Looking Forward of Tunnel Face by Use of Equi-traveltime Planes

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Abstract

Recently, the method called HSP (Horizontal Seismic Profiling) was used for the forward imaging of tunnel face. In HSP, the reconstruction of structure is the most important problem.

In the present paper, the algorithm of depth transform by use of equi-traveltime planes developed for cross-well and VSP survey was applied to the forward prediction of geological structure of tunnel face.

At first, in order to reconstruct the forward structure, the equation of equi-traveltime planes of waves which travel from source to receiver through reflection point on reflector is derived. The derived equation shows the equation of ellipsoid of which foci are source and receiver. This means that a reflection point on reflector is located on ellipsoid. Ellipsoids are drawn for the data of each pair of source and receiver. Consequently, reflector is determined by drawing a common tangent plane to these ellipsoids.

Next, this algorithm was applied to the field data that was observed in a tunnel.

The result of prediction of tunnel face by the proposed algorithm showed a good agreement with the actual geological observation report after the completion of tunnel.

So, it is concluded that the proposed algorithm is useful for the on-site check of geological condition using a personal computer with small computer time.

1. Derivation of equation of equi-traveltime planes

Let's find the locus of reflection points for the reflected waves propagating from source to receiver through reflection points on reflector in cases of cross-well reflection survey and offset VSP survey as shown in Fig. 1. X and Y coordinates in Fig. 1 are set on the ground surface and Z coordinate correspond to the vertical well. Defining $T_R$ is the traveltime of reflected waves and $V_1$ is the average velocity to reflector, the length of ray-path $L_w$ is expressed as;

$$L_w = T_R \cdot V_1$$

The sum of distance from source S $(X_s,Y_s,Z_s)$ to reflection point P $(X,Y,Z)$ and the distance from P to receiver R $(X_o,Y_o,Z_o)$ is $L_w$.

$$L_w = \sqrt{(X-X_s)^2+(Y-Y_s)^2+(Z-Z_s)^2} + \sqrt{(X-X_o)^2+(Y-Y_o)^2+(Z-Z_o)^2}$$

Then, the transform from XYZ coordinate system to $X'Y'Z'$ coordinate system shown in Fig. 1 (a) is performed by equation (3). Where, $X'Y'$ plane is parallel to the ground surface, $X'$ axis passes through the source and $Z'$ axis is set to the well.

$$\begin{align*}
X' &= x \cos \alpha - y \sin \alpha \\
Y' &= x \sin \alpha + y \cos \alpha \\
Z' &= z
\end{align*}$$

(3)
Where,
\[
\begin{aligned}
  x & = X - X_0 \\
  y & = Y - Y_0 \\
  z & = Z - Z_0
\end{aligned}
\]  
(4)

and \( \alpha = \tan^{-1}(Y_S - Y_G)/(X_S - X_G) \).

Then, the shift of origin \( O \) to the new origin \( O' \) which is the midpoint of source and receiver expressed by equation (5) is performed.

\[
\begin{aligned}
  x' & = X' - X_s' / 2 \\
  y' & = Y' \\
  z' & = Z' - Z_g' / 2
\end{aligned}
\]  
(5)

The transform of equation (2) from \( X'Y'Z' \) coordinate to \( x'y'z' \) coordinate expressed by equation (3) through equation (5) gives equation (6).

\[
L_w = \sqrt{(x' - X_s')^2 + y'^2 + (z' - Z_g')^2} + \sqrt{(x' + X_s')^2 + y'^2 + (z' - Z_g')^2}
\]  
(6)

Moreover, by rotating the\( xyz \) coordinate with \( \beta = \tan^{-1}Z_g'/X_s' \) in counter-clockwise direction around the origin \( O' \), the rotated coordinate \( (\xi, \eta, \zeta) \) as shown in Fig. 1 (b) is established by equation (7). Using this coordinate, the equation (6) is finally transformed to equation (8).

\[
\begin{aligned}
  \xi & = x \cos \beta - z \sin \beta \\
  \eta & = y \\
  \zeta & = x \sin \beta + z \cos \beta
\end{aligned}
\]  
(7)

\[
\xi^2 + \{L_w^2/(L_w^2 - X_s'^2 - Z_g'^2)\}(\eta^2 + \zeta^2) = L_w^2 / 4
\]  
(8)

Equation (8) is the equation of locus of reflection points in case of the cross-well reflection and VSP data.

Equation (8) is the equation of an ellipsoid of which foci are source and receiver. In these equation, \( X_s', Z_g' \) and \( \xi_0 \) are known from the location of source and receiver and \( L_w \) is calculated by equation (1) using the traveltimes of reflected waves and the average velocities to each reflector. The average velocities are estimated from the velocity analysis in case of surface reflection survey, or from the velocity log data within the wells and by dividing the distance from sources to receivers by the traveltimes of direct waves in case of offset VSP and cross-well reflection survey.

Ellipsoid is the locus of points of which the sum of distances from foci is constant. When the average velocities to each reflector are used, the equi-distance is expressed in other words as the equi-traveltime. Then, equation (8) expresses the equation of equi-traveltime planes. Consequently, as ellipsoids are drawn for each pair of source and receiver, the reflector is determined by drawing an common tangent plane of these ellipsoids.

2. Automatic drawing of reflector

A reflector is determined as a common tangent plane of many ellipsoids which are drawn using the traveltimes of reflected waves on seismograms, the average velocities to reflector and the location data of sources and receivers. However, the readings of traveltimes are tedious and some errors in readings might be incurred especially in case of data with low S/N ratio. Here, automatic drawing method of reflector is proposed as follows.
1) Survey area is divided into cubic cells of appropriate size.
2) The time on the seismograms for a pair of source and receiver to start depth transform is designated. This time should be later than the traveltimes of first break.
3) Changing the time with one sampling interval from the designated time, an ellipsoid for a pair of source and receiver is drawn by equation (8).
4) The intersecting points of the ellipsoid with the vertical lines of cells are shifted to the nearest cell corners.
5) The values of amplitude on seismograms which correspond to this sampling time are added to the values on these cell corners.
6) The procedures from step 2) to 5) are repeated for all pairs of source and receiver.

Though the amplitudes on the cell corners on which common tangent plane of ellipsoids pass are amplified by summation with in-phase, the amplitudes in the other cell corners would be canceled because of the summation with out-phase.

3. Examples

The algorithm developed for cross-well reflection and VSP data was applied to HSP data. When the survey was conducted, the tunnel face located at the T.D. 220 meters in tunnel. The geometry of shot points and geophones used for forward prediction of tunnel face is shown in Fig. 2. Also, Fig. 3 shows the hardware setting of shot points, geophones and recording instrument for the survey. The total length of holes for sources and receivers is 1.5 meters and 0.5 meters and the height of holes for sources and receivers from the ground surface is 0.5 meters and 1.5 meters, respectively. The number of channels is 24. The seismic records are observed sequentially with shifting by one geophone interval from the first to the twenty fifth geophone. Fig. 4 shows the seismic record at shot point no. 21 which is filtered with pass band from 100 to 1000 Hz. The looking ahead of tunnel face by use of the proposed equi-traveltime planes was carried out using these filtered sections. The velocity for reconstruction of structure is determined by dividing the distance from shot point to receiver with the arrivaltime of the first break signal.

Fig. 5 shows the three-dimensional display of reconstructed structure. The amplitudes scaled by the highest amplitude in the section were displayed by decibels. The z-axis of this figure represents the distance from tunnel face along the tunnel.

Fig. 6 is the three-dimensional display of reconstructed structure which the high amplitudes around the tunnel face and the low amplitudes among -50 to -60 dB in Fig. 5 were omitted.

Fig. 7 is the actual geological observation report after the completion of tunnel.

The comparison of Fig. 6 with Fig. 7 shows a very good agreement of the position of high amplitudes in reconstructed section with the fractured zones in tunnel.

4. Conclusions

A new algorithm for the reconstruction of forward prediction of tunnel face was proposed. This algorithm is based on the theory that a reflection point on reflector for each pair of source and receiver is located on an ellipsoid of which foci are source and receiver and consequently, reflector is determined by drawing a common tangent plane to all ellipsoids. Also, the method automatically drawing a common tangent plane was proposed. This algorithm was applied to the field data for
forward prediction of tunnel face. Consequently, it was concluded that a good agreement of the predicted structure of tunnel face with the actual geological observation report showed the effectiveness of the proposed algorithm.

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References


Fig. 1 Coordinate system for deriving the algorithm of depth transform.
Fig. 2 Geometry of shot points and geophones for seismic field survey.

Fig. 3 Hardware setting of shot point, geophone and recording instrument.
Fig. 4 Filtered seismic section.

Fig. 5 Three-dimensional display of reconstructed structure.
Fig. 6 Three-dimensional display which the high amplitude around the tunnel face and low amplitudes among -50 to -60 dB in Fig. 5 were omitted.

Fig. 7 Actual geological observation report after completion of tunnel.