Dear Mr. Schiavi,

Thank you for taking the time to speak with me last week regarding upcoming field work for the Cape Cod Canal Area Transportation Improvement Program. This Program will include the replacement of the Bourne and Sagamore bridges, as well as improvements to the approach roadway networks to address the multimodal deficiencies within the region. MassDOT is currently in the process of investigating the area surrounding the existing bridges to help inform their design plans for the approach roadway network. As discussed, the current field work will include geophysical investigations to map out sub surface conditions using the seismic refraction method and other similar methods. This work will be used to measure seismic waves, thus providing the Program Team with information on geological conditions including the depth of bedrock and water table. The equipment used for this type of field work, included in the attached photo, will not result in any ground disturbance. For more information on the seismic refraction method, please see the attached PDF document describing it in more detail. A photo of typical operation has also been attached.

Geophysical investigation over the next month will occur at the following locations:
- Various locations on US Army Corps of Engineers property
- Bourne Scenic Park Campground
- One private property located near the Sagamore Bridge

MassDOT has communicated directly with property owners/managers to coordinate this investigative work. Field work is expected to begin in December 2020 and last through January 2021. More information on the Program schedule, design concepts, public meetings, and outreach opportunities will be made available in the coming months on the Program's website: https://www.mass.gov/cape-cod-canal-area-transportation-improvement-program

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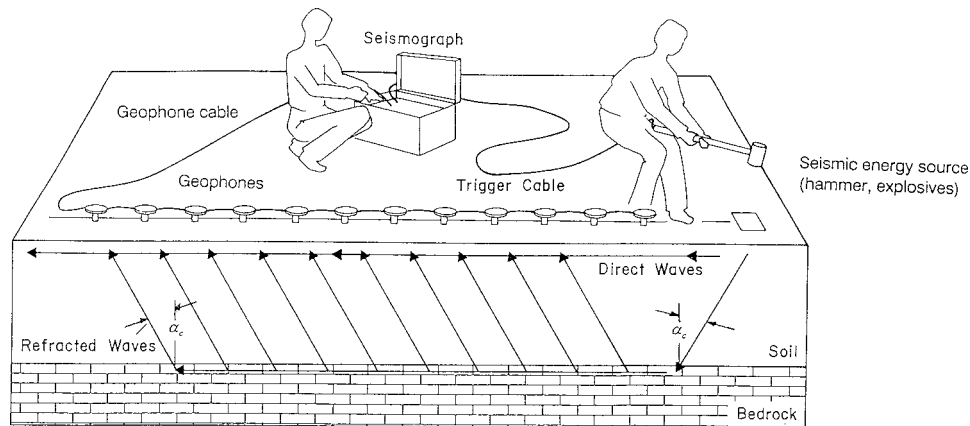
FIG. 1 Field Layout of a Twelve-Channel Seismograph Showing the Path of Direct and Refracted Seismic Waves in a Two-Layer Soil/Rock System (α_c = Critical Angle)

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.

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.
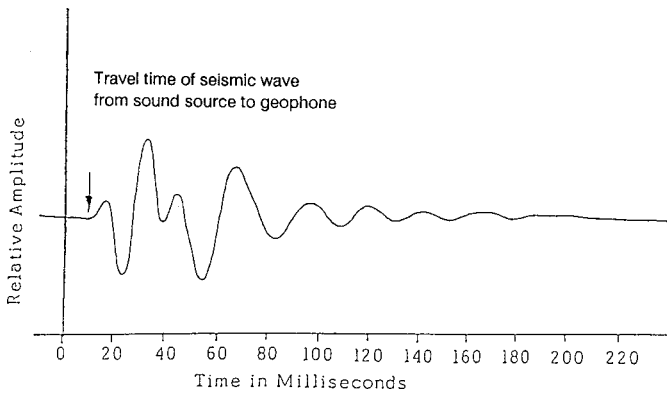
5. Significance and Use

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.

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[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.

NOTE—Arrow marks arrival of first compressional wave.
FIG. 2 A Typical Seismic Waveform from a Single Geophone

V_1 = seismic velocity in layer 1

V_2 = seismic velocity in layer 2

a).

b).

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

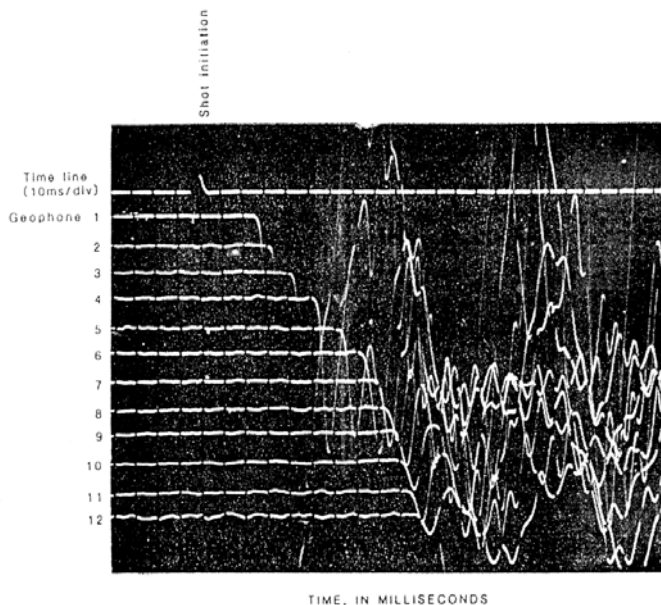**FIG. 3 Twelve-Channel Analog Seismograph Record Showing Good First Breaks Produced by an Explosive Sound Source (9)**

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

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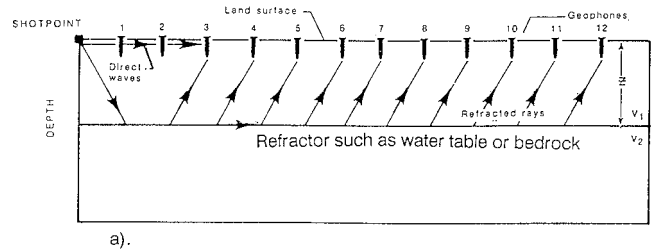
5.1.5 A number of elastic waves are produced by a seismic energy source. Because the compressional P-wave has the highest seismic velocity, it is the first wave to arrive at each geophone (see Fig. 2 and Fig. 3).

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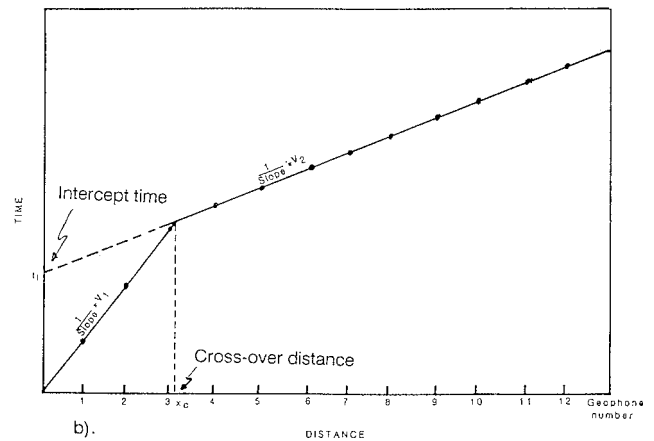
$$V_p = \sqrt{[(K + 4/3\mu)/\rho]} \qquad (1)$$

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:

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

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:

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

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

V_1 = seismic velocity in layer 1

V_2 = seismic velocity in layer 2
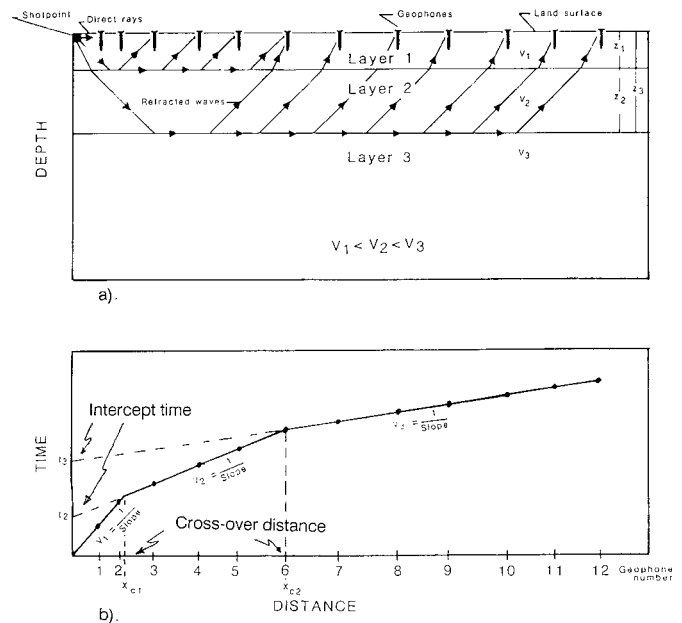
V_3 = seismic velocity in layer 3

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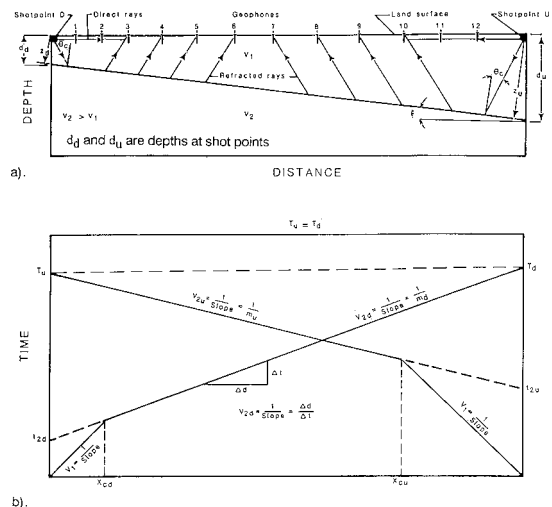

FIG. 6 (a) Seismic Raypaths and (b) Time-Distance Plot for a Two-Layer Model With A Dipping Boundary (9)

300 ft). However, with sufficient energy, refraction measurements can be made to depths of 300 m (1000 ft) and more (6).

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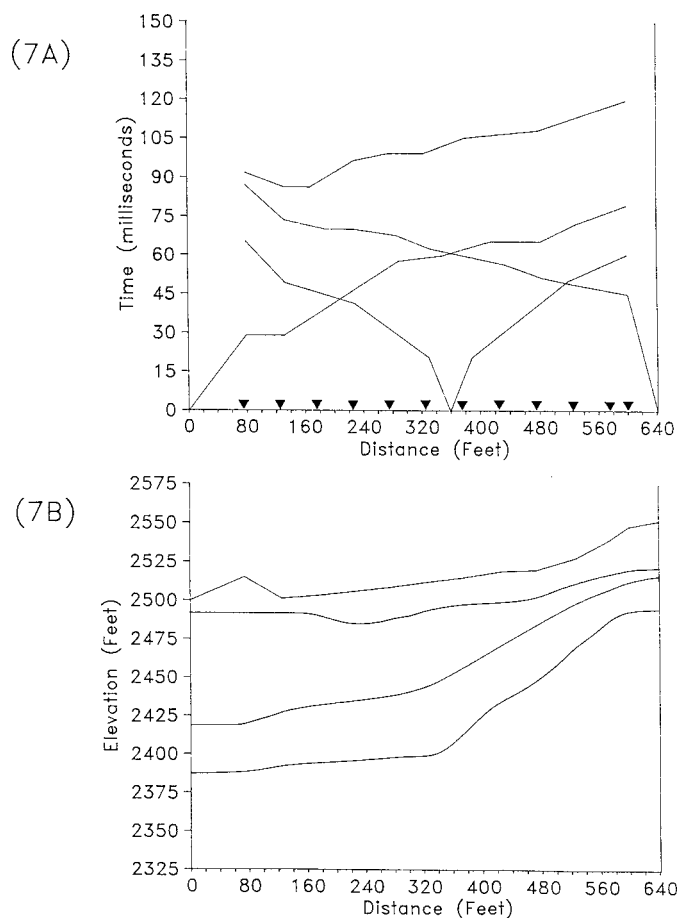
FIG. 7 Time Distance Plot (*a*) and Interpreted Seismic Section (*b*) (29)

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.

5.5 *Alternative Methods*—The limitations discussed above may prevent the use of the seismic refraction method, and other geophysical or non-geophysical methods may be required to investigate subsurface conditions (see Guide D5753).

6. Procedure

6.1 This section includes a discussion of personnel qualification, planning and implementing the seismic refraction survey, and interpretation of seismic refraction data.

6.1.1 *Qualification of Personnel*—The success of a seismic refraction survey, as with most geophysical techniques, is dependent upon many factors. One of the most important factors is the competence of the person(s) responsible for planning, carrying out the survey, and interpreting the data. An understanding of the theory, field procedures, and methods for interpretation of seismic refraction data and an understanding of the site geology is necessary to complete a seismic refraction survey. Personnel not having specialized training and experience, should be cautious about using this technique and solicit assistance from qualified practitioners.

6.2 *Planning the Survey*—Successful use of the surface seismic refraction method depends to a great extent on careful and detailed planning.

6.2.1 *Objective(s) of the Seismic Refraction Survey*:

6.2.1.1 Planning and design of a seismic refraction survey should consider the objectives of the survey and the characteristics of the site. These factors determine the survey design, the equipment used, the level of effort, the interpretation method selected, and budget necessary to achieve the desired results. Important considerations include site geology, depth of investigation, topography, and access. The presence of noise-generating activities (for example, on-site utilities, man-made structures), and operational constraints (for example, restrictions on the use of explosives), must also be considered. It is good practice to obtain as much relevant information (for example, data from any previous seismic refraction work, boring, geologic and geophysical logs in the study area, topographic maps or aerial photos, or both) as possible about the site prior to designing a survey and mobilization to the field.

6.2.1.2 A geologic/hydrologic model of the subsurface conditions at the site should be developed early in the design phase and should include the thickness and type of soil cover, depth and type of rock, depth to water table and a stratigraphic section with the horizons to be mapped with the seismic refraction method.

6.2.1.3 The objective of the survey may be a reconnaissance of subsurface conditions or it may provide the most detailed subsurface information possible. In reconnaissance surveys, such as regional geologic or ground water studies and preliminary engineering studies, the spacing between the geophone spreads, or geophone spacing, is large, a few shot-points are used, and topographic maps or hand-level elevations are sufficient. Under these conditions, the cost of obtaining seismic refraction data are relatively low, but the resulting subsurface data are not very detailed. In a detailed survey, the spacing between the geophone spreads, or geophone spacing, is small, multiple shot-points are used, and elevations and locations of geophones and shot-points are more accurately determined.

Under these conditions, the cost of obtaining seismic refraction data is higher, but can still be cost-effective because the resulting subsurface data is more detailed.

6.2.2 *Assess Seismic Velocity Contrast*:

6.2.2.1 One of the most critical elements in planning a seismic refraction survey is the determination of whether there is an adequate seismic velocity contrast between the two geologic or hydrologic units of interest.

6.2.2.2 Information from previous seismic refraction surveys in the area, knowledge of the geology, published references containing the seismic velocities of earth materials, and published reports of seismic refraction studies performed under similar conditions should be used.

6.2.2.3 When there is doubt that sufficient seismic velocity contrast exists, a pre-survey test is desirable at a control point, such as a borehole or well, where the stratigraphy is known and the seismic velocities can be determined. Three types of tests may be considered: a vertical seismic profile (VSP) **(8)** borehole log (such as a density log or sonic log, Guide D5753) that provide an indication of subsurface velocity layering, and a test refraction line near a known point of control. From this information, the feasibility of using the seismic refraction method at the site is assessed.

6.2.2.4 Forward modeling using mathematical equations **(7, 8, 9)** can be used to develop theoretical time distance plots. Given the thickness and the seismic velocity of the subsurface layers, these plots are used to assess the feasibility of conducting a seismic refraction survey and to determine the geometry of the field-survey. Sufficient information about layer thickness and seismic velocities may not be available to accurately model a site before field work is carried out. In this case, initial field measurements should be taken to assess whether an adequate seismic velocity contrast exists between the subsurface layers of interest.

6.2.3 *Selection of the Approach*:

6.2.3.1 The desired level of detail and geologic complexity will determine the interpretation method to be used for a refraction survey, which in turn will determine the field procedures to be followed **(4, 8, 9, 13-15)**.

6.2.3.2 Numerous approaches are used to quantitatively interpret seismic refraction data; however, the most commonly used interpretation methods are classified into two general groups: methods that are used to define planar refractors and methods that are used to define nonplanar refractors.

6.2.4 *Methods Used To Define Planar Refractors*:

6.2.4.1 The intercept time method (ITM) and crossover distance method are the simplest and probably the best known of all the methods for the interpretation of seismic refraction data **(8, 11)**. They can be described as the rigorous application of Snell's law to a subsurface model consisting of homogeneous layers and horizontal or dipping planar interfaces. The intercept time method requires that a constant seismic velocity exists in the overburden and in the refractor within a single geophone spread (between the shot points). The intercept time method uses simple field and interpretation procedures. Measurements are usually made from each end of the seismic refraction line (a minimum of one off-end shot-point on each end of the geophone spread). The results obtained using this

method include the thickness of the overburden and the dip of the refractor at two points (see Fig. 6). It is also common to place one shot in the middle of the geophone spread. Shots off of each end of the spread may also be made to provide additional data. Additional shot-points increase the number of points along the refractor where depth can be determined.

6.2.4.2 The intercept time or crossover distance method can be used under the following conditions: where a limited number of refractor depth determinations are required within a single geophone spread; the surface of the refractor can be satisfactorily approximated by a plane (horizontal or dipping); lateral variations in seismic velocity of the subsurface layers (over the length of the geophone spread) can be neglected; and thin intermediate seismic velocity layers and seismic velocity inversions can be neglected.

6.2.4.3 Additional discussion of survey design and field considerations for the intercept-time method are given by Refs (**4** and **9**).

6.2.5 *Methods Used To Define Nonplanar Refractors*—A number of methods can be viewed as an extension of the intercept time method, whereby the depth to the refractor is calculated at the shot-points and at each geophone location. These methods require a greater level of effort in data acquisition, processing, and interpretation.

6.2.6 *Common Reciprocal Methods*:

6.2.6.1 A group of methods (referred to as the common reciprocal methods (CRM) by Palmer (**11**)). These methods can provide a more detailed interpretation of nonplanar refractors. Depths are obtained under each geophone, thereby accounting for irregular refracting surfaces (nonplanar refractors). The CRM has many variations including the plus-minus method, the ABC Method and Hagiwaras Method. Most, but not all, of the methods are based on the assumption that within a single geophone spread, seismic velocity in the overlying units and in the refractor do not vary laterally. Fig. 7 shows an interpreted seismic refraction section of an irregular rock surface using this approach. All these methods usually require that travel times be measured in both forward and reverse directions from three to seven shot-points per single geophone spread. The resolution of the surface of the refractor obtained by the survey is dependent on the spacing between the geophones and the number of shot-points. Additional discussion of survey design and field considerations for these methods are given in Refs (**4**) and (**10**).

6.2.6.2 These methods can be applied where depths to the refractor are required at each geophone; the surface of the refractor has some relief; lateral variations in seismic velocity of the subsurface layers (over the length of the spread) can be neglected; and thin intermediate seismic velocity layers and seismic velocity inversions can be neglected.

6.2.7 *Generalized Reciprocal Method*:

6.2.7.1 The generalized reciprocal method (GRM), as described by Palmer (**12, 17-19**) and Lankston (**14, 20**), can aid in resolving complex conditions including undetected layers, lateral changes in seismic velocity and anisotropy. The GRM includes as special cases the delay time method and Hales method (**11**). The GRM method requires a large data set (in time and space) to achieve the necessary resolution; therefore,

a relatively small geophone spacing is required. This method usually requires that travel times be measured in both forward and reverse directions from five to seven shot-points per geophone spread. The generalized reciprocal method survey incorporates the strengths of most other seismic refraction methods and can provide the most detailed profile of a refractor, but requires considerably more effort in field data collection and interpretation. The full use of the generalized reciprocal method, which has been demonstrated by Palmer for model data and case histories, has still to achieve routine acceptance in engineering geophysics because it requires a greater field effort. The case histories in Palmer (**19**) demonstrate the application of the generalized reciprocal method to shallow targets of geotechnical significance.

6.2.7.2 The generalized reciprocal method can sometimes be used where lateral variations in seismic velocity within a single geophone spread, thin intermediate seismic velocity layers, and seismic velocity inversions cannot be neglected. Geophone spacing for this method is smaller to provide sufficient spatial data.

6.2.7.3 Additional discussions of survey design and field considerations for this method are given by Palmer (**17**); Lankston and Lankston (**20**); and Lankston (**14, 16**).

6.2.8 *Summary of Two Approaches*:

6.2.8.1 If it is acceptable to describe the surface of a refractor as a plane with a limited number of points, and lateral seismic velocity changes within a geophone spread can be neglected, then the intercept time or crossover distance methods may be sufficient.

6.2.8.2 If there is a need to define the depth and approximate shape of a non-planar refractor at each geophone location, and the lateral seismic velocity in subsurface layers within a geophone spread can be neglected, then one of the many common reciprocal methods that define nonplanar refractors can be used.

6.2.8.3 If there is a need to account for lateral seismic velocity changes in subsurface layers and account for intermediate seismic velocity layers and seismic velocity inversions, then the generalized reciprocal method can be used.

6.2.8.4 Table 2 summarizes the features and limitations of each of these methods. It is modified from Palmer (**11**).

6.2.8.5 The choice of interpretation method may vary from site to site and depends upon the detail required from the seismic refraction survey and the complexity of the geology at the site. The interpretation method in turn determines the approach and level of effort required in the field.

6.2.8.6 When selecting the approach for data acquisition the specific processing and interpretation method that is used must be considered since most processing and interpretation methods have specific requirements for data acquisition.

6.2.8.7 There are many field and interpretation methods that fall under the broad categories listed above. No attempt has been made to list all of the individual field and interpretation methods. Each one has strengths and weaknesses and must be selected to meet the project needs. The use of other field and interpretation methods not specifically mentioned are not precluded by this guide.

6.2.9 *Survey Design*:

TABLE 2 Features and Limitations of Methods (Modified from Ref (11))

Methods Used For Defining Planar Refractors
Include the Time Intercept and Crossover Distance Methods
These methods require the least field and interpretation effort and are, therefore, the lowest cost. They can be applied where: • Depth computations are provided near shot-points;   • The refractor is approximated by a plane (horizontal or dipping);   • Lateral variations in seismic velocity within a single geophone spread are neglected; and   • Thin intermediate velocity layers and velocity inversions are neglected.
Methods Used for Defining Non-Planar Refractors   The Common Reciprocal Method (CRM) Including Plus-Minus Method, the ABC Method, and the Hagiwaras Method
These CRM methods require additional field and interpretation effort and are intermediate in cost. They can be applied where: • Depth computations are provided at geophones;   • The refractor has some relief;   • Lateral variations in seismic velocity within a single geophone spread are neglected; and   • Thin intermediate velocity layers and velocity inversions are neglected.
The Generalized Reciprocal Method (GRM)   The Delay Time Method and Hales Method are special cases of the GRM
In addition to all the features of the CRM methods, the Generalized Reciprocal Method (GRM) may account for: • Lateral variation in seismic velocity within a single geophone spread;   • Thin intermediate velocity layers and velocity inversions.   The GRM requires the greatest level of field and interpretation effort and is the most costly.

6.2.9.1 *Location of Survey Lines*—Preliminary location of survey lines is usually done with the aid of topographic maps and aerial photos if an on-site visit is not possible. Consideration should be given to: the need for data at a given location; the accessibility of the area; the proximity of wells or test holes for control data; the extent and location of any asphalt or concrete surface, buried structures and utilities and other sources of cultural noise that will prevent measurements from being made, or introduce noise into the data (see section 5.7.3); and adequate space for the refraction line.

6.2.9.2 The geophone stations should lie along as straight a line as possible. Deviations from a straight path may result in inaccuracies unless the line is carefully surveyed and appropriate geometric corrections are applied to the data. Often the location of the line will be determined by topography. Line locations should be selected so that the ground surface along each geophone spread (cable) is as flat as possible or an interpretation method should be selected that accounts for topography.

6.2.9.3 *Coverage*—Survey coverage and orientation of survey lines should be designed to meet survey objectives. The area of survey should be larger than the area of interest so that measurements are taken in both "background" conditions and over any anomalous conditions. Consideration should be given to the orientation of lines with respect to geologic features of interest, such as, buried channels, faults, or fractures, etc. When mapping a buried channel, the refraction survey line

should cross over the channel so that its boundaries can be determined. The number and locations of shot-points will depend upon the method chosen to collect and interpret the seismic refraction data. Geophone spacing is determined by two factors: the expected depth of the refractor(s) and desired degree of definition (lateral resolution) of the surface of the refractor. The geophone to shot-point separation will be larger for deeper refractors and smaller for shallow refractors. For reconnaissance measurements that do not require extensive detailed mapping of the top of the refractor, widely spaced geophones may be used. For detailed mapping of the top of a refractor, more closely-spaced geophones are required. To define the surface of a refractor in detail, the geophone spacing must be smaller than the size of the spatial changes in the refractor. Geophone spacing can be varied from less than 1 m (3 ft) to more than 100 m (300 ft) depending upon the depth to the refractor and lateral resolution needed to define the top of a refractor. Examples of geophone spacing and shot distance needed to define various geologic conditions are given by Haeni (**9**). A refraction survey line may require a source-to-geophone distance of up to three to five times the required depth of investigation. Therefore, adequate space for the refraction line is a consideration. If the length of the geophone spread and the source to geophone offset are not sufficient to reach the maximum depth of investigation, then the source to geophone offset distance must be increased until a sufficient depth is obtained. If the length of the line to be surveyed is longer than a single geophone spread, data can be obtained by using multiple geophone spreads.

6.2.9.4 Refraction surveys along a line with multiple geophone spreads may be reconnaissance or detailed. For reconnaissance surveys, a gap may be left between the ends of successive spreads. As more detailed data is required, the gap will decrease until the geophone spreads overlap and provide a continuous profile of the refractor being mapped. The geophone spacing and the amount of overlap of the geophones from each cable spread will depend upon the detail and continuity required to map the desired refractor. Since the common reciprocal method and generalized reciprocal method are used to obtain depth to a refractor under individual geophones, the geophone spreads must be overlapped if continuous coverage of the refractor is desired. The overlap will commonly range from one to two geophones for common reciprocal method and from two to five geophones for generalized reciprocal method. Greater overlaps may be necessary for deeper refractors. The time-distance plots for the seismic refraction measurements can be constructed by combining and plotting together the data from each geophone spread by a process called phantoming. Phantoming is discussed by Lankston and Lankston (**13**).

6.2.10 *Data Acquisition Format*—A recommended standard for Seismic data files used in the personal computer (PC) environment written under the guidance of the Society of Exploration Geophysicists (SEG)—Engineering and Ground Water Geophysics Committee given by Pullan (**20**).

6.3 *Implementation of Survey*:

6.3.1 *On Site Check of Survey Plan*:

6.3.1.1 A systematic visual inspection of the site should be made upon arrival to determine if the initial survey plan is feasible. Modifications to the survey plan may be required.

6.3.1.2 If a feasibility test has not been previously conducted, the results of initial measurements can be used to confirm the existence of an adequate seismic velocity contrast and can also be used to assess signal to noise ratio at the site. Results of these initial measurements may require that changes be made to the original survey plan.

6.3.2 *Layout the Survey Lines*—Locate the best position for the refraction lines based on the survey design described in 6.2.4 and the on-site visit in 6.3.1.

6.3.3 *Conducting the Survey*:

6.3.3.1 Check for adequate space to lay out as straight a line as possible.

6.3.3.2 Locate the position of the first geophone.

6.3.3.3 Lay out the geophone cable.

6.3.3.4 Place geophones firmly in the ground and connect them to the cable. The geophone must be vertical and in contact with the soil or rock. Improper placement of geophones is a common problem resulting in poor detection of the seismic *P*-wave. Each geophone spike should be pushed firmly into the ground to make the contact between the soil and the geophone as tight as possible. Often the top few inches (10 cm) of soil is very loose and should be scraped off so that the geophone can be implanted into firm soil. Where rock is exposed at the surface the geophone spike may be replaced by a tripod base on the geophone. In both soil and rock, a good coupling between the ground and the geophones should be assured.

6.3.3.5 Test the geophones and geophone cable for short circuits and open circuits if possible (see seismograph instruction manual).

6.3.3.6 Set up the source at the first shot-point or a test point.

6.3.3.7 Test the seismic source and trigger cable.

6.3.3.8 Test for noise level and set gains and filters (see seismograph instruction manual).

6.3.3.9 The required degree of accuracy of the position and elevation of shot-points and geophones varies with the objectives of the project. If the ground is relatively flat or the accuracy of the refraction survey is not critical, the distance between source and geophone measured with a tape measure will be sufficient. Measurements (made by tape) to within 15- to 20-cm (about 0.5 ft) are adequate for most purposes. If there are considerable changes in surface elevation, shot-point and geophone elevations and their horizontal locations must be surveyed and referenced to the project datum.

6.3.3.10 Proceed with the refraction measurements, making sure that an adequate signal-to-noise ratio exists so that the first arrivals can be determined.

6.3.4 *Quality Control (QC)*—Quality control can be applied to seismic refraction measurements in the field. Quality-control procedures require that standard procedures be followed and documentation be made. The following items are recommended to provide QC of field operations and data acquisition:

6.3.4.1 Documentation of the field procedures and interpretation method that are planned to be used in the study. The method of interpretation will often dictate the field procedures, and the field procedures as well as site conditions used may limit the method of interpretation.

6.3.4.2 A field log in which field operational procedures used for the project are recorded.

6.3.4.3 Changes to the planned field procedures should be documented.

6.3.4.4 Conditions that could reduce the quality of the data (weather conditions, sources of natural and cultural noise, etc.) should be documented.

6.3.4.5 If data are being recorded (by a computer or digital-acquisition system) with no visible means of observing the data, it is recommended that the data be reviewed as soon as possible to check their quality.

6.3.4.6 Care should be taken to maintain accurate timing of the seismograph.

6.3.4.7 Ensure that a uniform method of picking first arrival time is employed.

6.3.4.8 During or after data acquisition, time-distance plots should be made to assure that the data are of adequate quality and quantity to support the method of interpretation and define the refractor of interest.

6.3.4.9 Both forward and reverse measurements are necessary to properly resolve dipping layers.

6.3.4.10 In addition to the time-distance curves, three additional tools can be used as a means of quality control for seismic refraction data: the irregularity test, the reciprocal time test, and the parallelism test.

6.3.4.11 The irregularity test checks for travel time consistency along the refraction profile. If there are deviations from the straight line slope, the time picks may be in error, time-distance curves may have an error in data entry or plotting, data may be noisy, or geologic conditions may be highly variable.

6.3.4.12 The reciprocal time test is used to check reciprocal time differences between forward and reverse profile curves. If differences between reciprocal times are excessive, then the time picks may be in error or the time distance curves may have an error in data entry or plotting.

6.3.4.13 The parallelism test is used to check the relative parallelism between selected forward or reverse time distance curves and another curve from the same refractor. If the slopes of the two curves are sufficiently different, then time picks for one of the sets of data may be in error or the time distance curves may have an error in data entry or plotting.

6.3.4.14 Finally, a check should be made to determine if the depths and seismic velocities obtained using the seismic refraction method make geologic sense.

6.3.5 *Calibration and Standardization*—In general, the manufacturer's recommendation should be followed for calibration and standardization. If no such recommendations are provided, a periodic check of equipment should be made. A check should also be made after each equipment problem and repair. An operational check of equipment should be carried out before each project and before starting field work each day.

6.4 *Interpretation of Seismic Refraction Data*:

6.4.1 *Method of Interpretation*:

6.4.1.1 In some limited cases, quantitative interpretation of the data may not be required and a simple qualitative interpretation may be sufficient. Examples of qualitative and semi-quantitative interpretation may include the lateral location of a buried channel without concern for its depth or minimum depth to rock calculations. In most cases, however, a quantitative interpretation will be necessary.

6.4.1.2 The level of effort involved in the interpretation will depend upon the objectives of the survey and the detail desired that in turn will determine the method of interpretation. A number of manual methods and computer programs are available for interpretation. While the solutions for these methods can be carried out manually, the process can be labor intensive for the more sophisticated methods.

6.4.1.3 A problem inherent in all geophysical studies is the non-unique correlation between possible geologic models and a single set of field data. This ambiguity can be resolved only through the use of geologic data and an experienced interpreter.

6.4.1.4 The first step in the interpretation process is to determine the time interval from the impact of the seismic source to the first arrival of energy at each geophone. When the first arrivals are sharp and there is no ambient noise, this procedure is straightforward (see Fig. 2 and Fig. 3). In many cases, noise in the data will make picking the first arrival times difficult. To minimize errors, a consistent approach to the picking of the arrival times must be used. Care should be taken to ensure that each trace is picked at the same point either at the first point of movement or the point of maximum curvature. This procedure will make the interpretation a more uniform process, as the data will be consistent from one trace to the next. In some cases, a first arrival pick from one or more geophones may be uncertain; then, one must rely upon the experience of the interpreter. If this is done, these picks should be noted. If a computer program is used to make first arrival picks, these picks must be checked (and re-adjusted as needed) by the individual(s) doing the processing and interpretation.

6.4.1.5 Corrections to travel time for elevation or other geometric factors are then made. The two main types of corrections are elevation corrections and weathering corrections. Both are used to adjust field-derived travel times to some selected datum, so that straight-line segments on the time-distance plot can be associated with subsurface refractors. These corrections can be applied manually (7) or by computer (21).

6.4.1.6 With the corrected travel-time data, a time-distance plot of arrival times versus shotpoint-to-geophone distance can be constructed. Lines are then fitted to these points to complete a time-distance plot. These time-distance plots are the foundation of seismic refraction interpretation. Examples of time-distance plots and their relationships to geologic models are shown by Zohdy (6) and Crice (22). Anyone undertaking seismic refraction measurements should be familiar with time-distance plots over a variety of geologic conditions and recognize the lack of a unique interpretation of these plots.

6.4.2 *Preliminary Interpretation*—Preliminary interpretation of field data should be labeled as draft or preliminary, and treated with caution because it is easy to make errors in an initial field interpretation and a preliminary analysis is never a complete and thorough interpretation. Analysis in the field is done mostly as a means of QC.

6.4.3 *Programs for Interpreting Planar Refractors*:

6.4.3.1 A wide variety of formulas, nomograms, and computer programs are available for solving seismic refraction problems using the intercept time (or the crossover distance method).

6.4.3.2 For manual interpretation techniques, see Palmer (11) and Haeni (9). Hand-held programmable calculator programs are available for solving the various seismic refraction equations (23). A number of computer programs are commercially available that are based on intercept time method.

6.4.4 *Programs for Interpreting Non-Planar Refractors*:

6.4.4.1 Manual interpretation techniques are given by Pakhiser and Black (24); Redpath (4); and Dobrin and Savit (7). Computer-assisted interpretation techniques are presented by Haeni, et al (25) and are discussed in Scott, et al (21, 26) and Haeni (9). A number of computer programs are commercially available that are based on the common reciprocal method.

6.4.4.2 Manual-interpretation techniques for the generalized reciprocal method are described by Palmer (16). However, due to the volume of data required for the method, interpretation is usually carried out on a computer. Computer programs are commercially available that are based on the generalized reciprocal method.

6.4.5 *Verification of Seismic Refraction Interpretation*—Seismic refraction interpretation can be verified by comparison with drilling data or other subsurface information. If such data is not available, this fact should be mentioned within the report.

6.4.6 *Presentation of Data*:

6.4.6.1 In some cases, there may be little need for a formal presentation of data or interpreted results.

6.4.6.2 The final seismic refraction interpretation is used to refine or confirm a geologic or hydrologic site model. Such a model is a simplified characterization of a site that incorporates all the essential features of the physical system under study. This model is usually represented as a cross-section, a contour map, or other drawings that illustrate the general geologic and hydrogeologic conditions and any anomalous conditions at a site.

6.4.6.3 If the original data are to be provided to the client, the data and related survey grid maps must be labeled.

7. Report

7.1 *Components of the Report*—The following is a list of the key items that should be contained within most reports. In some cases, there is no need for an extensive formal report:

7.1.1 The report should include a discussion of:

7.1.1.1 The purpose and scope of the seismic refraction survey;

7.1.1.2 The geologic setting;

7.1.1.3 Limitations of the seismic refraction survey;

7.1.1.4 Assumptions made;

7.1.1.5 The field approach, including a description of the equipment and the data acquisition parameters used;

7.1.1.6 The location of the seismic refraction line(s) on a site map;

7.1.1.7 The shot-point/geophone layout;

7.1.1.8 The approach used to pick first arrivals;

7.1.1.9 Corrections applied to field data, and justification for their use;

7.1.1.10 The results of field measurements, copies of typical raw records, and time-distance plots;

7.1.1.11 The method of interpretation used (intercept time method, common reciprocal method or generalized reciprocal method), and specifically what analytical method(s), or software program(s), were used;

7.1.1.12 The interpreted results and any qualifications and alternate interpretations;

7.1.1.13 The format of recording data (for example, note-book, hardcopy analog recorder, digital format, SEG, other);

7.1.1.14 If conditions occurred where a variance from this ASTM guide is necessary, the reason for the variance should be given;

7.1.1.15 Provide appropriate references for any supporting data used in the interpretation; and

7.1.1.16 Identify the person(s) responsible for the refraction survey and data interpretation.

7.2 *Quality Assurance of the Seismic Refraction Work and Report*—To provide quality assurance of the seismic refraction work, it is generally good practice to have the entire seismic refraction work, including the report, reviewed by a person knowledgeable with the seismic refraction method and the site geology but not directly involved with the project.

8. Precision and Bias

8.1 *Bias*—Bias is defined as a measure of the closeness to the truth.

8.1.1 The bias with which the depth and the shape of a refractor can be determined by seismic refraction methods depends on many factors. Some of these factors are:

8.1.1.1 Human errors in field procedures, record-keeping, picking of first arrivals, corrections to data, processing and interpretation;

8.1.1.2 Instrument errors in measuring, recording;

8.1.1.3 Geometry limitations, relating to geophone spacing, line location, topography, and noise;

8.1.1.4 Variation of the earth from simplifying assumptions used in the field and interpretation procedure;

8.1.1.5 Site-specific geologic limitations, such as dip, joints, fractures and highly weathered rock with gradual changes in seismic velocities with depth; and

8.1.1.6 Ability and experience of the field crew and interpreter.

8.1.2 Published references (**5, 6, 9, 27, 28**), indicate that the depth to a refractor can be determined to within ± 10 % of the true depth. Larger errors are usually due to difficult field situations or improper interpretation due to blind zone problems.

8.1.3 Arrival times must be picked with an accuracy of a millisecond. This is done using what appears to be the onset of the pulse (see Fig. 2 and Fig. 3). A 1-ms error could translate to a depth error of 1 to 10 ft (0.3 to 3 m) depending upon geometry and seismic velocities of the subsurface layers.

8.2 *Differences Between Depths Determined Using Seismic Refraction and Those Determined by Drilling*:

8.2.1 The bias of a seismic refraction survey is commonly thought of as how well the refraction results agree with

borehole data. In many cases, the depth obtained by refraction agrees with the borehole data. In other cases, there will be considerable disagreement between the refraction results and boring data. While a refraction measurement may be quite accurate, the interpreted results may disagree with a depth obtained from drilling for the reasons discussed in 8.2.2 through 8.2.4. It is important that the user of seismic refraction results be aware of these concepts and understand that the results of a seismic refraction survey will not always agree with drilling data.

8.2.2 *The Fundamental Differences Between Refraction and Drilling Measurements*:

8.2.2.1 The seismic refraction method is based upon a measure of travel time of the *P*-wave. In order to measure depth to a refractor, such as a soil-to-rock interface, a significant change in seismic velocity must exist between the two layers.

8.2.2.2 When the top of rock is defined by drilling it is often based upon refusal of the drill bit to continue to penetrate, the number of blow counts with a split-spoon sampler, or the first evidence of rock fragments. None of these necessarily agree with each other or the top of the rock surface measured by the seismic refraction method. The differences between seismic refraction and drilling interpretation can yield considerable differences in depth even when the top of rock is relatively flat.

8.2.3 *Lateral Geologic Variability*—Agreement between refraction and boring measurements may vary considerably along the seismic refraction line depending upon lateral geologic changes, such as dip as well as the degree of weathering and fracturing in the rock. Refraction measurements may not account for small lateral geologic changes and may only provide an average depth over them. In addition, the presence of a water table near the bedrock surface can in some cases lead to an error in interpretation. Therefore, it is not always possible to have exact agreement between refraction and boring data along a survey line.

8.2.4 *Positioning Differences*—The drilling location and the refraction measurement may not be made at exactly the same point. It is common to find that the boreholes are located on the basis of drill-rig access and may not be located along the seismic refraction line. Differences in position can easily account for up to 10 m (30 ft) of difference in depth where top of rock is highly variable (for example, karst).

8.3 *Precision*—For the purposes of this guide, precision is the repeatability between measurements, that is, the degree to which the travel times from two identical measurements in the same location with the same equipment match one another. Precision of a seismic refraction measurement will be affected by the sources used, the repeatability of the trigger signal timing, placement of geophones, soil conditions, the care involved in picking arrival times, and the level and variations of the noise impacting the measurements. If a refraction survey is repeated under identical conditions, the measurements would be expected to have a high level of precision.

8.4 *Resolution*:

8.4.1 *Lateral Resolution*—Lateral resolution of a seismic refraction survey is determined by geophone spacing and shot-point spacing. Close spacing of geophones will provide

higher lateral resolution, for example, greater definition of the shape of the top of the refractor.

8.4.2 *Vertical Resolution*:

8.4.2.1 Vertical resolution can be thought of in three ways: how small a change in depth can be determined by the refraction method; how thin a layer can be detected by the seismic refraction method; and how much relief or dip can be accurately mapped without smoothing or errors in depth determination.

8.4.2.2 The answers to all three of these questions is a complex function of the geophone spacing, the depth to the refractors and the seismic velocity contrasts and near surface conditions such as freezing, changes in materials on which sources and receivers are placed and fluctuating of water tables.

9. Keywords

9.1 geophysics; refraction; seismic refraction; surface geophysics

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