Processing of Downhole S-wave Seismic Survey Data by Considering Direction of Polarization

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ABSTRACT

Difficulties encountered in downhole S-wave (shear wave) surveys include the precise determination of shear wave travel times and determination of geophone orientation relative to the direction of polarization caused by the seismic source. In this study an S-wave enhancing and a principal component analysis method were adopted as a tool for determination of S-wave arrivals and the direction of polarization from downhole S-wave survey data. An S-wave enhancing method can almost double the amplitudes of S-waves, and the angle between direction of polarization and a geophone axis can be obtained by a principal component analysis. Once the angle is obtained data recorded by two horizontal geophones are transformed to principal axes, yielding so called scores. The scores gathered along depth are all in-phase, consequently, the accuracy of S-wave arrival picking could be remarkably improved. Applying this processing method to the field data reveals that the test site consists of a layered ground earth structure.

Key words: downhole seismic survey, S-wave, principal component analysis, polarization

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요 약: 하향식 시추공 횡파탐사의 어려움에는 횡파 주시를 정확하게 결정하는 문제와 입자의 분극 방향에 대한 지오폰의 상대적 방향을 결정하는 문제를 포함한다. 본 연구에서는 횡파 증진법과 주성분 분석법을 적용하여 횡파 주시와 입자의 분극 방향을 결정하였다. 횡파 증진법은 횡파의 진폭을 거의 두 배 가까이 키울 수 있었으며, 주성분 분석법을 통하여 입자의 분극 방향과 지오폰 방향과의 각도 차이를 알 수 있었다. 이렇게 구한 각도를 이용하여 지오폰에 수신된 기록을 주성분 방향에 투영하여 스코어를 산출하였다. 스코어를 이용하여 수집된 기록들은 모두 동일 위상을 갖게 되어 횡파주시 결정의 정확도를 크게 향상시킬 수 있었다. 이와 같은 자료처리 방법을 현장 자료에 적용시킨 결과 시험 현장이 층상구조를 갖고 있음을 밝힐 수 있었다.

주요어: 하향식 시추공 탄성파탐사, 횡파, 주성분 분석, 분극

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1. 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 (Chang *et al.*, 1999; Kim and Jung, 1997).

Determination of travel times of P-waves is relatively easier than that of 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 S-waves. This interference sometimes makes identification of the first S-wave arrival difficult. A conventional method to identify shear wave arrivals in the wave traces is to overlap two seismic traces of alternating strikes and find the beginning of "bow" type, which results from the 180° phase difference between the two shots.

Determination of the borehole geophone orientation is a problem in downhole S-wave surveys. Geophone orientation can be determined either by hardware design(Mok et al., 1988) or by the inversion of observations taken from the multi-component seismic data (Michaels, 2001). In this study, the direction of polarization relative to geophone orientation is determined by means of principal components analysis. For principal component analysis a hodogram is created by using two horizontal component seismic traces enhanced by subtracting each trace from an opposing polarity trace. Once the direction of polarization is determined, the S-wave travel time can be picked by observing onset time of the seismic traces transformed in the direction of polarization. In order to investigate in-line ground motion, a complex trace analysis method can be adopted to identify S-waves from seismic traces(Lee *et al.*, 2000).

This data processing method considering direction of polarization was tested with the data obtained at the BH1 test site in the Kansas Geological Survey, Kansas, and an S-wave velocity profile is obtained by a travel time tomography inversion.

2. Data Acquisition

A direct method was used for the downhole S-wave survey as shown in Fig. 1. 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 (Ch1), and horizontal movements are recorded at channels 2 (Ch2) and 3 (Ch3).

S-waves are generated by hammer impacts on both 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.

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

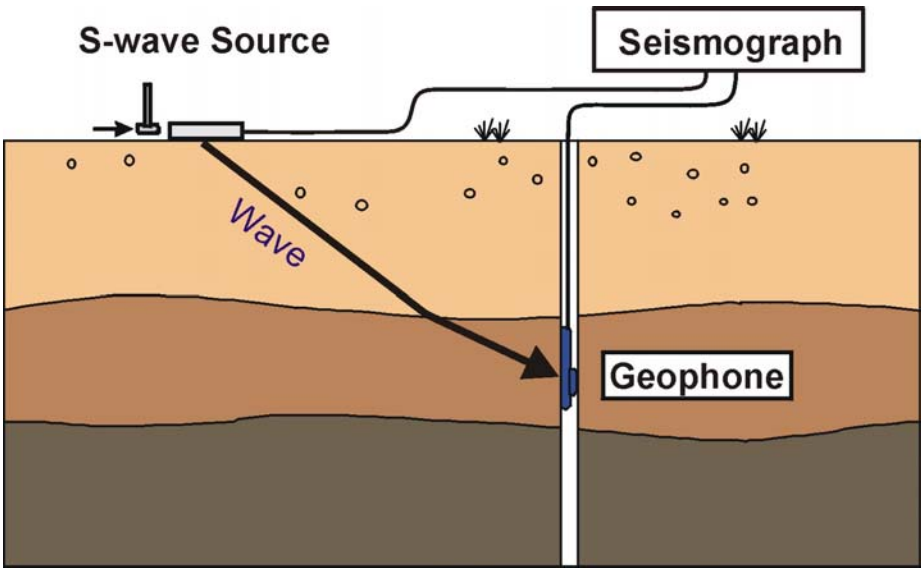

Fig. 1. A schematic diagram of downhole S-wave seismic survey (direct method).

the analog filters were open during recording.

3. Data Processing

Fig. 2 shows the data processing flowchart for downhole seismic data obtained by the direct method. Once the field data were downloaded to the computer from the seismograph, a series of preprocessing step including formatting and sorting is conducted. The preprocessing step also includes header editing, which adds some additional field parameters such as recording depth, offset of the source, survey direction, and shot directions to the header of the original seismic data. After setting all necessary field parameters, the downhole seismic data are ready for S-wave travel time picking.

3.1. Filtering and Overlapping

If the data contains ambient noises, it can be effectively removed with zero-phase band-pass filtering.

A conventional 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", which results from the 180° phase difference between the two shots. If Ch2 geophone is positioned parallel to the direction of polarization, or the angle between geophone axis and the direction of polarization is 0°, the "bow" might be symmetrical and has large amplitudes. In this case, Ch3 geophone axis is positioned perpendicular(90°) to the direction of polarization, so that the amplitudes of the "bow" might be small. If horizontal component geophones are rotated along the vertical axis, showing the angle between geophone axis and the direction of polarization is greater than 0° and less than 90°, the "bow" might be asymmetrical. In this case the S-wave travel time picking with overlapping method might be not easy, and may lead mis-picking.

3.2. S-wave enhancing

S-wave enhancement can be achieved as shown in Eq. (1) by subtracting a wave trace from a wave trace obtained by opposing shot direction.

$$y'_t = y_t^{\theta} - y_t^{\theta \pm \pi} \qquad (1)$$

where, y'_t is an S-wave enhanced wave trace, y_t^{θ} is a wave trace recorded when the angle between geophone axis and the direction of polarization is θ, and $y_t^{\theta \pm \pi}$ is a wave trace recorded with the opposing shot direction, which results in the angle between geophone axis and the direction of polarization would be $\theta \pm \pi$.

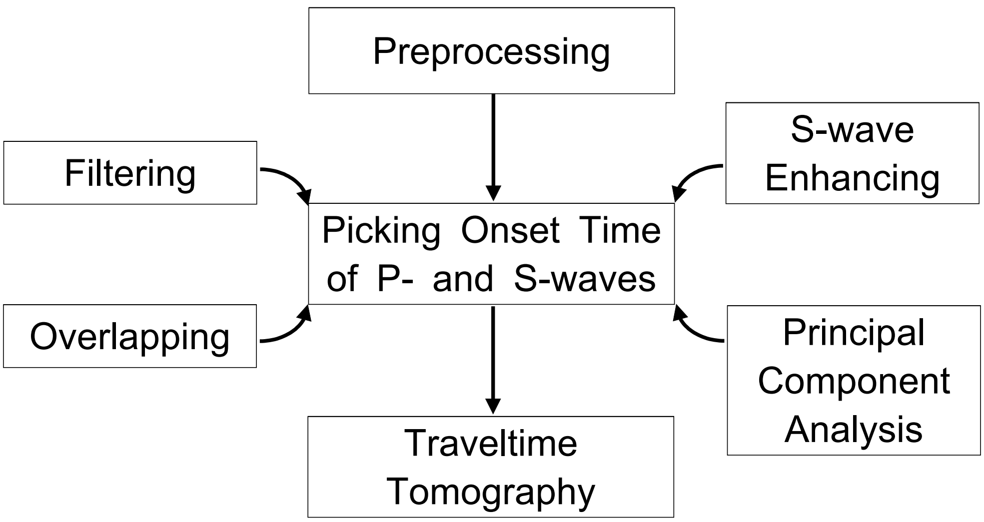

Fig. 2. A flowchart for downhole seismic data processing.

A standardization process is applied before subtraction by comparing vertical components of wave traces recorded at Ch1 geophone.

3.3. Principal Component Analysis

The particle motion of shear wave is polarized along the principal directions(Cheng and Cheng, 1998), and principal components are nothing more than the eigenvectors of a covariance matrix(Davis, 1973). If we make polarized shear wave signals, and obtain the hodogram plotted in Fig. 3 by using Ch2 and Ch3 measurements, we can find the principal direction from principal component analysis. Since we consider only horizontal movements, a 2×2 covariance matrix can be constructed, and from this we can extract 2 eigenvectors and 2 eigenvalues.

We define the mean value of N observations of variable $y(i)$ as

$$E(y)=\frac{1}{N}\sum_{i=1}^{N}y(i) \tag{2}$$

and covariance between two variables y_1 and y_2 as

$$Cov[y_1, y_2]=\frac{1}{N}\sum_{i=1}^{N}(y_1(i)-E(y_1))(y_2(i)-E(y_2)) \tag{3}$$

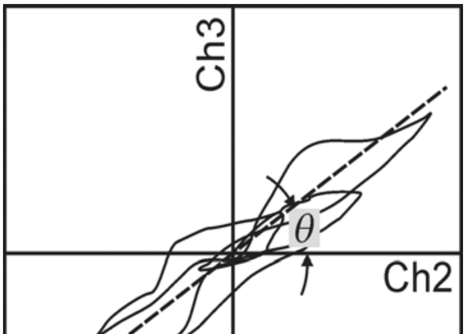

Fig. 3. A sample hodogram created by Ch2 and Ch3 data. The angle θ indicates the difference between the direction of polarization and Ch2 geophone axis.

For the two components of downhole S-wave data (y_{Ch2}, y_{Ch3}) recorded at Ch2 and Ch3 geophones, the covariance matrix C can be formed as

$$C=\begin{pmatrix} Cov[y_{Ch2}, y_{Ch2}] & Cov[y_{Ch2}, y_{Ch3}] \\ Cov[y_{Ch2}, y_{Ch3}] & Cov[y_{Ch3}, y_{Ch3}] \end{pmatrix} \tag{4}$$

If λ_1 and λ_2 are the eigenvalues of the covariance matrix C and $\lambda_1 \geq \lambda_2$, then the quantity

$$P=1-\frac{\lambda_2}{\lambda_1} \tag{5}$$

estimate the rectilinearity of the particle motion. When the rectilinearity is high $(\lambda_1 \gg \lambda_2)$ the particle motion is close to linear polarization. When the rectilinearity is low $(\lambda_1 \simeq \lambda_2)$ the particle motion is near circular.

The direction of polarization can be measured by considering the eigenvector associated with the largest eigenvalue. If we consider an eigenvector $[X]=(x_1, x_2)^T$, associated with the largest eigenvalue λ_1, the direction of polarization can be obtained as

$$\theta=\tan^{-1}\left(\frac{x_2}{x_1}\right) \tag{6}$$

Here, the direction of polarization θ can be considered as angle between Ch2 geophone axis and the shot direction, if the particle movements coincide with the shot direction. If Ch2 geophone is in-plane to the shot direction, θ will be zero, and if Ch3 geophone is in-plane of the shot direction, θ will be $\pi/2$, since Ch2 geophone and Ch3 geophone are oriented at right angle to each other.

Once the angle θ is obtained, each original wave trace is converted to what is called a *score* by projecting it on to the principal axes. This is done by

$$\begin{pmatrix} y_{Ch2}' \\ y_{Ch3}' \end{pmatrix}=\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} y_{Ch2} \\ y_{Ch3} \end{pmatrix} \tag{7}$$

which projects the wave traces onto the first and second principal axes, multiplying the observed values of y_{Ch2} and y_{Ch3} by the corresponding transform matrix.

In this study, S-wave enhanced wave traces described in the previous section (3.2) are used as original data.

4. Results

4.1. Filtering and Overlapping

Fig. 4 shows the Ch2 and Ch3 traces recorded at 3m of depth in the borehole as a part of the downhole S-wave survey. The alternating two shot records are overlapped to depict S-wave arrival as a conventional method. The S-waves travel time can be determined from either one of Ch2 or Ch3 record. Since the "bow" shown on the Ch3 record is near symmetrical, the Ch3 geophone might be closer to the direction of polarization than that of Ch2. In this circumstance, it is recommended that Ch3 would be used to determine S-wave travel times. The arrow shown in the figure indicates S-wave arrival as 16.625 *msec*. A zero-phase band-pass filter may be applied before picking in order to reduce noises.

4.2 S-wave Enhancing

Fig. 5 shows the S-wave enhanced Ch2 and Ch3 traces recorded at 3m of depth in the borehole obtained by equation (1). The alternating two shot records are subtracted one from another to help S-wave picking. The S-waves travel time can be determined from either one of Ch2 or Ch3 trace. Since the "bow" shown on the Ch3 record in Fig. 4 is near symmetrical,

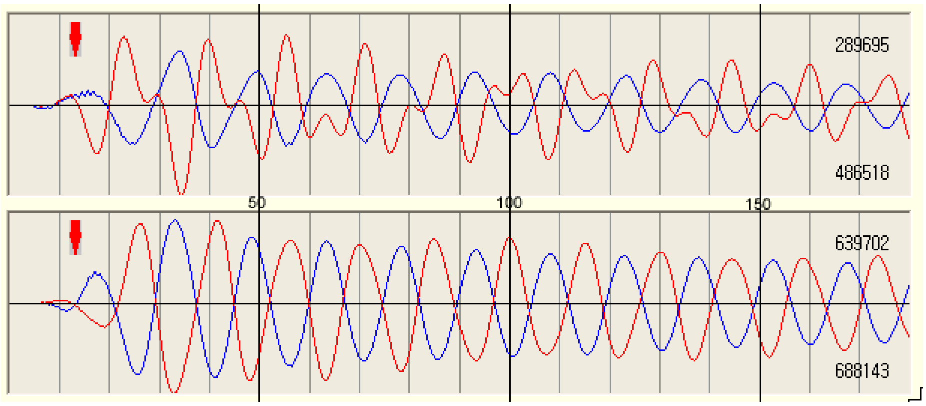

Fig. 4. An example of S-wave downhole data recorded by Ch2 (upper) and Ch3 (lower) geophones at 3 m in the borehole. The red arrows indicate onset time of the S-wave arrival.

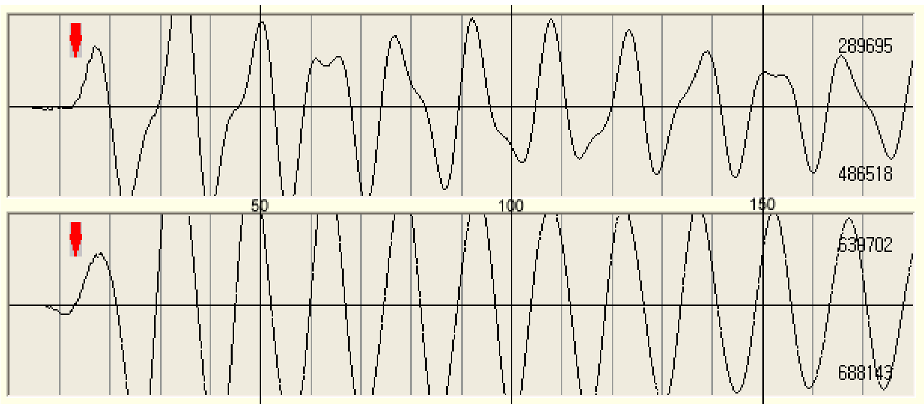

Fig. 5. An example of S-wave enhanced data of Ch2 (upper) and Ch3 (lower) records at 3 m depth. The red arrows indicate onset time of the S-wave arrival.

amplitude of the S-waved enhanced Ch3 record is almost doubled that of non-enhanced record. The arrow shown in the figure also indicates S-wave arrival as 16.625*msec*, which is the same as obtained from overlapping method. The S-wave enhancing sometimes provides high signal to noise ratio (SNR), so that the accuracy of S-wave picking could be improved.

4.3 Principal Component Analysis

Fig. 6 shows a hodogram created by S-wave enhanced Ch2 and Ch3 records as shown in Fig. 5. Since S-wave arrival is expected around 15~ 20 *msec*, data window from 12.5 *msec* to 50.0 *msec* is used to draw a hodogram. Selecting a beginning time and a width of data window is somewhat arbitrary, but the data window must include S-wave arrival time. The principal component analysis shows that the wave generated by S-wave source is well polarized, and the angle between principal axis and the Ch2 axis is 64°. This large angle indicates that the Ch3 geophone is closer to the direction of polarization than that of Ch2 as expected in 4.1.

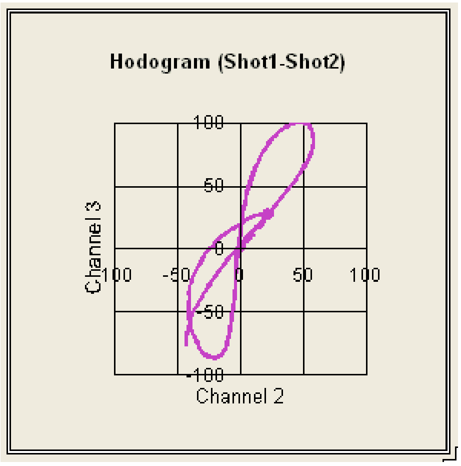

Fig. 6. A hodogram created by S-wave enhanced data of Ch2 and Ch3 records at 3 m depth.

Fig. 7 shows scores by projecting each record onto the principal axes using equation (7). The upper trace projects the Ch2 trace onto the first principal axis, and the lower trace projects the Ch3 trace onto the second principal axis. By transformation the amplitude of the trace on the first principal axis is maximized, whereas that on the second principal axis is minimized. The S-waves travel time can be determined from a trace of the first principal axis. The arrow shown in the figure also indicates that S-wave arrivals at 16.625 *msec*.

Fig. 8(a) shows a gather of Ch2 records along depth, and Fig. 8(b) shows a gather of records transformed onto the first principal axis. Some traces in Fig. 8(a) show out of phase compared to the adjacent traces, which may lead uncorrect S-wave arrival picking. On the other hand, all traces in Fig. 8(b) are in-phase, consequently, the accuracy of S-wave arrival picking could be remarkably improved. The dashed-lines in the figures indicate expected S-wave arrivals.

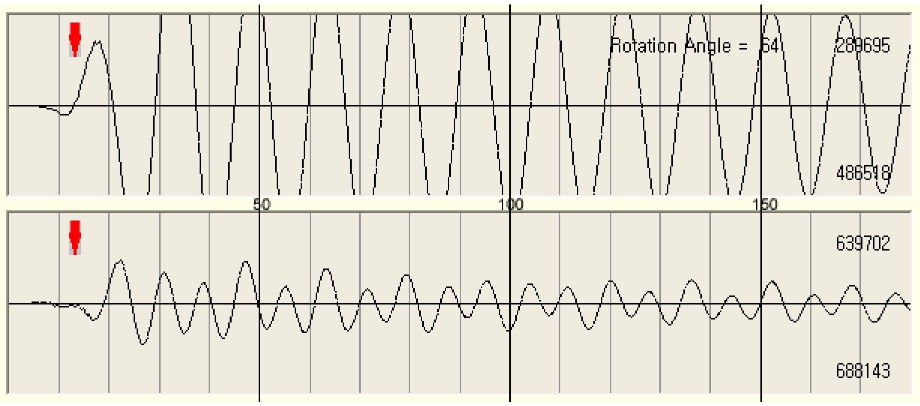

Fig. 7. S-wave enhanced data transformed onto the first principal axis (upper) and the second principal axis (lower).

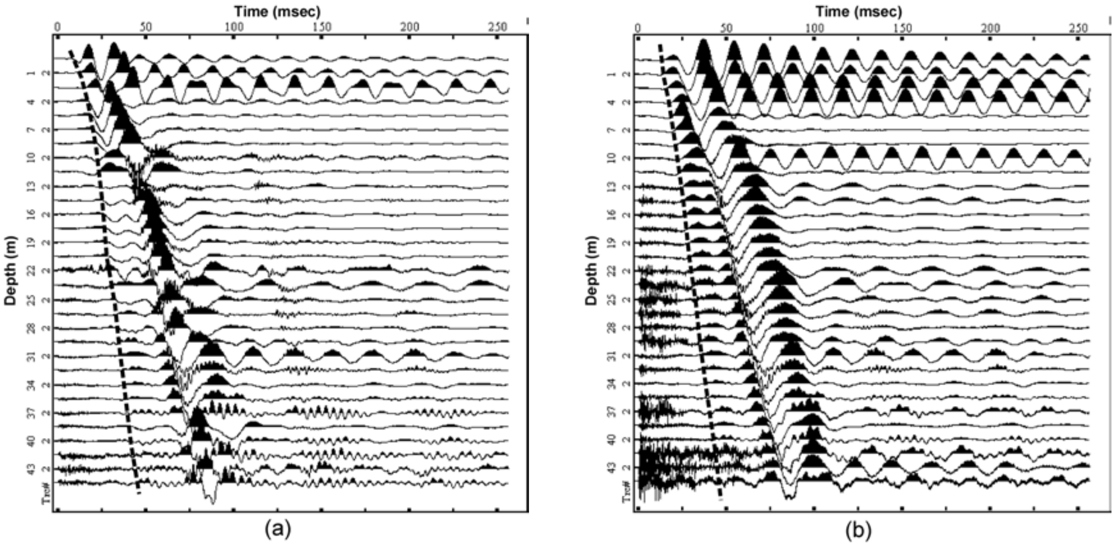

Fig. 8. (a) A gather of Ch2 records along depth, and (b) a gather of shot records transformed onto the first principal axis.

4.4 S-wave Velocity Profile

Fig. 9 represents an S-wave velocity profile obtained by travel time inversion, showing that the site is covered with top soil and underlain by weathered rock and weak rock. The top soil and weathered rock are about 5m and 3m thick, respectively. The S-wave velocity of the soil ranges from 0.16 to 0.33km/sec, and that of weathered rock is around 0.7km/sec. This figure also shows that there are weak rock layers from 8m, and the overall layer velocity increases slightly with depth. The S-wave velocity of the high velocity zones, denoted by A and B, in the weak rock ranges from 1.3 to 1.5 km/sec, whereas that of the low velocity zone is around 1.1km/sec. The low velocity zone is laid between high velocity layers, yielding a layered ground structure.

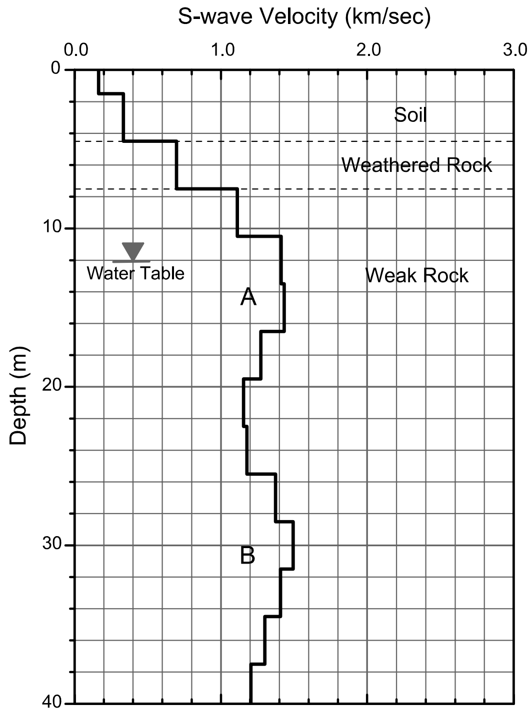

Fig. 9. An S-wave velocity profile obtained by travel time inversion, showing soil, weathered rock, and weak rock layers.

5. Conclusions

An S-wave enhancing and a principal component analysis technique were adopted in addition to the conventional overlapping method as a tool for determination of S-wave arrivals from downhole S-wave survey data. Since the S-waves generated on the ground for downhole survey are polarized with phase differences of 180°, an S-wave enhancing method almost doubles the amplitudes of S-waves, consequently, increases signal to noise ratios. When the direction of particle motion is not coincident with that of one of the horizontal geophones, the angle between direction of polarization and a geophone axis can be obtained by a principal component analysis. Once the angle is obtained data recorded by two horizontal geophones are transformed to principal axes, yielding so called scores. The scores gathered along depth are all in-phase, consequently, the accuracy of S-wave arrival picking could be remarkably improved.

These methods of picking S-wave arrivals for downhole survey were tested with the data obtained from a test site located in Kansas Geological Survey, which consists of layered ground structure. The travel time inversion results show that the test site is covered with soil and weathered rock. The thicknesses of soil and weathered rock are about 5m and 3m, 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 0.7km/sec. The S-wave velocity of the weak rock ranges from 1.1 to 1.5 km/sec.

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