
Introduction to Environmental Geophysics

Geophysics or physics pertaining to the Earth can be more readily defined as an interdisciplinary physical science dealing with the nature of the earth and its environment through the interpretation of contrasting physical properties of Earth materials. Geophysics applies the knowledge and methods of physics, mathematics and chemistry to understand the structure of Earth and its environment. Detailed characterization of the subsurface is critical in environmental, groundwater, and geotechnical investigations, as well as tectonics, mining, and petroleum reserve studies.

Environmental geophysics is a sub-discipline concerned with the non-invasive exploration of subsurface materials in the Earth through data collection, analyzing and interpreting physical quantities at the surface. The interpretative results allow the geophysicist to conceptualize a representative model of the subsurface at depth. In short, geophysics allows us to “image the subsurface”.

Geophysics enables us to “see” into the subsurface by interpreting the contrast in physical properties of adjacent earth materials. The question might arise: “what physical properties are used in geophysics?” The physical properties of concern measured by geophysicists include; the magnetic susceptibility, electrical conductivity (or resistivity), dielectric permittivity, natural radioactivity, acoustic velocity, thermal conductivity and density. Table 1 illustrates the relation between the different physical properties of earth materials, their application to environmental geophysics and the common geophysical methods employed to utilize each physical property.

Geophysical Applications

Groundwater and Hydrogeology
Surface geophysics is used to characterize subsurface conditions for geologic, hydrogeologic and engineering investigations. The most common application is determining the depth to bedrock beneath unconsolidated soils. Geophysics can detect and measure the amount of water in the subsurface, from partially saturated conditions near the surface, to completely saturated conditions below the water table. Once the presence/location of aquifers is determined, geophysics may be utilized by designing the engineers for optimal design development, including pre-drilling estimates of aquifer hydraulic characteristics, and to define geologic features controlling recharge or discharge of associated aquifers.

Environmental Assessment & Remediation
Surface geophysics is utilized to assess the occurrence and potential for impact of hazardous materials and chemical contamination in the subsurface. Background information is essential for a preliminary assessment of a potential or designated hazardous waste site. Geophysical studies can detect buried drums, underground storage tanks, buried pipelines and, delineate the distribution of contaminant plumes. When employed early in such studies, these investigations can optimize plans for exploratory test boring programs, test pits and trenching excavations.
Geophysical Methods

Geophysical investigation methods can be broken down into surface geophysical and subsurface (borehole studies) investigation techniques. During this course, we will concentrate on introducing the common applied surface geophysical methods. The most common methods employed in surface environmental geophysics are the electrical and potential field methods, however, seismic methods are used in some applications for environmental geophysical investigations.

Electrical Methods

The most common electrical methods applied to environmental geophysics include ground penetrating radar (GPR), electrical resistivity (ER) and electromagnetics (EM).

**Ground Penetrating Radar**
The ground penetrating radar (GPR) method has been used for a variety of civil engineering, ground water evaluation and hazardous waste site applications. The success of this geophysical method is the most site specific of all geophysical techniques, providing subsurface information ranging in depth from several tens of meters to only a fraction of a meter. A basic understanding of the function of the GPR instrument, together with knowledge of the geology and mineralogy of the site, can help determine if GPR will be successful in the site assessment. When possible, the GPR technique should be integrated with other geophysical and geologic data to provide the most comprehensive site assessment.

The GPR method uses a transmitter that emits pulses of high-frequency electromagnetic waves into the subsurface. The transmitter is either moved slowly across the ground surface or moved at fixed station intervals. The penetrating electromagnetic waves are scattered at changes in the complex dielectric permittivity, which is a property of the subsurface material dependent primarily upon the bulk density, clay content and water content of the subsurface (Olhoeft, 1984). The electromagnetic energy is reflected back to the surface receiving antenna and is recorded as a function of time.

Depth penetration of GPR is severely limited by attenuation and/or absorption of the transmitted electromagnetic (radar) waves into the ground. Generally, penetration of radar waves is reduced by a shallow water table, high clay content of the subsurface, and in areas where the electrical resistivity of the subsurface is less than 30 ohmmeters (Olhoeft, 1986). Ground penetrating radar works best in dry sandy soil where a deep water table exists. Under optimal conditions, depth penetration is between one and ten meters (Benson, 1982).

The analog plot produced by most GPR systems is analogous to a seismic reflection profile; that is, the data are usually presented with the horizontal axis as distance units (feet or meters) along the GPR traverse and the vertical axis as time units (nanoseconds). The GPR profile should not be confused with a geologic cross section which shows data as a function of horizontal distance versus depth. Very high resolution (as great as ± 0.1 meter) is possible using GPR. It is necessary to calibrate the recorded features with actual depth measurements from boreholes or from the results of other geophysical investigations for accurate depth determinations.

Under optimal conditions, GPR data can resolve changes in soil horizons, bedrock fractures, water-insoluble contaminants, geological features, man-made buried objects, voids, and hydrologic features such as water table depth and wetting fronts.
Various hand-held and sled drawn commercial GPR systems.

Figure 1. Schematic diagram of GPR system in use and the resultant radar scan depicting the subsurface geology. This scan could be interpreted as dipping sedimentary layers over bedrock.


**Suggested Readings**


**Electrical Resistivity**

The electrical resistivity method is used to map the subsurface electrical resistivity structure, which is interpreted by the geophysicist to determine geologic formations and/or physical properties of the geologic materials. The electrical resistivity of a geologic unit or target is measured in ohm-meters (Ω-m), and is a function of porosity, permeability, water saturation and the concentration of dissolved solids in pore fluids within the subsurface.

The resistivity of soils varies dramatically for various soil types, however, coarse dry soils tend to be more electrical resistive (low conductivity) than fine, wet soils. Common rocks show similar trends dependant on the available porespace and water content, as well as the electrical conductivity of the water filling the porespace/fractures. Table 2 shows the commonly observed ranges of electrical resistivity for rocks and soils.

![Electrical Resistivity Diagram](image)

Table 2. Commonly observed electrical resistivities on rocks and soils.

Electrical resistivity methods measure the bulk resistivity of the subsurface as do the electromagnetic methods. The difference between the two methods is in the way that electrical currents are forced to flow in the earth. In the electrical resistivity method, current is injected into ground through surface electrodes, whereas in electromagnetic methods, currents are induced by the application of time-varying magnetic fields.
Figure 1. Field setup: current (inner) and potential (outer) electrodes connected to a power supply and data logger.
**Figure 2.** Common potential and current electrode arrays employed during resistivity investigations

*Suggested Readings*


Electromagnetics
The electromagnetic method (EM) is a geophysical technique based on the physical principles of inducing and detecting electrical current flow within geologic strata (soil and/or rock). Commercially available EM setup are available and they are commonly composed of two coils (transmitter and receiver coils) connected by a cable of varying length (commonly referred to as s-spacing). The two coils are connected to a data logger and when the transmitter coil is activated an AC current is created in a wire loop, which produces a local magnetic field. This local magnetic field produces induced current flow in the subsurface. The current flow in the subsurface produces a secondary magnetic field which is detected by the receiver coil and is related to the conductivity of the soil and/or rock below.

EM should not be confused with the electrical resistivity method. The difference between the two techniques is in the way that the electrical currents are forced to flow in the subsurface. In the electromagnetic method, currents are induced in the subsurface by the application of time-varying magnetic fields (see Figure 3), whereas in the electrical resistivity method, current is injected into the ground through surface electrodes. The electromagnetic method measures the bulk conductivity (the inverse of resistivity) of subsurface material beneath the instrument’s transmitter and receiver coils. Electromagnetic readings are commonly expressed in conductivity units of millimhos/ meter (pronounced “milli-moess per meter”) or milliseimens/meter (1 millimho = 1 milliseimen). A “mho” is the reciprocal of an ohm.

Figure 4 shows a field crew using the EM-34 in the horizontal dipole coil arrangement to detect bulk soil resistivity.

Electromagnetics can be used to locate pipes, utility lines, cables, buried steel drums, trenches, buried waste, and concentrated contaminant plumes. The method can also be used to map shallow geologic features such as lithologic changes, clay layers, and fault zones.

Figure 4. Geonics EM-34 has three intercoil spacings with the capability of measuring the bulk resistivity at depth ranging from 7-60 meters.
Potential Field Methods

The potential field methods utilize the observed variations of the earth’s naturally occurring force fields to gather information about the subsurface. The magnetic field and the earth’s gravitational field are the two predominant forces utilized in geophysical investigations.

Magnetic Method

The Earth’s magnetic field can be compared to the field observed associated with a typical bar magnet. The strength of the measurable field varies spatially around the earth (magnet). This is due to the nature of the field itself (see Figure 3), but local variations occur due to the presence of geologic materials (magnetically susceptible minerals in rock or soil) and anthropogenic sources (ferrous objects such as automobiles, fences or buried drums). Figure 4 shows the strength of the magnetic field over North and South America.

Figure 3. Analogy between the magnetic field observed around a bar magnet and the Earth magnetic field. Note that the total strength of the magnetic field increases toward the poles.
Analysis of magnetic data can allow an experienced geophysicist to estimate the regional extent of buried ferrous targets, such as a steel tank, canister or drum. Often, areas of burial can be prioritized upon examination of the data, with high priority areas indicating a near certainty of buried ferrous material. In some instances, estimates of depth of burial can be made from the data. Most of these depth estimates are graphical methods of interpretation, such as slope techniques and half-width rules, as described by Nettleton (1976). The accuracy of these methods is dependent upon the quality of the data and the skill of the interpreting geophysicist.

A magnetometer is a hand-held instrument which measures magnetic field strength in units of gammas or nanoteslas (1 gamma = 1 nanotesla = 0.00001 gauss). Local variations, or anomalies, in the earth’s magnetic field are the result of disturbances caused mostly by variations in concentrations of ferromagnetic material in the vicinity of the magnetometer’s sensor. A buried ferrous object, such as a steel drum or tank, locally distorts the earth’s magnetic field and results in a magnetic anomaly. The common objective of conducting a magnetic survey at a hazardous waste or ground water pollution site is to map these anomalies and delineate the area of burial of the sources of these anomalies.

The magnetic method may also be used at a site to map various geologic features, such as igneous intrusions, faults, and some geologic contacts which may play an important role in the hydrogeology of a ground water pollution site. Figure 6 illustrates a residual magnetic profile recorded over buried tunnels. Similarly, the magnetic methods can be used in engineering applications to detect underground voids such as sinkholes which could pose a collapse threat to...
construction projects. Also, buried underground storage tanks containing hazardous materials can be detected.

![Residual magnetic profile trace over schematic diagram depicting the location of buried tunnels.](image)

**Figure 6.** Residual magnetic profile trace over schematic diagram depicting the location of buried tunnels.

**Magnetic Methods**


**Gravity Method**

The gravity method involves measuring the acceleration due to the earth’s gravitational field. These measurements are normally made on the earth’s surface. A gravity meter or gravimeter is used to measure variations in the earth’s true gravitational field at a given location. These variations in gravity depend upon lateral changes in the density of the subsurface in the vicinity of the measuring point. Because density variations are very small and uniform, the instruments used are very sensitive. The acceleration due to the earth’s gravity is approximately 980,000 milligal (the unit of measurement commonly used in gravity surveys). Many gravity meters have a sensitivity of 0.01 milligal. This allows the detection of a change of one part in 100 million of the earth’s gravitational field. The gravity method is useful in delineating buried valleys, bedrock topography, geologic structure and voids.

![Common gravimeter](image)

**Figure 6.** Common gravimeter used in determining the strength of the earth’s gravitational force.

![Gravity anomaly](image)

**Figure 7.** a) Gravity anomaly. b) Bedrock surface mapped from interpretation of gravity anomaly in (a). Borehole locations plotted to verify presence of bedrock surface.


**Suggested Readings**


**Other Methods**

Other, less common methods exist on environmental geophysical investigations. Induced polarization (IP) method is an electrical geophysical technique which measures the slow decay of voltage in the subsurface following the cessation of an excitation current pulse. Spontaneous Potential (SP)….

Surface seismic techniques used in ground water pollution site investigations are largely restricted to seismic refraction and seismic reflection methods. The equipment used for both methods is fundamentally the same and both methods measure the travel-time of acoustic waves propagating through the subsurface. In the refraction method, the travel-time of waves refracted along an acoustic interface is measured, and in the reflection method, the travel-time of a wave which reflects off an interface is measured. The advantages, limitations, and other details of each method are discussed separately below.

The interpretation of seismic data will yield subsurface velocity information, which is dependent upon the acoustic properties of the subsurface material. Various geologic materials can be categorized by their acoustic properties or velocities. Depth to geologic interfaces can be calculated using the velocities obtained from a seismic investigation.

The geologic information gained from a seismic investigation can then be used in the hydrogeologic assessment of a ground water pollution site and the surrounding area. The interpretation of seismic data can indicate changes in lithology or stratigraphy, geologic structure, or water saturation (water table). Seismic methods are commonly used to determine the depth and structure of geologic and hydrogeologic units (for example, depth to bedrock or water table), estimate hydraulic conductivity, detect cavities or voids, determine structure stability, detect fractures and fault zones, and estimate rippability. The choice of method depends upon the information needed and the nature of the study area. This decision must be made by a geophysicist who is experienced in both methods, is aware of the geologic information needed by the hydrogeologist, and is also aware of the environment of the study area.

**Suggested Readings**
References


Applications of Seismic Refraction Techniques to Hydrologic Studies (USGS)