INTERNATIONAL

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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.

~~ε[1] NOTE—Added a units statement as new 1.1.1 and revised Section 3 editorially in July 2011.~~

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~~of bedrock, or ~~to~~the 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.

1.1.1 The geotechnical industry uses English or SI units.

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~~ safety, health, and ~~health~~environmental 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.*

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[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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Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without 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.

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D420 Guide for Site Characterization for Engineering Design and Construction Purposes

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D2845 Test Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock (Withdrawn 2017)[3]

D4428/D4428M Test Methods for Crosshole Seismic Testing

D5088 Practice for Decontamination of Field Equipment Used at Waste Sites

D5608 Practices for Decontamination of Sampling and Non Sample Contacting Equipment Used at Low Level Radioactive Waste Sites

D5730 Guide for Site Characterization for Environmental Purposes With Emphasis on Soil, Rock, the Vadose Zone and Groundwater (Withdrawn 2013)[3]

D5753 Guide for Planning and Conducting Geotechnical Borehole Geophysical Logging

D6235 Practice for Expedited Site Characterization of Vadose Zone and Groundwater Contamination at Hazardous Waste Contaminated Sites

D6429 Guide for Selecting Surface Geophysical Methods

3. Terminology

3.1 *Definitions:*

3.1.1 ~~Definitions shall be in accordance with the terms and symbols given in~~For definitions of common technical terms used in this standard, refer to Terminology D653.

~~3.2 *Definitions of Terms Specific to This Standard:*~~

~~3.2.1 The majority of the technical terms used in this guide are defined in Refs (2) and (3).[4]~~

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~~ of the 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

[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 last approved version of this historical standard is referenced on www.astm.org.

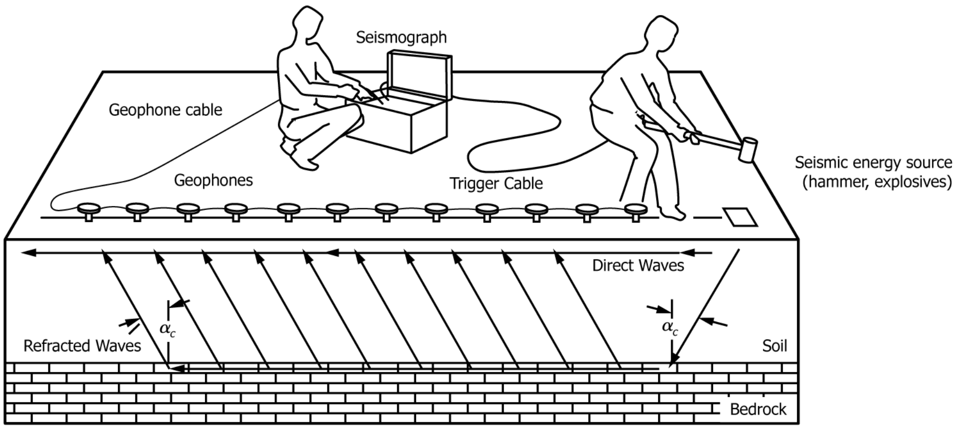


FIG. 1 Field Layout of a Twelve-Channel Seismograph Showing the Path of Direct and Refracted Seismic Waves in a Two-Layer Soil/Rock System (α_c = Critical Angle)

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.

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 (**53**, **64**). 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 (**53**):

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

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).

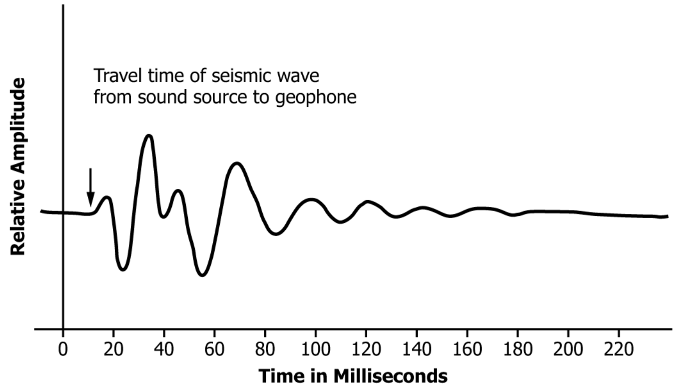
5.1.8 The travel times are plotted against the distance between the source and the geophone to make a time distance plot. Fig. 4 shows the source and geophone layout and the resulting idealized time distance plot for a horizontal two-layered earth.

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 toof the refractor and the seismic velocities of the materials through which the wave passes.

5.1.10 The depth toof 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 (**7-5-64**). 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 (**42**) 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:

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



NOTE 1—Arrow marks arrival of first compressional wave.

FIG. 2 A Typical Seismic Waveform from a Single Geophone

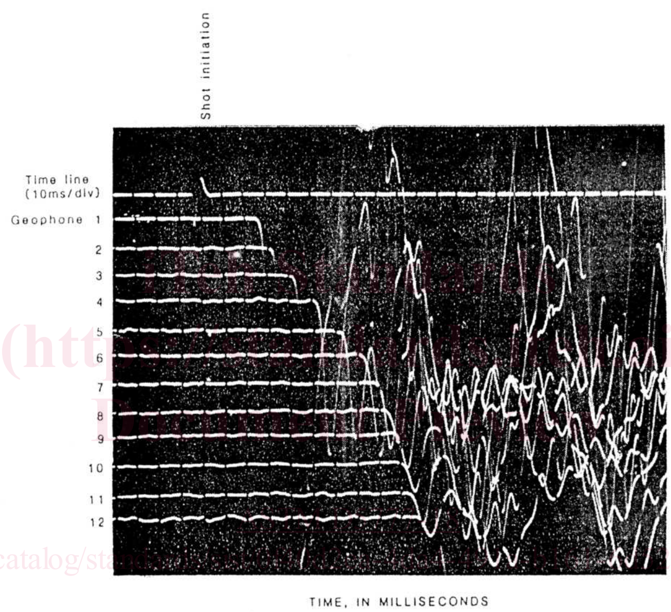


FIG. 3 Twelve-Channel Analog Seismograph Record Showing Good First Breaks Produced by an Explosive Sound Source (~~4~~2)

where:

~~z = depth to refractor two,~~
z = depth of 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:

$$z = \frac{x_c}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \tag{3}$$

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

5.1.10.3 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.

NOTE 1—While these equations are suitable for hand calculations, more advanced algorithms are used in commercially available software that is generally used to analyze seismic traces.

~~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.~~

V_1 = seismic velocity in layer 1

V_2 = seismic velocity in layer 2

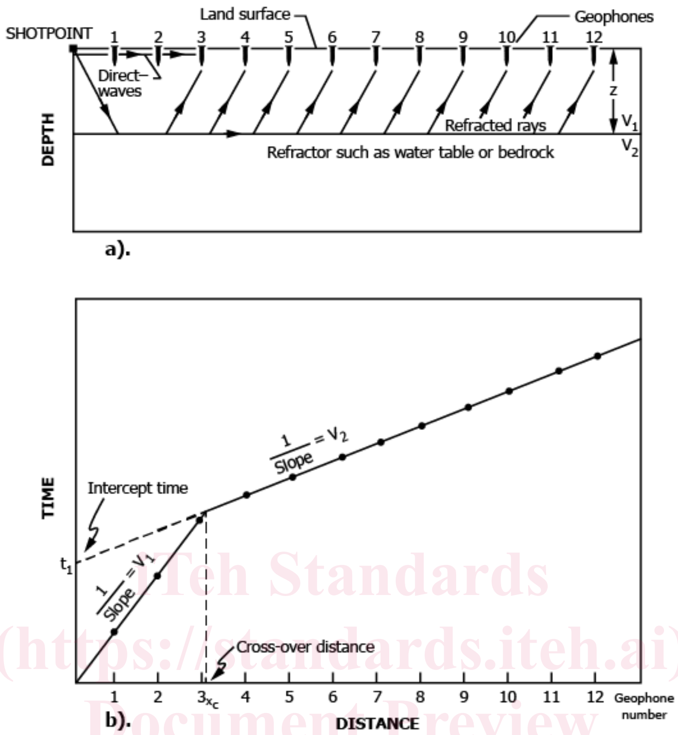


FIG. 4 (*a*) Seismic Raypaths and (*b*) Time-Distance Plot for a Two-Layer Earth With Parallel Boundaries (~~4~~2)

5.1.11 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~~of water table or bedrock.

5.1.12 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 (**~~4~~2**) 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~~of the refractor is obtained under each geophone by using a more sophisticated data collection and interpretation approach.

5.1.13 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 (**~~7~~5**).

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 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;

V_1 = seismic velocity in layer 1

V_2 = seismic velocity in layer 2

V_3 = seismic velocity in layer 3

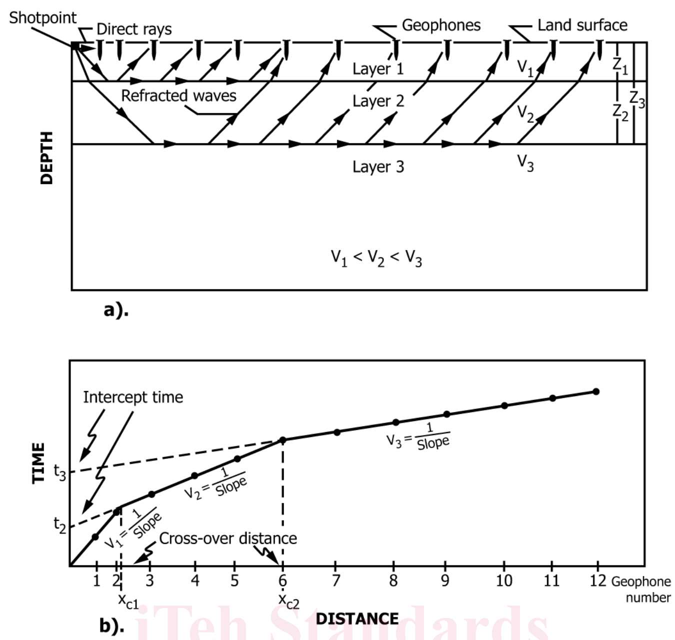


FIG. 5 (*a*) Seismic Raypaths and (*b*) Time-Distance Plot for a Three-Layer Model With Parallel Boundaries (42)

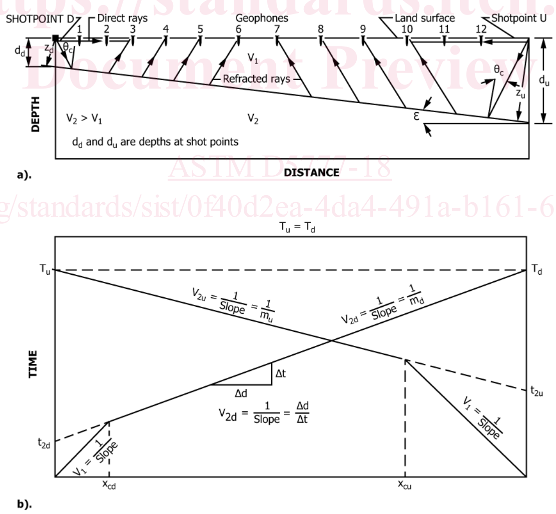


FIG. 6 (*a*) Seismic Raypaths and (*b*) Time-Distance Plot for a Two-Layer Model With A Dipping Boundary (42)

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.