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# Standard Guide for Selecting Surface Geophysical Methods[1]

This standard is issued under the fixed designation D6429; 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.

ε[1] NOTE—Editorially revised Section 3 in July 2011.

## 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 D420, D5730, D5753, D5777, and D6285, as well as Practices D5088, D5608, D6235, and Test Method G57.

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:*[3]

D420 Guide to Site Characterization for Engineering Design and Construction Purposes (Withdrawn 2011)[4]
D653 Terminology Relating to Soil, Rock, and Contained Fluids
D4428/D4428M Test Methods for Crosshole Seismic Testing
D5088 Practice for Decontamination of Field Equipment Used at Waste Sites

[1] This guide is under the jurisdiction of ASTM Committee D18 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] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] The last approved version of this historical standard is referenced on www.astm.org.

D5608 Practices for Decontamination of Field Equipment Used at Low Level Radioactive Waste Sites
D5730 Guide for Site Characterization for Environmental Purposes With Emphasis on Soil, Rock, the Vadose Zone and Groundwater (Withdrawn 2013)[4]
D5753 Guide for Planning and Conducting Borehole Geophysical Logging
D5777 Guide for Using the Seismic Refraction Method for Subsurface Investigation
D6235 Practice for Expedited Site Characterization of Vadose Zone and Groundwater Contamination at Hazardous Waste Contaminated Sites
D6285 Guide for Locating Abandoned Wells
G57 Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method

## 3. Terminology

3.1 *Definitions:*

3.1.1 Definitions shall be in accordance with the terms and symbols given in Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 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



**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.

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.

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 D5777, the dynamic modulus measured between boreholes in Test Methods D4428/D4428M, soil resistivity in Test Method G57, and density, porosity measurements and seismic velocity measurements in boreholes in Guide D5753.

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 D6285 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 D5777 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