Designation: D 4428/D 4428M – 91 (Reapproved 1995)

Designation: D 4428/D 4428M – 00

Standard Test Methods for Crosshole Seismic Testing[1]

This standard is issued under the fixed designation D 4428/D 4428M; 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 horizontally traveling compression (*P*) and shear (*S*) seismic waves at test sites consisting primarily of soil materials (as opposed to rock). A preferred test method intended for use on critical projects where the highest quality data must be obtained is included. Also included is an optional method intended for use on projects which do not require measurements of a high degree of precision.

1.2 Various applications of the data will be addressed and acceptable interpretation procedures and equipment, such as seismic sources, receivers, and recording systems will be discussed. Other items addressed include borehole spacing, drilling, casing, grouting, deviation surveys, and actual test conduct. Data reduction and interpretation is limited to the identification of various seismic wave types, apparent velocity relation to true velocity, example computations, effective borehole spacing, use of Snell's law of refraction, assumptions, and computer programs.

1.3 It is important to note that more than one acceptable device can be used to generate a high-quality P wave or S wave, or both. Further, several types of commercially available receivers and recording systems can also be used to conduct an acceptable crosshole survey. Consequently, these test methods primarily concern the actual test procedure, data interpretation, and specifications for equipment which will yield uniform test results.

1.4 The values stated in either SI units or inch-pound units are to be regarded as standard. Within the text, the inch-pound units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system must be used independently of the other.

1.5 *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. Significance and Use

2.1 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 input into static/dynamic analyses, as a means for computing shear modulus, Young's modulus, and Poisson's ratio, or simply for the determination of anomalies that might exist between boreholes.

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

2.2.1 Horizontal layering is assumed.

2.2.2 Snell's laws of refraction will apply. If Snell's laws of refraction are not applied, velocities obtained will be unreliable.

3. Apparatus

3.1 The basic data acquisition system consists of the following:

3.1.1 *Energy Sources*—These energy sources are chosen according to the needs of the survey, the primary consideration being whether P-wave or S-wave velocities are to be determined. The source should 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 should transmit energy to the ground primarily by directionalized distortion. 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 at least twice that of the P-wave train. Fig. 1 and Fig. 2 show examples of impulse and vibratory seismic sources.

3.1.2 *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 arrival. Typical examples include geophones and accelerometers. The

---

[1] These test methods are under the jurisdiction of ASTM Committee D~~-~~18 on Soil and Rock and are the direct responsibility of Subcommittee D18.09 on Dynamic Properties of Soils.

Current edition approved ~~May 15, 1991.~~ Jan. 10, 2000. Published ~~July 1991.~~ March 2000. Originally published as D 4428/D 4428M – 84. Last previous edition D 4428/D 4428M – ~~84~~91(1995).

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

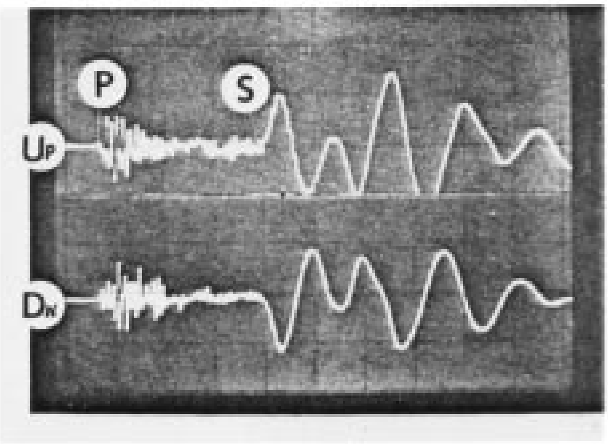


FIG. 1 Reversible Impulse Seismic Source (Produces Both P and S Wave Trains)

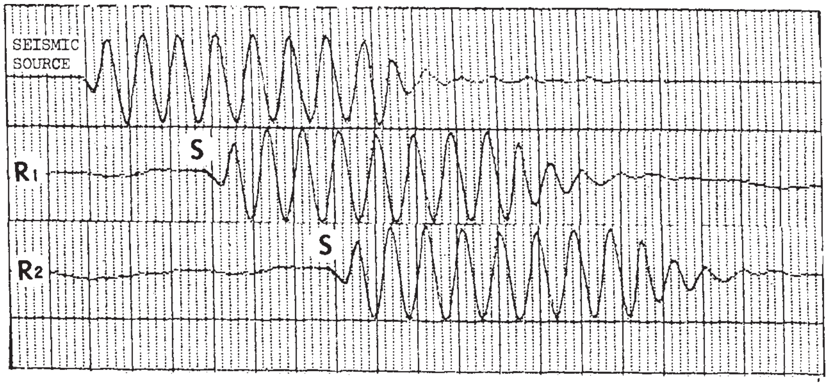


FIG. 2 Borehole Vibratory Seismic Source (Produces S Wave Train Only)

frequency response of the transducer must not vary more than 5 % over a range of frequencies from ½ to 2 times the predominant frequency of the site-specific S-wave train. Each receiving unit will consist of at least three transducers combined orthogonally to form a triaxial array, that is, one vertical and two horizontal transducers mounted at right angles, one to the other. In this triaxis arrangement, only the vertical component will be acceptable for S-wave arrival determinations. In cases where P-wave arrivals are not desired, a uniaxial vertical transducer may be used. P-wave arrivals will be determined using the horizontal transducer oriented most nearly radially to the source. The transducer(s) shall be housed in a single container (cylindrical shape preferred) not exceeding 450 mm [18 in.] in length. Provision must be made for the container to be held in firm contact with the sidewall of the borehole. Examples of acceptable methods include: air bladder, wedge, stiff spring, or mechanical expander.

3.1.3 *Recording System*— The system shall consist of separate amplifiers, one for each transducer being recorded, having identical phase characteristics and adjustable gain control. Only digital signal filtering will be acceptable. Analog filtering, active or passive, will not be acceptable because of inherent phase delays. The receiver signals shall be displayed 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 when materials other than rock are being tested. Timing accuracy shall be demonstrated both immediately prior to and immediately after the conduct of the crosshole test. Demonstrate accuracy by inducing and recording on the receiver channels an oscillating signal of 1000 Hz derived from a quartz-controlled oscillator, or, a certified laboratory calibration obtained within the time frame recommended by the instrument manufacturer. Further, the timing signal shall be recorded at every sweep rate or recorder speed, or both, used during conduct of the crosshole test. As an optional method, the true zero time shall be determined by (*1*) a simultaneous display of the triggering mechanism along with at least one receiver, or (*2*) a laboratory calibration (accurate to 0.1 ms) of the triggering mechanism which will determine the lapsed time between the trigger closure and development of that voltage required to initiate the sweep on an oscilloscope or seismograph. Permanent records of the seismic events shall be made by either scope-mounted camera or oscillograph.

4. Procedure

4.1 *Borehole Preparation*:

4.1.1 *Preferred*—The preferred method for preparing a borehole set for crosshole testing incorporates three boreholes in line, spaced 3.0 m [10 ft] apart, center-to-center on the ground surface, as illustrated in Fig. 3. If, however, it is known that S wave

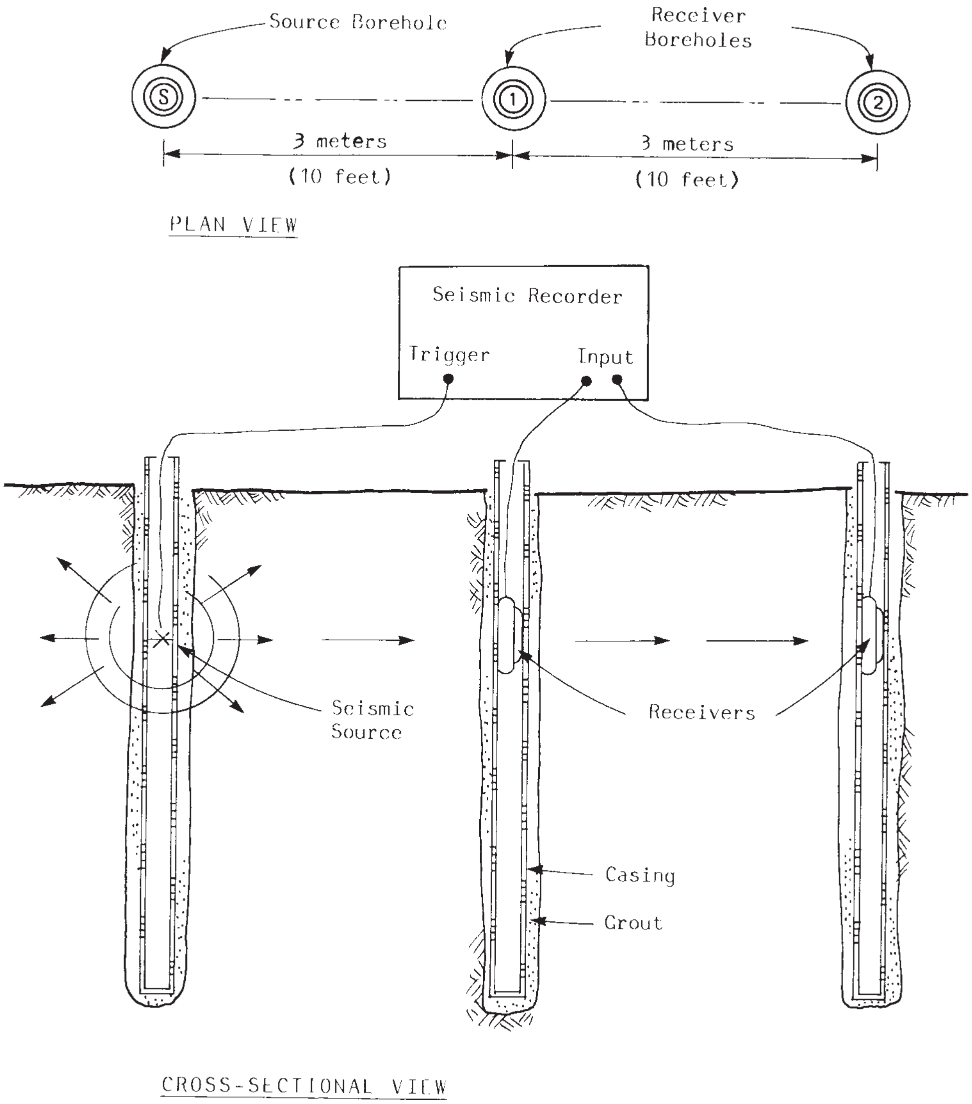


FIG. 3 Crosshole Seismic Test

velocities will exceed 450 m/s [1500 ft/s], such as is often encountered in alluvial materials, borehole spacings may be extended to 4.5 m [15 ft].

4.1.1.1 Drill the boreholes, with minimum sidewall disturbance, to a diameter not exceeding 165 mm [6.5 in.]. After the drilling is completed, case the boring with either 75 or 100 mm [3 or 4 in.] inside diameter PVC pipe or aluminum casing. Before inserting the casing, close the bottom of the pipe with a cap which has a one way ball-check valve capable of accommodating 38 mm [1½ in.] outside diameter grout pipe. Center the casing with spacers and insert it into 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 (side A)), or (*2*) by a small diameter grout tube inserted to the bottom of the borehole between the casing and the borehole sidewall (Fig. 4 (side B)). Another acceptable method would be to fill the borehole with grout which would be displaced by end-capped fluid-filled casing. The grout mixture should be formulated to approximate closely the density of the surrounding in situ material after solidification. That portion of the boring that penetrates rock should be grouted with a conventional portland cement which will harden to a density of about 2.20 Mg/m^3 [140 lb/ft^3]. That portion of the boring in contact with soils, sands, or gravels should be grouted with a mixture simulating the average density of the medium (about 1.80 to 1.90 Mg/m ^{3} [110 to 120 lb/ft^3]) by premixing 450 g [1 lb] of bentonite and 450 g [1 lb] of portland cement to 2.80 kg [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 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 using the boreholes for crosshole testing. If shrinkage occurs near the mouth of the borehole, additional grout should be inserted until the annular space is filled flush with the ground surface **(4)**.

4.1.2 *Optional*—If the scope or intended use of a particular project does not warrant the time and expense which would be

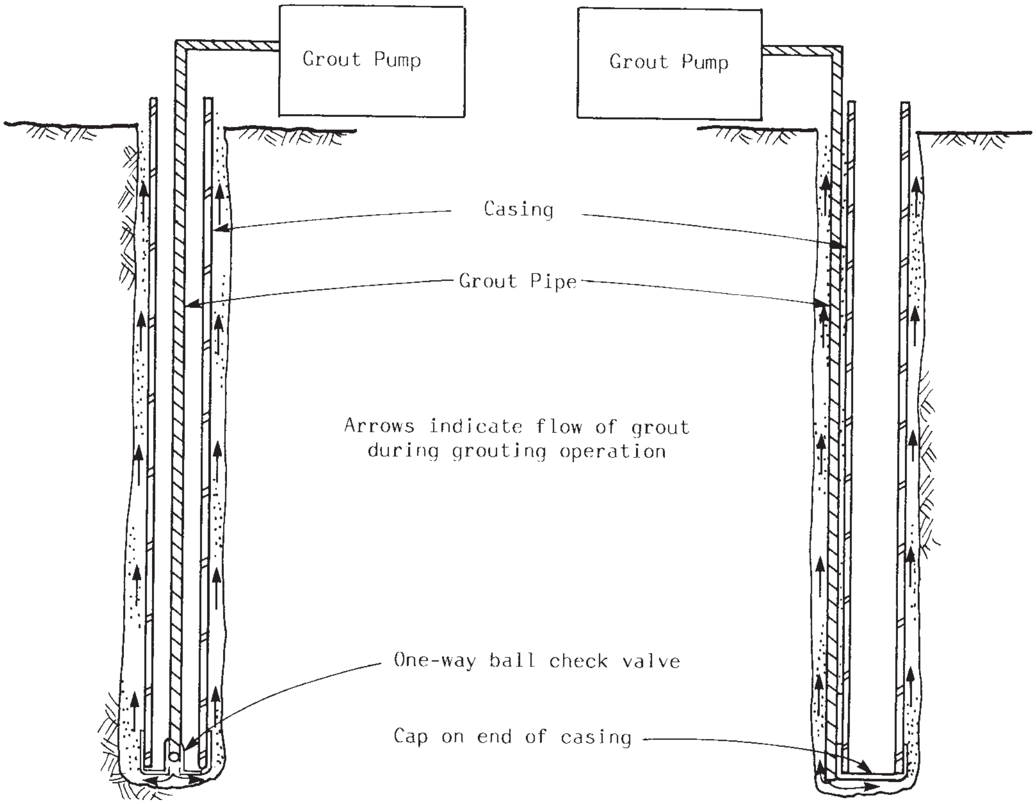


FIG. 4 Acceptable Grouting Techniques

incurred by the preferred method, or if the specific project such as an investigation beneath a relatively small machine foundation is undertaken, this optional method may be used.

4.1.2.1 In all cases, a minimum of two boreholes must be used. If the borings are to be 15 m [50 ft] deep or less, verticality will be controlled using a level on the drill stem extending into the borehole. Center-to-center surface borehole spacing will be determined by the nature of the project. Borings may be used either with or without casing; however, if casing is used, grout must be injected between the casing and sidewall of the borehole to ensure good contact in the manner described in 4.1.1.1. If the center-to-center surface borehole spacing exceeds 6.0 m [20 ft], the probability of measurement of refracted waves rather than a direct wave in each layer greatly increases. As a consequence, data obtained by the optional method must be used with caution.

4.2 *Borehole Deviation Survey*—A borehole deviation survey must be conducted to determine accurately the horizontal distance between borings.

4.2.1 *Preferred Method*— Conduct a borehole deviation survey in all three crosshole borings with an instrument capable of measuring the precise vertical alignment of each hole. The instrument must have the capability of determining horizontal orientation with a 2° sensitivity and an inclination range from 0 to 30° with a sensitivity of 0.1°. Information thus obtained will enable the investigator to compute true vertical depth and horizontal position at any point within the borehole so that actual distance between the holes can be computed to within ±2 % to a depth of about 30.0 m [100 ft].

4.2.1.1 Proceed with the survey beginning at the mouth of the borehole obtaining 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 intervals not exceeding 6.0 m [20 ft] so that closure can be determined at the mouth of the borehole.

4.2.2 *Optional Method*— If the scope of a project dictates the use of the optional procedure described in 4.1.2, the following precautions must be undertaken to ensure verticality of the borings.

4.2.2.1 Level the borehole drilling apparatus using a level placed on the drill stem extending into the mouth of the borehole.

4.2.2.2 As drilling progresses, recheck the drill stem at 3.0 m [10 ft] depth intervals and realign as necessary.

4.2.2.3 Limit the maximum depth of investigation to less than 15 m [50 ft]. If the depth of investigation exceeds 15 m [50 ft] a deviation survey such as described in 4.2.1 must be conducted.

4.2.2.4 If casing is used, grout as described in 4.1.1, then evacuate all fluid from the interior and insert a lighted plumb-bob observing its attitude at 3-m [10-ft] intervals. If the plumb-bob strikes the sidewall, note that depth and the direction of deviation.

4.2.2.5 Estimate the distance between borings and provide appropriate caution statements on all data.

4.3 *Crosshole Test*:

4.3.1 *Preferred Method*— Begin the crosshole test by placing the energy source in an end 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.

4.3.1.1 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. Do not overrange memory circuitry. A clipped signal is unacceptable. 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 at intervals of 1.5 m [5 ft] until the maximum borehole depth has been reached. During withdrawal of the energy source and receivers from the boreholes, perform repeat tests at 6.0-m [20-ft] intervals until the ground surface is reached.

4.3.2 *Optional Method*— Use a minimum of two boreholes. If, however, only two boreholes are used, the importance of true zero time determination as described in 3.1.3 cannot be overemphasized. Place the energy source in one borehole at a depth dictated by test objectives and the receiver at the same elevation in the second borehole. Activate the seismic source and display the trigger mechanism and the receiver simultaneously on the recording device. Adjust the sweep rate so that the P-wave train or S-wave train, or both, are displayed in their entirety. If enhancement/stacking equipment is being used, the seismic source should be activated repeatedly until optimum results are displayed. After wave trains have been identified and duly recorded in their entirety, sweep rates may be expanded for optimum determination of arrival times. Additional permanent records should then be made. Overranging of memory circuitry resulting in a clipped signal is not acceptable. Repeat the test at a second location as predetermined by known stratification information and repeat the above procedure. Perform succeeding tests at intervals of about 1.5 m [5 ft], or intervals determined by stratification.

5. Data Reduction and Interpretation

5.1 *Deviation Survey*— The primary objective of the borehole deviation survey is to establish the correct horizontal distance between the three in-line borings. Seismic wave velocities compensating for borehole deviation 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.

5.1.1 The following equation determines the straight-line distance, *l*, from source to geophone using the data of 5.1:

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

The apparent velocity is equal to *1* divided by the travel time. Use the same method to determine the straight-line distances between the geophone holes.

5.2 *Wave Train Identification*:

5.2.1 Identify the P-wave train arrival time as the first departure of the static horizontal receiver trace after time $T = 0$. It should be noted that the horizontally oriented geophones will often (correctly) respond earlier than the vertically oriented because of the longitudinal particle motion associated with the P wave **(5)**. If both wave trains (P and S) are displayed simultaneously on the records, the S wave will be identified on the seismic signature by the following characteristics:

5.2.1.1 A sudden increase in amplitude of at least two times that of the P-wave train, and

5.2.1.2 An abrupt change in frequency coinciding with the amplitude change which results in a period increase of at least two times that of the characteristic period of the P wave.

5.2.1.3 *Optional*—If a reversible polarity seismic source is used, the S wave arrival will be determined as that point meeting the criteria of 5.2.1.1 and 5.2.1.2 and where a 180° polarity change is noted to have occurred.

5.2.2 The above characteristics are displayed in Fig. 1. Determine the arrival time for the P wave or S wave directly from the record as the lapsed time between time zero (activation of the seismic source) and the arrival of the respective wave trains at each of the receivers. If a vertically polarized S wave vibratory source is used, the arrival time of the S wave will be determined from the time lapsed between the start up of the seismic source monitor geophone and the first arrival of a seismic signal bearing the same characteristic frequency. No discernible P-wave signal is present; consequently, the vibratory source is unacceptable for P wave determinations (see Fig. 2).

5.3 *Data Tabulation*:

5.3.1 Three separate travel times observed in the field and recorded are as follows:

5.3.1.1 Source to Receiver 1,

5.3.1.2 Source to Receiver 2, and

5.3.1.3 Time difference between Receivers 1 and 2.

5.3.2 Tabulate the data in a manner similar to that shown in Fig. 5. Determine preliminary velocity in the field (recognizing that borehole deviations have not been taken into account) by dividing the measured surface distance between source and receivers by the arrival time at each respective receiver. Determine incremental velocity by dividing the measured distance between receivers R_1 and R_2 by the difference in arrival times between source and R_2 and source and R_1.

NOTE 1—Under ideal circumstances, (that is, nonlayered homogeneous materials, vertical boreholes, and no trigger delays in the recording equipment) all three computed velocities ($S - R_1$, $S - R_2$, and $R_1 - R_2$) should be the same value. In normal testing, however, this will rarely be true. Trigger delays up to 3 ms have been observed in some equipment, causing erroneously high computed velocities between $S - R_1$ and $S - R_2$. If this occurs, $S - R_1$ will compute the highest velocity, followed by $S - R_2$. The incremental $R_1 - R_2$ velocity will not be affected by trigger errors. Other factors which can affect incremental velocity determinations are: (*a*) dissimilar materials between borings 1–2 and 2–3, (*b*) faulting or drastically inclined layering, and (*c*) refraction caused by the presence of a nearby higher velocity layer. Items (*a*) and (*b*) can only be determined by other direct tests. If such conditions exist, the usefullness of the crosshole test should be judged according to the purpose of the site investigation. Item (*c*) can be accounted for by proper use of Snell's law of refraction. Therefore, the standard crosshole velocity will be determined from the incremental time recorded between receiver holes R_1 and R_2 **(5)**.

5.4 *Data Reduction*:

5.4.1 In materials where abrupt changes in density or elasticity occur, the ray travel path of the wave might not be a straight line **(6)**. In such cases, Snell's law of refraction must be used. Examples are shown in Fig. 6 and the Appendixes.

NOTE 2—Table 1 illustrates the differences between apparent and true velocities in a crosshole survey. This survey was conducted at 1.5-m [5-ft] increments to a depth of 18 m [60 ft] at the hypothetical site characterized by the true profile shown in the table. Assuming the data were obtained at the same elevations in receiver holes located about 6 to 30 m [20 to 100 ft] from the source, the user will observe that as borehole spacing increases, the low velocity zone located at a spacing increases, the low velocity zone located at a depth of 14 m [46 ft] becomes appreciably less evident at distances greater than 6 m [20 ft]; hence, the overall philosophy of limiting borehole spacing for a crosshole standard test to a maximum of 9 m [30 ft].

5.4.2 *Calculations*—Due to the nature and number of calculations which are involved in a typical application of the crosshole technique to a layered site where refractions are likely to occur, a computer program for crosshole seismic data interpretation may be used **(7)**. The program must apply Snell's law to develop a true velocity interpretation consistent with all the data from a given survey. An acceptable example output of a computer program capable of solving the corrected distances, true velocities using Snell's law, and interface depths is shown in Table 2. Computerized or manual data reduction and interpretation shall incorporate the following information:

5.4.2.1 Source and receiver depths,

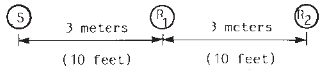
5.4.2.2 Arrival times of P waves or S waves, or both,

5.4.2.3 Surface distance between holes, and

5.4.2.4 Borehole deviations (N–S and E–W).

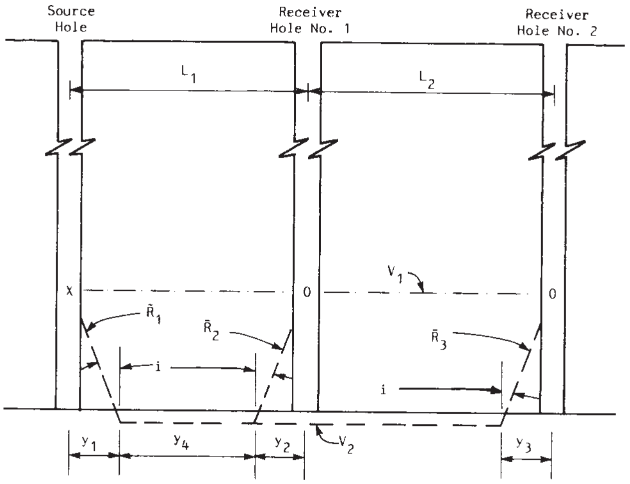
5.4.3 The procedure used in either computer programs or hand calculations begins by assuming that the apparent velocity measured in either the shallowest or deepest crosshole test is a true velocity (Note 3). Layer interfaces are tentatively assumed to exist at middepth between successive test points in the hole, and arrival times from the second test point are computed for all possible paths from the apparent velocities and critical angles. The arrival time(s) at the geophone at the level consistent with the data is the plausible true path. The procedure is repeated until a consistent explanation for all of the data from all of the tests in the borehole is determined. Fig. 6 and the Appendixes provide a numerical (hand) example of the process.

NOTE 3—The better practice is to use the shallowest depth since this velocity can be independently checked by a surface survey.



Depth m (ft)	Travel Time (msec)						Apparent Velocity mps (fps)					
	$S - R_1$		$S - R_2$		$R_1 - R_2$		$S - R_1$		$S - R_2$		$R_1 - R_2$	
	P	S	P	S	P	S	P	S	P	S	P	S

FIG. 5 Crosshole Data Tabulation



LEGEND:		Velocity	f/s	m/s
X	Location of Source	V_1	3500	1100
O	Location of Receivers	V_2	10000	3000
—·—	Straight Line Distance Travel Point			
— —	Refracted Travel Path			
		Distance	Feet	Metres
$L_1 = L_2$			10.00	3.00
$\bar{R}_1 = \bar{R}_2 = \bar{R}_3$			5.34	1.61
$y_1 = y_2 = y_3$			1.87	0.59
$y_4 = L_1 - (y_1 + y_2)$			6.26	1.82

FIG. 6 Example Crosshole Computation

TABLE 1 Apparent Velocity as a Function of Hole Spacing

Depth, m [ft]	Time velocity profile, m/s [ft/s]	Interface depth, m [ft]	Apparent velocities[A] for hole spacings of:				
			6 m [20 ft]	12 m [40 ft]	18 m [60 ft]	21 m [70 ft]	30 m [100 ft]
1.5 [5.0]	300 [1000]		300 [1000]	367 [1245]	423 [1424]	532 [1760]	630 [2086]
3.0 [10.0]	300 [1000]		427 [1485]	499 [1705]	551 [1833]	682 [2252]	796 [2630]
		3.70 [12.0]					
4.5 [15.0]	600 [2000]		600 [2000]	600 [2000]	707 [2295]	858 [2792]	985 [3210]
6.0 [20.0]	600 [2000]		600 [2000]	697 [2363]	873 [2816]	1038 [3360]	1171 [3801]
7.5 [25.0]	600 [2000]	8.50 [28.0]	761 [2632]	931 [3175]	1141 [3644]	1313 [4218]	1444 [4658]
9.0 [30.0]	1200 [4000]		1200 [4000]	1286 [4000]	1522 [4726]	1675 [5264]	1783 [5651]
10.5 [35.0]	1200 [4000]		1286 [4000]	1675 [4981]	1862 [5697]	1973 [6139]	2046 [6439]
12.0 [40.0]	1200 [4000]	12.0 [42.0]	2400 [5942]	2400 [6819]	2400 [7172]	2400 [7362]	2400 [7482]
13.5 [45.0]	2400 [8000]		2400 [8000]	2400 [8000]	2400 [8000]	2400 [8000]	2400 [8000]
		14.0 [46.0]					
15.0 [50.0]	1800 [6000]		1855 [6000]	2092 [6801]	2186 [7158]	2236 [7527]	2290 [7782]
16.5 [55.0]	1800 [6000]		2022 [7355]	2312 [8095]	2428 [8376]	2491 [8524]	2530 [8615]
		17.4 [57.0]					
18.0 [60.0]	2700 [9000]		2700 [9000]	2700 [9000]	2700 [9000]	2700 [9000]	2700 [9000]

[A] All velocities are expressed in m/s [ft/s].

NOTE 4—*Example Calculation*—Consider the hypothetical case illustrated in Fig. 6. A seismic source and receivers are located at an assumed depth in a medium having a P wave velocity of 1100 m/s [3500 ft/s]. The receiver holes are spaced at distances of 0 and 6.0 m [0 and 20 ft] respectively, from the source hole. A zone of 3000 m/s [10 000 ft/s] velocity is assumed to be encountered at a depth 1.5 m [5 ft] below the source and receivers (Computations are given in Table 3). Example 1, in Appendix X1. and Appendix X2., is a case where the seismic source is located at a 3.0 m [10 ft] distance from the geophone. When Snell's law is applied, the shortest travel time results when the wave front travels through the 1100 m/s [3500 ft/s] velocity zone. Example 2 of Appendix X3 and Appendix X4. is a case where the seismic source is located 6.0 m [20 ft] from the geophone. In this example, the application of Snell's law shows that the shortest travel time would be along a path influenced by the 3000 m/s [10 000 ft/s] velocity zone. Example 2, a case involving the same velocity profile and a 6.0 m [20 ft] spacing, shows a case where analysis reveals that the measured travel time is not an arrival via a straight-line path and that the apparent velocity is not a true velocity.

5.5 *Comparisons With Other Data*—After the reduction and interpretation of the crosshole data, the results must be analyzed in conjunction with other data, including surface refraction and available boring data, and a velocity zone profile descriptive of subsurface conditions made.

TABLE 2 Results and Interpretation of Data from Crosshole Computer Program

Crosshole Data—S-wave, no name dam, downstream slope (horizontal distance between holes is 10.0)

Depth		Direct Path Distance	Time Increment	Apparent Velocity	Rec_1		Rec_2	
Rec_1	Rec_2				X-Dev	Y-Dev	X-Dev	Y-Dev
Crosshole Data								
5.0	5.0	10.0	0.0110	908	−0.07	−0.03	−0.06	−0.07
10.0	10.0	10.0	0.0095	1051	−0.14	−0.07	−0.11	−0.14
15.0	15.0	10.0	0.0100	998	−0.14	−0.07	−0.11	−0.14
20.0	20.0	10.0	0.0098	1024	−0.14	−0.07	−0.11	−0.14
25.0	25.0	10.0	0.0088	1141	−0.16	−0.09	−0.13	−0.16
30.0	30.0	10.0	0.0085	1175	−0.18	−0.11	−0.14	−0.18
35.0	35.0	10.0	0.0090	1109	−0.11	−0.07	−0.08	−0.14
40.0	40.0	10.0	0.0085	1175	−0.04	−0.03	−0.01	−0.10
45.0	45.0	10.0	0.0085	1175	0.05	−0.00	0.09	−0.07
50.0	50.0	10.0	0.0075	1331	0.15	0.02	0.18	−0.05

Computed Travel Times, s

Rec_1 Depth	Rec_2 Depth	True Velocity Average	Interface Depth	Direct	Down 1 Layer	Down 2 Layer	Down 3 Layer	Up 1 Layer	Minimum Time	Apparent Velocities	
										Computed	Measured
Crosshole Interpretation—S-wave, no name dam, downstream slope											
5.0	5.0	908		0.0120	0.0110		0.0230		0.0110	908	908
		1051	6.3								
10.0	10.0			0.0095		0.0185	0.0442		0.0095	1051	1051
			14.2								
15.0	15.0	998		0.0100	0.0146	0.0382		0.0100	0.0100	998	998
20.0	20.0	998		0.0100	0.0097	0.0316		0.0131	0.0097	1024	1024
			21.0								
25.0	25.0	1142		0.0087	0.0266				0.0087	1142	1141
30.0	30.0	1142		0.0087	0.0221				0.0087	1142	1175
35.0	35.0	1142		0.0087	0.0176				0.0087	1142	1109
40.0	40.0	1142		0.0087	0.0131				0.0087	1142	1175
45.0	45.0	1142		0.0087	0.0086				0.0086	1158	1175
50.0	50.0	1331	46.2	0.0075					0.0075	1331	1331

Crosshole Diagnostic—S-wave, no name dam, downstream slope

Caution—The interface calculated to be at 6.3 could be anywhere between 6.3 and 10.0	Execution Check	Layer 1	Depth 1	Down 1
Caution—The interface calculated to be at 14.2 could be anywhere between 10.0 and 14.2.	Execution Check	Layer 2	Depth 2	Down 1
Caution—At geophone depth 20.0, the 1024 could be a true velocity.	Execution Check	Layer 3	Depth 3	Down 1
Caution—The interface calculated to be at 25.6 could be anywhere between 25.6 and 30.0.	Execution Check	Layer 4	Depth 5	Down 1
Caution—The interface calculated to be at 34.2 could be anywhere between 30.0 and 34.2.	Execution Check	Layer 5	Depth 6	Up 1
Caution—At geophone depth 40.0, the 1175 could be a true velocity.	Execution Check	Layer 6	Depth 7	Down 1
Caution—The interface calculated to be at 46.2 could be anywhere between 46.2 and 50.0.	Execution Check	Layer 7	Depth 9	Down 1

6. Precision and Bias

~~6.1 The variability~~

6.1 *Precision*— Test data on precision is not prresented due to the nature of the soil and ~~resultant inability to determine a true reference value prevent development of a meaningful statement of bias. Data are~~ rock materials being ~~evaluated to determine the precision of~~ tested by this test method. It is not feasible, and~~d~~ too costly at this time to have ten or more agencies participate in an in situ testing program at a given site. Also, it is not feasible and too costly to produce multiple test locations having uniform properties. Any variation observed in the ~~subcommittee~~ data is just as likely to be due to specimen variation as operator or laboratory testing variation.

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

7. Keywords

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

APPENDIXES

(Nonmandatory Information)

X1. Example 1 of the Application of Snell's Law in SI Units

X1.1 Assume seismic source and receiver 3.0 m apart in velocity layer and above a 3000 m/s velocity layer:

X1.1.1 The critical angle of refraction is:

$$I = \arcsin\left(\frac{V_1}{V_2}\right) = \frac{1100\text{ m/s}}{300\text{ m/s}} = 21.5° \tag{X1.1}$$

X1.1.2 Hypotenuse distances:

$$\bar{R}_1 = (1.5\text{ m}/\cos 21.5°) = 1.61\text{ m} \tag{X1.2}$$

$$\bar{R}_2 = (1.5\text{ m}/\cos 21.5°) = 1.61\text{ m}$$

X1.1.3 Abscissa distances:

$$Y_1 = 1.5\tan(21.5°) = 0.59\text{ m} \tag{X1.3}$$

$$Y_2 = 1.5\tan(21.5°) = 0.59\text{ m}$$

X1.2 Assume possible travel path through both 1100 m/s and 3000 m/s materials:

X1.2.1 Travel time in 1100 m/s material:

$$t_1 = 2(1.61)/1100 = 0.003\text{ s} \tag{X1.4}$$

X1.2.2 Travel time in 3000 m/s material:

$$t_2 = (3 - 2(0.59))/3000 = 0.00061\text{ s} \tag{X1.5}$$

X1.2.3 Total travel time:

$$(t_1 + t_2) = 0.00361\text{ s} \tag{X1.6}$$

X1.3 Assume possible travel path through 1100 m/s material only using straight line distance method:

X1.3.1 Then travel time:

$$1.5\text{ m (at 1100 m/s)} = 3.0/1100 = 0.0027\text{ s} \tag{X1.7}$$

X1.3.2 Actual measured time = 0.0027 s.

X1.3.3 Since travel time by direct path is equal to measured time and less than possible refracted path travel time, it is concluded that the velocity is true and indicative of a path through the lower velocity layer only.

X2. Example 1 of the Application of Snell's Law in Inch-Pound Units

X2.1 Assume seismic source and receiver 10 ft apart in 3500 ft/s velocity and 5 ft above a 10 000 ft/s velocity layer:

X2.1.1 The critical angle of refraction is:

$$I = \arcsin\frac{V_1}{V_2} = \frac{3500\text{ ft/s}}{10\ 000\text{ ft/s}} = 20.5° \tag{X2.1}$$

X2.1.2 Hypotenuse distances are:

$$\bar{R}_1 = (5\text{ ft}/\cos 20.5°) = 5.34\text{ ft} \tag{X2.2}$$

$$\bar{R}_2 = (5\text{ ft}/\cos 20.5°) = 5.34\text{ ft}$$

X2.1.3 Abscissa distances are:

$$Y_1 = 5\tan 20.5° = 1.87\text{ ft} \tag{X2.3}$$

$$Y_2 = 5\tan 20.5° = 1.87\text{ ft}$$

X2.2 Assume possible travel path through both 3500 ft/s and 10 000 ft/s materials:

X2.2.1 Travel time in 3500 ft/s material:

$$t_{3500} = (2(5.34)/3500) = 0.003\ s \tag{X2.4}$$

X2.2.2 Travel time in 10 000 ft/s material:

$$t_{10\ 000} = (10 - (2 \times 1.87)/10\ 000) = 0.00063\ \mathrm{s} \tag{X2.5}$$

X2.2.3 Total travel time, $(t_{3500} + t_{10\ 000}) \approx 0.00363$ s

X2.3 Assume possible travel path through 3500 ft/s material only using straight-line distance method:

X2.3.1 Travel time, $5_{3500} = \frac{10}{3500} = 0.0029$ s.

X2.3.2 Actual measured travel time = 0.0029 s

X2.3.3 Since travel time by direct path is equal to measured time and less than possible refracted path travel time, it is concluded that the velocity is true and indicative of a path through the lower velocity layer only.

X3. Example 2 of the Application of Snell's Law in SI Units

X3.1 Assume seismic source and receiver geophone 6 m apart in 1100 m/s velocity layer and 1.5 m above a 3000 m/s velocity layer:

X3.1.1 The critical angle of refraction is:

$$I = \arcsin \frac{V_1}{V_2} = 1100\ \mathrm{m/s}/3000\ \mathrm{m/s} = 21.5° \tag{X3.1}$$

X3.1.2 Hypotenuse distances:

$$\bar{R}_1 = 1.5/\cos (21.5°) = 1.61\ \mathrm{m} \tag{X3.2}$$
$$\bar{R}_2 = 1.5/\cos (21.5°) = 1.61\ \mathrm{m}$$

X3.1.3 Abscissa distances:

$$Y_1 = 1.5 \tan (21.5°) = 0.59\ \mathrm{m} \tag{X3.3}$$
$$Y_3 = 1.5 \tan (21.5°) = 0.59\ \mathrm{m}$$

X3.2 Assume possible travel path through both 1100 m/s and 3000 m/s materials:

X3.2.1 Travel time in 1100 m/s material:

$$t_1 = 2(1.61)/1100 = 0.003\ \mathrm{s} \tag{X3.4}$$

X3.2.2 Travel time in 3000 m/s material:

$$t_2 = (6 - (2 \times 0.59))/3000 = 0.00161\ \mathrm{s} \tag{X3.5}$$

X3.2.3 Total travel time:

$$(t_1 + t_2) = 0.003 + 0.00161 = 0.00461\ \mathrm{s} \tag{X3.6}$$

X3.3 Assume possible travel path through 1100 m/s material only using straight line distance method:

X3.3.1 Then travel time:

$$t_1 = 6/1100 = 0.0055\ \mathrm{s} \tag{X3.7}$$

X3.3.2 Actual measured travel time = 0.0055 s.

X3.3.3 Since travel time by the possible refracted path is equal to the measured time and less than the direct path travel time, it is concluded that the ray path was refracted. If the velocity had been computed from the straight line distance (6 m) divided by the measured time (0.0055), the value 1300 m/s would be apparent rather than true.

X4. Example 2 of the Application of Snell's Law in Inch-Pound Units

X4.1 Assume seismic source and receiver geophone 20 ft apart in 3500 ft/s velocity layer and 5 ft above a 10 000 ft/s velocity layer:

X4.1.1 The critical angle of refraction is:

$$I = \arcsin\frac{V_1}{V_2} = \frac{3500\text{ ft/s}}{10\ 000\text{ ft/s}} = 20.5° \tag{X4.1}$$

X4.1.2 Hypotenuse distances are:

$$\bar{R}_1 = (5\text{ ft}/\cos 20.5°) = 5.34\text{ ft} \tag{X4.2}$$

$$\bar{R}_2 = (5\text{ ft}/\cos 20.5°) = 5.34\text{ ft}$$

X4.1.3 Abscissa distances are:

$$Y_1 = 5\tan 20.5° = 1.87\text{ ft} \tag{X4.3}$$

$$Y_3 = 5\tan 20.5° = 1.87\text{ ft}$$

X4.2 Assume possible travel path through both 3500 ft/s and 10 000 ft/s materials:

X4.2.1 Travel time in 3500 ft/s material:

$$t_{3500} = (2(5.34)/3500) = 0.003\text{ s} \tag{X4.4}$$

X4.2.2 Travel time in 10 000 ft/s material:

$$t_{10\ 000} = (20 - (2 \times 1.87)/10\ 000) = 0.00163\text{ s} \tag{X4.5}$$

X4.2.3 Total travel time $(t_{3500} + t_{10\ 000}) = 0.003 + 0.00163 = 0.00463$ s.

X4.3 Assume possible travel path through 3500 ft/s material only using straight-line distance method:

X4.3.1 Travel time, $t_{3500} = 20/3500 = 0.0057$ s.

X4.3.2 Actual measured travel time = 0.0046 s

X4.3.3 Since travel time by the possible refracted path is equal to the measured time and less than the direct path travel time, it is concluded that the ray path was refracted. If the velocity had been computed from the straight-line distance (20 ft) divided by the measured time (0.0046), the value 4350 ft/s would be apparent rather than true.

REFERENCES

(**1**) Woods, Richard D.,“ Measurement of Dynamic Soil Properties,” *Proceedings of the ASCE Geotechnical Engineering Division Specialty Conference on Earthquake Engineering and Soil Dynamics*, ASCE, Vol I, 19–21 June 1978, pp. 91–178.

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

(**3**) Auld, B., “Cross-Hole and Down-Hole V_s by Mechanical Impulse,” *Geotechnical Engineering Division*, ASCE, Vol 103, GT12, December 1977, pp. 1381–1398.

(**4**) Department of the Army, Engineer Manual EM 1110-1-1802, “Geophysical Exploration,” May 1979, Washington, DC.

(**5**) Stokoe, K. H., II, and Hoar, R. J., “Variables Affecting In Situ Seismic Measurements,” *Proceedings of the ASCE Geotechnical Engineering Division Specialty Conference on Earthquake Engineering and Soil Dynamics* , ASCE, Vol II, 19–21 June 1978, pp. 919–939.

(**6**) Butler, Dwain K., and Curro, Joseph R., Jr., “Crosshole Seismic Testing—Procedures and Pitfalls,” *Geophysics*, Vol 46, No. 1, January 1981, pp. 23–29.

(**7**) Butler, Dwain K., Skoglund, George R., and Landers, Glenn B., “Crosshole: An Interpretive Computer Code for Crosshole Seismic Test Results, Documentation, and Examples,” Miscellaneous Paper No. S-78-8, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS July 1978.

SUMMARY OF CHANGES

Committee D18 has identified the location of selected changes to this stnadard since the last issue that may impact the use of this standard.

(1) Revised Precision and Bias statemetn to conform to D18 policy.
(2) Added Summary of Changes.

ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org).