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Standard Guide for Using the Seismic Refraction Method for Subsurface Investigation[1]

This standard is issued under the fixed designation D5777; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 *Purpose and Application*—This guide covers the equipment, field procedures, and interpretation methods for the assessment of subsurface conditions using the seismic refraction method. Seismic refraction measurements as described in this guide are applicable in mapping subsurface conditions for various uses including geologic, geotechnical, hydrologic, environmental (**1**), mineral exploration, petroleum exploration, and archaeological investigations. The seismic refraction method is used to map geologic conditions including depth to bedrock, or to water table, stratigraphy, lithology, structure, and fractures or all of these. The calculated seismic wave velocity is related to mechanical material properties. Therefore, characterization of the material (type of rock, degree of weathering, and rippability) is made on the basis of seismic velocity and other geologic information.

1.2 *Limitations*:

1.2.1 This guide provides an overview of the seismic refraction method using compressional (*P*) waves. It does not address the details of the seismic refraction theory, field procedures, or interpretation of the data. Numerous references are included for that purpose and are considered an essential part of this guide. It is recommended that the user of the seismic refraction method be familiar with the relevant material in this guide and the references cited in the text and with appropriate ASTM standards cited in 2.1.

1.2.2 This guide is limited to the commonly used approach to seismic refraction measurements made on land. The seismic refraction method can be adapted for a number of special uses, on land, within a borehole and on water. However, a discussion of these other adaptations of seismic refraction measurements is not included in this guide.

1.2.3 There are certain cases in which shear waves need to be measured to satisfy project requirements. The measurement of seismic shear waves is a subset of seismic refraction. This guide is not intended to include this topic and focuses only on *P* wave measurements.

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

1.2.5 Technical limitations and interferences of the seismic refraction method are discussed in D420, D653, D2845, D4428/D4428M, D5088, D5730, D5753, D6235, and D6429.

1.3 *Precautions*:

1.3.1 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 are used.

1.3.2 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.

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

1.5 *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*

[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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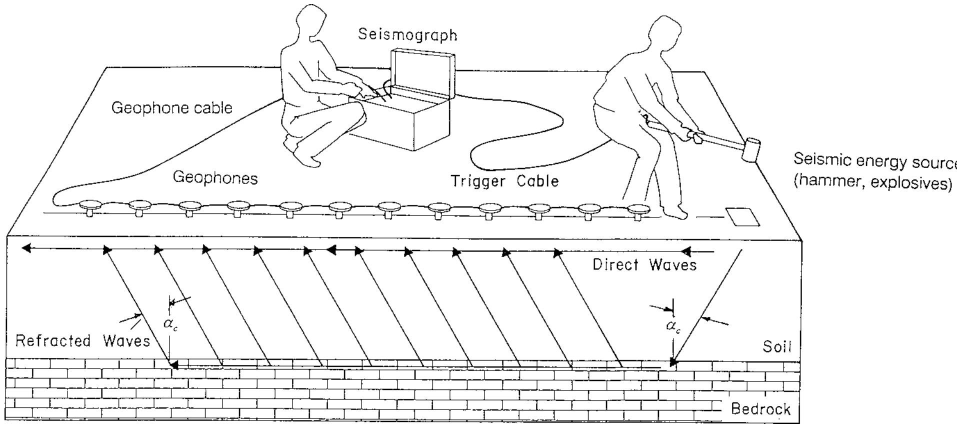


FIG. 1 Field Layout of a Twelve-Channel Seismograph Showing the Path of Direct and Refracted Seismic Waves in a Two-Layer Soil/ Rock System (α_c = Critical Angle)

replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this guide means only that the document has been approved through the ASTM consensus process.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D420 Guide to 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
D4428/D4428M Test Methods for Crosshole Seismic Testing
D5088 Practice for Decontamination of Field Equipment Used at Waste Sites
D5608 Practices for Decontamination of Field Equipment Used at Low Level Radioactive Waste Sites
D5730 Guide for Site Characterization for Environmental Purposes With Emphasis on Soil, Rock, the Vadose Zone and Ground Water
D5753 Guide for Planning and Conducting Borehole Geophysical Logging
D6235 Practice for Expedited Site Characterization of Vadose Zone and Ground Water Contamination at Hazardous Waste Contaminated Sites
D6429 Guide for Selecting Surface Geophysical Methods

3. Terminology

3.1 *Definitions:*

3.1.1 The majority of the technical terms used in this guide are defined in Refs (**2**) and (**3**).[3] Also see Terminology D653.

[2] 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.

[3] The boldface numbers given in parentheses refer to a list of references at the end of the text.

4. Summary of Guide

4.1 *Summary of the Method*—Measurements of the travel time of a compressional (*P*) wave from a seismic source to a geophone(s) are made from the land surface and are used to interpret subsurface conditions and materials. This travel time, along with distance between the source and geophone(s), is interpreted to yield the depth to refractors refractors (refracting layers). The calculated seismic velocities of the layers are used to characterize some of the properties of natural or man-made man subsurface materials.

4.2 *Complementary Data*—Geologic and water table data obtained from borehole logs, geologic maps, data from outcrops or other complementary surface and borehole geophysical methods may be necessary to properly interpret subsurface conditions from seismic refraction data.

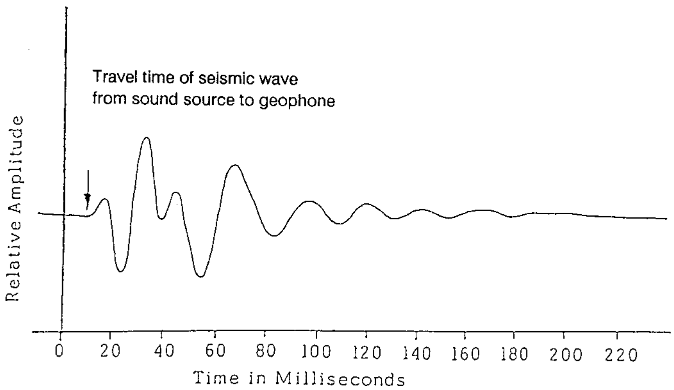
5. Significance and Use

5.1 *Concepts*:

5.1.1 This guide summarizes the equipment, field procedures, and interpretation methods used for the determination of the depth, thickness and the seismic velocity of subsurface soil and rock or engineered materials, using the seismic refraction method.

5.1.2 Measurement of subsurface conditions by the seismic refraction method requires a seismic energy source, trigger cable (or radio link), geophones, geophone cable, and a seismograph (see Fig. 1).

5.1.3 The geophone(s) and the seismic source must be placed in firm contact with the soil or rock. The geophones are usually located in a line, sometimes referred to as a geophone spread. The seismic source may be a sledge hammer, a mechanical device that strikes the ground, or some other type of impulse source. Explosives are used for deeper refractors or special conditions that require greater energy. Geophones convert the ground vibrations into an electrical signal. This electrical signal is recorded and processed by the seismograph. The travel time of the seismic wave (from the source to the geophone) is determined from the seismic wave form. Fig. 2 shows a seismograph record using a single geophone. Fig. 3 shows a seismograph record using twelve geophones.



NOTE—Arrow marks arrival of first compressional wave.

FIG. 2 A Typical Seismic Waveform from a Single Geophone

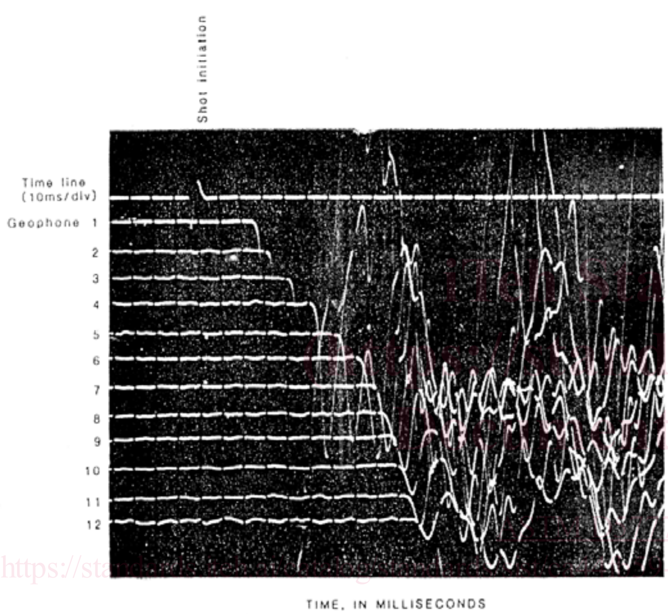


FIG. 3 Twelve-Channel Analog Seismograph Record Showing Good First Breaks Produced by an Explosive Sound Source (9)

5.1.4 The seismic energy source generates elastic waves that travel through the soil or rock from the source. When the seismic wave reaches the interface between two materials of different seismic velocities, the waves are refracted according to Snell's Law (**4, 8**). When the angle of incidence equals the critical angle at the interface, the refracted wave moves along the interface between two materials, transmitting energy back to the surface (Fig. 1). This interface is referred to as a refractor.

5.1.5 A number of elastic waves are produced by a seismic energy source. Because the compressional *P*-wave has the highest seismic velocity, it is the first wave to arrive at each geophone (see Fig. 2 and Fig. 3).

5.1.6 The *P*-wave velocity V_p is dependent upon the bulk modulus, the shear modulus and the density in the following manner (**4**):

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

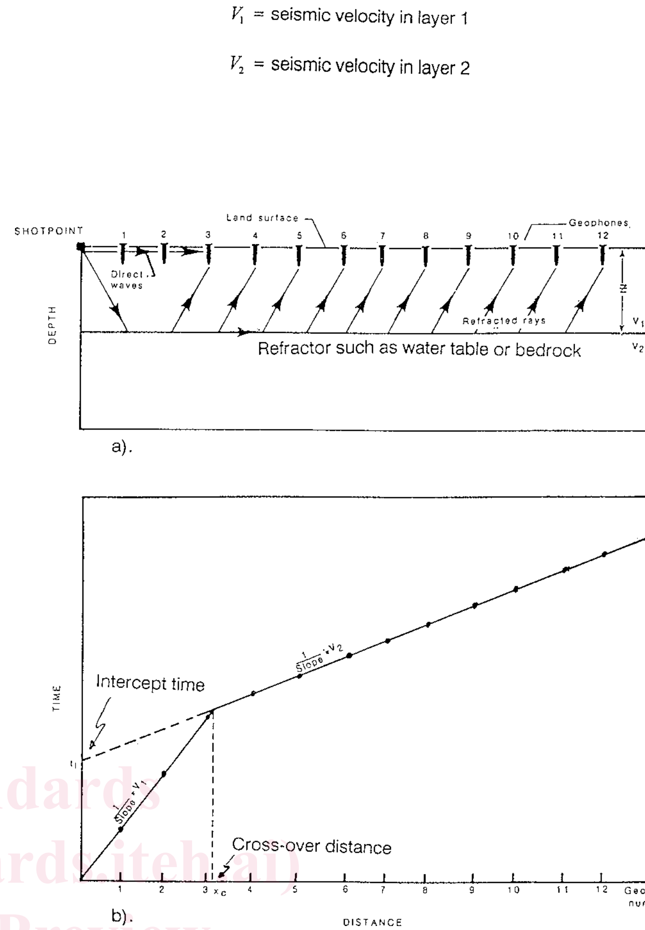


FIG. 4 (*a*) Seismic Raypaths and (*b*) Time-Distance Plot for a Two-Layer Earth With Parallel Boundaries (9)

where:

V_p = compressional wave velocity,
K = bulk modulus,
μ = shear modulus, and
ρ = density.

5.1.7 The arrival of energy from the seismic source at each geophone is recorded by the seismograph (Fig. 3). The travel time (the time it takes for the seismic *P*-wave to travel from the seismic energy source to the geophone(s)) is determined from each waveform. The unit of time is usually milliseconds (1 ms = 0.001 s).

5.1.8 The travel times are plotted against the distance between the source and the geophone to make a time distance plot. Fig. 4 shows the source and geophone layout and the resulting idealized time distance plot for a horizontal two-layered earth.

5.1.9 The travel time of the seismic wave between the seismic energy source and a geophone(s) is a function of the distance between them, the depth to the refractor and the seismic velocities of the materials through which the wave passes.

5.1.10 The depth to a refractor is calculated using the source to geophone geometry (spacing and elevation), determining the apparent seismic velocities (which are the reciprocals of the slopes of the plotted lines in the time distance plot), and the intercept time or crossover distances on the time distance plot (see Fig. 4). Intercept time and crossover distance-depth formulas have been derived in the literature (**6-8**). These derivations are straightforward inasmuch as the travel time of the seismic wave is measured, the velocity in each layer is calculated from the time-distance plot, and the raypath geometry is known. These interpretation formulas are based on the following assumptions: (*1*) the boundaries between layers are planes that are either horizontal or dipping at a constant angle, (*2*) there is no land-surface relief, (*3*) each layer is homogeneous and isotropic, (*4*) the seismic velocity of the layers increases with depth, and (*5*) intermediate layers must be of sufficient velocity contrast, thickness and lateral extent to be detected. Reference (**9**) provides an excellent summary of these equations for two and three layer cases. The formulas for a two-layered case (see Fig. 4) are given below.

5.1.10.1 Intercept-time formula:

$$z = \frac{t_i}{2} \frac{V_2 V_1}{\sqrt{(V_2)^2 - (V_1)^2}} \quad (2)$$

where:

z = depth to refractor two,
t_i = intercept time,
V_2 = seismic velocity in layer two, and
V_1 = seismic velocity in layer one.

5.1.10.2 Crossover distance formula:

$$z = \frac{x_c}{2} \sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \quad (3)$$

where:

z, V_2 and V_1 are as defined above and x_c = crossover distance.

5.1.11 Three to four layers are usually the most that can be resolved by seismic refraction measurements. Fig. 5 shows the source and geophone layout and the resulting time distance plot for an idealized three-layer case.

5.1.12 The refraction method is used to define the depth to or profile of the top of one or more refractors, or both, for example, depth to water table or bedrock.

5.1.13 The source of energy is usually located at or near each end of the geophone spread; a refraction measurement is made in each direction. These are referred to as forward and reverse measurements, sometimes incorrectly called reciprocal measurements, from which separate time distance plots are made. Fig. 6 shows the source and geophone layout and the resulting time distance plot for a dipping refractor. The velocity obtained for the refractor from either of these two measurements alone is the apparent velocity of the refractor. Both measurements are necessary to resolve the true seismic velocity and the dip of layers (**9**) unless other data are available that indicate a horizontal layered earth. These two apparent velocity measurements and the intercept time or crossover distance are used to calculate the true velocity, depth and dip of the refractor. Note that only two depths of the planar refractor are obtained using this approach (see Fig. 7). Depth to the refractor is obtained under each geophone by using a more sophisticated data collection and interpretation approach.

5.1.14 Most refraction surveys for geologic, engineering, hydrologic and environmental applications are carried out to determine depths of refractors that are less than 100 m (about 300 ft). However, with sufficient energy, refraction measurements can be made to depths of 300 m (1000 ft) and more (**6**).

V_1 = seismic velocity in layer 1

V_2 = seismic velocity in layer 2

V_3 = seismic velocity in layer 3

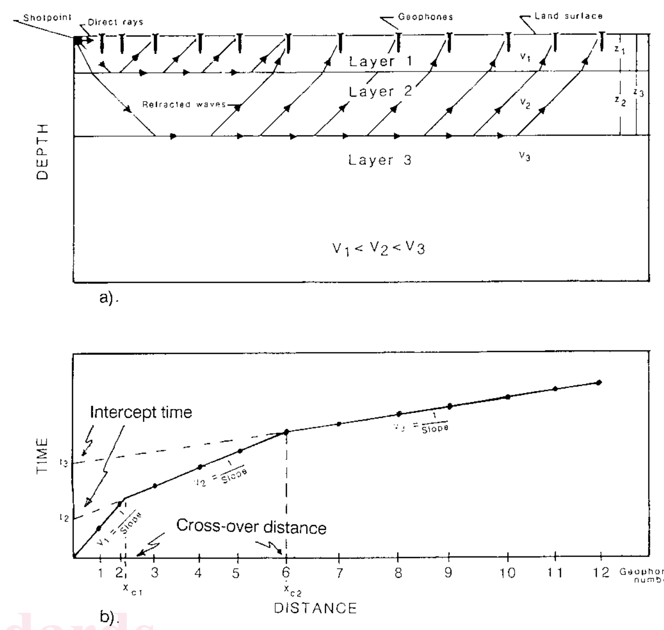


FIG. 5 (*a*) Seismic Raypaths and (*b*) Time-Distance Plot for a Three-Layer Model With Parallel Boundaries (9)

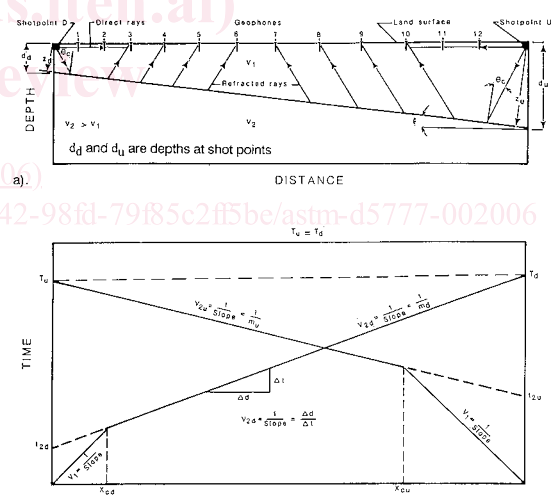


FIG. 6 (*a*) Seismic Raypaths and (*b*) Time-Distance Plot for a Two-Layer Model With A Dipping Boundary (9)

5.2 *Parameter Measured and Representative Values*:

5.2.1 The seismic refraction method provides the velocity of compressional *P*-waves in subsurface materials. Although the *P*-wave velocity is a good indicator of the type of soil or rock, it is not a unique indicator. Table 1 shows that each type of sediment or rock has a wide range of seismic velocities, and many of these ranges overlap. While the seismic refraction technique measures the seismic velocity of seismic waves in

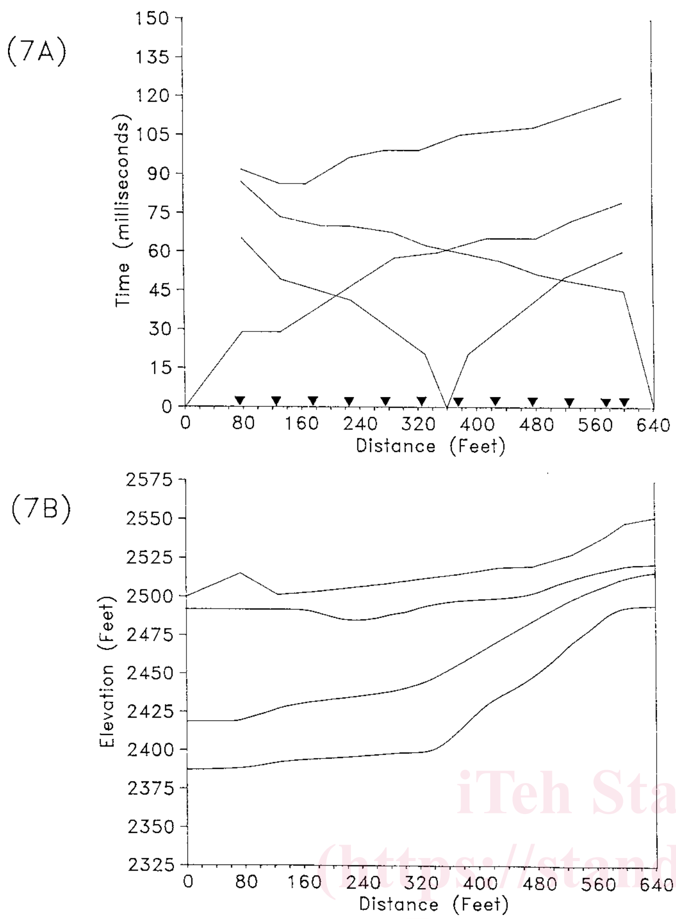


FIG. 7 Time Distance Plot (*a*) and Interpreted Seismic Section (*b*) (29)

TABLE 1 Range of Velocities For Compressional Waves in Soil and Rock (4)

Materials	Velocity	
Natural Soil and Rock	ft/s	m/s
Weathered surface material	800 to 2000	240 to 610
Gravel or dry sand	1500 to 3000	460 to 915
Sand (saturated)	4000 to 6000	1220 to 1830
Clay (saturated)	3000 to 9000	915 to 2750
Water[A]	4700 to 5500	1430 to 1665
Sea water[A]	4800 to 5000	1460 to 1525
Sandstone	6000 to 13 000	1830 to 3960
Shale	9000 to 14 000	2750 to 4270
Chalk	6000 to 13 000	1830 to 3960
Limestone	7000 to 20 000	2134 to 6100
Granite	15 000 to 19 000	4575 to 5800
Metamorphic rock	10 000 to 23 000	3050 to 7000

[A]Depending on temperature and salt content.

earth materials, it is the interpreter who, based on knowledge of the local conditions and other data, must interpret the seismic refraction data and arrive at a geologically feasible solution.

5.2.2 *P*-wave velocities are generally greater for:

5.2.2.1 Denser rocks than lighter rocks;

5.2.2.2 Older rocks than younger rocks;

5.2.2.3 Igneous rocks than sedimentary rocks;

5.2.2.4 Solid rocks than rocks with cracks or fractures;

5.2.2.5 Unweathered rocks than weathered rocks;

5.2.2.6 Consolidated sediments than unconsolidated sediments;

5.2.2.7 Water-saturated unconsolidated sediments than dry unconsolidated sediments; and

5.2.2.8 Wet soils than dry soils.

5.3 *Equipment*—Geophysical equipment used for surface seismic refraction measurement includes a seismograph, geophones, geophone cable, an energy source and a trigger cable or radio link. A wide variety of seismic geophysical equipment is available and the choice of equipment for a seismic refraction survey should be made in order to meet the objectives of the survey.

5.3.1 *Seismographs*—A wide variety of seismographs are available from different manufacturers. They range from relatively simple, single-channel units to very sophisticated multichannel units. Most engineering seismographs sample, record and display the seismic wave digitally.

5.3.1.1 *Single Channel Seismograph*—A single channel seismograph is the simplest seismic refraction instrument and is normally used with a single geophone. The geophone is usually placed at a fixed location and the ground is struck with the hammer at increasing distances from the geophone. First seismic wave arrival times (Fig. 2 and Fig. 3) are identified on the instrument display of the seismic waveform. For some simple geologic conditions and small projects a single-channel unit is satisfactory. Single channel systems are also used to measure the seismic velocity of rock samples or engineered materials.

5.3.1.2 *Multi-Channel Seismograph*—Multi-channel seismographs use 6, 12, 24, 48 or more geophones. With a multi-channel seismograph, the seismic wave forms are recorded simultaneously for all geophones (see Fig. 3).

5.3.1.3 The simultaneous display of waveforms enables the operator to observe trends in the data and helps in making reliable picks of first arrival times. This is useful in areas that are seismically noisy and in areas with complex geologic conditions. Computer programs are available that help the interpreter pick the first arrival time.

5.3.1.4 *Signal Enhancement*—Signal enhancement using filtering and stacking that improve the signal to noise ratio is available in most seismographs. It is an aid when working in noisy areas or with small energy sources. Signal stacking is accomplished by adding the refracted seismic signals for a number of impacts. This process increases the signal to noise ratio by summing the amplitude of the coherent seismic signals while reducing the amplitude of the random noise by averaging.

5.3.2 *Geophone and Cable*:

5.3.2.1 A geophone transforms the *P*-wave energy into a voltage that is recorded by the seismograph. For refraction work, the frequency of the geophones varies from 8 to 14 Hz. The geophones are connected to a geophone cable that is connected to the seismograph (see Fig. 1). The geophone cable has electrical connection points (take outs) for each geophone, usually located at uniform intervals along the cable. Geophone placements are spaced from about 1 m to hundreds of meters (2 or 3 ft to hundreds of feet) apart depending upon the level of detail needed to describe the surface of the refractor and the depth of the refractor(s). The geophone intervals may be adjusted at the shot end of a cable to provide additional seismic velocity information in the shallow subsurface.

5.3.2.2 If connections between geophones and cables are not waterproof, care must be taken to assure they will not be shorted out by wet grass, rain, etc. Special waterproof geophones (marsh geophones), geophone cables and connectors are required for areas covered with shallow water.

5.3.3 *Energy Sources*:

5.3.3.1 The selection of seismic refraction energy sources is dependent upon the depth of investigation and geologic conditions. Four types of energy sources are commonly used in seismic refraction surveys: sledge hammers, mechanical weight drop or impact devices, projectile (gun) sources, and explosives.

5.3.3.2 For shallow depths of investigation, 5 to 10 m (15 to 30 ft), a 4 to 7 kg (10 to 15 lb) sledge hammer may be used. Three to five hammer blows using signal enhancement capabilities of the seismograph will usually be sufficient. A strike plate on the ground is used to improve the coupling of energy from the hammer to the soil.

5.3.3.3 For deeper investigations in dry and loose materials, more seismic energy is required, and a mechanized or a projectile (gun) source may be selected. Projectile sources are discharged at or below the ground surface. Mechanical seismic sources use a large weight (of about 100 to 500 lb or 45 to 225 kg) that is dropped or driven downward under power. Mechanical weight drops are usually trailer mounted because of their size.

5.3.3.4 A small amount of explosives provides a substantial increase in energy levels. Explosive charges are usually buried to reduce energy losses and for safety reasons. Burial of small amounts of explosives (less than 1 lb or 0.5 kg) at 1 to 2 m (3 to 6 ft) is effective for shallow depths of investigation (less than 300 ft or 100 m) if backfilled and tamped. For greater depths of investigation (below 300 ft or 100 m), larger explosives charges (greater than 1 lb or 0.5 kg) are required and usually are buried 2 m (6 ft) deep or more. Use of explosives requires specially-trained personnel and special procedures.

5.3.4 *Timing*—A timing signal at the time of impact ($t = 0$) is sent to the seismograph (see Fig. 1). The time of impact ($t = 0$) is detected with mechanical switches, piezoelectric devices or a geophone (or accelerometer), or with a signal from a blasting unit. Special seismic blasting caps should be used for accurate timing.

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 cannot be associated with a unique set of subsurface conditions. In most situations, surface geophysical measurements alone cannot resolve all ambiguities, and some additional information, such as borehole data, is required. Because of this inherent limitation in the geophysical methods, a seismic refraction survey is not a complete assessment of subsurface conditions. Properly integrated with other geologic information, seismic refraction surveying is an effective, accurate, and cost-effective method of obtaining subsurface information.

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

5.4.2 *Limitations Specific to the Seismic Refraction Method*:

5.4.2.1 When refraction measurements are made over a layered earth, the seismic velocity of the layers are assumed to be uniform and isotropic. If actual conditions in the subsurface layers deviate significantly from this idealized model, then any interpretation also deviates from the ideal. An increasing error is introduced in the depth calculations as the angle of dip of the layer increases. The error is a function of dip angle and the velocity contrast between dipping layers (**10**, **11**).

5.4.2.2 Another limitation inherent to seismic refraction surveys is referred to as a blind-zone problem (**4**, **9**, **12**). There must be a sufficient contrast between the seismic velocity of the overlying material and that of the refractor for the refractor to be detected. Some significant geologic or hydrogeologic boundaries have no field-measurable seismic velocity contrast across them and consequently cannot be detected with this technique.

5.4.2.3 A layer must also have a sufficient thickness in order to be detected (**12**).

5.4.2.4 If a layer has a seismic velocity lower than that of the layer above it (a velocity reversal), the low seismic velocity layer cannot be detected. As a result, the computed depths of deeper layers are greater than the actual depths (although the most common geologic condition is that of increasing seismic velocity with depth, there are situations in which seismic velocity reversals occur). Interpretation methods are available to address this problem in some instances (**13**).

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

5.4.3.1 The seismic refraction method is sensitive to ground vibrations (time-variable noise) from a variety of sources. Geologic and cultural factors also produce unwanted noise.

5.4.3.2 *Ambient Sources*—Ambient sources of noise include any vibration of the ground due to wind, water movement (for example, waves breaking on a nearby beach), natural seismic activity, or by rainfall on the geophones.

5.4.3.3 *Geologic Sources*—Geologic sources of noise include unsuspected variations in travel time due to lateral and vertical variations in seismic velocity of subsurface layers (for example, the presence of large boulders within a soil).

5.4.3.4 *Cultural Sources*—Cultural sources of noise include vibration due to movement of the field crew, nearby vehicles, and construction equipment, aircraft, or blasting. Cultural factors such as buried structures under or near the survey line also may lead to unsuspected variations in travel time. Nearby powerlines may induce noise in long geophone cables.

5.4.3.5 During the course of designing and carrying out a refraction survey, sources of ambient, geologic, and cultural noise should be considered and its time of occurrence and location noted. The interference is not always predictable because it depends upon the magnitude of the noises and the geometry and spacing of the geophones and source.