Chapter 13

SURFACE GEOPHYSICAL INVESTIGATIONS

Introduction

Surface geophysical surveys have been applied to mineral and petroleum exploration for many years. A magnetic compass was used in Sweden in the mid-1600s to find iron ore deposits. The lateral extent of the Comstock ore body was mapped using self-potential methods in the 1880s. A very crude type of seismic survey measured the energy resulting from blasting operations in Ireland in the late 1800s. The idea that energy travels through a material with a certain velocity came from this survey. During World War I, geophysical techniques were used to locate artillery pieces. Anti-submarine warfare in World War II led to magnetic and sonar surveys.

The main emphasis of geophysical surveys in the formative years was petroleum exploration. Technology developed for oil and gas surveys led to the use of geophysical surveys in many important facets of geotechnical investigations. Geophysical surveys have been applied to civil engineering investigations since the late 1920s, when seismic and electrical resistivity surveys were used for dam siting studies. A seismic survey was performed in the 1950s in St. Peter's Basilica to locate buried catacombs prior to a renovation project. From the late 1950s until the present time, geophysical techniques have had an increasing role in both groundwater exploration and in geotechnical investigations. Geophysical surveys are now used routinely as part of geological investigations and to provide information on site parameters (i.e., in place dynamic properties, cathodic protection, depth to bedrock) that in some instances are not obtainable by other methods. Values derived from seismic geophysical surveys are obtained at strain levels different from some site parameters obtained by other means.

All geophysical techniques are based on the detection of contrasts in different physical properties of materials. If contrasts do not exist, geophysical methods will not work. Reflection and refraction seismic methods contrast compressional or shear wave velocities of different materials. Electrical methods depend on the contrasts in electrical resistivities. Contrasts in the densities of different materials permit gravity surveys to be used in certain types of investigations. Contrasts in magnetic susceptibilities of materials permit magnetic surveying to be used in some investigations. Contrasts in the magnitude of the naturally existing electric current within the earth can be detected by self-potential (SP) surveys.

Seismic refraction surveys are used to map the depth to bedrock and to provide information on the compressional and shear wave velocities of the various units overlying bedrock. Velocity information also can be used to calculate in place small-strain dynamic properties of these units. Electrical resistivity surveys are used to provide information on the depth to bedrock and information on the electrical properties of bedrock and the overlying units. Resistivity surveys have proven very useful in delineating areas of contamination within soils and rock and also in aquifer delineation. Gravity and magnetic surveys are not used to the extent of seismic and resistivity surveys in geotechnical investigations, but these surveys have been used to locate buried utilities. Self-potential surveys have been used to map leakage from dams and reservoirs.

Geophysical surveys provide indirect information. The objective of these surveys is to determine characteristics of subsurface materials without seeing them directly. Each type of geophysical survey has capabilities and limitations and these must be understood and considered when designing a geophysical investigations program.

Geophysical interpretations should be correlated with real "ground-truth" data such as drill hole logs. It is very important that the results of geophysical surveys be integrated with the results of other geologic investigations so that accurate interpretation of the geophysical surveys can be made.

The following sections provide the theory behind and guidelines for uses of geophysical surveys, particularly in geotechnical investigations. Although this chapter does not provide all the detail necessary, the theory and interpretation methods involved in geophysical surveying are included in references in the bibliography. The references should be used to supplement the materials presented in this chapter.

Seismic Surveys

Seismic Refraction Surveys

Purpose.—Seismic refraction surveys are used to determine the compressional wave velocities of materials from the ground surface to a specified depth within the earth. For most geotechnical investigations, the maximum depth of interest will be specified by the nature of the project. In many cases the objective of a seismic refraction survey is to determine the configuration of the bedrock surface and the compressional wave velocities of the underlying materials. Bedrock may be defined by compressional wave velocities. The information obtained from a seismic refraction survey is used to compute the depths to various subsurface layers and the configurations of these layers. The thickness of the layers and the velocity contrasts between the layers govern the effectiveness and the accuracy of the survey. Seismic refraction surveys do not provide all compressional wave velocities or delineate all subsurface layers. Seismic refraction interpretation assumes that layer velocities increase with depth.

Applications.—Seismic refraction surveys have been used in many types of exploration programs and geotechnical investigations. The initial application of these surveys was mapping of salt domes in the early days of oil exploration. Seismic refraction surveys are now routinely used in foundation studies for construction projects and siting studies, fault investigations, dam safety analyses, and tunnel alignment studies. Seismic refraction surveys are also used to estimate rippability (Appendix C). Figure 13-1 is a schematic of a seismic refraction test.

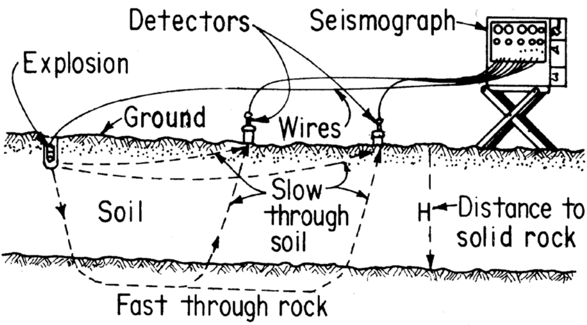

Figure 13-1.—Simplified diagram of a seismic refraction test.

Seismic Reflection Surveys

Purpose.—Seismic reflection surveys have been used successfully in petroleum and geothermal exploration projects and to investigate for shallow coal. The information obtained from seismic reflection surveys can be used to define the geometry of the different subsurface layers and structural features.

Applications.—High resolution seismic reflection surveys provide definitive information on the locations and types of faults, as well as the location of buried channels. Shallow, high resolution seismic reflection surveys are playing an increasingly important role in geotechnical investigations. When correctly used, seismic reflection surveys may provide data that seismic refraction surveys can not (e.g., velocity reversal information). However, compressional (P) wave velocity information derived from reflection surveys may not be as accurate as from refraction surveys. The compressional wave velocities are needed for the analysis of the reflection records themselves and for seismic refraction surveys, uphole velocity surveys, and sonic logs.

Shear Wave Surveys

Purpose.—Shear (S) waves travel through a medium at a slower velocity than compressional (P) waves and arrive after compressional waves. Other types of secondary arrivals also exist due to reflections, combinations of reflections and refractions, and surface waves. Field survey techniques are designed to suppress compressional and unwanted reflected or refracted wave arrivals. The field procedure optimizes shear wave generation as well as the polarity of the wave energy.

Applications.—For geotechnical investigations, shear wave velocities provide information on the low-strain dynamic properties of a given material. The relationships between compressional wave velocity, shear wave velocity, density, and in place dynamic properties of materials are shown in table 13-1. The compressional wave velocity can be determined from refraction surveys, the shear wave velocity from shear wave surveys, and the density from borehole geophysics or laboratory testing. The cross-hole seismic method is a common procedure used to determine

Table 13-1.—Determining moduli and ratios for typical velocities of earth materials from refraction surveys

V_p = Compressional wave velocity	(ft/s) (m/s)
V_s = Shear wave velocity	(ft/s) (m/s)
E = Young's Modulus	(lb/in^2) (MPa)
G = Shear Modulus	(lb/in$^{2)}$ (MPa)
K = Bulk Modulus	(lb/in$^{2)}$ (MPa)
μ = Poisson's Ratio	
ρ = Density (in situ)	(lb/ft$^{3)}$ (kg/m^3)

Shear Modulus: $G = \rho V_s^2$
Young's Modulus: $E = 2G(1+\sigma)$
Bulk Modulus: $K = \rho(V_p\text{-}4/3V_s^2)$
Velocity Ratio: V_p/V_s
Poisson's Ratio: $\mu = (.05)\,[V_p/V_s]^2\text{-}2/[V_p/V_s]^2\text{-}1\backslash$

material dynamic properties. Compressional waves and shear waves are generated in one drill hole, and the seismic wave arrivals are received in companion drill hole(s). The seismic source(s) and receiver(s) are located at equal depths (elevations) for each recording. Drill hole deviation surveys are performed in each drill hole to accurately determine the distances between each of the drill holes at all recording intervals. For typical seismic velocities of earth materials, see table 13-2.

Surface Wave Surveys

Purpose.—Surface wave surveys produce and record surface waves and their characteristics. Surface waves have lower frequencies and higher amplitudes than other seismic waves. Surface waves result from the constructive and destructive interference of refracted and reflected seismic waves. Surface waves that travel along the boundaries of a body are called Stanley waves. Surface waves are the slowest type of seismic

Table 13-2.—Typical velocities of earth materials

Material	Velocity (feet per second)	Velocity (meters per second)
Dry silt, sand, loose gravel, loam, loose rock, talus, and moist fine-grained topsoil	600-2,500	200-800
Compact till, indurated clays, gravel below water table*, compact clayey gravel, sand, and sand-clay	2,500-7,500	800-2,300
Weathered, fractured, or partly decomposed rock	2,000-10,000	600-3,000
Sound shale	2,500-11,000	800-3,400
Sound sandstone	5,000-14,000	1,500-4,000
Sound limestone, chalk	6,000-20,000	2,000-6,100
Sound igneous rock	12,000-20,000	3,700-6,100
Sound metamorphic rock	10,000-16,000	3,100-4,900
*Water (saturated materials should have velocities equal to or exceeding that of water)	4,700	1,400

wave, traveling along the boundaries between different materials. The characteristics must be determined in addition to recording the waves. Normally, surface waves are filtered out of seismic data or are ignored. The term. "ground roll," in the oil exploration industry denotes surface waves. Special care is taken in seismic reflection surveys to filter out surface waves because they can interfere with desired reflections. The different types of surface waves and their characteristic motions are shown in figure 13-2.

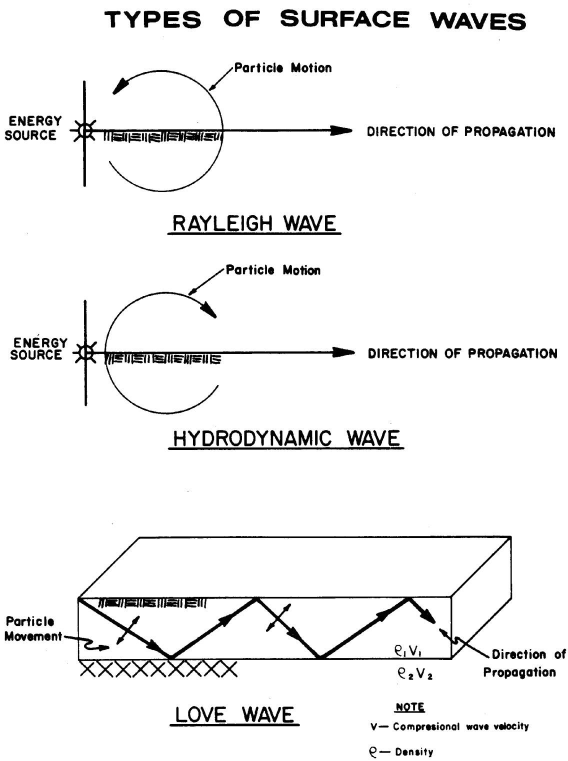

Figure 13-2.—Types of surface waves.

Applications.—The principal application of surface wave surveying for geotechnical investigations is to determine the type and characteristics of surface waves that can exist at a site. This information is used to determine preferred site frequencies and for earthquake design analysis.

Vibration Surveys

Purpose.—Vibration surveys measure the vibration levels produced by mechanical or explosive sources. Once these levels are determined, structures can be designed to reduce the possibility of vibration damage.

Applications.—Vibration surveys have been performed for quarrying and mining operations, excavations, measuring the effects of traffic on sensitive equipment, and measuring the effects of aircraft (sonic vibrations) on urban areas and historical buildings. Many manufacturing and research facilities contain extremely sensitive equipment with very small vibration tolerances. Vibration surveys can be very useful in determining the exact levels of allowable vibration and in designing procedures to reduce vibration levels produced by construction and blasting activities. The same type of vibration survey can be used in quarrying and/or mining operations to reduce vibration levels while maintaining rock breakage and fragmentation.

Electrical Resistivity Surveys

The electrical resistivity of any material depends largely on its porosity and the salinity of the water in the pore spaces. Although the electrical resistivity of a material may not be diagnostic, certain materials have specific ranges of electrical resistivity. In all electrical resistivity surveying techniques, a known electrical current is passed through the ground between two (or more) electrodes. The potential (voltage) of the electrical field resulting from the application of the current is measured between two (or more) additional electrodes at various locations. Since the current is known, and the potential can be measured, an apparent resistivity can be calculated. The separation between the current electrodes depends on the type of surveying being performed and the required investigation depth.

For representatives values of resistivity, see table 13-3.

Table 13-3.—Representative values of resistivity

Material Resistivity	(ohm-m)
Clay and saturated silt	1-100
Sandy clay and wet silty sand	100-250
Clayey sand and saturated sand	250-500
Sand	500-1,500
Gravel	1,500-5,000
Weathered rock	1,000-2,000
Sound rock	1,500-40,000

Electrical Resistivity Profiling Surveys

Electrical resistivity survey profiling is based on lateral changes in the electrical properties of subsurface materials.

Purpose.—Electrical resistivity profiling is used to detect lateral changes in the electrical properties of subsurface material, usually to a specified depth. Electrode spacing is held constant.

Applications.—Electrical resistivity has been used to map sand and gravel deposits, determine parameters for cathodic protection, map contamination plumes in hazardous waste studies, and used in fault studies.

Electrical Resistivity Sounding Surveys

Electrical resistivity sounding surveys measure vertical changes in the electrical properties of subsurface materials. The electrode spacing used for resistivity sounding is variable, with the center point of the electrode array remaining constant. The depth of investigation increases as the electrode spacing increases.

Purpose.—Resistivity soundings are used to investigate variations of resistivity with depth. Electrode spacing is varied.

Applications.—Electrical resistivity soundings are commonly used for aquifer and aquaclude delineation in groundwater investigations. The technique has been used for bedrock delineation studies where there is not a sufficient velocity contrast to permit seismic surveying. Vertical electrical soundings have been used for large scale mineral investigations, geothermal investigations, cathodic protection and toxic waste studies, and in conjunction with self-potential surveys for seepage investigations.

Electrical Resistivity Dipole-Dipole Surveys

Dipole-dipole surveying potential electrodes may have any position with respect to the pair of current electrodes. When the current and potential electrodes are positioned along the same line, the array is referred to as an axial dipole array (figure 13-3). The current electrodes are separated from the potential electrodes by an interval, n, which is some multiple of the current and potential electrodes separation, a. The separation of the current and potential electrodes is normally equal.

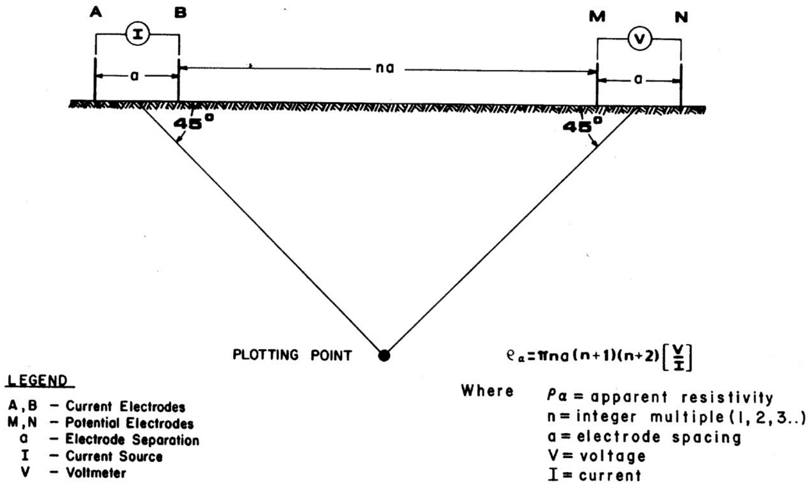

Figure 13-3.—Dipole resistivity array.

Purpose.—Dipole-dipole arrays are used to determine both the lateral and vertical changes in electrical properties of subsurface materials with one electrode array.

Applications.—The dipole-dipole array has limited applications in engineering and groundwater geophysics. This type of electrode array has been used primarily in mineral and geothermal exploration. The method has been used to delineate abandoned mines, mapping saltwater/fresh water interfaces, and mapping buried stream channels.

Electromagnetic Conductivity Surveys

Electromagnetic Conductivity Profiling Surveys

Electromagnetic (EM) surveying uses time-varying, low frequency, electromagnetic fields induced into the earth. A transmitter, receiver, and a buried conductor are coupled by electrical circuitry through electromagnetic induction. The characteristics of electromagnetic wave propagation and attenuation by a material can permit interpretation of the electrical conductivities of the subsurface materials.

Purpose.—Since electrical conductivity is the reciprocal of electrical resistivity, electromagnetic surveys are used to provide resistivity information on subsurface materials. Electromagnetic conductivity profiling surveys are specifically used to determine lateral changes in conductivity of the subsurface materials.

Applications.—Electromagnetic surveys have been used primarily for mineral exploration; and with the exception of magnetic surveys, EM surveys are the most commonly used geophysical surveys for minerals. EM surveys have been used in engineering and groundwater investigations. The method is found to be particularly useful in mapping contaminant plumes and buried metallic waste such as metal drums containing hazardous chemicals. EM surveys are suited to hazardous waste studies because the surveying procedure does not require equipment to touch potentially contaminated ground. The method has been used to locate buried pipes and cables and to locate landmines.

Electromagnetic Conductivity Sounding Surveys

Purpose.—Electromagnetic conductivity sounding surveys are used to determine vertical changes in conductivity of subsurface material.

Applications.—Electromagnetic sounding surveys can locate areas of permafrost, gravel deposits, map bedrock topography, and provide general geological information. EM sounding and profiling surveys have been applied to mapping areas of salt water intrusion, archaeological investigations, and fault studies.

Ground Penetrating Radar Surveys

Purpose

Ground penetrating radar (GPR) surveys have the same general characteristics as seismic surveys. The depth of investigation with GPR is extremely shallow when compared to seismic surveys. This disadvantage is partially offset by the much better resolution of GPR.

Applications

Ground penetrating radar surveys can be used for a variety of very shallow geotechnical investigations, including the locations of pipes or other buried manmade objects such as timbers, very high resolution mapping of near-surface geology, and detecting cavities, piping, and leakage in dams. The applications are limited by the very shallow penetration depth of the very high radar frequencies. Silts, clays, salts, saline water, the water table, and any other conductive materials in the subsurface severely restrict or stop penetration of radar.

Self-Potential Surveys

Purpose

Self-potential ([SP] spontaneous potential or natural potential) is the natural electrical potential existing within the earth due to many causes. These causes can be classified broadly into two groups (excluding manmade causes):

Mineralization Potential.—Mineralization potential is commonly the result of chemical concentration cells formed when conductive mineral deposits, such as graphite or sulfide, are intersected by the water table. Mineralization potentials are almost always negative and may have values up to several hundred millivolts. Background potentials can be either positive or negative and usually have values of only a few tens of millivolts.

Background Potential.—Background potential is commonly the result of (a) two electrolytes of different concentration being in contact with one another, (b) electrolytes flowing through a capillary system or porous media, (c) an electrolyte in contact with a solid, and (d) electromagnetically induced telluric (large scale flow in the earth's crust) currents.

The background potentials developed by electrolytes flowing through a capillary system or porous media (called electro-filtration or streaming potentials) are used to study seepage. Water flowing through a capillary system collects and transports positive ions from the surrounding materials. The positive ions accumulate at the exit point of the capillary, leaving a net positive charge. The untransported negative ions accumulate at the entry point of the capillary leaving a net negative charge. If the streaming potentials developed by this process are of sufficient magnitude to measure, the entry point and the exit point of zones of concentrated seepage may be determined from the negative and positive self potential anomalies.

Applications

Self-potential surveys have been used to map the lateral extent of mineral deposits and, in some instances, provide information of the configuration of the deposits. Another exploration application has been to map the depth to and configuration of certain geothermal areas. Normally, in geothermal applications, self-potential surveying is used in conjunction with other geophysical surveys (gravity, seismic, and electrical).

In geotechnical investigations, self-potential surveys have been used to map leakage paths from dams. Self-potential surveying has also been used to map leaks from canals and buried pipelines that transport liquids. Detachment walls and lateral limits of some landslide masses have been mapped with self-potential surveys.

Self-potential surveying may play an important role in hazardous waste investigations and in monitoring leakage from dams.

Magnetic Surveys

Purpose

Magnetic surveys measure anomalous conditions within the Earth's magnetic field. The Earth's magnetic field resembles the field of a bar magnet. The field is twice as strong in the polar regions than at the equator. The intensity of the field in the polar regions is approximately 60,000 gammas; while at the equator, the intensity is approximately 30,000 gammas. The Earth's magnetic field is not symmetrical but contains many large perturbations due to local variations in magnetic materials and larger magnetic features. Within the Earth's field, anomalies on the order of one gamma to several thousand gammas are detected by magnetic surveys. The smaller anomalies can be detected with complex instruments, and the larger anomalies can be detected with simpler instruments and field techniques.

Applications

Magnetic surveys have their widest applications in petroleum and mineral exploration programs. For applications in petroleum exploration, the application is somewhat simpler because the sources of most magnetic anomalies lie within the basement complex and the overlying sediments are often "transparent" to magnetic surveys.

In geotechnical investigations, magnetic surveys have been used to detect buried barrels of contaminated materials and to detect and map buried pipelines. Magnetic surveys have also been used in archaeological investigations.

Gravity Surveys

Purpose

Gravity anomalies are the result of contrasts in densities of materials in the Earth. If all the materials within the Earth were layered horizontally and were of uniform density, there would be no density contrasts. Density contrasts of different materials are controlled by a number of different factors; the most important are the grain density of the particles forming the material, the porosity of the material, and the interstitial fluids within the material. Generally, soil and shale specific gravities range from 1.7 to 2.2. Massive limestone specific gravities average 2.7. While this range of values may appear to be fairly large, local contrasts will be only a fraction of this range. A common order of magnitude for local density contrasts is 0.25. Density contrasts can be determined by calculating the gravity effect of a known model and comparing that effect with the observed gravity determined from a gravity survey.

Applications

Gravity surveys provide an inexpensive determination of regional structures that may be associated with groundwater aquifers or petroleum traps. Gravity surveys have been one of the principal exploration tools in regional petroleum exploration surveys. Gravity surveys have somewhat limited applications in geotechnical investigations. Gravity surveys have been used to obtain information on bedrock depths and the top of rock configuration in areas where it has not been possible or practical to use other geophysical techniques. Microgravity (high-precision) surveys have been used in a few instances to obtain information on the success of grouting programs. In these cases, microgravity surveys are performed before and after grouting operations and density contrasts of the two surveys are compared. Microgravity surveys have been used for archaeological investigations.

Glossary

A

Accelerometer – Transducer with output proportional to acceleration. A moving coil geophone (type of transducer) with a response proportional to frequency may operate as an accelerometer.

Acoustic Logging – borehole log of any of several aspects of acoustic-wave propagation (e.g., a sonic, amplitude, character, or three-dimensional log).

Air Wave – Energy from a shot which travels in the air at the velocity of sound.

Amplitude – The size of a signal, either in the ground or after amplification. Usually measured from the zero or rest position to a maximum excursion. The amplitude of a signal has units based on the measurement of the signal (e.g., acceleration (inch per square second [in/sec^2]), velocity (inches per second [in/sec]) or displacement (inches [in]).

Analog – (1) A continuous physical variable (such as voltage or rotation) that has a direct relationship to another variable (such as acceleration) with one proportional to the other. (2) Continuous as opposed to discrete or digital.

Anomaly – A deviation from normal or the expected. For example, a travel time anomaly, Bouger anomaly, free-air anomaly.

Apparent Velocity – (1) The velocity that a wave-front registers on a line of geophones. (2) The inverse slope of a time-distance curve.

Automatic Gain Control (AGC) – The output amplitude controls the gain of a seismic amplifier, usually individual for each channel; but sometimes, multi-channel devices are used.

B

Basement (Complex) – (1) generally of igneous and metamorphic rocks overlain unconformably by sedimentary strata. (2) Crustal layer beneath a sedimentary layer and above the Mohorovicic discontinuity.

Bedrock – Any solid rock exposed at the surface of the earth or overlain by unconsolidated material.

Bit – A binary digit; either a 1 (one) or 0 (zero).

Body Waves – The only waves that travel through the interior of a body consisting of P-waves and S-waves.

Byte – Word.

C

Cable – The assembly of electrical conductors used to connect geophone groups or other instruments.

Casing – Tubing or pipe used to line drill holes or shot-holes to keep them from caving.

Cathodic Protection – Electrical corrosion protection for pile foundations, electrical grounding mats, buried pipelines, or any metal subject to corrosion.

Channel – (1) A single series of interconnected devices through which geophysical data can flow from source to recorder. (2) An elongated depression or geological feature. (3) An allocated portion of the radio frequency spectrum.

Channel Wave – An elastic wave propagated in a layer of lower velocity than layers on either side. Energy is largely prevented from escaping from the channel because of repeated total reflection at the channel boundaries or because rays that tend to escape are refracted back toward the channel.

Character. – (1) The recognizable aspect of a seismic event, usually displayed in the waveform that distinguishes the event from other events. Usually, a frequency or phasing effect, often not defined precisely and dependent upon subjective judgment.

Common Depth Point (CDP). – The same portion of subsurface that produces reflections at different offset distances on several profiles.

Compressional Wave – An elastic body wave with particle motion in the direction of propagation. Same as P-waves, longitudinal wave, dilatation wave, irrotational.

Converted Wave – A wave that is converted from longitudinal to transverse, or vice versa, upon reflection or refraction at oblique incidence from an interface.

Critical Angle – Angle of incidence, θ_c, for which the refracted ray grazes the contact between two media (of velocities V_1 and V_2):

$$\sin \theta_c = V_1/V_2$$

Critical Distance – (1) The offset at which a refracted event becomes the first break; cross-over distance. (2) The offset at which the reflection time equals the refraction time (i.e., the offset at which the reflection occurs at the critical angle).

Crossfeed (Crosstalk) – Interference resulting from the unintentional pickup of information or noise from another channel.

D

Datum – (1) The arbitrary reference level to which measurements are corrected. (2) The surface from which seismic reflection times or depths are measured, corrections having been made for local topographic and/or weathering variations. (3) The reference level for elevation measurements, often sea level.

Delay Time – (l) In refraction work, the additional time taken for a wave to follow a trajectory to and along a buried marker over that which would have been taken to follow the same marker hypothetically at the ground surface or at a reference level. Normally, delay time exists separately under a source and under a detector and depends on the depth of the marker at wave incidence and emergence points. Shot delay time plus geophone delay time equals intercept time. (2) Delay produced by a filter. (3) Time lag introduced by a delay cap.

Diffraction – (1) Scattered energy which emanates from an abrupt irregularity, particularly common where faults cut reflecting interfaces. The diffracted energy shows greater curvature than a reflection (except in certain cases where there are buried foci), although not necessarily as much as the curve of maximum convexity. Diffraction frequently blends with a reflection and obscures the fault location or becomes confused with dip. (2) Interference produced by scattering at edges. (3) Causes energy to be transmitted laterally along a wave crest. When a portion of a wave train is interrupted by a barrier, diffraction allows waves to propagate into the region of the barrier's geometric shadow.

Digital – Representation of quantities in discrete units. An analog system represents data as a continuous signal.

Dipole – A pair of closely spaced current electrodes that approximates a dipole field from a distant pair of voltage detecting electrodes.

E

Elastic Constants –

(1) Bulk modulus, $\boldsymbol{k}$. – The stress-strain ratio under hydrostatic pressure.

$$\boldsymbol{k} = \frac{\Delta \boldsymbol{P}}{\Delta \boldsymbol{V} / \boldsymbol{V}}$$

where ΔP = pressure change, V = volume, and ΔV = volume change.

(2) Shear modulus, μ. – rigidity modulus, Lame's constant. The stress-strain ratio for simple shear.

$$\mu = \frac{\boldsymbol{F_t} / \boldsymbol{A}}{\Delta \boldsymbol{L} / \boldsymbol{L}}$$

where F_t = tangential force, A = cross-sectional area, L = distance between shear planes, and ΔL = shear displacement. Shear modulus can also be expressed in terms of other moduli as:

$$\mu = \frac{\boldsymbol{E}}{(1+\sigma)}$$

where E = Young's modulus, and σ = Poisson's ratio.

(3) Young's modulus, E. – The stress-strain ratio when a rod is pulled or compressed.

$$\boldsymbol{E} = \frac{\Delta \boldsymbol{F} / \boldsymbol{A}}{\Delta \boldsymbol{L} / \boldsymbol{L}}$$

where $\Delta F/A$ = stress (force per unit area), L = original length, and ΔL = change in length.

(4) Lame' constant, λ. – a tube is stretched in the up-direction by a tensile stress, S, giving an upward strain, s, and S' is the lateral tensile stress needed to prevent lateral contraction, then:

$$\lambda = \frac{\boldsymbol{S}'}{\boldsymbol{s}}$$

This constant can also be expressed in terms of Young's modulus, E, and Poisson's ratio, σ:

$$\lambda = \frac{\sigma E}{(1+\sigma)(1-2\sigma)}$$

Electromagnetic – Periodically varying field, such as light, radio waves, radar.

End Line – Shotpoints that are shot near the end of the spread.

F

Fan Shooting – An early use of the refraction seismograph to find salt domes within a thick, low-velocity section; detectors located in widely spaced fan-like arrays radiating from the shot locations.

Filter – (1) A device that discriminates against some of the input information. The discrimination is usually on the basis of frequency, although other bases such as wavelength or moveout (see velocity filter) may be used. The act of filtering is called convolution. (2) Filters may be characterized by their impulse response or, more usually, by their amplitude and phase response as a function of frequency. (3) Band-pass filters are often specified by successively listing their low-cutoff and high-cutoff points. (4) Notch filters reject sharply at a particular frequency. (5) Digital filters filter data numerically in the time domain. Digital filtering can be the exact equivalent of electrical filtering. Digital filtering is very versatile and permits easy filtering according to arbitrarily chosen characteristics.

First Break or First Arrival – The first recorded signal attributable to seismic wave travel from a source. First breaks on reflection records provide information about weathering. Refraction work is based principally on the first breaks, although secondary (later) refraction arrivals are also used.

Frequency – The repeat rate of a periodic wave, measured in hertz. Angular frequency, measured in radians per second.

G

Galvanometer – A coil suspended in a constant magnetic field. The coil rotates through an angle proportional to the electrical current flowing through the coil. A small mirror on the coil reflects a light beam proportional to the galvanometer rotation.

Geophone (Seismometer, Jug) – Instrument used to convert seismic energy (vibration) into electrical energy.

Geophone Station – Location of a geophone on a spread.

Gravimeter. – An instrument for measuring variations in gravitational attraction.

Gravity Survey – A survey performed to measure the gravitational field strength, or derivatives, that are related to the density of different rock types.

Group Velocity – The velocity at which most of the energy in a wave train travels. In dispersive media where velocity varies with frequency, the wave train changes shape as it progresses so that individual wave crests appear to travel at velocities (the phase velocity) different from the overall energy as approximately enclosed by the envelope of the wave train. The velocity of the envelope is the group velocity. Same as dispersion.

H

Head Wave – See refraction wave.

Hidden Layer – A layer that cannot be detected by refraction methods; typically, a low velocity layer beneath a high velocity layer.

Hydrodynamic Wave – A seismic surface wave propagated along a free surface. The particle motion is elliptical and prograde (M2 type Rayleigh or Sezawa) (e.g., Rayleigh-type wave dependent upon layering).

Hydrophone (Pressure Detector) – A detector sensitive to variations in pressure, as compared to a geophone, which is sensitive to motion. Used when the detector can be placed below a few feet of water such as in marine or marsh applications or as a well seismometer. The frequency response of the hydrophone depends on the depth beneath the surface.

I

In-line Offset – Shot points that are in line, but offset to a spread.

L

Lead – An electrical conductor (wire cable) used to connect electrical devices. Geophones are connected to cables at the takeouts via leads on the geophones.

Love Wave – A surface seismic wave associated with layering. This wave is characterized by horizontal motion perpendicular to the direction of propagation, with no vertical motion.

Low-velocity Layer (LVL) – The surface layer that has low seismic velocity.

M

Magnetic Survey – A survey to measure the magnetic field or its components as a means of locating concentrations of magnetic materials or determining depth to basement.

Mis-tie – (1) The time difference obtained on carrying a reflection event or some other measured quantity around a loop; or the difference of the values at identical points on intersecting lines or loops. (2) In refraction shooting, the time difference from reversed profiles that gives erroneous depth and dip calculations.

Multiple – Seismic energy that has been reflected more than once (e.g., long-path multiple, short-path multiple, peg-leg multiple, and ghosts).

N

Noise – (1) Any undesired signal or disturbance that does not represent any part of a message from a specified source. (2) Sometimes restricted to random energy. (3) Seismic energy that is not resolvable as reflections. Noise can include microseisms, shot-generated noise, tape-modulation noise, and harmonic distortions. Sometimes divided into coherent noise (including non-reflection coherent events) and random noise (including wind noise, instrument noise, and all other energy which is non-coherent). (3) Random noise can be attenuated by compositing signals from independent measurements. (4) Sometimes restricted to seismic energy not derived from the shot explosion. (5) Disturbances in observed data due to more or less random inhomogeneities in surface and near-surface material.

Noise Analysis – A profile or set of profiles used to gather data for an analysis of coherent noise. Used to design geophone arrays in reflection surveys.

Noise Survey (Ground Noise Survey) – A survey of ambient, continuous seismic noise levels within a given frequency band. This technique is a useful tool for detecting some geothermal reservoirs because they are a source of short-period seismic energy.

O

On-line – Shot points that are not at any point on a spread other than at the ends.

Original Data – (1) Any element of data generated directly in the field in the investigation of a site. (2) A new element of data resulting from a direct manipulation or compilation of field data.

Oscillograph – A device that records oscillations as a continuous graph of corresponding variation in an electric current or voltage.

Oscilloscope – A device that visually displays an electrical wave on a screen (e.g., on a cathode ray tube).

P

Phase Velocity – The velocity of any given phase (such as a trough or a wave of single frequency); it may differ from group velocity because of dispersion.

Plant – The manner in which a geophone is placed or the coupling to the ground.

Primacord – An explosive rope that can be used to either connect explosive charges or to detonate separately as a primary energy source.

Profile – The series of measurements made from several shotpoints to a recording spread from which a seismic data cross section or profile can be constructed.

R

Radar – An exploration method where microwaves are transmitted into a medium and are reflected back by objects or layers. The reflected microwaves are received and processed to provide an image of the subsurface. May be used for shallow penetration surveys.

Rayleigh Wave – A seismic wave propagated along a free surface. The particle motion is elliptical and retrograde.

Ray Path – The path of a seismic wave. A line everywhere perpendicular to wave-fronts (in isotropic media).

Reconnaissance – (1) A general examination of a region to determine its main features, usually preliminary to a more detailed survey. (2) A survey to determine regional geological structures or to determine whether economically prospective features exist, rather than to map an individual structure.

Reflection Survey – A survey of geologic structure using measurements made of arrival times of seismic waves that have been reflected from acoustic impedance change interfaces.

Refraction Survey – A survey of geologic structure using compressional or head waves. Head waves involve energy that enters a high-velocity medium (refractor).

Refraction Wave (Headwave, Mintrop Wave, Conical Wave) – Wave travel from a point source obliquely downward to and along a relatively high velocity formation or marker and then obliquely upward. Snell's law is obeyed throughout the trajectory. Angles of incidence and of emergence at the marker are critical angles. Refracted waves typically following successively deeper markers appear as first arrivals with increasing range (shot to detector distance). Refracted waves following different markers may have different arrival times for any given range. Refracted waves cannot arise for angles of incidence less than the critical angle for any given marker. At the critical angle, the refracted wave path (and travel time) coincides with that of a wide angle reflection.

Refractor (Refraction Marker) – An extensive, relatively high-velocity layer underlying lower velocity layers that transmits a refraction wave nearly horizontally.

Resistivity – An electrical property of rock reflecting the conductivity of an electrical current. Resistivity is the ratio of electric field intensity to current density.

Resistivity Meter – A general term for an instrument used to measure the in place resistivity of soil and rock materials.

Resistivity Survey – A survey that measures electric fields and earth resistivity of a current induced into the ground.

Reverse Profile – A refraction seismic profile generated by shooting both ends of a spread.

Roll-along – A mechanical or electrical switch that connects different geophones (or geophone groups) to the recording instruments. The use of a roll-along switch permits common depth point reflection data to be easily acquired in the field.

S

Seismic Amplifier – An electronic device used to increase the electrical amplitude of a seismic signal.

Seismic Camera – A recording oscillograph used to make a seismic record.

Seismic Cap – A small explosive designed to be detonated by an electric current that detonates another explosive. These caps are designed to provide very accurate time control on the shot.

Seismic Velocity – The rate of propagation of seismic waves through a medium.

Seismogram – A seismic record.

Self-potential (Spontaneous Potential, Natural Potential, SP) – The direct current or slowly varying natural ground voltage between nearby non-polarizing electrodes.

Shear Wave – A body wave with the particle motion perpendicular to the direction of propagation. (Same as S-wave, equivoluminal, transverse wave.)

Shooter – The qualified, licensed individual (powder-man) in charge of all shot point operations and explosives on a seismic crew.

Shot Depth – The distance from the surface down to the explosive charge. The shot depth is measured to the center or bottom of the charge with small charges. The distances to both the top and bottom of the column of explosives are measured with large charges.

Shot Instant (Time Break, TB, Zero Time) – The instant at which a shot is detonated.

Shot Point – Location of the energy source used in generating a particular seismogram.

Signal Enhancement – A process used in seismographs and resistivity systems to improve the signal-to-noise ratio by real-time adding (stacking) of successive waveforms from the same source point. Random noise tends to cancel out, and the coherent signal tends to add or stack.

Snell's Law – When a wave crosses a boundary between two isotropic mediums, the wave changes direction such that the sine of the angle of incidence of the wave divided by the velocity of the wave in the first medium equals the sine of the angle of refraction of the wave in the second medium divided by the velocity of the wave in the second medium (see critical angle).

Spread – The layout of geophone groups from which data from a single shot are simultaneously recorded.

Stanley Wave – A type of seismic surface wave propagated along an interface.

Surface Wave – Energy that travels along or near the surface (ground roll).

T

Takeout – The connections on a multiconductor cable for connecting geophones. May refer to the short cable leads from the geophones (pigtails).

Time Break – The mark on a seismic record that indicates the shot instant or the time the seismic wave was generated.

Trace – A record of one seismic channel. This channel may contain one or more geophones.

V

Vibration Monitor – A sensitive, calibrated recorder of ground and structural acceleration and velocity. Measurements are made to determine vibration amplitudes and modal frequencies of buildings, towers, etc., under ambient conditions, as well as to detect potentially damaging vibrations caused by blasting, pile driving, etc.

Vibroseis – A seismic energy source consisting of controlled frequency input into the earth by way of large truck mounted vibrators. Trademark of Continental Oil Company (Conoco).

W

Wave Length – The distance between successive similar points on two adjacent cycles of a wave measured perpendicular to the wavefront.

Wave Train – (1) The sum of a series of propagating wave fronts emanating from a single source. (2) The complex wave form observed in a seismogram obtained from an explosive source.

Weathering Spread – A short-spaced geophone interval refraction spread used to provide corrections to refraction data caused by delay times in near-surface, low-velocity materials.

WWV(B) – The National Institute of Standards and Technology (NIST) radio stations that broadcast time and frequency standards.

For the definition of other geophysical terms used in this manual, refer to: *Glossary of Terms Used in Geophysical Exploration,* Society of Exploration Geophysicists, Tulsa, Oklahoma, 1984.

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