Standard Test Methods for Crosshole Seismic Testing[1]

This standard is issued under the fixed designation D4428/D4428M; 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 These test methods are limited to the determination of the velocity of two types of horizontally travelling seismic waves in soil materials; primary compression (*P-wave*) and secondary shear (*S-wave*) waves. The standard assumes that the method used to analyze the data obtained is based on first arrival times or interval arrival times over a measured distance.

1.2 Acceptable interpretation procedures and equipment, such as seismic sources, receivers, and recording systems are discussed. Other items addressed include borehole spacing, drilling, casing, grouting, deviation surveys, and actual test procedures.

1.3 These test methods are primarily concerned with the actual test procedure, data interpretation, and specifications for equipment which will yield uniform test results.

1.4 All recorded and calculated values shall conform to the guide for significant digits and rounding established in Practice D6026.

1.4.1 The procedures used to specify how data are collected/recorded and calculated in these test methods are regarded as the industry standard. The procedures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives. Measurements made to more significant digits or better sensitivity than specified in these test methods shall not be regarded a nonconformance with this standard.

1.5 *Units*—The values stated in either SI units or inch-pound units [presented in brackets] are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard. Reporting of test results in units other than SI shall not be regarded as nonconformance with this test method.

1.6 *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.*

2. Referenced Documents

2.1 *ASTM Standards:*

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D6026 Practice for Using Significant Digits in Geotechnical Data

3. Terminology

3.1 *Definitions:*

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

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *seismic wave train*—the recorded motion of a seismic disturbance with time.

4. Summary of Test Method

4.1 The Crosshole Seismic Test makes direct measurements of P-wave velocities, or S-wave velocities, in boreholes advanced primarily through soil. At selected depths down the borehole, a borehole seismic source is used to generate a seismic wave train. Downhole receivers are used to detect the arrival of the seismic wave train in offset borings at a recommended spacing of 3 to 6 m [10 to 20 ft]. The distance between boreholes at the test depths is measured using a borehole deviation survey. The borehole seismic source is connected to and triggers a data recording system that records the response of the downhole receivers, thus measuring the travel time of the wave train between the source and receivers.

[1] These test methods are under the jurisdiction of ASTM Committee D18 on Soil and Rock and are the direct responsibility of Subcommittee D18.09 on Cyclic and Dynamic Properties of Soils.

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*A Summary of Changes section appears at the end of this standard

The P-wave or S-wave velocity is calculated from the measured distance and travel time for the respective wave train.

5. Significance and Use

5.1 The seismic crosshole method provides a designer with information pertinent to the seismic wave velocities of the materials in question (**1**).[2] This data may be used as follows:

5.1.1 For input into static/dynamic analyses;

5.1.2 For computing shear modulus, Young's modulus, and Poisson's ratio (provided density is known or assumed);

5.1.3 For determining Seismic Site Class using the appropriate Building Code; and

5.1.4 For assessing liquefaction potential.

5.2 Fundamental assumptions inherent in the test methods are as follows:

5.2.1 Horizontal layering is assumed.

5.2.2 Snell's law of refraction applies to P-waves and S-waves and to the velocities derived from crosshole tests. If Snell's law of refraction is not considered in the analysis of Crosshole seismic testing data, the report shall so state, and the P-wave and S-wave velocities obtained may be unreliable for certain depth intervals near changes in stratigraphy (**2**).

NOTE 1—The quality of the results produced by these test methods is dependent on the competence of the personnel performing it and the suitability of the equipment and facilities. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing/sampling/inspection and so forth. Users of these test methods are cautioned that compliance with Practice D3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.

[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

6. Apparatus

6.1 The basic data acquisition system consists of the following:

6.1.1 *Energy Sources*—The source shall be rich in the type of energy required, that is, to produce good P-wave data, the energy source must transmit adequate energy to the medium in compression or volume change. Impulsive sources, such as explosives, hammers, or air guns, are all acceptable P-wave generators. To produce an identifiable S-wave, the source shall transmit energy to the ground primarily by distortion. Vertically polarized S-waves (SV) are most commonly measured, but horizontally polarized S-waves are also very useful. Fig. 1 and Fig. 2 show examples of impulse and vibratory seismic source wave trains respectively. For good S-waves, energy sources must be repeatable and, although not mandatory, reversible. The S-wave source must be capable of producing an S-wave train with an amplitude greater than the P-wave train.

6.1.2 *Receivers*—The receivers intended for use in the crosshole test shall be transducers having appropriate frequency and sensitivity characteristics to determine the seismic wave train arrivals. Typical examples include geophones and accelerometers. S-waves are typically in the range of 50 to 500 Hz depending on the soil properties and signal source mechanism while P-waves may be as high as 2000 Hz. It is important that the receivers have a flat response over this range of frequencies. This can be accomplished by using geophones with a resonance at or below 10 Hz or accelerometers with a resonance at or above 10 000 Hz. It is important that all receivers used in the testing be of the same type and with matched characteristics. Each receiving unit will normally consist of three receivers combined orthogonally to form a triaxial array, that is, one vertical and two horizontal receivers

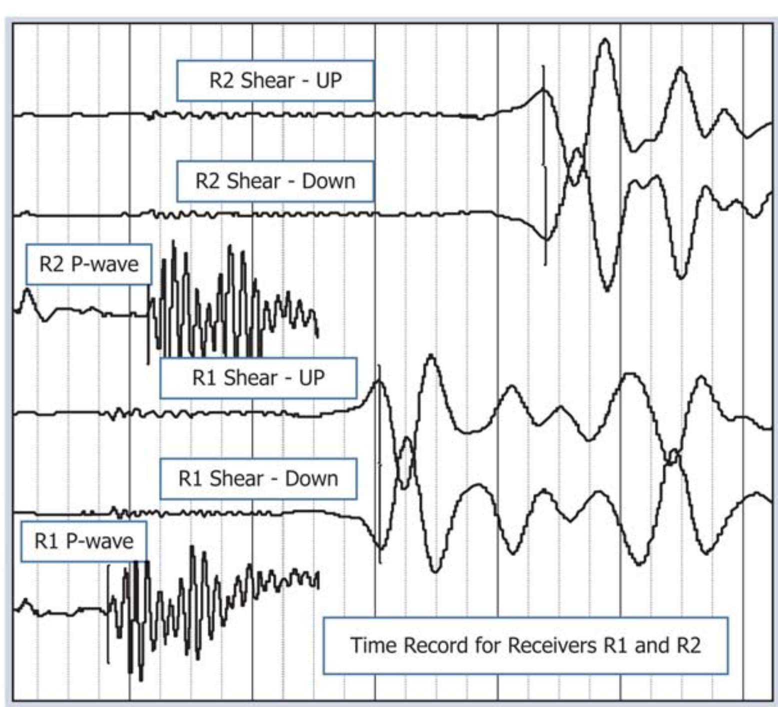


FIG. 1 Reversible Impulse Seismic Source Time Plot Showing Both P-Wave and S-Wave Trains

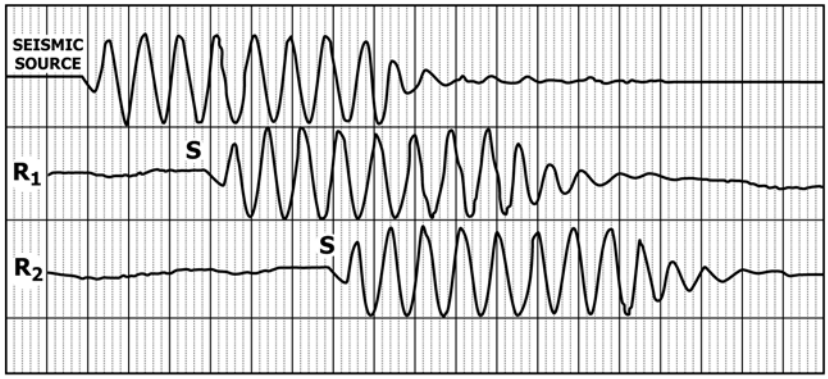


FIG. 2 Borehole Vibratory Seismic Source Time Plot (Produces S-Wave Train Only)

mounted at right angles, one to the other. In this triaxial arrangement, only the vertical component will be acceptable for determining the arrival of an SV-wave (S-wave in the vertical plane). Horizontally oriented receivers must be used for determining the arrival of an SH-wave (S-wave in the horizontal plane). The P-wave may be detected by any of the three components. The one oriented radially will provide the best sensitivity. Provision must be made for the receivers(s) to be held in firm contact with the sidewall of the borehole or casing. Examples of acceptable methods include: air bladder, wedge, stiff spring, or mechanical expander.

6.1.3 *Recording System:*

6.1.3.1 The system shall consist of separate recording channels, one for each receiver being recorded, having at least 12 bits of resolution. The timing accuracy of all instruments that are used in the travel time measurements shall be calibrated traceable to an appropriate government standards agency. Time scale accuracy may be demonstrated by inducing and recording an oscillating square wave signal of 1000 Hz derived from a calibrated quartz-controlled oscillator. Timing shall be to a resolution of 0.1 msec. Timing accuracy shall be demonstrated for all time scales used during the conduct of the tests.

6.1.3.2 Raw data shall be recorded directly without filtering except for the application of anti-aliasing filters which are set between 0.3 to 0.4 times the sampling frequency. Filtering or other post processing must pay attention to possible time shifting or distortion of the seismic wave train arrivals.

6.1.3.3 When velocities are determined using the travel time between a source (S) and two receivers (R1 and R2), the signals shall be recorded in a manner such that precision timing of the P- and S-wave arrival referenced to the instant of seismic source activation can be determined within 0.1 ms. For example, a seismic in-hole source and two receivers could be recorded multiple times to demonstrate accurate and consistent triggering by comparing the velocities determined for S-R1 and S-R2 with R1-R2 paths. When only two boreholes are used and velocities are determined by time interval S-R1, documentation of the trigger accuracy relative to the instant of seismic source generation must be provided. When velocities are determined using only the time interval between R1 and R2 and a simultaneous recording of R1 and R2, the trigger time is not needed.

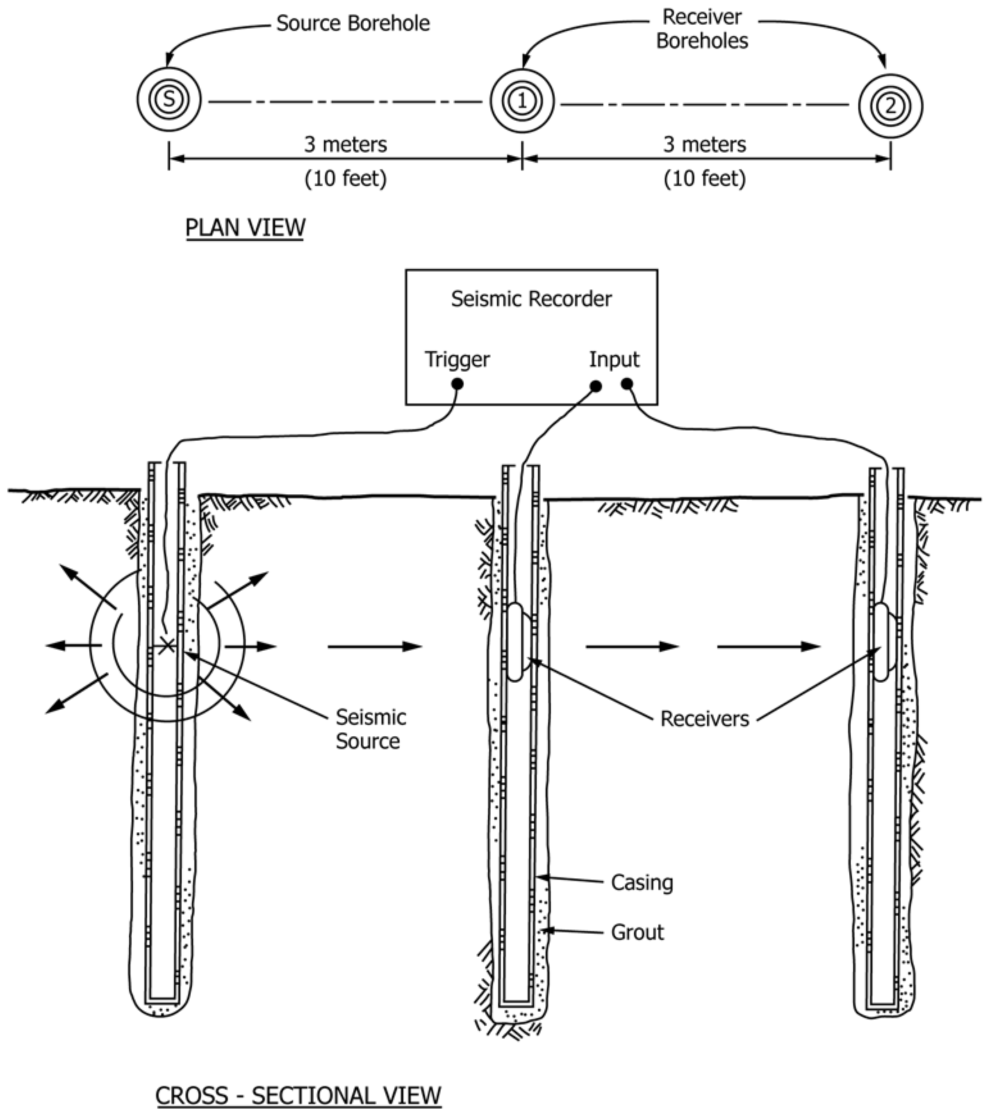
6.1.3.4 Permanent records shall be made of the seismic events to allow for subsequent review and analysis of the data.

7. Procedure

7.1 *Borehole Preparation:*

7.1.1 The recommended layout for crosshole testing incorporates three or more boreholes in line although two boreholes may be used. Three holes provide a level of redundancy not provided with two holes. Use of only two holes will be in compliance with this procedure if trigger accuracy is demonstrated and documented (6.1.3.3). Borehole spacing must be measured to a resolution of ±0.02 m. Borehole azimuth must be measured to a resolution of ±1 degrees of a designated reference direction. Borehole elevations must be measured to a precision of ±0.1 m. Spacing between the source borehole and the first receiver borehole shall be 1.5 to 3 m [5 to 10 ft] and the distance between subsequent receiver boreholes shall be 3 to 6 m [l0 to 20 ft] apart. A typical layout is illustrated in Fig. 3. For two boreholes, spacing between the source borehole and the receiver borehole shall be 1.5 to 5 m [5 to 15 ft].

7.1.1.1 *Borings with Casing*—If casing is used to house the receivers it shall be grouted in place. Drill the boreholes, with minimum sidewall disturbance, to a diameter no greater than required to perform the test. After the drilling is completed, case the borings with 50 to 100 mm [2 to 4 in.] inside diameter PVC pipe or aluminum casing, taking into consideration the size of the borehole source and downhole receivers. Before inserting the casing, close the bottom of the casing pipe with a cap which has a one way ball-check valve capable of accommodating 38 mm [1½ in.] outside diameter grout pipe. If a tremie pipe is used for the grouting, a ball check valve is not needed. Insert the casing down to the bottom of the borehole. Grout the casing in place by (*1*) inserting a 38 mm [1½ in.] PVC pipe through the center of the casing, contacting the one-way valve fixed to the end cap (Fig. 4 (left side)), or (*2*) by a small diameter grout tube inserted to the bottom of the borehole between the casing and the borehole sidewall (Fig. 4 (right side)). Another acceptable method would be to fill the borehole with grout which would be displaced by end-capped fluid-filled casing. The grout mixture shall be formulated to approximate closely the unit weight of the surrounding in situ material after solidification. That portion of the boring that penetrates rock shall be grouted with ordinary portland cement



NOTE 1—Spacing may vary with site conditions.

FIG. 3 Typical Crosshole Seismic Test

which will harden to a unit weight of about 22 kN/m^3 [unit weight of 140 lb/ft^3]. That portion of the boring in contact with soils, sands, or gravels shall be grouted with a mixture simulating the average unit weight of the medium (about 18 to 19 kN/m^3 [110 to 120 lb/ft^3]) by premixing 4.4 N [1 lb] of bentonite and 4.4 N [1 lb] of portland cement to 27N [6.25 lb] of water. Anchor the casing and pump the grout using a conventional, circulating pump capable of moving the grout through the grout pipe to the bottom of the casing and upward from the bottom of the borehole (Fig. 4). Using this procedure, the annular space between the sidewall of the borehole and the casing will be filled from bottom to top in a uniform fashion displacing mud and debris with minimum sidewall disturbance. Keep the casing anchored and allow the grout to set before deviation measurement or crosshole testing is performed. This grout mix will not set hard but will become a "rigid" gel. If shrinkage occurs near the mouth of the borehole, additional grout shall be inserted until the annular space is filled flush with the ground surface (**3**).

7.1.1.2 *Borings without Casing*—In some situations the survey may be performed without casing in the receiver holes. The receivers must be held in firm contact with the sidewall of the borehole during the measurements. The Borehole Deviation Survey (7.2) may be conducted with casing (if necessary) temporarily installed without being grouted in place.

7.2 *Borehole Deviation Survey*—A borehole deviation survey must be conducted in order to accurately determine the spacing at the elevations of the seismic tests.

7.2.1 Conduct a borehole deviation survey in all crosshole borings with an instrument capable of measuring the precise vertical alignment of each hole. The instrument must have the capability of determining tilt with a sensitivity of 0.3°. Information thus obtained will enable the investigator to compute

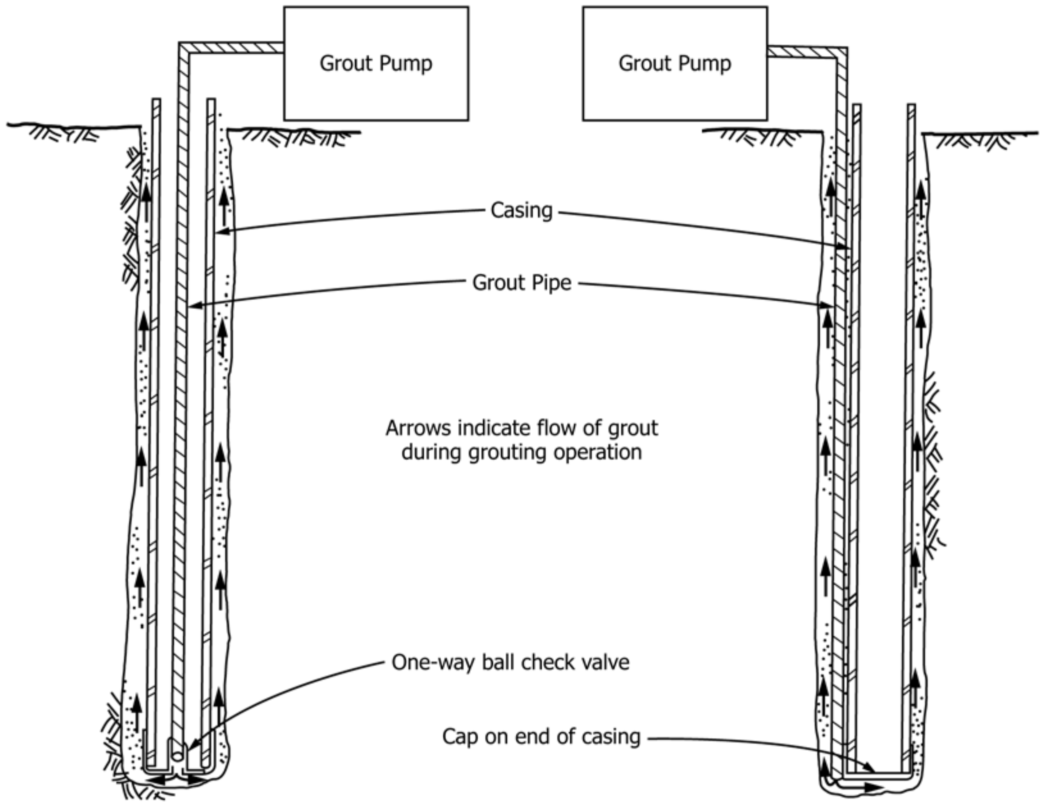


FIG. 4 Acceptable Grouting Techniques

the horizontal position at any depth within the borehole so that the actual distance between the holes can be computed.

7.2.1.1 Obtain deviation data at intervals not exceeding 3.0 m [10 ft] to the bottom of the boring. Repeat the measurements on the withdrawal trip at the same intervals so that closure can be determined at the mouth of the borehole.

7.3 *Crosshole Test:*

7.3.1 Begin the crosshole test by placing the energy source in the source hole at a depth no greater than 1.5 m [5 ft] (Fig. 3) into the stratum being investigated. Place the two receivers at the same elevation in each of the designated receiver holes. Clamp the source and receivers firmly into place. Check recording equipment and verify timing. Activate the energy source and display both receivers simultaneously on the recording device. Adjust the signal amplitude and duration such that the P-wave train or S-wave train, or both, are displayed in their entirety.

7.3.1.1 Best results will be obtained by performing two separate tests: one optimized for P-wave recovery (fastest sweep/recorder rate, higher gain settings) and the second for S-wave recovery (slower sweep/recorder rate, lower gain settings). If enhancement equipment is being used, repeatedly activate the energy source until optimum results are displayed. Perform the second test by lowering the energy source and receivers to a depth dictated by known stratification, but no greater than 1.5 m [5.0 ft] from the previous test locations in the borings and repeat the above procedure. Perform succeeding tests at intervals determined by stratification, or tests at depth intervals of 1.5 m [5 ft] until the maximum borehole depth has been reached.

8. Data Reduction and Interpretation

8.1 *Deviation Survey*—The primary objective of the borehole deviation survey is to establish the spatial position of the boreholes at all depths. Seismic wave velocities will be computed by determining the straight-line distance, *l*, from source to receivers. To do this, the following data are needed:

E_S = elevation of the top of the source hole,

E_G = elevation of the top of the geophone hole,

D_S = depth of the seismic source,

D_G = depth of the geophone,

L = horizontal distance between the top of the source hole and geophone hole,

ϕ = azimuth with respect to north from the top of the source hole to the geophone hole,

x_S = the north deviation of the source borehole at the source depth,

y_S = the east deviation of the source borehole at the source depth,

x_G = the north deviation of the geophone borehole at the geophone depth, and

y_G = the east deviation of the geophone borehole at the geophone depth.

8.1.1 The following equation determines the straight-line distance, *l*, from source to geophone using the data of 8.1:

$$l = \sqrt{[(E_S - D_S) - (E_G - D_G)]^2 + (L\cos\phi + x_G - x_S)^2 + (L\sin\phi + y_G - y_S)^2} \quad (1)$$

The apparent velocity is equal to l divided by the travel time between the source and the receiver. When computing the apparent velocity between two receivers, the distance is the difference between the distances from the source to the respective receivers.

8.2 *Wave Train Identification:*

8.2.1 Under ideal conditions the identification of the P-wave and S-wave arrivals will be similar to that shown in Fig. 1. In other situations some judgment is required to identify the S-wave arrival. The S-wave may often be identified on the seismic signature by the following characteristics:

8.2.1.1 A sudden increase in amplitude above that of the P-wave train, and

8.2.1.2 An abrupt change in frequency coinciding with the amplitude change.

8.2.1.3 If a reversible polarity seismic source is used, the S-wave arrival will be determined as that point meeting the criteria of 8.2.1.1 and 8.2.1.2 and where a 180° polarity change is noted to have occurred. An unclipped recording of the entire waveform under consideration must be made. A subsequent recording at higher gain may be made with wave clipping after a clearly identified arrival has been recorded.

8.2.2 If a vertically polarized S-wave vibratory source (as opposed to an impact source) is used, the time difference between Receivers 1 and 2 may provide the time interval information needed for S-wave velocity calculations without a well-defined initial arrival. (See Note 2 below.) This type of source does not generally produce easily identified P-wave signals.

NOTE 2—Other than ideal conditions often exist where first arrivals such as those shown in Fig. 1 cannot easily be determined from the time trace. This may be caused by wave reflections and other phenomena as the signal travels between the source and receiver. Signal analysis techniques that account for such effects must then provide a means for the determination of the S-wave and possibly P-wave wave velocities. These techniques are not addressed in this standard but are acceptable if documented in the report.

8.3 *Data Tabulation:*

8.3.1 Three separate travel times are computed from the measurements as follows:

8.3.1.1 Source to Receiver 1,

8.3.1.2 Source to Receiver 2, and

8.3.1.3 Time difference between Receivers 1 and 2.

8.3.2 Determine incremental velocity by dividing the difference in radial distances between the source and receivers R1 and R2 by the difference in arrival times between and R2 and R1. (See Note 3.)

NOTE 3—If the source trigger is not precisely calibrated or identified due to trigger errors, the only accurate velocity measurement is computed using the time difference between Receivers 1 and 2 along with the difference in radial distances from the source to each receiver.

9. Report: Test Data Sheet(s)/Form(s)

9.1 The methodology used to specify how data are recorded on the test data sheet/form, as given below, is covered in 1.4.

9.2 Record as a minimum the following general information (data):

9.2.1 Project description, operator, and weather conditions.

9.2.2 Make and model of borehole seismic source, downhole receivers, and recording equipment.

9.2.3 Borehole information, method of installation, casing diameter(s).

9.2.4 Distance between each borehole or borehole coordinates at ground surface.

9.3 Record as a minimum the following test data at each measurement depth:

9.3.1 Measured deviations of each bore hole,

9.3.2 Distance between each pair of borehole sets,

9.3.3 Travel time and velocity from Source to R1,

9.3.4 Travel time and velocity from Source to R2, and

9.3.5 Travel time and velocity between borehole pairs R1 and R2.

10. Precision and Bias

10.1 *Precision*—Test data on precision are not presented due to the nature of the soil tested by these test methods. It is either not feasible or too costly to have ten or more laboratories participate in a round-robin testing program at sites with uniform soil deposits covering the range of expected shear wave velocities Any variation observed in the data is just as likely to be due to geologic variation as to operator or field testing variation.

10.1.1 Subcommittee D18.09 is seeking any data from users of this test method that might be used to make a limited statement on precision.

10.2 *Bias*—There is no accepted reference value for these test methods; therefore, bias cannot be determined.

11. Keywords

11.1 accelerometers; compression waves; geophones; machine foundations; seismic waves; shear waves; wave velocity

REFERENCES

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(2) Wightman, W. E., Jalinoos, F., Sirles, P., and Hanna, K., "Application of Geophysical Methods to Highway Related Problems," Federal Highway Administration, Central Federal Lands Highway Division, Lakewood, CO, Publication No. FHWA-IF-04-021, September 2003.

(3) Ballard, R. F., Jr., "Method for Crosshole Seismic Testing," *Geotechnical Engineering Division* , ASCE, Vol 102, No. GT12, December 1976, pp. 1261–1273.

SUMMARY OF CHANGES

Committee D18 has identified the location of selected changes to this standard since the last issue (D4428/D4428M – 07) that may impact the use of this standard. (Approved March 1, 2014.)

(1) Revised Sections 1, 3, 5, 8, 9, and 10.
(2) Expanded Sections 6 and 7.
(3) Updated Figs. 1-4 and References Section.
(4) Removed Figs. 4 and 5, Tables 1 and 2, and Appendixes Section.