrasting layers can be obtained.

6.5.6 *Limitations*—EM measurements are susceptible to interference from nearby metal pipes, fences, vehicles, noise from power lines and atmospheric storms. The effectiveness of electromagnetic measurements decreases at very low conductivities and the measurements become nonlinear at high conductivity values.

6.5.7 *References*—McNeill **(19)** provides an excellent introduction and overview of the method.

6.6 *Time Domain Electromagnetics (TDEM)*:

6.6.1 *Introduction*—The time domain electromagnetic method measures the electrical resistivity of subsurface conditions by inducing pulsed currents in the ground with a transmitter loop. The decay of the induced currents results in a secondary magnetic field. This decaying secondary field is then measured with a separate receiver coil. Electrical resistivity is a function of the soil and rock matrix, percentage of fluid saturation, and the conductivity of pore fluids.

6.6.2 *Applications*—Time domain electromagnetic measurements are primarily used for soundings to determine depth and thickness of geologic and hydrologic layers. They also can be applied to detection and mapping of inorganic plumes, seepage from brine pits, and salt-water intrusion. Time domain EM soundings provide similar data to DC resistivity soundings.

6.6.3 *Depth*—Depth measurements can be made from about

6 to 1000 m (20 to 3000 ft) or more. Shallow measurements can be made with a small transmitter loop of 1 to 10 m (3 to 30 ft). Deeper measurements can require a large transmitter loop of 300 to 600 m (1000 or 2000 ft). TDEM methods can be used whenever there is a measurable resistivity contrast between subsurface layers.

6.6.4 *Ease of Use*—Time domain electromagnetic measurements are relatively easy to make but are relatively slow. The method is not intrusive and measurements are made on a station by station basis. Deeper measurements with large transmitter loops are labor intensive. TDEM measurements are usually used in a sounding mode and processing of data is required to determine layer thickness and depth. Measurements also can be made in a profiling mode.

6.6.5 *Resolution*—TDEM measurements provide better lateral resolution than DC resistivity measurements for the same depth of penetration because of the relatively smaller loop size compared to the length of a resistivity array. Lateral resolution is limited by transmitter loop size and by the spacing between sounding measurements. Typically, three to four layers can be resolved.

6.6.6 *Limitations*—Measurements are susceptible to interference from nearby metal pipes, cables, fences, vehicles, noise from power lines and atmospheric storms.

6.6.7 *References*—McNeill **(8)** provides an introduction to the method along with some applications. Fitterman and Stewart **(9)** provides case histories for groundwater application.

6.7 *VLF (Very Low Frequency)*:

6.7.1 *Introduction*—VLF measurements are made by measuring the distortions of a VLF electromagnetic plane wave (15 to 30 kHz) from a distant high power military transmitter. These distortions occur because of local changes in electrical conductivity usually found within steeply dipping fractures, shear zones and dikes or other geologic features. The increase in electrical conductivity is a function of the presence of conductive material, such as water, clays, inorganic contaminants, or minerals within these features.

6.7.2 *Applications*—VLF measurements are primarily used for location and mapping of near vertical contacts, fractures or faults, and sources of water or minerals. The VLF method can also be used in a resistivity mode by placing two electrodes in contact with the ground to map conductive organic plumes at landfills and to determine the depth to bedrock and depth to clay.

6.7.3 *Depth*—The exploration depth varies with the conductivity of the subsurface material. At a typical site with a resistivity of 100 ohm-Ωm, exploration depth is about 20 m (60 ft).

6.7.4 *Ease of Use*—VLF measurements are relatively easy and rapid to make. The resulting data are plotted as profiles or contour maps and indicate the presence of a high conductivity zone. Usually some corrections and filtering are done to the data and some data processing may be necessary.

6.7.5 *Resolution*—Lateral resolution is a function of station spacing between measurements. VLF resistivity measurements will resolve two and sometimes three layers.

6.7.6 *Limitations*—The axis of a steeply dipping feature must be oriented approximately inline (±45°) toward the VLF transmitter for maximum response. VLF measurements are susceptible to interference from nearby metal pipes, cables, fences, vehicles, noise from power lines and atmospheric storms.

6.7.7 *References*—McNeill and Labson **(10)** provide a comprehensive review of the VLF method.

6.8 *Pipe and Cable Locator*:

6.8.1 *Introduction*—Pipe and cable locators operate in the frequency domain using a separate transmitter and receiver. The receiver coil is oriented perpendicular to the transmitter. The transmitter coil creates an alternating magnetic field and induces eddy currents in a metallic target. These eddy currents produce a secondary field, which is measured as a change in the primary field. This change results in an audio signal or meter deflection in the instrument. The pipe locator can be used as a metal detector with an effective coil diameter (the distance between the transmitter and receiver coils) of about 1 m. Its most effective use is to couple the transmitter directly or inductively to a metallic pipe or cable, and then to use the receiver to trace the length of the pipe or cable.

6.8.2 *Applications*—Pipe and cable locators are commonly used to trace buried pipes and cables and to locate large underground storage tanks and shallow 200 L (55-gal) drums. The large effective coil size makes the pipe and cable locator insensitive to small pieces of metallic debris at the surface.

6.8.3 *Depth*—The exploration depth of a pipe and cable locator in the metal detector mode varies with the surface area of the target but is limited to about 3 m.

6.8.4 *Ease of Use*—Pipe and cable locators are efficient tools for mapping buried metallic utilities.

6.8.5 *Resolution*—Pipe and cable locators are most often used to map buried utilities with some surface or near surface expression. Lateral resolution is extremely good.

6.8.6 *Limitations*—Pipe and cable locators are not calibrated. The response generated by buried metallic objects is, therefore, qualitative.

6.8.7 *References*—Benson **(2)** provides a diagram and discussion of pipe and cable locators.

6.9 *Metal Detector*:

6.9.1 *Introduction*—A metal detector responds to the presence of both ferrous and nonferrous metals. Metal detectors induce secondary EM currents in metal objects. Metal detectors are either frequency domain (continuous frequency) or time domain (pulsed) systems. The response of most metal detectors offsets the zero of a mechanical null or an electronic null of a bridge circuit. Time domain electromagnetic metal detectors transmit a pulse that induces eddy currents in metal objects. The decay rate of this secondary EM field is then measured at the receiver coil. A wide range of metal detectors is commonly available.

6.9.2 *Applications*—Metal detector measurements can be used to detect the presence of buried metal trash, drums and tanks, and to trace buried utilities. They also are used to detect unexploded ordnance (UXO).

6.9.3 *Depth*—The metal detector response is a function of the surface area of the metal object and its depth. The response to a metal target is approximately proportional to the reciprocal of the depth to the sixth power, therefore, response decreases with depth.

6.9.4 *Ease of Use*—Metal detector measurements are relatively easy and rapid to make. Since they do not require ground contact, continuous profile measurements can be made. Instruments can be carried or transported by a vehicle. Data can be plotted along a profile line or as a contour map.

6.9.5 *Resolution*—Metal detector measurements often provide better lateral definition of shallow buried targets than do magnetometer measurements.

6.9.6 *Limitations*—Frequency domain metal detector measurements are susceptible to interferences from nearby fences, pipes, cables, vehicles, buildings and metallic surface debris. Time domain metal detectors can be used in close proximity to fences and buildings without interference. Pipes, utilities, and metallic surface debris that affect time domain instruments can usually be seen and avoided. Some metal detectors can provide an estimate of the size and depth of buried targets.

6.9.7 *References*—Benson **(2)** provides an overview of metal detectors.

6.10 *Ground Penetrating Radar*:

6.10.1 *Introduction*—Ground penetrating radar is a reflection technique that uses high frequency electromagnetic (EM) waves (from 10 to 3000 mHz) to acquire subsurface information. A transmitter generates a short pulse of EM energy that is radiated into the ground. Energy is reflected back to the receiving antenna from interfaces having a sufficient contrast in EM properties. GPR responds to changes in EM properties that are a function of soil and rock materials and of their pore fluids.

6.10.2 *Applications*—GPR is used to obtain high resolution cross sections of soil and rock stratigraphy, to locate anomalous conditions, and to detect some contaminants. GPR commonly is used to locate buried materials, tanks, and utilities. It can be used to locate small targets such as steel rebar in concrete. GPR is also used for detection of unexploded ordnance (UXO).

6.10.3 *Depth*—The primary limitation of radar is its depth of penetration, which is site specific. GPR penetration can be more than a 30 m (100 ft) in materials having conductivity of a few milliSiemens/meter, (massive salt deposits and ice), but penetration is commonly less than 10 m (30 ft) in most soil and rock. Penetration in mineralogic clays and in materials having conductive pore fluids may be limited to less than 1 m (3 ft). GPR measurements also can be made in lakes and rivers with low conductivity (fresh) water.

6.10.4 *Ease of Use*—GPR measurements are relatively easy to make and are not intrusive. Antennas may be pulled by hand or with a vehicle at speeds from 0.8 to 8 kph (0.5 to 5 mph), or more, that can produce considerable data/unit time. Station profile measurements are slower but can be made in more difficult terrain (brush, steep hills). GPR data can often be interpreted without data processing. Graphic displays of these data often resemble geologic cross sections.

6.10.5 *Resolution*—GPR provides the highest lateral and vertical resolution of any surface geophysical method. Various frequency antennas (10 to 3000 mHz) can be selected so that the resulting data can be optimized to the project needs. Lower frequencies provide greater penetration with less resolution. Higher frequencies provide less penetration with higher resolution. Vertical resolution ranges from a few centimeters to a meter (inches to more than a foot). Horizontal resolution is determined by the distance between station measurements, or the sample rate, or both, and with the towing speed of the antenna.

6.10.6 *Limitations*—The major limitation of radar is its site specific performance. Often, the depth of penetration is limited by the presence of mineralogic clays or high conductivity pore fluids.

6.10.7 *References*—Daniels **(6)** and Sharma **(20)** provide excellent introductions to GPR.

6.11 *Magnetics*:

6.11.1 *Introduction*—A magnetometer is used to measure the intensity of the earth's magnetic field. Deviations of magnetic intensity are caused by variations in concentrations of natural ferrous minerals or by the presence of ferrous metals. There are two types of measurements that are commonly made, total field and gradient. Total field data requires the use of a base station so that diurnal and other temporal variations in the earth's magnetic field can be removed from the data. Gradiometer measurements are not affected by diurnal changes in the earth's field and are not much affected by cultural interference, but have less sensitivity.

6.11.2 *Applications*—Magnetic measurements can be used for geologic mapping to provide an estimate of the thickness of nonmagnetic sediments overlying magnetic rock and location of structure and faults within magnetic rock. Magnetic measurements are commonly used for location and mapping of buried ferrous metals, for example, metal wastes, drums or underground tanks and utilities). Magnetic measurements also are used for detection of unexploded ordnance (UXO).

6.11.3 *Depth*—A magnetic anomaly is proportional to the mass of whatever is causing the anomaly and is inversely proportional to the depth of the object.

6.11.4 *Ease of Use*—Magnetic measurements are relatively easy and rapid to make and can be made by one person. Since they do not require ground contact, continuous profile measurements can be made as well as station measurements. Measurements also can be made from a vehicle. Data can be plotted along a profile line or as a contour map. Data often are used with little processing.

6.11.5 *Resolution*—Horizontal resolution is a function of the anomaly size and the station spacing or sample interval. Gradient measurements provide better horizontal resolution than total field measurements.

6.11.6 *Limitations*—Magnetic measurements are susceptible to interference from steel pipes, fences, vehicles, and buildings as well as from natural fluctuations in the earth's field.

6.11.7 *References*—Breiner **(17)** provides a technical overview of magnetic methods.

6.12 *Gravity*:

6.12.1 *Introduction*—Gravity measurements detect changes in the earth's gravitational field caused by local changes in the density of soil and rock or the presence of engineered structures. Lateral variations or anomalies in gravity data are attributed to lateral variations in the densities of subsurface materials, for example, buried channels, caves, or structures. Microgravity measurements are used to detect very small changes in gravity.

6.12.2 *Applications*—Standard gravity measurements are primarily applied to mapping regional geologic structures using widely spaced stations 30 to 300 m (100 to 1000 ft) apart. Microgravity measurements use closely spaced measurements 2 to 15 m (5 to 50 ft) apart and are used to characterize localized geologic conditions, such as bedrock channels, caves, and abandoned tunnels and mines, usually within 30 m (100 ft) of the surface. Gravity measurements have also been used to delineate the boundaries, thickness, and volume of landfills.

6.12.3 *Depth*—The size of a gravity anomaly decreases as the target depth increases.

6.12.4 *Ease of Use*—Gravity station measurements are slow to make. While they do not require ground coupling, they must be made station by station. Gravity measurements require very accurate elevation measurements, within 3 mm (0.01 ft). A base station must be occupied periodically to account for instrument drift. Extensive corrections must be applied to gravity data before it can be interpreted. Data are presented as profile lines or a contour map, or both.

6.12.5 *Resolution*—Lateral resolution is a function of station spacing. Vertical resolution is a function of the ability to accurately estimate density of the geologic units.

6.12.6 *Limitations*—Gravity measurements are susceptible to manmade and natural vibrations; however, a gravity survey can be undertaken in areas where cultural effects may preclude the use of other geophysical methods. Gravity measurements can be made inside buildings and structures and in urban areas.

6.12.7 *References*—Butler **(18)** provides an overview of the micro gravity method.

7. Field Considerations

7.1 *Survey Grids and Data Density of Geophysical Surveys*:

7.1.1 An important aspect of any geophysical survey is to establish the location of the measurements. Single survey lines are used and placed in strategic locations over the area of interest. A survey grid with multiple lines and multiple stations is used to provide areal coverage of a site.

7.1.2 Measurements along a geophysical survey line and spacing between lines is dependent upon the target size, depth, and detectability.

7.1.3 If the spacing of measurements along a line and between lines is too large, small targets can be missed.

7.1.4 In general, survey lines should be oriented perpendicular to any linear feature, for example, buried channel, fracture, fault, or a pipeline. In some cases, survey lines in multiple directions may be necessary, especially if the orientation of the feature is unknown. In all cases, the survey line(s) or grid should extend into background conditions.

7.2 *Limitations*:

7.2.1 Each surface geophysical method has specific advantages and limitations. There is no single, universally applicable surface geophysical method to meet all site characterization needs. Furthermore, some methods are quite site specific in their performance. Each method measures some specific physical, electrical or chemical parameter. The geophysical method or methods should be selected carefully with the specific site conditions and project requirements in mind.

7.2.2 *Natural and Cultural Limitations*—A wide range of natural and cultural factors can cause interference with surface geophysical measurements. Cultural interferences can include buildings, fences, vehicles, underground utilities, overhead power lines, or ground vibrations. Natural interferences can include rain, earthquakes, solar flares, and atmospheric storms. When one method is so affected by site conditions as to render it useless, another method might be used effectively in the same environment.

7.2.3 *Non-Unique Interpretations*—A fundamental limitation of all geophysical methods lies in the fact that a given set of data cannot be associated with a unique set of subsurface conditions. In most situations, surface geophysical measurements alone cannot resolve all ambiguities, and some additional information, such as geophysical, geologic, hydrologic or contaminant data, or combination thereof, is required.

8. Keywords

8.1 DC resistivity; frequency domain electromagnetics; geophysical methods; geophysics; gravity; ground penetrating radar (GPR); magnetics; metal detector; pipe/cable location; self-potential; seismic reflection; seismic refraction; site characterization; time domain electromagnetics; VLF electromagnetics

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