Estimation of the penetration angle of a man-made tunnel using time of arrival measured by short-pulse cross-borehole radar

Sang-Wook Kim, Se-Yun Kim, and Sangwook Nam

ABSTRACT

The relatively fast propagation of electromagnetic signals through empty man-made tunnels has played a key role in detecting deep underground tunnels using a short-pulse cross-borehole radar system. Our cross-borehole radar system measured the pulse signatures of an obliquely penetrating tunnel using short pulse borehole pairs at a test site in Korea. Compared to the arrival times of the first peak, the arrival times of the first received signal at an appropriate amplitude level provided an increasingly clear indication of the empty tunnel penetration angle became more oblique. A quadratic relationship between the arrival time of the first received signal and the oblique angle of the empty tunnel was obtained in pure granite.

INTRODUCTION

Locating underground tunnels using conventional borehole radar systems has been a challenge in geophysical exploration. Since the 1980s, several cross-borehole radar systems have been used in Korea to detect deeply located empty tunnels with diameters of about 7 m. Underground rock is highly weathered, jointed, and fractured, so the detection of such empty tunnels is very difficult because of the strong noise level generated from scattering by faults, joints, lodes, and underground water. Researchers (Schneider and Peden, 1993; Zhou and Sato, 2004; Ellis and Peden, 1997; Takahashi and Sato, 2006; Kim et al., 2007) have struggled to find an effective way of extracting tunnel signatures from received signal patterns with significant noise contamination.

Until now, two types of cross-borehole radar systems have been operated in Korea. One is stepped-frequency continuous-wave (CW) radar, characterized by the double-dip pattern in the received signal (Lytte et al., 1979). Strong attenuation at specific frequencies has been observed at positions corresponding to the tunnel boundary. (Lee et al., 1989). The double-dip pattern was constructed by superimposing two out-of-phase waves diffracted at the top and bottom boundaries of an empty tunnel (Peden et al., 1992). This system played a key role in detecting a fourth tunnel in that area (Kim and Ra, 1993).

The other type of cross-borehole radar system is pulse radar. Its relatively fast pulse propagation through an empty tunnel has detected a tunnel's depth position using a pulsed cross-borehole radar system. The tunnel boundary causes severe attenuation, and multiple reflections inside the tunnel distort signal shapes. Olofson (1988) investigated these characteristics features by extracting the first and second peaks of the received signal in a time domain. Using several offset measurement data, he determined the vertical and horizontal positions and the size of an empty tunnel based on those parameters. Olofson (1993). These parameters were used mainly to analyze actual measured radar data because of their simplicity and accuracy. In particular, the propagation velocity was estimated by the time of peak (TOP), which denotes the arrival time of the first peak.

Despite the excellent capability of these methods in detecting a perpendicularly penetrating tunnel, it is commonly accepted that an obliquely penetrating tunnel is not detectable. The double-dip pattern in the stepped-frequency CW radar system suffers from severe degradation as the oblique angle of an empty tunnel becomes increasingly oblique (Lee et al., 1989). As for the pulse-radar system, the variation in Olofson's features according to the oblique angle of an empty tunnel has been the subject of research. Moran and Greenfield (1993) have developed an analytic solution for a 2.5D tunnel; they investigate the effects of variations in the horizontal and vertical angles of the tunnel axis. The arrival time of the first peak result appears when all energy reflected as the angle of incidence on the tunnel boundary becomes larger than the critical angle. In this case, only diffracted signals at the tunnel boundary can reach the receiving antenna. Thus, relatively fast propagation through an obliquely penetrating tunnel cannot be accounted for properly using this propagation model.

In contrast, Allemann et al. (1993) analyze the radar data measured in a suitable tunnel test site. Their results show that the pulse signal
propagates faster than predicted by the raypath method as the penetration angle of the empty tunnel becomes more oblique. To explain this phenomenon, they use a waveguide model. However, it is unreasonable to explain wave propagation inside an obliquely penetrating tunnel using the waveguide model. In general, Snell’s law used in the raypath method provides the shortest time path connecting the transmitting and receiving antennas. Hence, a field with multiple reflections inside the tunnel cannot propagate faster than in the raypath model.

We wanted to find an appropriate way to estimate the oblique angle of an empty man-made tunnel using arrival-time data measured by short-pulse cross-borehole radar. In 2008, we fabricated and operated short-pulse cross-borehole radar (Kim et al., 2007) at a suitable tunnel site in Korea. The 2-m-diameter tunnel was located at a depth of 73 m. We measured the received pulse signals at depths of 63–83 m, where the empty tunnel was penetrated by eight borehole pairs connecting four transmitting (Tx) and two receiving (Rx) boreholes. The TOA was then extracted from the measured data. The horizontal distances between the eight borehole pairs varied, so we normalized the original TOP data to see only the relative arrival times at the depth of the tunnel. The normalized TOP data were partially distorted. Hence, it was nearly impossible to find any simple relationship between the TOP and the oblique angle of the tunnel.

As an alternative, we considered the time of arrival (TOA), which denotes the time of the first signal arriving in the received data (Kelly et al., 1992). The measured data were contaminated by noise generated by the receiver of our short-pulse cross-borehole radar; thus, setting the amplitude level of the first received signal is important. We tested four amplitude levels for the TOA: 0.5%, 1%, 5%, and 10% of the maximum amplitude of the received signal. If a very-low-amplitude level was selected, the corresponding TOA data were contaminated by noise. In contrast, the behavior of the TOA pattern approached that of the TOP as its amplitude increased. Thus, the TOA set at an appropriate amplitude level is very effective for estimating the oblique angle of a deep man-made tunnel.

**EXPERIMENTAL METHOD**

In 2008, we developed a short-pulse cross-borehole radar. This radar operates with a transmitter in one borehole and a receiver in another borehole for hole-to-hole measurements of electromagnetic (EM) pulse propagation through underground rock. The main task of the radar system is to detect deeply located man-made tunnels, about 2 m in diameter, penetrating between two boreholes. In particular, our aim was to form an angular relationship between the tunnel axis and the alignment of a borehole pair. Hence, we conducted extensive measurements using our radar system in a suitable tunnel test site in Korea.

Figure 1a shows the 3D geometry of the tunnel penetrating through six neighboring boreholes in the test site. The empty tunnel, with a 2 × 2-m cross section, was located at a depth of 73 m. The surrounding rock was pure granite with a relative permittivity of 5.8 from 63 to 83 m deep. The transmitter was inserted into one of four boreholes (T1–T4), and the receiver operated inside one of two boreholes (R1–R2). Figure 1b depicts the horizontal view at 73 m in depth. It was then possible to generate eight hole-to-hole pairs through which the tunnel penetrated. Table 1 summarizes the oblique angle θ of the tunnel axis compared to the direction of the plane of the borehole pair involved and the distance from Tx boreholes to tunnel axis on the measurement path. The deviation of each borehole was measured using the deviation measurement system. As expected, the distance between each borehole pair differs slightly at the tunnel depth compared to the surface as a result of the difference in the deviations of the two boreholes.

While the transmitter radiated an EM pulse with a 5-ns width in one borehole, the receiver in another borehole detected the pulse signatures, including the information on the man-made tunnel passing obliquely between the two boreholes. The transmitter was raised from 83 to 63 m in depth. To detect the EM pulse propagated through the underground rock, the receiver in the other borehole maintained the same depth as the transmitter. Figure 2 illustrates the pulse signal patterns received at scan depths from 83 to 63 m with the receiver in borehole R1. It denotes the measured data for the transmitter in boreholes T1–T4. In Figure 2a, the received pulse signal patterns arrive faster at the tunnel depth than at other depths. The phenomenon of faster arrival at the tunnel depth becomes more significant as the tunnel axis more closely approaches the alignment of the borehole pair. But the amplitude of the faster arriving signal is...
Estimation of tunnel oblique angle

gradually reduced as the obliqueness of the tunnel angle $\theta$ increases.

We repeated the same measurements with the receiver in borehole $R_i$. Figure 3 denotes the measured data for the transmitter in boreholes $T_i$. Compared with Figure 3b, the received signal pattern in Figure 3d illustrates the same phenomenon of faster arrival and weaker amplitude at the tunnel depth.

RESULTS AND DISCUSSION

The remaining problem was to identify a simple empirical relationship between the faster arrival and the oblique angle of the empty tunnel.

Time of peak

To extract the relatively fast arrival time of the received signal patterns at the depth of the empty tunnel, we assumed the most intuitive approach might be to detect the arrival time of its first peak. Olofert (1988) investigates the characteristic features of fast pulse propagation through empty underground tunnels by extracting the first peak of the received signal data.

First, we considered the raw data in Figure 2a, in which $\theta$ of the empty tunnel is 4.3° and the hole-to-hole horizontal distance of the path $M_{i1}$ is 16.3 m at a tunnel depth of 73 m. Figure 4a shows the corresponding signals received at 63 and 73 m. The TOP at 63 m (dotted line) occurs at 133.4 ns. However, the first peak at 73 m (bold line) appears early, at 128.5 ns, because of the fast pulse propagation through the air-filled region of the tunnel. This renders the extracted TOP effective in detecting unknown man-made tunnels.

Next, the same extraction of the TOP was applied to the raw data in Figure 2d, in which $\theta$ of the empty tunnel is 59.7° and the hole-to-hole horizontal distance of the path $M_{i1}$ is 22.8 m at tunnel depth. Figure 4b shows the signals received at 63 and 73 m. The first peak of the signal far from the tunnel (dotted line) appears at 183.4 ns. The pulse shape is similar to that of the dotted line in Figure 4a, although a 50-ns delay between two TOP times occurs because of the

Figure 2. Raw data measured by operating the receiver of our short-time cross-borehole radar inside the borehole $R_i$; (a) $M_{i1}$, (b) $M_{i1}$, (c) $M_{i1}$, and (d) $M_{i1}$

Table 1. Angles between the measured raypaths and the tunnel axis, the distance from Tx holes to tunnel axis, and the separations between the boreholes on the surface and at the tunnel center depth ($D = 73$ m).

<table>
<thead>
<tr>
<th>Measurement path</th>
<th>Tx</th>
<th>Rx</th>
<th>Oblique angle $\theta$ (°)</th>
<th>Distance from Tx hole ($D = 73$ m)</th>
<th>Separation (m)</th>
<th>Tunnel center depth ($D = 73$ m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{i1}$</td>
<td>$T_1$</td>
<td>$R_1$</td>
<td>4.3</td>
<td>8.3</td>
<td>14.1</td>
<td>16.3</td>
</tr>
<tr>
<td>$M_{i2}$</td>
<td>$T_2$</td>
<td>$R_1$</td>
<td>30.9</td>
<td>9.0</td>
<td>16.9</td>
<td>16.5</td>
</tr>
<tr>
<td>$M_{i3}$</td>
<td>$T_2$</td>
<td>$R_1$</td>
<td>44.3</td>
<td>7.2</td>
<td>17.4</td>
<td>17.8</td>
</tr>
<tr>
<td>$M_{i4}$</td>
<td>$T_1$</td>
<td>$R_1$</td>
<td>59.7</td>
<td>9.6</td>
<td>22.9</td>
<td>22.8</td>
</tr>
<tr>
<td>$M_{i5}$</td>
<td>$T_1$</td>
<td>$R_1$</td>
<td>31.2</td>
<td>8.8</td>
<td>15.0</td>
<td>17.0</td>
</tr>
<tr>
<td>$M_{i6}$</td>
<td>$T_2$</td>
<td>$R_1$</td>
<td>3.9</td>
<td>7.0</td>
<td>15.1</td>
<td>14.2</td>
</tr>
<tr>
<td>$M_{i7}$</td>
<td>$T_1$</td>
<td>$R_1$</td>
<td>19.0</td>
<td>6.2</td>
<td>13.7</td>
<td>13.9</td>
</tr>
<tr>
<td>$M_{i8}$</td>
<td>$T_1$</td>
<td>$R_1$</td>
<td>45.0</td>
<td>6.3</td>
<td>17.1</td>
<td>16.9</td>
</tr>
</tbody>
</table>
different separation distances. In contrast, the TOP at the tunnel depth occurs at 185.8 ns (bold line). This result apparently conflicts with the fact that an EM pulse propagates faster through the air-filled region of an empty underground tunnel.

However, energy is being received earlier than the data measured at $D = 63$ m. This may be explained by pulse distortion resulting from the loss of background rock medium as well as scattering by the empty tunnel. In a pulse cross-borehole radar system, many propagation paths connect the transmitter to the receiver. The received signal may be composed of several delayed pulses along the lower attenuated paths. The peak is formed when the main components are in phase. The TOP velocity is regarded as the average velocity of the major components in all possible paths.

As shown in Table 1, the horizontal hole-to-hole distance ranged from 13.7 to 22.9 m, according to the measurement path. Hence, the absolute values of the extracted TOP patterns were unsuitable for investigating the effect of $\theta$ on TOP variation. This led us to normalize the absolute TOP patterns. For each TOP pattern, the TOP without tunnel at every depth was calculated by a linear interpolation, assuming a straight line connecting two TOP values at 63 and 83 m in case there was no tunnel. The normalized TOP was obtained by subtracting the TOP without tunnel from the absolute TOP with tunnel at every depth. One may expect an empty tunnel to be recognized easily by searching for the fast-arrival region in the normalized TOP pattern.

The normalized TOP patterns corresponding to Figure 2 are shown in Figure 5a. One may find significant variation in the TOP pattern around the tunnel depth. However, it is nearly impossible to establish a simple relationship between $\theta$ and the corresponding TOP variation. As $\theta$ increases from $4.3^\circ$ in path $M_{11}$ to $30.9^\circ$ in path $M_{21}$, the normalized TOP value in the tunnel depth decreases from $-8.4$ to $-13.9$ ns. However, some abrupt changes appear in the TOP patterns for paths $M_{11}$ and $M_{21}$. In particular, the normalized TOP value at 73 m becomes positive in path $M_{21}$ with $\theta = 59.7^\circ$. Such abrupt behaviors in the normalized TOP patterns are also found in Figure 5b, obtained from the raw data in Figure 3.

**Time of arrival**

To remedy the drawback of the TOP, we sought a more realistic approach for extracting the arrival time of the received pulse signal. The TOA may be determined by the fastest route among all possible paths. Hence, we expect the TOA will have an efficient relationship to the oblique angle of the empty tunnel. In practice, however, the raw data inevitably contain noise because of the limited detectable level of the receiver of our short-time cross-borehole radar. When
the amplitude of the first received signal is set very low, the corresponding TOA data may be contaminated by noise. In contrast, the behavior of the TOA pattern may approach that of the TOP if the amplitude is higher. This led us to adjust the amplitude level of the first received signal above the receiver noise level but below the amplitude of the first peak.

We tested four TOA amplitude levels: 0.5%, 1%, 5%, and 10% of the maximum amplitude of the received signal. Figure 6a shows the TOAs extracted from the raw data in Figure 2a for signals received at 63 and 73 m. Because θ of the empty tunnel is 4.3° and the hole-to-hole horizontal distance of path M1 is 16.3 m at the tunnel depth of 73 m, the absolute amplitude of the maximum peak does not show severe attenuation. Compared to the TOAs at 63 m (dotted line), the corresponding TOAs at 73 m (bold line) occur earlier but in a similar manner. One may then consider that the TOA with a 10% amplitude level is more effective because of its robust behavior relative to receiver noise.

The same extraction of the four TOAs was applied to the raw data in Figure 2b; the corresponding TOAs at 63 and 73 m are shown in Figure 6b. In this case, θ of the empty tunnel is 59.7° and the hole-to-hole horizontal distance of path M1 is 22.8 m at the tunnel depth. Because the absolute amplitude of the maximum peak is significantly attenuated, a noise signal appears in the received time-domain voltage pattern normalized by the maximum peak (Figure 6b). As the amplitude level of the TOA decreases, the time difference between 63 m (dotted line) and 73 m (bold line) increases, but the effect of the noise is more serious. The absolute TOA patterns extracted from the raw data in Figure 2 are normalized in the same manner as the normalization process for the TOP pattern. As expected, Figure 7a shows that the normalized TOA pattern at the 0.5% amplitude level is seriously contaminated by noise. The significant fluctuation may be reduced by applying a technique similar to that of picking the first break in seismic measurements (Cho and Mendel, 1994). When the amplitude level increases to 1%, one obtains the much clearer TOA pattern in Figure 7b. In particular, the normalized arrival time decreases monotonically as the oblique angle of the empty tunnel increases from 4.3° for path M1 to 59.7° for path M4. Such a nearly linear variation of the 1% TOA according to the oblique angle of the tunnel may help us to formulate a simple relationship between the tunnel axis and the measured TOA data. However, the variation in the TOA at tunnel depth is reduced as its amplitude level increases to 5% (Figure 7c). When the amplitude level of the TOA increases to 10%, the corresponding TOA variation is further reduced (Figure 7d). A similar tendency is found in Figure 8, which is obtained from the raw data in Figure 5.
Relationship of tunnel angle to arrival time

The remaining problem was to formulate a practical and useful relationship between the oblique angle of the empty tunnel and the arrival time extracted from the raw data. The eight TOP values at 73 m were extracted from Figure 5. The corresponding TOA values at 0.5%, 1%, 5%, and 10% were extracted from Figures 7 and 8. The results are summarized in Table 2 and plotted in Figure 9. We can easily assume that the arrival time of a transmitted pulse would be significantly earlier if an empty tunnel is more obliquely penetrated by the measurement path between two involved boreholes because the air portion in the traveling path between the Tx and Rx antennas increases. However, as shown in Figure 9, the arrival time of the transmitted pulse shows some complicated behavior because strong distortion results from the multiple reflections inside the empty tunnel and inhomogeneous background rock. Hence, with an increase in the tunnel's oblique angle, monotonic variation is not easily discovered in the measured data. This result is explained by the waveguide model of Allemann et al. (1993) and the critical angle of Moran and Greenfield (1993).

To select the optimum curve among several complicated TOA data, we used a simple rule based on the concept of the signal-to-noise ratio (S/N). To assume the monotonic variation of the normalized arrival time according to the tunnel oblique angle, the measured data are approximated by the curve of the second-order polynomials as depicted with the bold lines without symbols in Figure 9. The corresponding curve-fitting errors are calculated as the rms errors listed in Table 3. The wider variation of the normalized arrival times according to the tunnel oblique angle renders the estimation of the tunnel oblique angle more accurate. If the variation width of the normalized arrival time were defined with the difference between the arrival times at 3.6° and 59.7° extracted from the curve-fitting model, it would be considered the meaning of the signal in the S/N.

In addition, the rms error of the curve-fitting model is regarded as the noise in the S/N. The calculated variation width and the rms error of the curve-fitting models are listed in Table 3. Then the S/N, which is used as the criterion for selecting the optimum value among several TOA data, is defined as

\[
S/N = \frac{S}{N} = \frac{\Delta t(3.6°) - \Delta t(59.7°)}{\text{rms error}}
\]

where \(\Delta t(\theta)\) denotes the normalized arrival times in nanoseconds at the tunnel oblique angle \(\theta\) in degrees. Table 3 shows the S/N values corresponding to the data in Figure 9. As the amplitude level of the TOA picking decreases, the variation width of the curve-fitting model increases gradually; at the same time, the rms error varies drastically. Because the rms error increases drastically in the case of a 0.5% TOA, the case of a 1% TOA is the optimal curve to estimate tunnel oblique angle. In addition, TOA is excluded because it has a negative variation width.

In Figure 9, the normalized TOA with a 1% amplitude level became negative in every case of an oblique angle. This led us to introduce the normalized time advancement \(\Delta T\) by imposing a minus sign on the normalized TOA with a 1% amplitude level. Figure 10 shows the change in \(\theta\) according to the variation in the normalized time.
Table 2. Comparison of normalized arrival time at the tunnel center depth according to obliqueness of tunnel angle $\theta$.

<table>
<thead>
<tr>
<th>Tunnel oblique angle $\theta$ (°)</th>
<th>Measurement path</th>
<th>TOA (1%)</th>
<th>TOA (5%)</th>
<th>TOA (10%)</th>
<th>TOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.9</td>
<td>$M_{22}$</td>
<td>-10.3</td>
<td>-10.9</td>
<td>-10.3</td>
<td>-13.3</td>
</tr>
<tr>
<td>4.3</td>
<td>$M_{21}$</td>
<td>-9.6</td>
<td>-9.0</td>
<td>-8.4</td>
<td>-8.4</td>
</tr>
<tr>
<td>19</td>
<td>$M_{22}$</td>
<td>-9.7</td>
<td>-8.5</td>
<td>-8.5</td>
<td>-1.2</td>
</tr>
<tr>
<td>31.2</td>
<td>$M_{22}$</td>
<td>-13.3</td>
<td>-13.9</td>
<td>-13.3</td>
<td>-12.7</td>
</tr>
<tr>
<td>44.3</td>
<td>$M_{20}$</td>
<td>-20.6</td>
<td>-17.0</td>
<td>-11.5</td>
<td>3.6</td>
</tr>
<tr>
<td>45</td>
<td>$M_{22}$</td>
<td>-16.9</td>
<td>-12.1</td>
<td>-11.5</td>
<td>-3.0</td>
</tr>
<tr>
<td>59.7</td>
<td>$M_{21}$</td>
<td>-24.2</td>
<td>-17.5</td>
<td>-12.7</td>
<td>-3.0</td>
</tr>
</tbody>
</table>

Figure 9. Variation of the TOP and four different TOAs and the corresponding curve-fitting model according to the oblique angle of the empty tunnel.

Figure 10. Tunnel angle estimation model.

The dashed line in Figure 10 illustrates the smoothing curve corresponding to equation 2. In this case, the rms error posed in equation 2 is approximately 6.59°. The parameters in equation 2 may be modified if the background rock around another tunnel is quite different from the granite in our tunnel test site. However, it is not easy to construct several tunnel test sites. As an alternative, numerical simulations will be needed to consider the effect of the electrical properties of the background rock around empty underground tunnels.

**CONCLUSION**

A practically applicable and noise-robust method for estimating the oblique angle of a deep man-made tunnel was investigated experimentally. The raw data were measured by operating our short-pulse cross-borehole radar at a suitable test site in Korea. Compared to the TOP, the TOA with a 1% amplitude level of the maximum peak provided a quadratic relationship between the tunnel axis and the alignment of a pair of boreholes. However, this relationship must be modified if the rock around the tunnel is not granite. We currently are investigating the effects of the electrical properties of underground rock surrounding the tunnel by performing numerical simulations based on the finite-difference time-domain method.
ACKNOWLEDGMENTS

This research has been supported by the Intelligent Microsystem Center (IMC) and, in part, by the Korea Institute of Science and Technology under contract 2E21711.

REFERENCES


