P- and S-wave Down-Hole Surveys at the KGS BH1 Test Site in Lawrence, Kansas

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Abstract

Difficulties encountered in downhole shear wave surveys include the precise determination of shear wave travel times and determination of geophone orientation relative to the polarization direction of the seismic source. A PC program to pick S-wave travel times from downhole seismic survey data is developed and tested with the data obtained from a test site. Results show that the program is very useful to pick both S-wave and P-wave arrivals precisely, and the hodogram analysis provides information about the tool orientation. Once the geophone orientation is determined, the S-wave travel time can be picked on the seismic trace recorded by the geophone which is oriented parallel to the shot directions.

Introduction

A downhole seismic survey is commonly used to determine compressional (P) and shear (S) wave velocity profiles along depth. These velocity data are used to help assess the seismic response and determine elastic modulus and stratigraphy of a particular site (Kim and Jung, 1997).

Determination of travel times of P-waves is relatively easier than for S-waves, and can be achieved by commonly used first arrival picking software. Since S-waves travels slower than P-waves, P-waves often interfere with shear waves. This interference sometimes makes identification of the first shear wave arrival difficult. A general method to identify shear wave arrivals in the wave traces is to overlap two seismic traces of alternating strikes and find the beginning of a "bow-typed" shape, which results from the 180° phase difference between the two shots. In this study a PC software is developed which is written in MS Visual Basic and runs under Windows with a graphical user interface. It displays three channels of overlapping traces on the screen simultaneously and has the capability of picking P- and S-wave travel times precisely.

Determination of the borehole geophone orientation is a problem in S-wave downhole surveys. Geophone orientation can be determined either by hardware design or by the inversion of observations taken from the recorded seismic data (Michaels, 2001). In this study, geophone orientation is determined by observing a hodogram created by two horizontal component data traces enhanced by subtracting traces from opposing polarity records. Once the geophone orientation is determined, the S-wave travel time can be picked on the seismic traces recorded by the geophone oriented parallel to the shot direction.

The S-wave pick program was tested with the data obtained at the BH1 test site at the Kansas Geological Survey (KGS) in Lawrence, Kansas. P- and S-wave velocity profiles are obtained by a travel time tomography inversion.

Data Acquisition

A direct method was used for the P- and S-wave downhole surveys. In the direct method, three channels of data are recorded with a triaxial borehole geophone at a selected depth: vertical movements are recorded at channel 1, and horizontal movements are recorded at channels 2 and 3. P-waves are generated by striking a steel plate downward with a 12-lb sledge hammer as shown in Fig. 1. The plate has an offset of 2.0 m from the borehole.

Shear waves (SH-waves) are generated by hammer impacts on alternate ends of a specially designed wood plank, which is located at a distance of 2.0m from the borehole to minimize direct coupling of the seismic energy to the casing (Fig. 2).

Fig. 1 Generation of P-waves with vertical hammer impact.

Fig. 2 Generation of S-waves with horizontal hammer impact.

Downhole data have been collected every 1.5 m for the first 45 m, moving a geophone downward, and then data have been collected every 3.0 m until the geophone reached a depth of 75 m. In order to obtain two opposing polarity records at a depth, a first shot has been given toward 315° (NW direction) and a second shot has been given toward 135° (SE direction) in azimuth. The sampling interval was set at 0.125 msec and all the analog filters were open during recording.

Data Processing

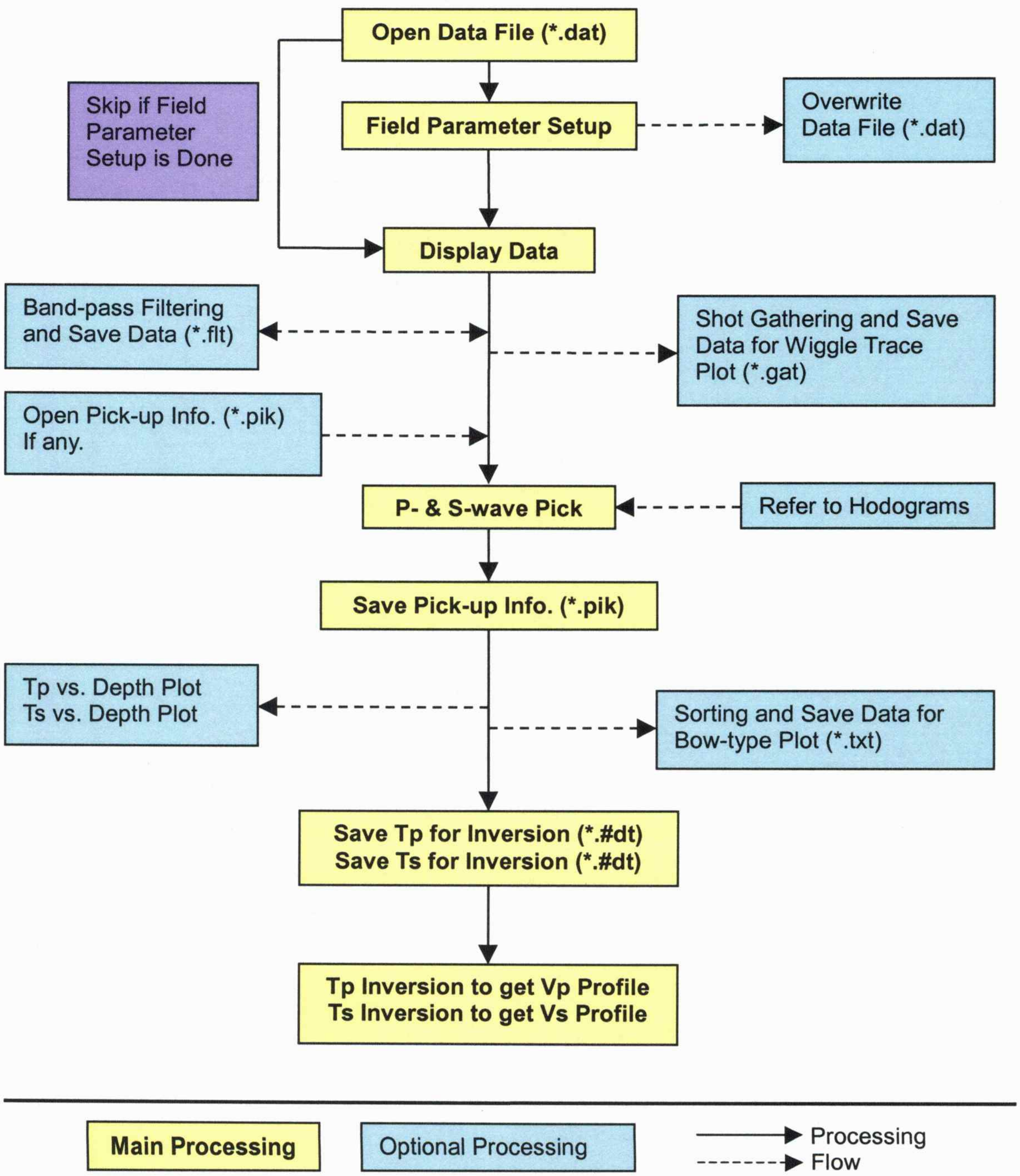


Fig. 3 A flowchart for downhole data processing.

Fig. 3 shows the data processing flowchart of downhole data obtained by the direct method.

Once the field data were downloaded to the computer from the seismograph, it is necessary to extract P-wave data and S-wave data. This can be done using a data sorting routine. After extraction, some additional field parameters such as recording depth, offset of the source, survey direction, and shot directions must be added to the header of the seismic data. After setting all necessary field parameters, the downhole data are ready for P- and S-wave travel time picking.

Data Display

Fig. 4 shows the display of the traces recorded at 3 m of depth in the borehole as part of the P-wave downhole survey. The signal recorded by a vertically oriented geophone is shown at the top (Ch1). The middle and bottom traces are signals recorded by two horizontally oriented geophones (Ch2 and Ch3). The P-waves travel time can be determined from any of the three traces, but since the Ch1 trace records vertical movements, it is recommended that P-wave travel times be determined from the Ch1 trace. In this figure red arrows indicate arrivals of P-waves.

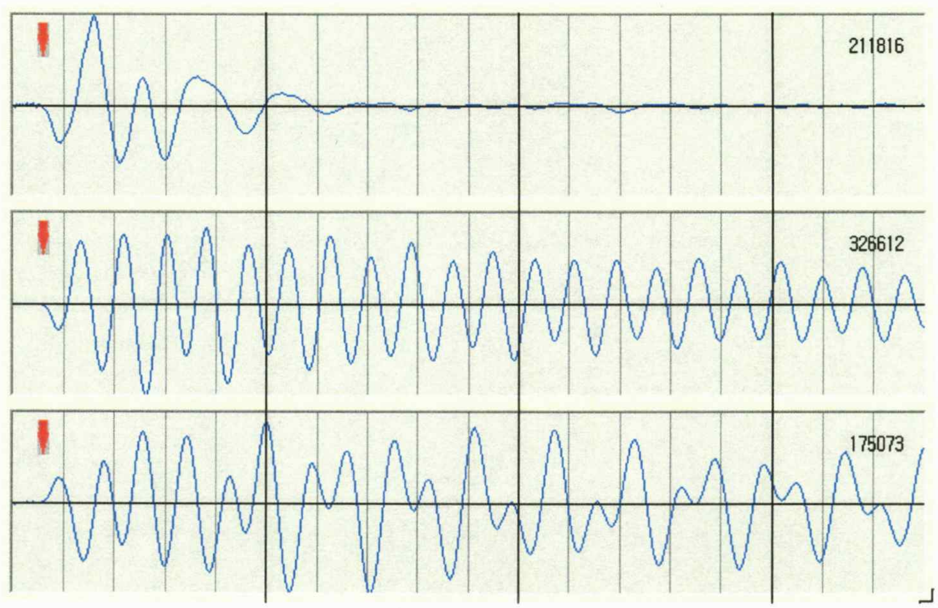


Fig. 4 An example of P-wave downhole data recorded at 3 m in the borehole.

Fig. 5 shows the traces recorded at 3 m of depth in the borehole as part of the S-wave downhole survey. Again, Ch1 (top trace) is from a vertically oriented geophone and Ch2 and Ch3 (middle and bottom traces) are from horizontally oriented geophones. The blue trace represents shot 1 and the red trace represents shot 2. Since there is 180° of phase difference between the two shots, this signal overlapping technique gives a "bow" shape, and is very useful to identify S-wave arrivals. The S-waves travel time can be determined from either the Ch2 or Ch3 traces. If the Ch3 geophone is oriented parallel to the strike direction, it is recommended that Ch3 be used to determine S-wave travel times. The orientation of the geophone can be determined by examining the hodogram, described later. In this figure the red arrows indicate arrivals of S-waves.

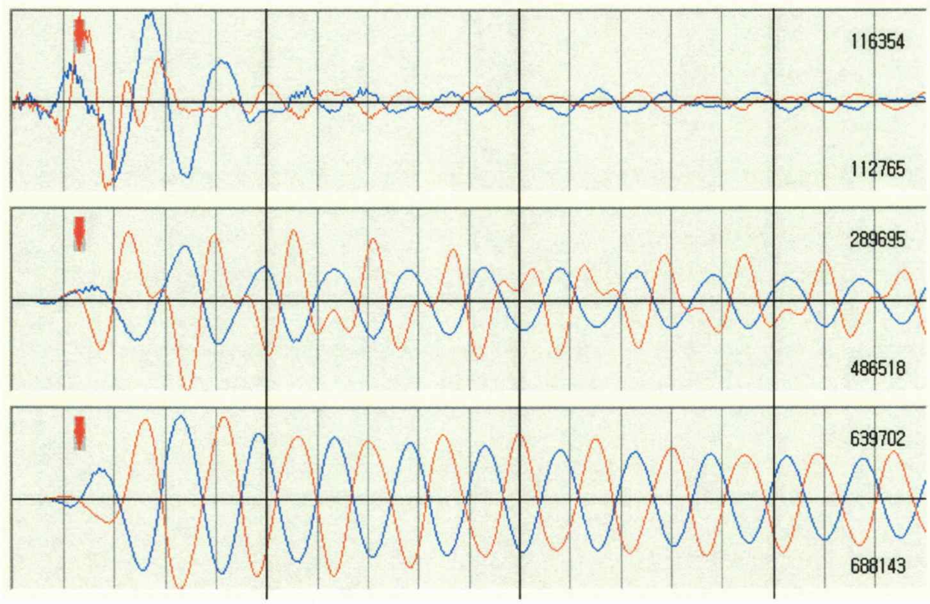


Fig. 5 An example of S-wave downhole data recorded at 3 m in the borehole.

P-wave Pick

Fig. 6 shows an example of P-wave arrival picking. The Ch1 trace from the P-wave downhole survey is displayed in the pick-up window. The onset time of 7.375 msec is picked as a first arrival. If the data are too noisy to pick arrivals, a digital filter can be applied to the data before picking. First arrival picking continues until every recording station is scanned.

Fig. 7 represents a collection of Ch1 data obtained from P-wave downhole survey. The field data are band-pass filtered (32-256 Hz). In this figure P-wave arrivals are connected by a solid red line, and the borehole, BH1, filled with water up to 12 m is shown on the left. The interval velocity of the layers can be determined by slope analysis of the red line or travel time inversion.

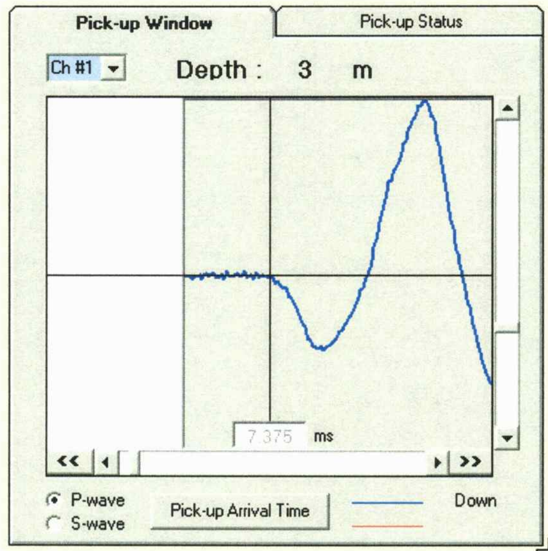


Fig. 6 An example of P-wave arrival picking.

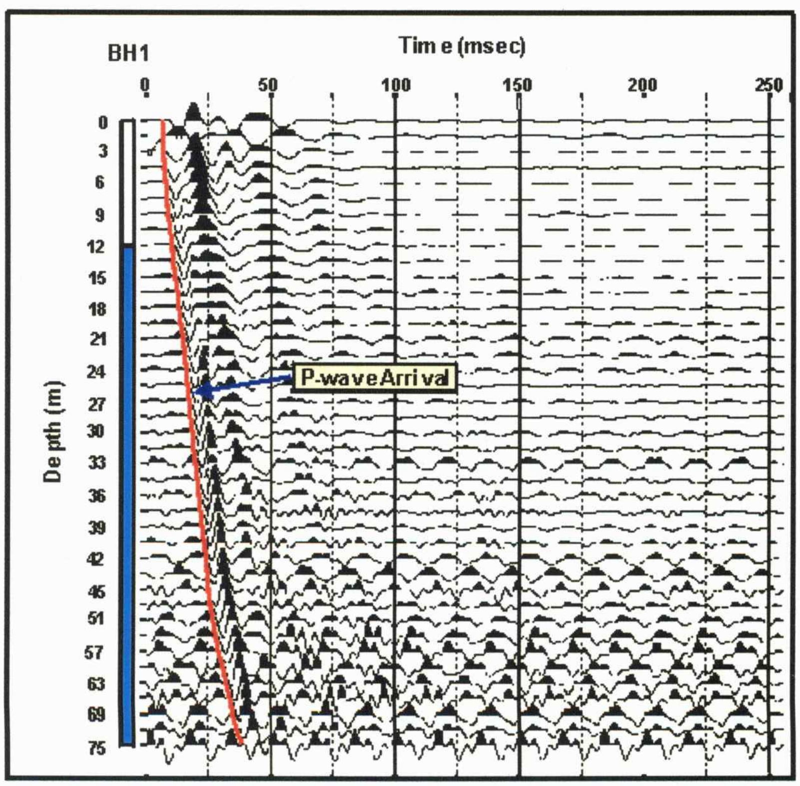


Fig. 7 A collection of Ch1 data obtained from a P-wave downhole survey.

S-wave Pick

Fig. 8 shows an example of S-wave arrival picking. The Ch3 trace from the S-wave down-hole survey is displayed in the pick-up window. The blue trace represents shot 1, striking a plank in the direction of 315° (NW). The red trace represents shot 2, striking a plank in the direction of 135° (SE). Hence, the two traces should show 180° of phase differences between them as shown in the figure. The onset time of 16.625 msec is picked as an S-wave arrival. S-wave arrival picking continues until every recording station is examined.

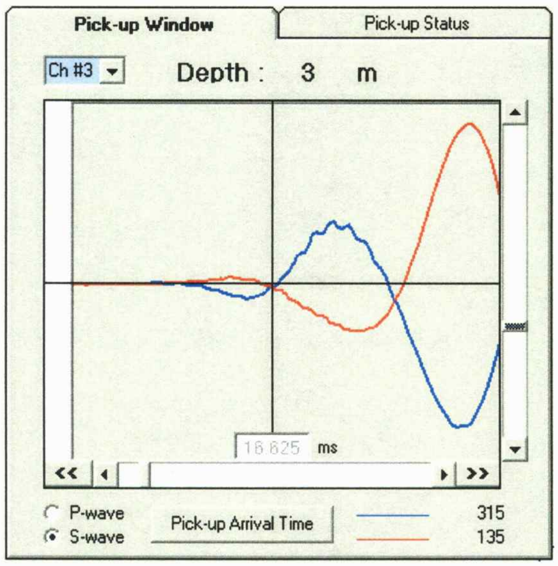


Fig. 8 An example of S-wave arrival picking.

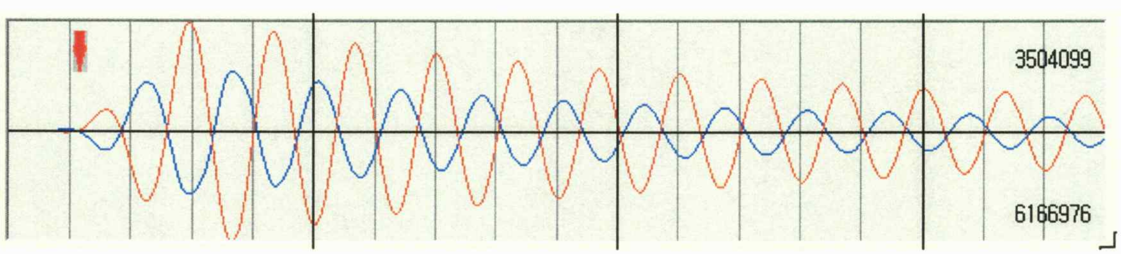


Fig. 9 A "bow-type" representation of the traces.

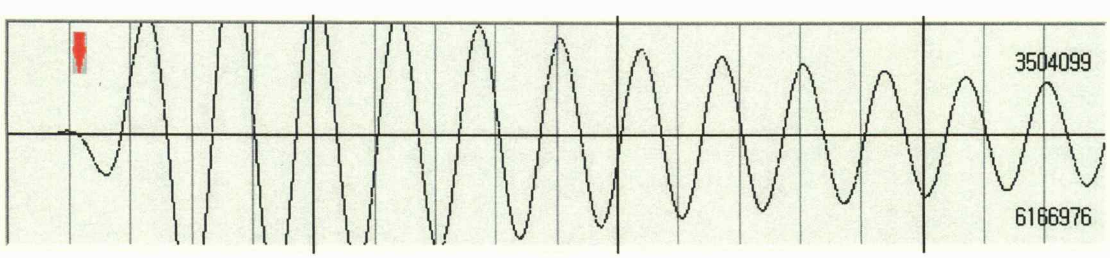
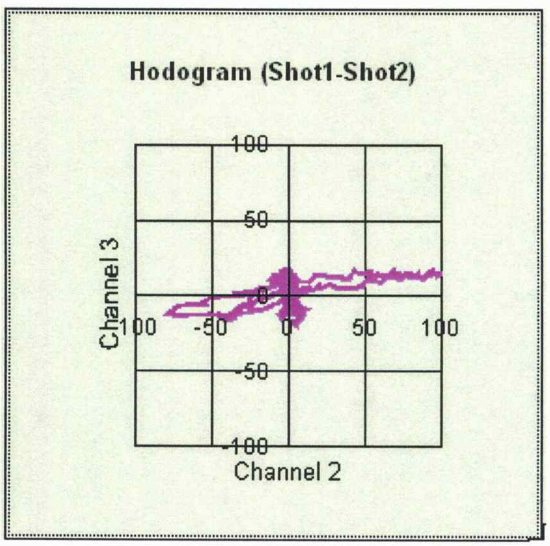


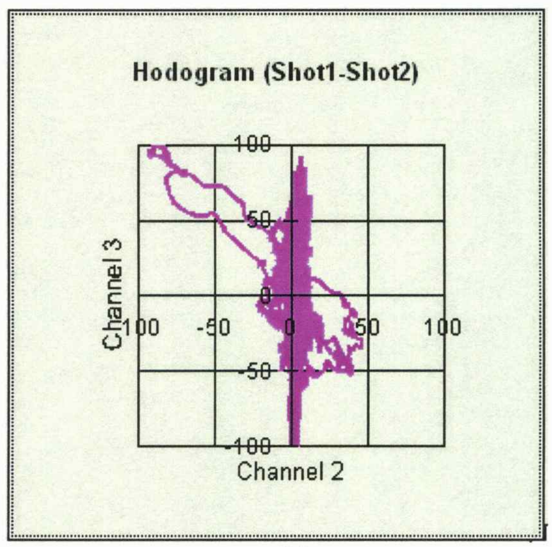
Fig. 10 Enhanced S-wave representation of the traces shown in Fig. 9.

Signal enhancement can be achieved by subtracting signals of shot 2 from those of shot 1 or vice versa. Fig. 9 illustrates the "bow-type" plot of two opposite direction shots, shot 1 in blue and shot 2 in red. Fig. 10 shows enhancement of S-wave signals obtained by subtracting the signal of shot 2 from that of shot 1. Since the signal subtracting should nullify background noise and the vertical component of energy in the traces, this signal enhancement technique would be very useful for picking S-wave arrivals, especially when the traces are noisy or when a lot of Rayleigh and P-wave energy is included in the S-wave traces.

A common problem in downhole S-wave surveying is the determination of the geophone orientation relative to the seismic source polarization direction. In order to figure out tool orientation, a hodogram of Ch 3 data vs. Ch 2 data are generated using the enhanced S-wave data. If the data are scattered along the Ch 2 axis, as shown in the Fig. 11(a), it indicates that the Ch 2 geophone is nearly parallel to the shot direction. In this case, the trace of Ch 2 might have the best potential to show 180° of phase difference between two alternating shots. The more accurate S-wave arrival picking should be made from the trace of Ch 2 rather than from the trace of Ch 3. If the data are scattered along the axis of Ch 3, as in the Fig. 11(b), it indicates that the Ch 3 geophone is nearly parallel to the shot direction. In this case the Ch 3 data should be used for picking S-wave arrival.



(a)



(b)

Fig. 11 Hodograms generated by enhanced S-wave data.
(a) Data scattered along the Ch2 axis, (b) Data scattered along the Ch3 axis.

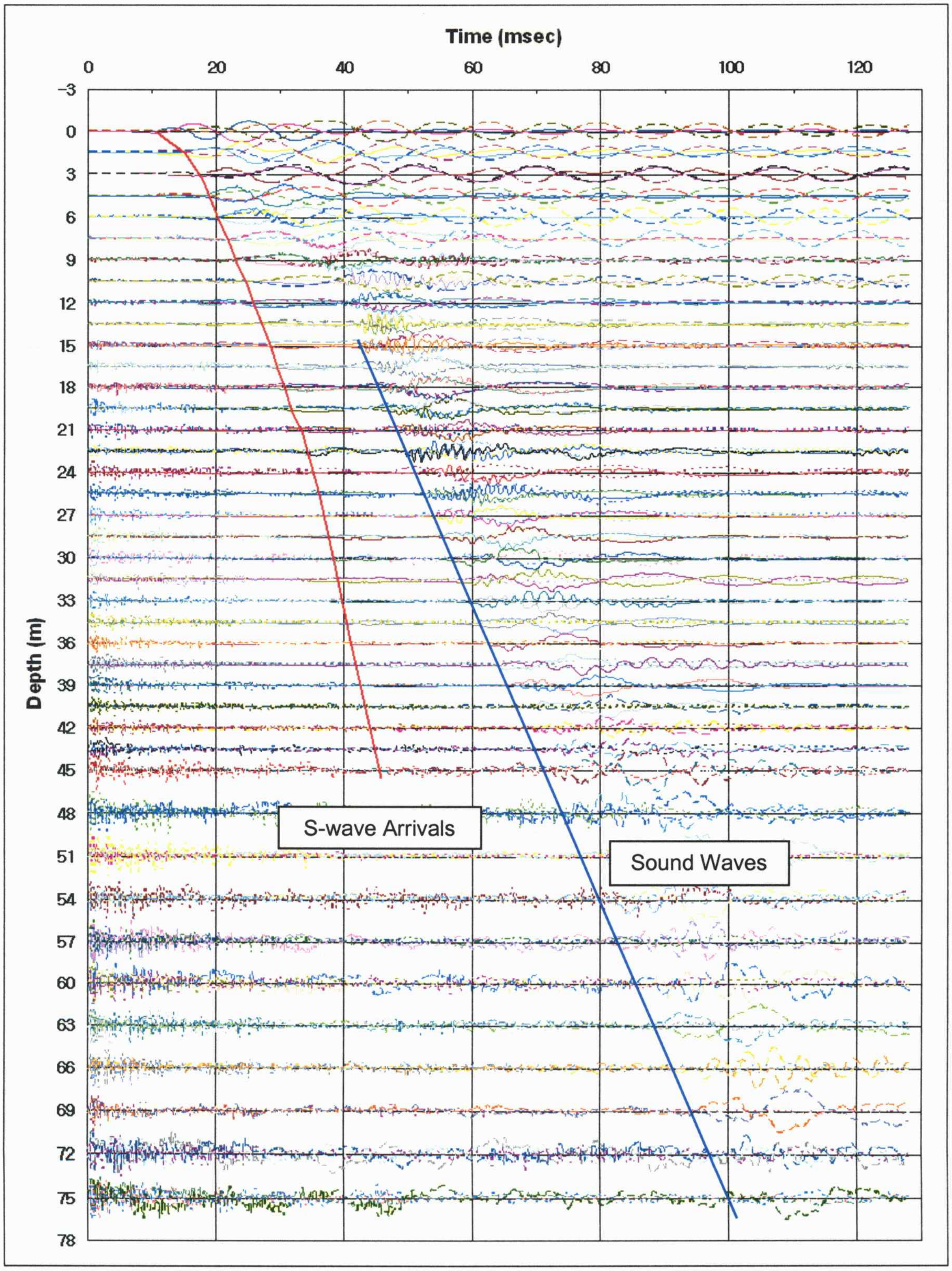


Fig. 12 A collection of Ch2 and Ch3 data obtained from a S-wave downhole survey.

The field data collected in the S-wave downhole survey have been sorted to display the entire Ch 2 and Ch 3 traces in a "bow" type plot. In Fig. 12, S-wave arrivals are connected by a solid red line. The signals beyond 45 m of depth are too noisy to pick S-wave arrivals. The estimated S-wave arrivals are drawn by blue dashed line. The interval velocity of the layers can be determined by slope analysis of the red line or travel time inversion. The high amplitude signals modulated by high frequency signals are followed by S-wave signals. Arrivals of those signals are connected by a solid black line. These signals are recognized as sound waves traveling inside the borehole. Characteristics of the sound waves are discussed later.

Travel Time Inversion

P-wave and S-wave travel times for different source-to-receiver pairs are saved for the travel time inversion. Generally, a travel time inversion provides more accurate velocity profiles than a slope analysis technique does, especially for the direct method. A travel time tomography inversion program has been used for the inversion process. In the inversion process a homogeneous medium is assumed as an initial model, and a rectangular grid system of 5 horizontal cells by 25 vertical cells has been used for P-wave travel time inversion, and 5 horizontal cells by 15 vertical cells has been used for S-wave travel time inversion. During the inversion process the S-wave velocities have been constrained so as not to yield a negative Poisson's ratio, and the process has been iterated until the relative RMS error becomes less than 5%.

Results

P-wave Profile

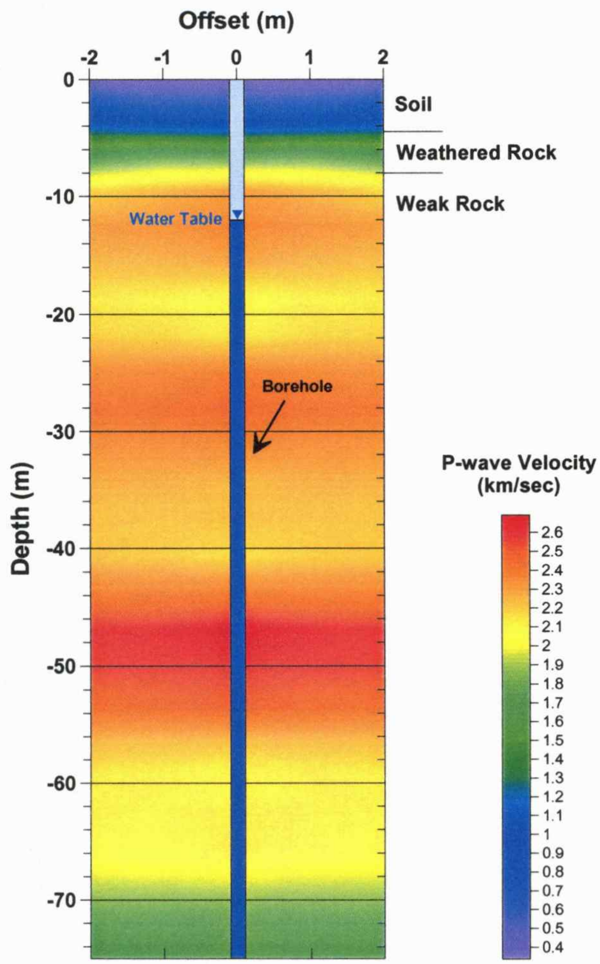


Fig. 13 A P-wave velocity image around the borehole.

Fig. 13 presents our P-wave travel time inversion results, showing a site that is covered with top soil and underlaid by weathered rock and weak rock. The top soil and weathered rock are about 5 m and 3 m thick, respectively. The weak rock is characterized by a series of layered structure. The P-wave velocity of the higher velocity zone in the weak rock ranges from 2.3 to 2.6 km/sec, whereas that of the lower velocity zone ranges from 2.0 to 2.3 km/sec. The velocity distribution beyond 68 m is unreliable, since insufficient data were available at that depth to use in the inversion process.

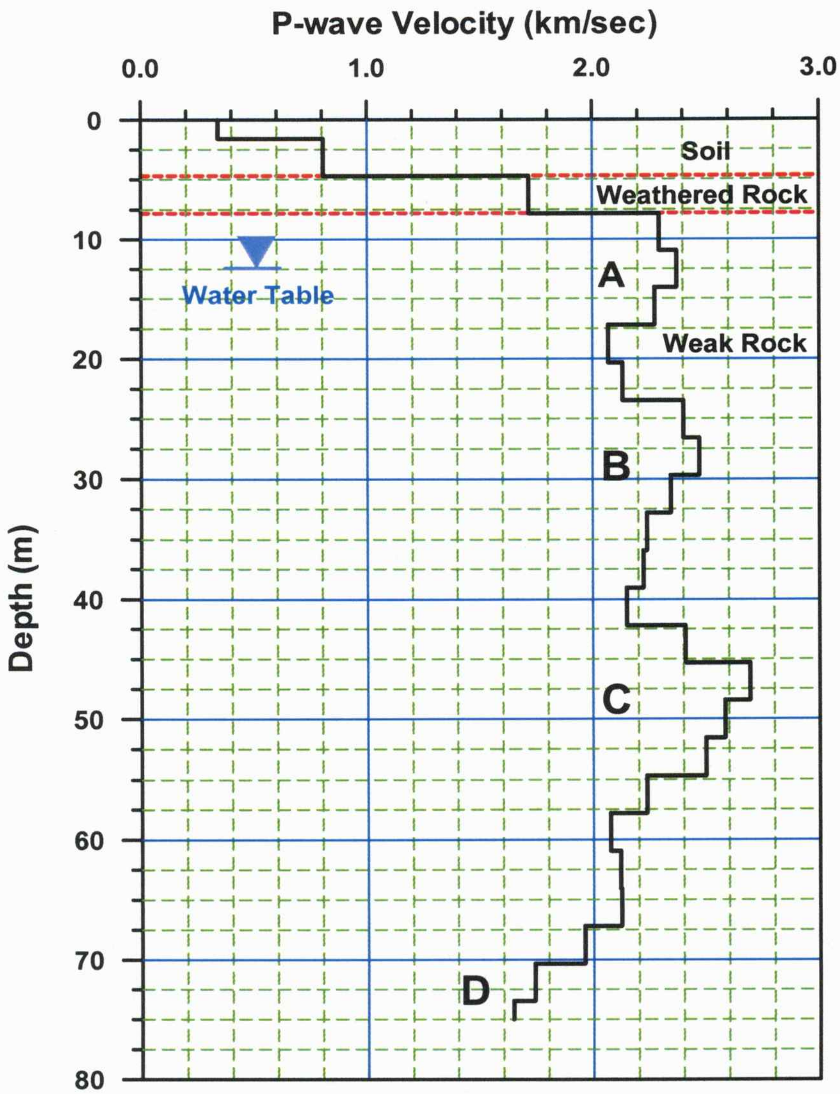


Fig. 14 A P-wave velocity profile at the test site.

Fig. 14 is a conventional representation of the P-wave velocity profile. The P-wave velocity of the soil layer ranges from 0.35 to 0.8 km/sec and the velocity of weathered rock is around 1.7 km/sec. There are three high velocity layers in the weak rock, denoted by A, B, and C, and the layer velocity increases slightly with depth. The low velocity layers are laid between high velocity layers, building a layered structure. The existence of a low velocity zone (indicated by D) may or may not be true, since insufficient data were available at that depth to use in the inversion process.

S-wave Profile

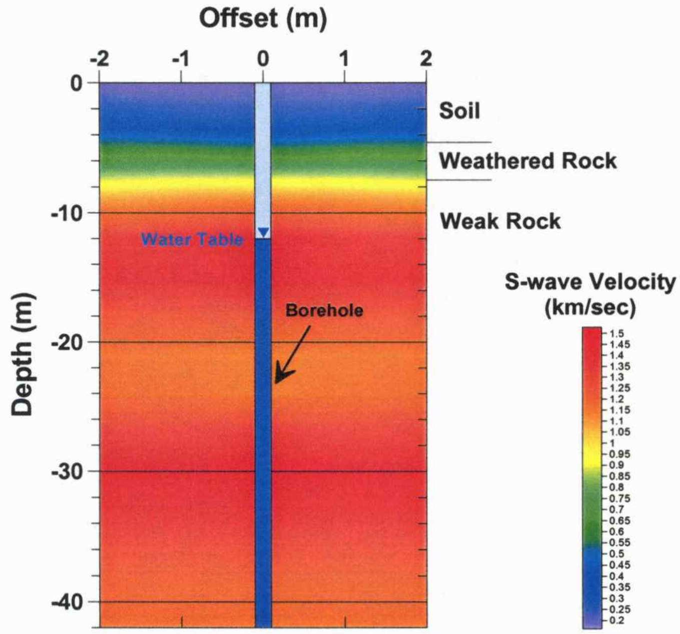


Fig. 15 An S-wave velocity image around the borehole.

Fig. 15 presents our S-wave travel time inversion results, showing that the site is covered with top soil and underlaid by weathered rock and weak rock. The stratigraphy shown in the figure is very similar to that shown in Fig. 13. The top soil and weathered rock are about 5 m and 3 m thick, respectively. The S-wave velocity of the soil ranges from 0.16 to 0.33 km/sec, and that of weathered rock is around 0.7 km/sec. This figure also shows that the weak rock consists of a layered structure. The S-wave velocity of the higher velocity zone in the weak rock ranges from 1.3 to 1.5 km/sec, whereas that of the lower velocity zone is around 1.1 km/sec. The travel time inversion beyond 40 m could not be made because the seismic energy is too weak to accurately pick S-wave arrivals.

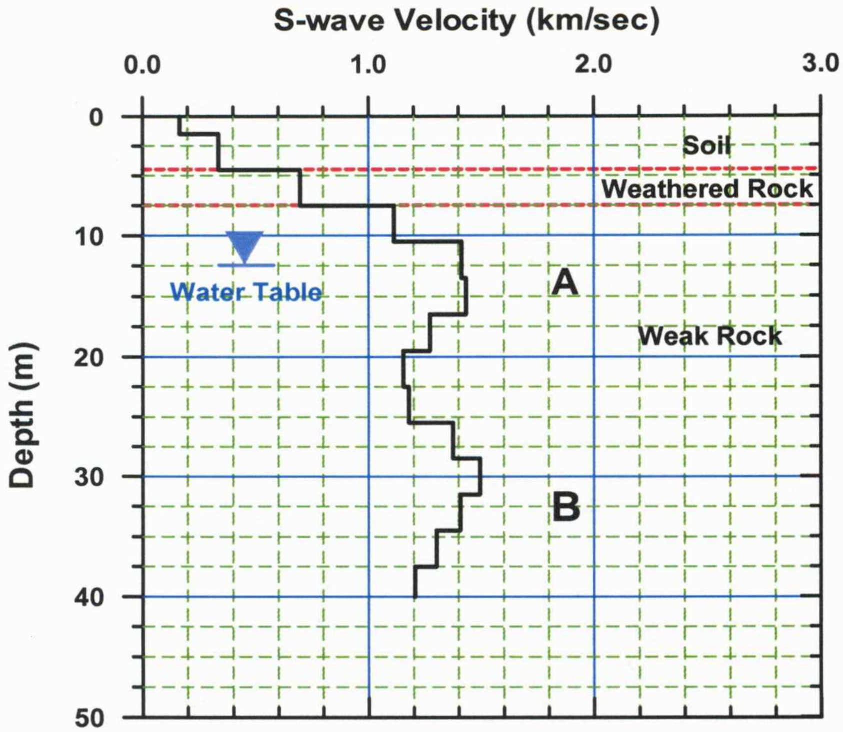


Fig. 16 An S-wave velocity profile at the test site.

Fig. 16 is a conventional representation of the S-wave velocity profile. The S-wave velocity of the soil layer ranges from 0.16 to 0.33 km/sec and the velocity of weathered rock is around 0.7 km/sec. There are two high velocity layers in the weak rock, denoted by A and B, and the layer velocity increases slightly with depth. The low velocity layers are laid between high velocity layers, yielding a layered structure. An unconstrained travel time inversion might have resulted in an erroneously high velocity distribution in zones A or B, yielding a negative Poisson's ratio in those zones. For this reason the S-wave velocities may need to be constrained so as to not yield a negative Poisson's ratio during the inversion process.

P- and S-wave Velocity Profiles

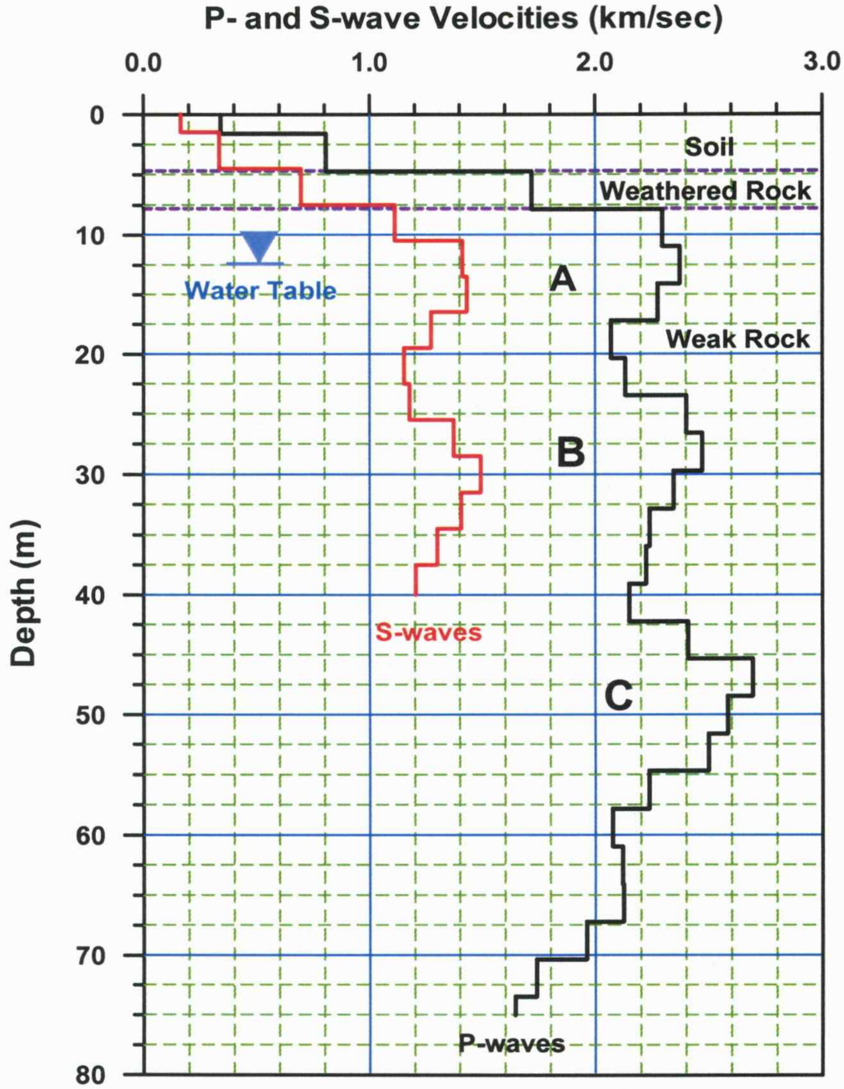


Fig. 17 P- and S-wave velocity profiles at the test site.

Fig. 17 shows P- and S-wave velocity profiles for our test site. The soil and weathered rock are overlaid by weak rock which consists of three high velocity zones (A, B, and C) and three low velocity zones, forming a layered structure. The existence of the water table appears not to affect P- or S-wave velocities of the weak rock.

Sound Waves Propagating Along the Borehole

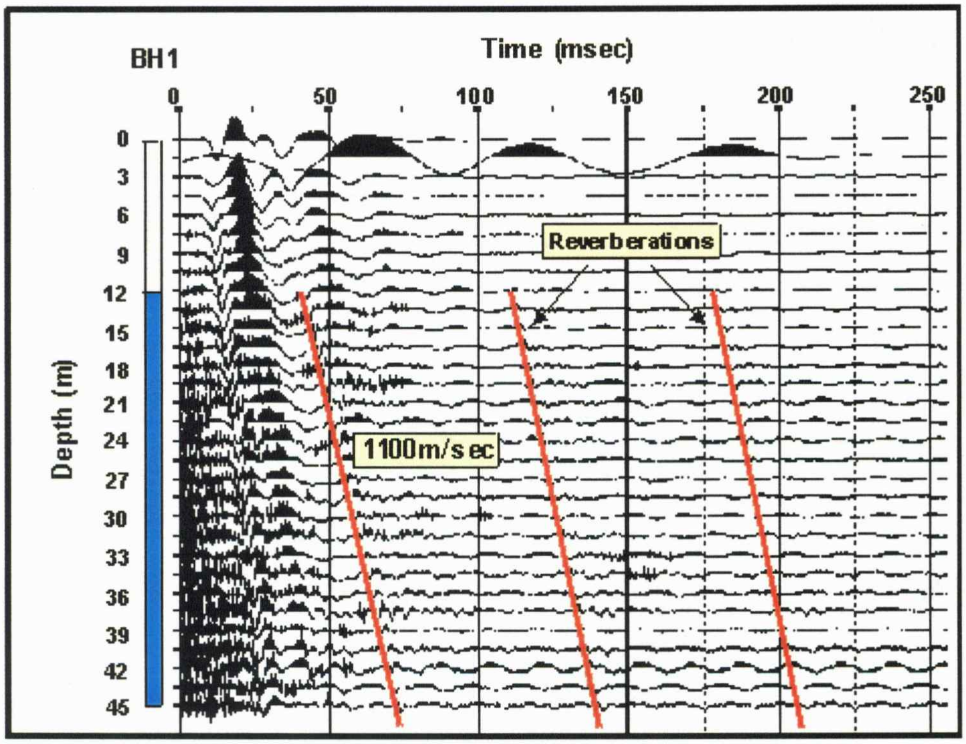


Fig. 18 Sound waves recorded in Ch1 for the P-wave survey.

Fig. 18 shows a seismic record obtained by the vertical geophone in the borehole. The source signal is generated by vertical hammer strikes with 2 m of offset from the borehole. The groundwater table is located at a depth of 12 m. From this depth coherent high frequency signals are recorded (marked by straight red lines). The velocity of these signals, obtained by slope analysis, is around 1,100 m/sec. These signals could be tube waves. The sound generated when the hammer strikes the plate travels along the borehole. When it enters the water in the borehole, it continues to travel along the borehole, and is guided by the borehole wall. The guided sound waves travel slower than the direct sound waves traveling along the water column in the borehole.

The first reverberations are also recorded around 70 msec after the first tube waves are recorded as shown by the second and the third red lines from the left in Fig. 18. If these reverberations are due to the wave being trapped between the ground surface and water table in the borehole, the time lag between reverberations might be calculated as

$$\text{Two-way distance / Sound velocity in the air} = 24(\text{m}) / 340(\text{m/sec}) = 70.6 \text{ msec}$$

The close similarity between calculated time lag and the one read on the figure shows that the reverberations are created by the ground surface and the water table.

At a depth of 12 m, the high-frequency wave arrives at 39.75 msec. The velocity of this wave by considering offsets of 2 m can be obtained as

Distance / Travel time = (12+2)(m) / 0.03975(sec) = 352 m/sec,

which is close to the sound velocity in the air. So the high frequency waves shown in the figure would be the sound wave generated by the hammer hitting the plate.

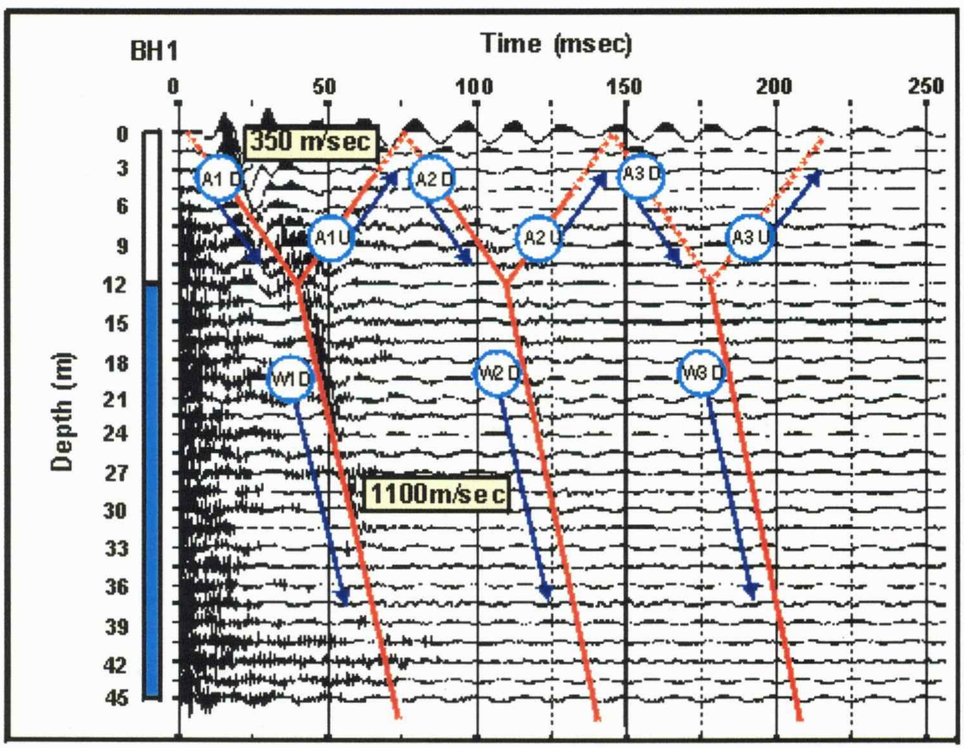


Fig. 19 Sound waves recorded in Ch1 for the S-wave survey.

Fig. 19 shows a seismic record obtained by the vertical geophone in the borehole. In this case the source signal is generated by horizontal hammer strikes with 2 m of offset from the borehole. Sound waves and reverberations propagating along the water column in the borehole are distinguishable, and are denoted by W1D, W2D, and W3D. The velocity of those down going waves is around 1,100m/sec. The field record also shows sound waves and reverberations traveling along the air column in the upper part of borehole. The estimated sound velocity in the air column is calculated by slope analysis to be around 350 m/sec.

When the sound waves hit the water surface in the borehole, some of this energy is reflected back to the ground surface, generating up-going waves such as A1U. This up-going wave is reflected again at the ground surface, generating down-going wave A2D. This down-going wave, A2D, makes reverberations such as W2D, W3D in the water column and A2U, A3D, A3U in the air column. The reverberations in the air column generates a "chevron-shaped" seismic event on the record, and the bottom of the chevron coincides with the depth of the water table.

Conclusions

A PC program to pick S-wave travel times from downhole seismic survey data is developed and tested with the data obtained from a test site at KGS. Some of the results show that the program is very useful to precisely pick both S-wave and P-wave arrivals, and the hodogram analysis provides information about the tool orientation. Once the geophone orientation is determined, the S-wave travel time can be picked on the seismic trace recorded by the geophone that is oriented parallel to the shot directions.

From this study we conclude that the test site is covered with soil and weathered rock. The thicknesses of soil and weathered rock are about 5 m and 3 m, respectively. A weak rock layer, consisting of alternating high and low velocity zones, is underlain by weathered rock.

The S-wave velocity of the soil ranges from 0.16 to 0.33 km/sec, and that of weathered rock is around 0.7 km/sec. The S-wave velocity of the weak rock ranges from 1.1 to 1.5 km/sec.

Since sound waves, guided waves, and their reverberations would be recorded in the downhole data, caution must be exercised to prevent incorrect picking of S-wave arrivals.

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