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Standard Guide for Using the Seismic-Reflection Method for Shallow Subsurface Investigation[1]

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1. Scope

1.1 *Purpose and Application:*

1.1.1 This guide summarizes the technique, equipment, field procedures, data processing, and interpretation methods for the assessment of shallow subsurface conditions using the seismic-reflection method.

1.1.2 Seismic reflection measurements as described in this guide are applicable in mapping shallow subsurface conditions for various uses including geologic (**1**), geotechnical, hydrogeologic (**2**), and environmental (**3**).[2] The seismic-reflection method is used to map, detect, and delineate geologic conditions including the bedrock surface, confining layers (aquitards), faults, lithologic stratigraphy, voids, water table, fracture systems, and layer geometry (folds). The primary application of the seismic-reflection method is the mapping of lateral continuity of lithologic units and, in general, detection of change in acoustic properties in the subsurface.

1.1.3 This guide will focus on the seismic-reflection method as it is applied to the near surface. Near-surface seismic reflection applications are based on the same principles as those used for deeper seismic reflection surveying, but accepted practices can differ in several respects. Near-surface seismic-reflection data are generally high-resolution (dominant frequency above 80 Hz) and image depths from around 6 m to as much as several hundred meters. Investigations shallower than 6 m have occasionally been undertaken, but these should be considered experimental.

1.2 *Limitations:*

1.2.1 This guide provides an overview of the shallow seismic-reflection method, but it does not address the details of seismic theory, field procedures, data processing, 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 the seismic-reflection method be familiar with the relevant material in this guide, the references cited in the text, and Guides D420, D653, D2845, D4428/D4428M, Practice D5088, Guides D5608, D5730, D5753, D6235, and D6429.

1.2.2 This guide is limited to two-dimensional (2-D) shallow seismic-reflection measurements made on land. The seismic-reflection method can be adapted for a wide variety of special uses: on land, within a borehole, on water, and in three dimensions (3-D). However, a discussion of these specialized adaptations of reflection measurements is not included in this guide.

1.2.3 This guide provides information to help understand the concepts and application of the seismic-reflection method to a wide range of geotechnical, engineering, and groundwater problems.

1.2.4 The approaches suggested in this guide for the seismic-reflection method are commonly used, widely accepted, and proven; however, other approaches or modifications to the seismic-reflection method that are technically sound may be equally suited.

1.2.5 Technical limitations of the seismic-reflection method are discussed in 5.4.

1.2.6 This guide discusses both compressional (P) and shear (S) wave reflection methods. Where applicable, the distinctions between the two methods will be pointed out in this guide.

1.3 *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 guide 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*

[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 in parentheses refer to the list of references at the end of this standard.

consideration for a project's many unique aspects. The word "Standard" in the title of this guide means only that the document has been approved through the ASTM consensus process.

1.4 The values stated in SI units are regarded as standard. The values given in parentheses are inch-pound units, which are provided for information only and are not considered standard.

1.5 *Precautions:*

1.5.1 *It is the responsibility of the user of this guide to follow any precautions within the equipment manufacturer's recommendations, establish appropriate health and safety practices, and consider the safety and regulatory implications when explosives or any high-energy (mechanical or chemical) sources are used.*

1.5.2 *If the method is applied at sites with hazardous materials, operations, or equipment, it is the responsibility of the user of this guide to establish appropriate safety and health practices and determine the applicability of any regulations prior to use.*

1.5.3 *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~~ safety, health, and ~~health~~environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D420 Guide for Site Characterization for Engineering Design and Construction Purposes
D653 Terminology Relating to Soil, Rock, and Contained Fluids
D2845 Test Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock (Withdrawn 2017)[4]
D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction
D4428/D4428M Test Methods for Crosshole Seismic Testing
D5088 Practice for Decontamination of Field Equipment Used at Waste Sites
D5608 Practices for Decontamination of Sampling and Non Sample Contacting 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 Geotechnical 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
D6429 Guide for Selecting Surface Geophysical Methods
D6432 Guide for Using the Surface Ground Penetrating Radar Method for Subsurface Investigation

3. Terminology

3.1 ~~*Definitions*—~~*Definitions:* ~~For general terms, See Terminology D653. Additional technical terms used in this guide are defined in Refs (4) and (5) .~~

3.1.1 For definitions of common technical terms used in this standard, refer to Terminology D653.

3.2 *Definitions Specific to This Guide*

3.2.1 *acoustic* ~~*impedance*—~~*impedance, n—*product of seismic compressional wave velocity and density. Compressional wave velocity of a material is dictated by its bulk modulus, shear modulus, and density. Seismic impedance is the more general term for the product of seismic velocity and density.

3.2.2 *automatic gain control* ~~*(AGC)*—~~*(AGC), n—*trace amplitude adjustment that varies as a function of time and the amplitude of adjacent data points. Amplitude adjustment changing the output amplitude so that at least one sample is at full scale deflection within a selected moving window (moving in time).

3.2.3 *blind seismic deconvolution, n—*a very challenging and yet common seismic deconvolution problem is where the source wave is unknown and has the potential for time variation. Identifies the case where we have one known (measured seismogram with additive noise) and two unknowns (source wave and reflection coefficients).

3.2.4 *body* ~~*waves*—~~*waves, n—P*- and *S*-waves that travel through the body of a medium, as opposed to surface waves which travel along the surface of a half-space.

3.2.5 *bulk modulus,* ~~*(elastic*~~ *n—* ~~*constant)*—~~the resistance of a material to change its volume in response to the hydrostatic load. Bulk modulus (K) is also known as the modulus of compression.

[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.

3.2.6 *check shot survey—survey (downhole survey), n—*direct measurement of traveltime between the surface and a given depth. Usually sources on the surface are recorded by a seismic receiver in a well to determine the time-to-depth relationships at a specified location. Also referred to as downhole survey.

3.2.7 *coded source—source, n—*a seismic energy-producing device that delivers energy throughout a given time in a predetermined or predicted fashion.

3.2.8 *common mid-point (CMP) or common depth point (CDP) method—method, n—*a recording-processing method in which each source is recorded at a number of geophone locations and each geophone location is used to record from a number of source locations. After corrections, these data traces are combined (stacked) to provide a common-midpoint section approximating a coincident source and receiver at each location. The objective is to attenuate random effects and events whose dependence on offset is different from that of primary reflections.

3.2.8.1 *Discussion—*

After corrections, these data traces are then combined (stacked) to provide a common-midpoint section approximating a coincident source and receiver at each location. The objective is to attenuate random effects and events whose dependence on offset is different from that of primary reflections.

3.2.9 *compressional wave velocity—velocity (P-wave velocity), n—*also known as P-wave velocity. In seismic usage, velocity refers to the propagation rate of a seismic wave without implying any direction, that is, velocity is a property of the medium. Particle displacement of a compressional wave is in the direction of propagation.

3.2.10 *dynamic range—range, n—*the ratio of the maximum reading to the minimum reading which can be recorded by and read from an instrument without change of scale. It is also referred to as the ability of a system to record very large and very small amplitude signals and subsequently recover them. Integral to the concept of dynamic range is the systems Analog to Digital converter (A/D). A systems A/D is rated according to the number of bits the analog signal is segmented into to form the digital word. A/D converters in modern seismographs usually range from 16 to 24 bits.

3.2.11 *fold (or(redundancy), redundancy)—n—*the multiplicity of common-midpoint data or the number of midpoints per bin. Where the midpoint is the same for 12 source/receiver pairs, the stack is referred to as "12-fold" or 1200 percent.

3.2.11.1 *Discussion—*

Where the midpoint is the same for 12 source/receiver pairs, the stack is referred to as "12-fold" or 1200 percent.

3.2.12 *G-force—G-force, n—*measure of acceleration relative to the gravitational force of the earth.

3.2.13 *impedance contrast—contrast, n—*ratio of the seismic impedance across a boundary. Seismic boundary or seismic impedance of the lower layer divided by the seismic impedance of the upper layer. A value of 1 implies total transmittance. Values increase or decrease from 1 as the contrast increases, that is, more energy reflection from a boundary. Values less than 1 are indicative of a negative reflectivity or reversed reflection wavelet polarity.

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3.2.14 *normal moveout (NMO)—(NMO), n—*the difference in reflection-arrival time as a function of shot-to-geophoneshot-to-receiver distance because the geophonereceiver is not located at the source point. It is the additional traveltime required because of offset, assuming that the reflecting bed is not dipping and that raypaths are straight lines. This leads to a hyperbolic shape for a reflection.

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3.2.15 *normal moveout velocity (stacking velocity)—velocity), n—*velocity to a given reflector calculated from normal-moveout measurements, assuming a constant-velocity model. Because the raypath actually curves as the velocity changes, fitting a hyperbola assumes that the actual velocity distribution is equivalent to a constant NMO velocity, but the NMO velocity changes with the offset. However, the assumption often provides an adequate solution for offsets less than the reflector depth. Used to calculate NMO corrections to common-midpoint gathers prior to stacking.

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Because the raypath actually curves as the velocity changes, fitting a hyperbola assumes that the actual velocity distribution is equivalent to a constant NMO velocity, but the NMO velocity changes with the offset. However, the assumption often provides an adequate solution for offsets less than the reflector depth. Used to calculate NMO corrections to common-midpoint gathers prior to stacking.

3.2.16 *Nyquist ~~frequency—~~frequency, n—*also known as the aliasing or folding frequency, is equal to half the sampling frequency or rate. ~~Any frequency arriving at the recording instrument greater than the Nyquist will be aliased to a lower frequency and cannot be recovered.~~

3.2.17 *optimum ~~window—~~window, n—*range of offsets between source and receiver that provide reflections with the best signal-to-noise ratio.

~~3.2.17 *Poisson's ratio*—the ratio of the transverse contraction to the fractional longitudinal extension when a rod is stretched. If density is known, specifying Poisson's ratio is equivalent to specifying the ratio of V_s/V_p, where V_s and V_p are *S* - and *P*-wave velocities. Values ordinarily range from 0.5 (no shear strength, for example, fluid) to 0, but theoretically they range from 0.5 to −1.0; {$\mu = \sqrt{1-0.5(V_p/V_s)^2} / 1-(V_p/V_s)^2$}.~~

3.2.18 *~~raypath—~~raypath, n—*a line everywhere perpendicular to wavefronts (in isotropic media). ~~A raypath is characterized by its direction at the surface. While seismic energy does not travel only along raypaths, raypaths constitute a useful method of determining arrival time by ray tracing.~~

3.2.19 *~~reflection—~~reflection, n—*the energy or wave from a seismic source that has been reflected (returned) from an acoustic-impedance contrast (reflector) or series of contrasts within the earth.

3.2.20 *reflection series, n—*the reflection coefficients defining a stratigaphic profile.

3.2.21 *~~reflector—~~reflector, n—*an interface having a contrast in physical properties (elasticity and/or density) that reflects seismic energy.

3.2.22 *roll-along ~~switch—~~switch, n—*a switch that connects different geophone groups to the recording instruments, used in common-midpoint recording.

3.2.23 *seismic convolution, n—*the convolution between the reflection series and source wave.

3.2.24 *seismic deconvolution, n—*the process of removing the characteristics of the source wave from the recorded seismic time series so that one is ideally left with only the reflection coefficients.

3.2.25 *seismic ~~impedance—~~impedance, n—*product of seismic wave velocity and density. ~~Different from acoustic impedance as it includes shear waves and surface waves where acoustic impedance, by strict definition, includes only compressional waves.~~

3.2.25.1 *Discussion—*

The seismic impedance includes shear waves and surface waves, whereas acoustic impedance, by strict definition, includes only compressional waves.

3.2.26 *seismic ~~sensor—~~sensor, n—*receivers designed to couple to the earth and record vibrations (for example, geophones, accelerometers, hydrophones).

3.2.27 *seismic sensor group ~~(spread)—~~(spread), n—*multiple receivers connected to a single recording channel, generally deployed in an array designed to enhance or attenuate specific energy.

~~3.2.25 *seismogram*—a seismic record or section.~~

3.2.28 *shear modulus (G) ~~(elastic constant)—~~(rigidity modulus), n—*the ratio of shear stress to shear strain of a material as a result of loading ~~and is also known as the rigidity modulus, equivalent to the second Lamé constant m mentioned in books on continuum theory. For small deformations, Hooke's law holds and strain is proportional to stress.~~

3.2.28.1 *Discussion—*

G is equivalent to the second Lamé constant. For small deformations, Hooke's law holds and strain is proportional to stress.

3.2.29 *shear wave velocity (S-wave ~~velocity)—~~velocity), n—*speed of energy traveling with particle motion perpendicular to its direction of ~~propagation (see~~ propagation.~~Eq 2).~~

3.2.30 *shot ~~gather—~~gather (field files), n—*a side-by-side display of seismic traces that have a common source location. ~~Also referred to as "field files."~~

3.2.31 *source to seismic sensor ~~offset—~~offset, n—*the distance from the source-point to the seismic sensor or to the center of a seismic sensor (group) spread.

3.2.32 *source wave, n—*seismic source wave generated to travel thorough stratigraphic profile under investigation.

3.2.33 *stacking, n—*adding seismic traces from different records to reduce noise and improve overall data quality.

3.2.34 ~~*takeout—*~~*takeout, n—*a connection point on a multiconductor cable where seismic sensors can be connected. ~~Takeouts are usually physically polarized to reduce the likelihood of making the connection backwards.~~

3.2.34.1 *Discussion—*

Takeouts are usually physically polarized to reduce the likelihood of making the connection backwards.

3.2.35 *tap* ~~*test—*~~*test, n—*gently touching a receiver while monitoring on real-time display, to qualitatively appraise sensor response.

3.2.36 *twist* ~~*test—*~~*test, n—*light rotational pressure applied to each seismic sensor to ensure no motion and, therefore, a solid ground coupling point.

3.2.37 *wavetrain* ~~*(wavefield)—*~~*(wavefield), n—(1)* spatial perturbations at a given time that result from passage of a wave; and *(2)* all components of seismic energy traveling through the earth as the result of a single impact.

3.2.38 *wide-angle* ~~*reflections—*~~*reflections, n—*reflections with an angle of incidence near or greater than the critical angle. ~~The critical angle is defined as the unique angle of incidence at which rays incident to a boundary (boundary defined as an abrupt vertical increase in velocity) "refract" and travel in the lower, higher velocity media parallel to the boundary. Wide-angle reflections become asymptotic to refractions at increasing offset and can possess exceptionally large amplitudes. If they are included in CMP stacked sections they can disproportionately contribute to the stacked wavelet.~~

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3.2.39 *wiggle* ~~*trace—*~~*trace, n—*a single line display of seismic sensor output as a function of time.

4. Summary of Guide

4.1 *Summary of the Method—*The seismic-reflection method utilizes seismic energy that propagates through the earth, reflects off subsurface features, and returns to the surface. The seismic waves travel from a source to seismic sensors deployed in a known geometry. Sound waves traveling downward will reflect back to the surface wherever the velocity or density of subsurface materials increases or decreases abruptly (for example, water table, alluvium/bedrock contact, limestone/shale contact).

4.1.1 Images of reflectors (velocity or density contrast) are used to interpret subsurface conditions and materials. Reflections returning from reflectors to seismic sensors will follow travel paths determined by the velocities of the materials through which they propagate. Reflection arrivals on seismic data recorded with multiple seismic sensors at different offsets (distance between source and seismic sensor) from the source can be collectively used to estimate the velocity (approximately average) of the material between the reflection point and seismic sensor. Reflections can be used to characterize properties of the subsurface such as continuity, thickness, and depth of layers and changes in velocity and material type.

4.1.2 The seismic-reflection method depends on the presence of discrete seismic-velocity or mass-density changes in the subsurface that represent acoustical impedance changes. Mathematically, acoustic impedance is proportional to the product of mass density and acoustic wave velocity. Reflection may or may not occur at natural boundaries between geologic layers or at manmade boundaries such as tunnels and mines. The classic use of the seismic reflection method is to identify boundaries of layered geologic units. However, the technique can also be used to search for localized anomalies such as sand or clay lenses and faults.

4.1.3 Seismic energy in the earth travels in the form of body waves and surface waves. Body waves propagating through the earth behave similarly to sound waves propagating in air. When sound waves traveling in air from voices, explosions, horns, etc., come in contact with a wall, cliff, or building (all acoustic contrasts), it is common to hear an echo, which is reflected sound. When a body wave propagating in the subsurface comes in contact with a volume of material with a different acoustical impedance in the subsurface, reflections (echoes) are also generated. In the subsurface, the situation is complex because some of the body wave energy arriving at an acoustic interface can be transmitted, refracted, or converted to other types of seismic waves at the interface. Surface waves are the dominant (in total energy) part of a seismic energy pulse and propagate along the free surface of the earth much like a wave on the ocean moves toward shore. Surface waves penetrate into the earth to a depth that is a function of their wavelength.

4.1.4 The seismic-reflection method requires contrasts in the physical properties of earth materials, much like ground penetrating radar (GPR) (see Guide D6432). The measurable physical parameters (seismic velocity and density) upon which the seismic-reflection method depends are quite different from the physical parameters (conductivity and dielectric constant) on which

GPR depends, but the concept of reflected energy is analogous. The similarities between seismic reflection and electrical methods (resistivity, spontaneous potential), electromagnetic (EM), or potential fields (gravity or magnetics) are substantially less.

4.2 *Complementary Data*—Geologic and hydrogeologic data obtained from borehole logs, geologic maps, data from outcrops, or other surface and borehole geophysical methods are generally necessary to uniquely interpret subsurface conditions from seismic-reflection data. The seismic-reflection method provides a non-unique representation of the subsurface that, without supporting or complementary data, cannot be definitively interpreted.

5. Significance and Use

5.1 *Concepts:*

5.1.1 This guide summarizes the basic equipment, field procedures, and interpretation methods used for detecting, delineating, or mapping shallow subsurface features and relative changes in layer geometry or stratigraphy using the seismic-reflection method. Common applications of the method include mapping the top of bedrock, delineating bed or layer geometries, identifying changes in subsurface material properties, detecting voids or fracture zones, mapping faults, defining the top of the water table, mapping confining layers, and estimating of elastic-wave velocity in subsurface materials. Personnel requirements are as discussed in Practice D3740.

5.1.2 Subsurface measurements using the seismic-reflection method require a seismic source, multiple seismic sensors, multi-channel seismograph, and appropriate connections (radio or hardwire) between each (Fig. 1, also showing optional roll-along switch).

5.1.3 Seismic waves generated by a controlled seismic energy source propagate in the form of mechanical energy (particle motion) from the source through the ground or air to seismic sensors where the particle (ground) motion is converted to electrical voltage and transmitted to the seismograph.

5.1.3.1 Seismic energy travels away from the source both through the ground and air. In the ground, the energy travels as an elastic wave, with compressional waves (Eq 1) and shear waves (Eq 2) moving away from the source in a hemispherical pattern, and surface waves propagating away in a circular pattern on the ground surface.

$$V_p = \sqrt{[(K + 4G/3)/\rho]} \quad (1)$$

$$V_s = (G/\rho)^{1/2} = \{E/[2\rho\,(1+\mu)]\}^{1/2} \quad (2)$$

where:

V_p = compressional wave velocity,
K = bulk modulus,
G = shear modulus,
ρ = density,
E = Young's modulus,

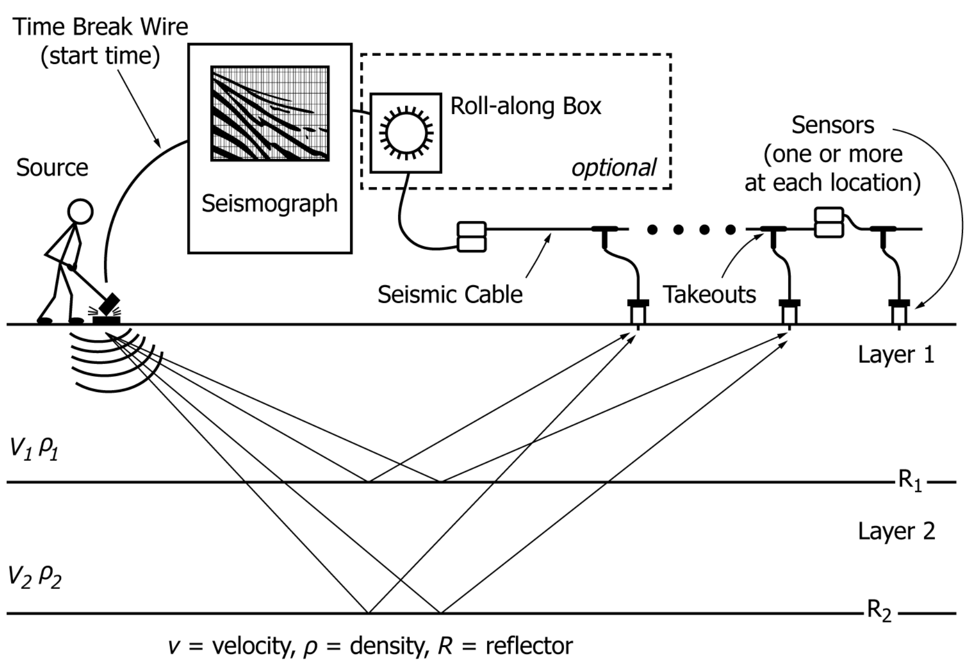


FIG. 1 Schematic of Equipment and Deployment of Equipment for a Seismic Reflection Survey

μ = Poisson's ratio, and
V_s = shear wave velocity.

Seismic energy propagation time between seismic sensors depends on wave type, travel path, and seismic velocity of the material. The travel path of reflected body waves (compressional (P) and shear (S) waves) is controlled by subsurface material velocity and geometry of interfaces defined by acoustic impedance (product of velocity and density) changes. A difference in acoustic impedance between two layers results in an impedance contrast across the boundary separating the layers and determines the reflectivity (reflection coefficient) of the boundary; for example, how much energy is reflected versus how much is transmitted (Eq 3). At normal incidence:

$$R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} \quad \text{and} \quad A = \frac{\rho_2 V_2}{\rho_1 V_1} \tag{3}$$

where:

R = reflectivity = reflection coefficient,
$V_1 V_2$ = velocity of layers 1 and 2,
$\rho_1 \rho_2$ = density of layers 1 and 2,
$V\rho$ = acoustic impedance, and
A = impedance contrast.

Snell's law (Eq 4) describes the relationship between incident, refracted, and reflected seismic waves:

$$\frac{V_1}{\sin i} = \frac{V_1}{\sin r} = \frac{V_1}{\sin t} \tag{4}$$

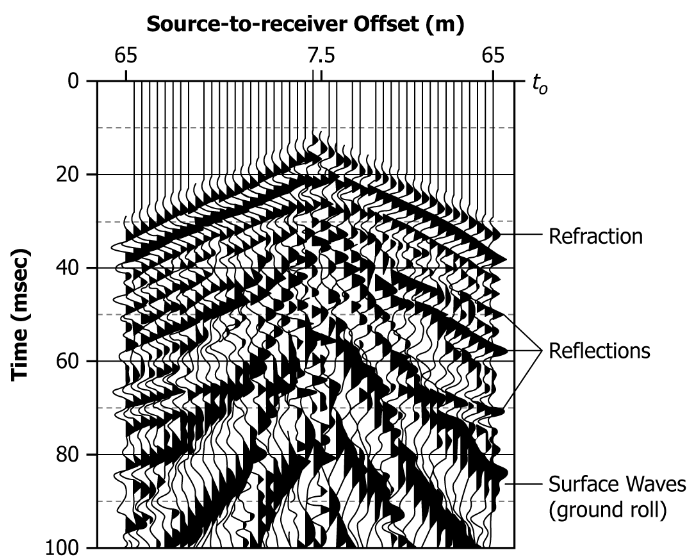
where:

i = incident angle,
r = reflected angle, and
t = refracted angle.

At each boundary represented by a change in the product of velocity and density (acoustic impedance), the incident seismic wave generates a reflected P, reflected S, transmitted P, and transmitted S wave. This process is described by the Zoeppritz equations (for example, Telford et al. (64)).

5.1.3.2 Analysis and recognition of seismic energy arrival patterns at different seismic sensors allows estimation of depths to reflection coefficients (reflectors) and average velocity between the reflection coefficient and the earth's surface. Analog display of the seismic waves recorded by each seismic sensor is generally in wiggle trace format on the seismogram (Fig. 2) and represents the particle motion (velocity or acceleration) consistent with the orientation and type of the seismic sensor (geophone or accelerometer) and source.

5.1.4 A multichannel seismograph simultaneously records the wave field at a number of seismic sensors as a function of time (Fig. 2). Multichannel seismic data are typically displayed as a time and source-to-seismic sensor distance representation of the



NOTE 1—Shows the entire wavefield.
NOTE 2—Acquired with vertical geophones.

FIG. 2 48-Channel Seismograph Record Acquired with a Seismic Source 7.5 m Away from the Nearest Seismic Sensors

source-induced particle motion propagating in the earth. This particle motion, also known as the elastic wave field, can be complex and is modified in a predictable way by the seismic sensors and instrumentation used for recording the seismic signal. A wave field is generally displayed in wiggle trace format, with the vertical (time) axis of the display typically referenced to the instant the seismic energy was released (t_0) and the horizontal axis showing the linear source-to-seismic-sensor distance (Fig. 2). The arrivals of the wavefield at each seismic sensor are synchronized in time based on the selected digital sampling rate of the seismograph. Each seismic event of the wavefield represents different travel paths, particle motions, and velocities of the energy spreading outward from the seismic source. Fig. 2 shows data acquired from a shot in the center of a line of seismic sensors

5.2 *Parameters Measured and Representative Values*—Tables 1 and 2 provide generalized material properties related to the seismic-reflection method.

5.2.1 The seismic-reflection method images changes in the acoustic (seismic) impedance of subsurface layers and features, which represent changes in subsurface material properties. While the seismic reflection technique depends on the existence of non-zero reflection coefficients, it is the interpreter who, based on knowledge of the local conditions and other data, must interpret the seismic-reflection data and arrive at a geologically feasible solution. Changes in reflected waveform can be indicative of changes in the subsurface such as lithology (rock or soil type), rock consistency (that is, fractured, weathered, competent), saturation (fluid or gas content), porosity, geologic structure (geometric distortion), or density (compaction).

5.2.2 *Reflection Coefficient or Reflectivity*—Reflectivity is a measure of energy expected to return from a boundary (interface) between materials with different acoustic impedance values. Materials with larger acoustic impedances overlying materials with smaller acoustic impedances will result in a negative reflectivity and an associated phase reversal of the reflected wavelet. Intuitively, wavelet polarity follows reflection coefficients that are negative when faster or denser layers overlie slower or less dense (for example, clay over dry sand) layers and positive when slower or less dense layers overlie faster or denser (for example, gravel over limestone) layers. A reflectivity of one means all energy will be reflected at the interface.

5.3 *Equipment*—Geophysical equipment used for surface seismic measurement can be divided into three general categories: source, seismic sensors, and seismograph. Sources generate seismic waves that propagate through the ground as either an impulsive or a coded wavetrain. Seismic sensors can measure changes in acceleration, velocity, displacement, or pressure. Seismographs measure, convert, and save the electric signal from the seismic sensors by conditioning the analog signal and then converting the analog signal to a digital format (A/D). These digital data are stored in a predetermined standardized format. A wide variety of seismic surveying equipment is available and the choice of equipment for a seismic reflection survey should be made to meet the objectives of the survey.

5.3.1 *Sources*—Seismic sources come in two basic types: impulsive and coded. Impulsive sources transfer all their energy (potential, kinetic, chemical, or some combination) to the earth instantaneously (that is, usually in less than a few milliseconds). Impulsive source types include explosives, weight drops, and projectiles. Coded sources deliver their energy over a given time interval in a predetermined fashion (swept frequency or impulse modulated as a function of time). Source energy characteristics are highly dependent on near-surface conditions and source type (**8-6-119**). Consistent, broad bandwidth source energy performance is important in seismic reflection surveying. The primary measure of source effectiveness is the measure of signal-to-noise ratio and resolution potential as estimated from the recorded signal.

5.3.1.1 Selection of the seismic source should be based upon the objectives of the survey, site surface and geologic conditions and limitations, survey economics, source repeatability, previous source performance, total energy and bandwidth possible at survey site (based on previous studies or site specific experiments), and safety.

5.3.1.2 Coded seismic sources will generally not disturb the environment as much as impulsive sources for a given total amount of seismic energy. Variable amplitude background noise (such as passing cars, airplanes, pedestrian traffic, etc.) affects the quality

TABLE 1 Approximate Material Properties

Material	*P*-Wave[A] Velocity (m/s)	*S*-Wave[A] Velocity (m/s)	Density (kg/m^3)	Acoustic Impedance[B]
Dry sand/gravel	750[C]	200	1800	1.35×10^6
Clay	900	300	2000	1.80×10^6
Saturated sand	1500	350	2100	3.15×10^6
Saturated clay	1800	400	2200	3.96×10^6
Shale	3500	1500	2500	8.75×10^6
Sandstone	2850	1400	2100	5.99×10^6
Limestone	4000	2200	2600	10.4×10^6
Granite	6000	3500	2600	15.6×10^6

[A] Velocities are mean for a range appropriate for the material (**75**).
[B] Acoustic impedance is velocity multiplied by density, specifically for compressional waves; the equivalent for shear waves is referred to as seismic impedance (units of kg/s·m ^{2}).
[C] Subsonic velocities have been reported by researchers studying the ultra-shallow near surface .

TABLE 2 Approximate Reflectivity of Interfaces Between Common Materials

Material Middle Layer[A]	Material Bottom Layer[B]	Approximate Reflectivity[C]
Dry Sand	Dry Sand	0.0
Dry Sand	Dry Clay / Saturated Clay	0.14 / 0.5
Dry Sand	Gravel	−0.08
Dry Sand	Saturated Sand	0.43
Dry Sand	Limestone	0.75
Dry Sand	Shale	0.72
Dry Sand	Sandstone	0.63
Dry Sand	Granite	0.84
Saturated Sand	Granite	0.66
Clay	Dry Sand	−0.14
Clay	Clay	0.0
Clay	Gravel	−0.17
Clay	Saturated Sand	−0.27
Clay	Limestone	0.71
Clay	Shale	0.66
Clay	Sandstone	0.54

[A] Layer 1 on Fig. 1.
[B] Layer 2 on Fig. 1.
[C] *R* in Eq 3, Absolute value *R* = 1 total reflectance.

of data collected with coded sources less than for impulsive sources. Coded sources require an extra processing step to compress the time-variable signal wavetrain down to a more readily interpretable pulse equivalent. This is generally done using correlation or shift and stack techniques.

5.3.1.3 In most settings, buried small explosive charges will result in higher frequency and broader bandwidth data, in comparison to surface sources. However, explosive sources generally come with use restrictions, regulations, and more safety considerations than other sources. Most explosive and projectile sources are designed to be invasive, while weight drop and most coded sources are generally in direct contact with the ground surface and therefore are non-invasive.

5.3.1.4 Sources that shake, impact, or drive the ground so that the dominant particle motion is horizontal to the surface of the ground are shear-wave sources. Sources that shake, impact, or drive the ground so that the dominant particle motion is vertical to the surface of the ground are compressional sources. Many sources can be used for generating both shear and compressional wave energy.

5.3.2 *Seismic Sensors*—Seismic sensors convert mechanical particle motion to electric signals. There are three different types of seismic sensors: accelerometers, geophones (occasionally referred to as seismometers), and hydrophones.

5.3.2.1 Accelerometers are devices that measure particle acceleration. Accelerometers generally require pre-amplifiers to condition signal prior to transmission to the seismograph. Accelerometers generally have a broader bandwidth of sensitivity and a greater tolerance for high G-forces than geophones or hydrophones. Accelerometers have a preferred direction of sensitivity.

5.3.2.2 Geophones consist of a stationary cylindrical magnet surrounded by a coil of wire that is attached to springs and free to move relative to the magnet. Geophones measure particle velocity and therefore produce a signal that is the derivative of the acceleration measured by accelerometers. Geophones are generally robust, durable, and have unique response characteristics proportional to their natural frequency and coil impedance. The natural frequency is related to the spring constant and the coil impedance is a function of the number of wire windings in the coil.

5.3.2.3 Hydrophones are used when measuring seismic signals propagating in liquids. Because shear waves are not transmitted through water, hydrophones only respond to compressional waves. However, shear waves can be converted to compressional waves at the water/earth interface and provide an indirect measurement of shear waves. Hydrophones are pressure-sensitive devices that are usually constructed of one or more piezoelectric elements that distort with pressure.

5.3.2.4 Geophones and accelerometers can be used for compressional or shear wave surveys on land. Orientation of the seismic sensor determines the seismic sensor response and sensitivity to different particle motion. Some seismic sensors are omnidirectional and are sensitive to particle motion parallel to the motion axis of the sensor, regardless of the sensor's spatial orientation direction. Others seismic sensors are designed to be used in one orientation or the other (*P* or *S*). Shear wave seismic sensors are sensitive to particle motion perpendicular to the direction of propagation (line between source and seismic sensors) and are sensitive to vertical (*SV*) or horizontal (*SH*) transverse wave motion. Compressional wave seismic sensors are sensitive to particle motion parallel to the direction of propagation (line between source and seismic sensor) and thus the motion axis of the seismic sensor needs to be in a vertical position.

5.3.3 *Seismographs*—Seismographs measure the voltages generated by seismic sensors as a function of time and synchronize them with the seismic source. Seismographs have differing numbers of channels and a range of electronic specifications. The choice of an appropriate seismograph should be based on survey objectives. Modern multichannel seismographs are computer based and require minimal fine-tuning to adjust for differences or changes in site characteristics. Adjustable seismograph acquisition settings that will affect the accuracy or quality of recorded data are generally limited to sampling rate, record length, analog filter settings, pre-amplifier gains, and number of recording channels. There is limited need for selectable analog filters and gain adjustments with modern, large dynamic range (>16 bits) seismographs. Seismographs store digital data in standard formats (for example, SEGY, SEGD, SEG2) that are generally dependent on the type of storage medium and the primary design application of the system. Seismographs can be single units (centralized), with all recording channels (specifically analog circuitry and A/D converters) at a single location, or several autonomous seismographs can be distributed around the survey area. Distributed seismographs are characterized by several small decentralized digitizing modules (1–24 channels each) located close to the geophones to reduce signal loss over long-cable seismic sensors. Digital data from each distributed module are transmitted to a central system where data from multiple distributed units are collected, cataloged, and stored.

5.3.4 *Source and Seismic Sensor Coupling*—The seismic sensors and sources must be coupled to the ground. Depending on ground conditions and source and seismic sensor configuration, this coupling can range from simply resting on the ground surface (for example, land streamers, weight drop, vibrator) to invasive ground penetration or burial (for example, spike, buried explosives, projectile delivery at bottom of a hole). Hydrophones couple to the ground through submersion in water in a lake, stream, borehole, ditch, etc.

5.3.5 *Supporting Components*—Additional equipment includes a roll-along switch, cables, time-break system (radio or hardwire telemetry between seismograph and source), quality control (QC) and troubleshooting equipment (seismic sensor continuity, earth leakage, cable leakage, seismograph distortion and noise thresholds, cable and seismic sensor shorting plug), and land surveying equipment.

5.4 *Limitations and Interferences:*

5.4.1 *General Limitations Inherent to Geophysical Methods:*

5.4.1.1 A fundamental limitation of all geophysical methods is that a given set of data does not uniquely represent a set of subsurface conditions. Geophysical measurements alone cannot uniquely resolve all ambiguities, and some additional information, such as borehole measurements, is required. Because of this inherent limitation in geophysical methods, a seismic-reflection survey will not completely represent subsurface geological conditions. Properly integrated with other geologic information, seismic-reflection surveying can be an effective, accurate, and cost-effective method of obtaining detailed subsurface information. All geophysical surveys measure physical properties of the earth (for example, velocity, conductivity, density, susceptibility) but require correlation to the geology and hydrology of a site. Reflection surveys do not directly measure material-specific characteristics (such as color, texture, and grain size), or lithologies (such as limestone, shale, sandstone, basalt, or schist), except to the extent that these lithologies may have different velocities and densities.

5.4.1.2 All surface geophysical methods are inherently limited by signal attenuation and decreasing resolution with depth.

5.4.2 *Limitations Specific to the Seismic-Reflection Method:*

5.4.2.1 Theoretical limitations of the seismic-reflection method are related to the presence of a non-zero reflection coefficient, seismic energy characteristics, seismic properties (velocity and attenuation), and layer geometries relative to recording geometries. In a homogenous earth, no reflections are produced and therefore none can be recorded. When reflection measurements are made at the surface of the earth, reflections can only be returned from within the earth if layers with non-zero reflection coefficients are present within the earth. Layers, for example, defined by changes in lithology without measurable changes in either velocity or density cannot be imaged with the seismic reflection method. Theoretical limits on bed or object-resolving capabilities of a seismic data set are related to frequency content of the reflected energy (see 8.4).

5.4.2.2 Successful imaging of geologic layers dipping at greater than 45 degrees may require non-standard deployments of sources and seismic sensors.

5.4.2.3 Resolution (discussed in 8.4) and signal-to-noise ratios are critical factors in determining the practical limitations of the seismic-reflection method. Source configuration, source and seismic sensor coupling, near-surface materials, specification of the recording systems, relative amplitude of seismic events, and arrival geometry of coherent source-generated seismic noise are all factors in defining the practical limitations of seismic-reflection method.

(1) Highly attenuative near-surface materials such as dry sand and gravel, can adversely affect the resolution potential and signal strength with depth of seismic energy (~~12~~10). Attenuation is rapid reduction of seismic energy as it propagates through an earth material, usually most pronounced at high frequencies. Attenuative materials can prevent survey objectives from being met.

(2) While it is possible to enhance signal not visible on raw field data, it is safest to track all coherent events on processed seismic reflection sections from raw field data through all processing steps to CMP stack. Noise can be processed to appear coherent on CMP stacked sections.

(3) Differences in water quality do not appear to change the velocity and density sufficiently that they can be detected by the seismic-reflection method (~~13~~11).

5.4.3 *Interferences Caused by Natural and by Cultural Conditions:*

5.4.3.1 The seismic-reflection method is sensitive to mechanical and electrical noise from a variety of sources. Biologic, geologic, atmospheric, and cultural factors can all produce noise.

(1) Biologic Sources—Biologic sources of noise include vibrations from animals both on the ground surface and underground in burrows as well as trees, weeds, and grasses shaking from wind. Examples of animals that can cause noise include mice, lizards, cattle, horses, dogs, and birds. Animals, especially livestock, can produce seismic vibrations several orders of magnitude greater than seismic signals at longer offset traces on high-resolution data.