LETTER

IEICE Electronics Express, Vol.12, No.2, 1–6

Estimation of water level collected in an empty tunnel using cross-borehole pulse radar

Ji-Hyun Jung and Se-Yun Kim[a)]

Korea Institute of Science and Technology,

5, Hwarang-ro 14-gil, Seongbuk-gu, Seoul 136–791, Korea

a) *ksy@imrc.kist.re.kr*

Abstract: Cross-borehole pulse radar has been employed to explore an empty tunnel using the fast propagation of its excited pulse through the air region inside the tunnel. However, a partially water-filled tunnel is not properly interpreted yet. An effective conversion model to estimate the water level collected in an empty tunnel is developed using the finite-difference time-domain (FDTD) simulation data. As the collected water level inside the tunnel increases, the depth at the fastest time of peak (TOP) deviates exponentially from that at the fasted time of arrival (TOA). This conversion model renders the collected water level inside the tunnel to be estimated with average error of 0.044 m.

Keywords: cross-borehole, pulse radar, finite-difference time-domain (FDTD) method, time of peak, time of arrival, tunnel

Classification: Electromagnetic theory

References

[1] G. R. Olhoeft: 3rd Tech. Symp. Tunnel Detection (1988) 616.
[2] S.-W. Kim, S.-Y. Kim and S. Nam: Geophysics **75** [3] (2010) J11. DOI:10.1190/1.3374356
[3] S.-W. Kim and S.-Y. Kim: Radio Sci. **47** (2012) 1. DOI:10.1029/2011RS004741
[4] H. Zhou and M. Sato: IEEE Trans. Geosci. Remote Sens. **42** (2004) 335. DOI:10.1109/TGRS.2003.817215
[5] M. L. Moran and R. J. Greenfield: 4th Tunnel Detection Symp. Subsurface Exploration Technology (1993) 71.
[6] G. A. Ellis and I. C. Peden: IEEE Trans. Geosci. Remote Sens. **33** (1995) 535. DOI:10.1109/36.387570
[7] J.-H. Jung, S.-W. Kim, Y.-S. Kim and S.-Y. Kim: IEEE Trans. Antennas Propag. **58** (2010) 1683. DOI:10.1109/TAP.2010.2044338
[8] A. Taflove and S. C. Hagness: in *Computational Electrodynamics: Finite-Difference Time-Domain Method* (Artech, Norwood, 2000).
[9] J. A. Roden and S. D. Gedney: Microw. Opt. Technol. Lett. **27** (2000) 334. DOI:10.1002/1098-2760(20001205)27:5<334::AID-MOP14>3.0.CO;2-A

DOI: 10.1587/elex.11.20141129
Received December 1, 2014
Accepted December 10, 2014
Publicized December 26, 2014
Copyedited January 25, 2015

1 Introduction

Deeply located intrusion tunnels with cross section about 2.1 m by 2.1 m have been explored using cross-borehole pulse radar [1, 2, 3, 4]. A transmitting antenna inserted in one borehole radiates an electromagnetic pulse. Propagated pulse through the underground rock is picked out by a receiving antenna inserted in the other borehole. Then, both antennas are pulled upward direction with uniform distance interval and the same measurement is repeated. Collected pulses at the receiving antenna are stacked in sequence and provided as one B-scan image.

An empty tunnel has been detected by extracting some intrinsic features related with the fast propagation of pulse through the tunnel [1, 2, 3]. In practice, however, an empty tunnel may be partially filled with underground water oozed out of highly weathered and fractured granite in Korea. A fully water-filled tunnel was interpreted using analytic method but only pulse waveforms were calculated [5]. For a half water-filled tunnel, TE and TM scattering cases were analyzed in the presence of an air-earth interface [6]. However, the features related to a partially water-filled tunnel are not properly considered yet. It leads us to find a proper way on estimating the collected water level precisely.

In this letter, our numerical simulator [7] which utilizes the finite-difference time-domain (FDTD) method [8] is employed instead of field experiments to precisely consider widely varied dielectric properties of surrounding rocks. B-scan images of partially water-filled tunnels are calculated by changing the height of collected water and electrical properties of surrounding granite. As the height of collected water inside the tunnel increases monotonically, both depths corresponding to the fastest time of peak (TOP) and time of arrival (TOA) deviate separately. Thus, the relation between the difference in the depth deviation and the collected water level is formulated into a simple curve model and utilized to explore a partially water-filled tunnel.

2 Numerical model and results

Cross-borehole pulse radar operated at the well-suited tunnel test site in Korea [2] is mirrored into a 3-dimensional numerical model as displayed in Fig. 1. At the depth of 73 m, an arch-shaped man-made intrusive tunnel with cross-section of 2.1 m by 2.1 m is approximated into a trapezoid. Two water-filled boreholes with diameter of 0.18 m are separated by 15.9 m. The radius and height of two dipole antennas immersed in two boreholes are 0.03 m and 3.0 m, respectively. The tunnel and two boreholes are surrounded by lossy and dispersive underground rock of granite. In Korea, the dielectric property of granite suffers from a great variation. To cope with the inhomogeneous underground rock, sufficiently low and high dielectric properties of granite are selected based on the measured electrical properties of extracted granite [3]. Low, medium, and high dielectric properties of dispersive granites are expressed by Debye's formula:

$$\varepsilon_r(\omega) = \left(\varepsilon_{r\infty} + \frac{\varepsilon_{rs} - \varepsilon_{r\infty}}{1 + j\omega\tau}\right) + \frac{\sigma}{j\omega\varepsilon_0}, \tag{1}$$

where $\varepsilon_{r\infty}$ is the high frequency permittivity, ε_{rs} is the zero frequency permittivity, τ is the relaxation time, σ is the conductivity, and ε_0 is the permittivity in free space.

DOI: 10.1587/elex.11.20141129
Received December 1, 2014
Accepted December 10, 2014
Publicized December 26, 2014
Copyedited January 25, 2015

IEICE Electronics Express, Vol.12, No.2, 1–6

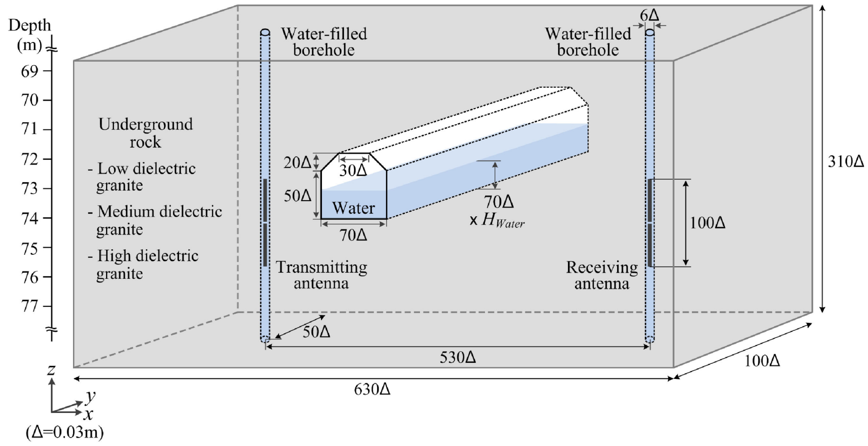

Fig. 1. Three-dimensional numerical model of cross-borehole pulse radar operated at the well-suited test site in Korea.

Table I. Three different dielectric properties of underground rock in Korea

	ε_{rs}	$\varepsilon_{r\infty}$	τ (s)	σ (S/m)
Low dielectric granite	5.8	3.0	2.0×10^{-12}	0.0010
Medium dielectric granite	9.0	3.0	2.0×10^{-12}	0.0032
High dielectric granite	12.0	3.0	2.0×10^{-12}	0.0050

Parameters related with electrical properties of three granites are summarized in Table I and the parameters of water are $\varepsilon_{r\infty} = 5.2$, $\varepsilon_{rs} = 80.4$, $\tau = 9.45 \times 10^{-12}$ s, and $\sigma = 0.0$ S/m. In our numerical model, uniform spatial resolution ($\Delta = \Delta x = \Delta y = \Delta z$) of 0.03 m is taken by considering the high dielectric property of water and the pulse width of the excited pulse, 10 ns. The time step (Δt) is chosen by 51.9615 ps to satisfy the stability condition [8]. The height of collected water inside the empty tunnel is described using the height ratio of water inside the tunnel H_{Water} and total height of tunnel 70Δ as $70\Delta \times H_{Water}$. The width, length, and height of the 3-dimensional numerical model is 630Δ, 100Δ, and 310Δ, respectively. Finally, the convolutional perfectly matched layer (CPML) [9] is set in the outer region of the numerical model as an absorbing boundary.

In the case of medium dielectric granite, FDTD simulations are performed for an empty tunnel and a half water-filled tunnel. Two antennas are winding up from the depth of 77.75 m to 68.25 m with uniform distance interval of 0.15 m to reduce computational burden. Calculated B-scan images of an empty tunnel and a half water-filled tunnel are displayed in a gray scale in Fig. 2(a) and (b), respectively. Well known features of an empty tunnel, the TOP and the TOA, are extracted and also plotted on the B-scan images. The TOP is the arrival time of the first positive peak and the TOA is the arrival time corresponding to the 1% of the amplitude of the first positive peak. As shown in Fig. 2(a), the depths corresponding to the fastest TOP D_{TOP} and the fastest TOA D_{TOA} are observed near the central depth of the tunnel, 73 m, when the tunnel is empty [2]. However, the depths D_{TOP} and D_{TOA}

DOI: 10.1587/elex.11.20141129
Received December 1, 2014
Accepted December 10, 2014
Publicized December 26, 2014
Copyedited January 25, 2015

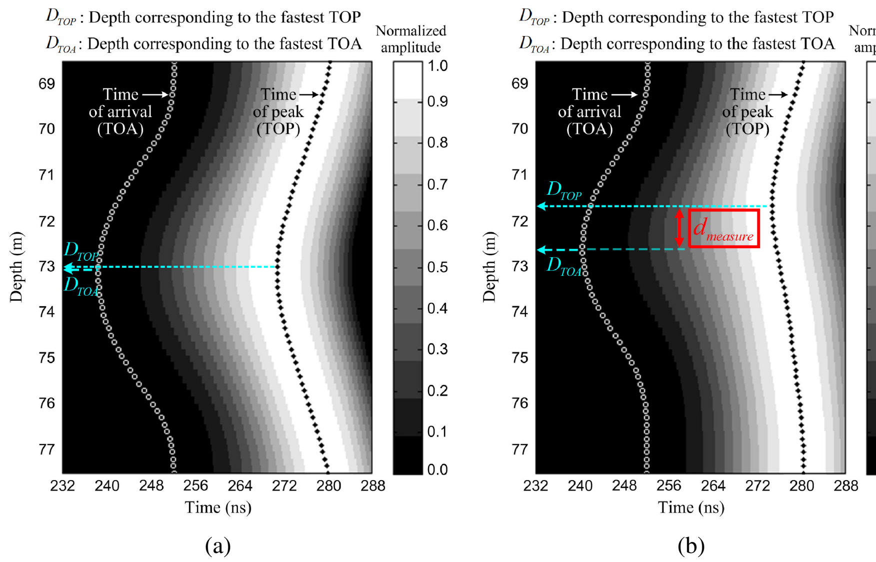

Fig. 2. B-scan images computed by applying the FDTD method to the numerical model displayed in Fig. 1. (a) An empty tunnel ($H_{Water} = 0.0$). (b) A half water-filled tunnel ($H_{Water} = 0.5$).

go upward direction from the central depth of the tunnel as displayed in Fig. 2(b) when half of the tunnel is filled with water. Differently deviated depths D_{TOP} and D_{TOA} from the central depth of the tunnel, 71.650 m and 72.625 m, do not meet the features related with an empty tunnel. Thus, the deviated depths D_{TOP} and D_{TOA} may cause confusion whether an empty tunnel exists or not.

3 Estimated height of collected water in an empty tunnel

Deviated depth D_{TOP} from the central depth of the tunnel may be caused to avoid the growing effect of the collected water in the bottom of the empty tunnel since the TOP is affected by pulses propagated through diverse paths. On the other hand, depth D_{TOA} may be deviated from the central depth of tunnel owing to the decreased portion of the air region inside the tunnel because the TOA is dominantly affected by pulses propagated through the fastest route. To find the effect of certain height of collected water inside a tunnel on two depths in detail, FDTD simulations are performed additionally for 4 different height ratio of water in the tunnel H_{Water}. In the case of medium dielectric granite, the depth D_{TOP} corresponding to the height ratio of water in the tunnel H_{Water} of 0.1, 0.2, 0.3, and 0.4 is 72.775 m, 72.400 m, 72.100 m, and 71.875 m, respectively. And the depth D_{TOA} corresponding to the height ratio of water in the tunnel H_{Water} of 0.1, 0.2, 0.3, and 0.4 is 73.075 m, 72.925 m, 72.775 m, and 72.700 m, respectively. As expected, depths D_{TOP} and D_{TOA} gradually go upward direction depending on the increased height ratio of water inside the tunnel H_{Water}.

In this letter, gradually increased difference between depths D_{TOP} and D_{TOA} depending on the increased height of collected water is defined as measurable depth deviation $d_{measure}$. The measurable depth deviation $d_{measure}$ is expressed as:

$$d_{measure}(H_{Water}) = D_{TOA}(H_{Water}) - D_{TOP}(H_{Water}). \tag{2}$$

DOI: 10.1587/elex.11.20141129
Received December 1, 2014
Accepted December 10, 2014
Publicized December 26, 2014
Copyedited January 25, 2015

IEICE Electronics Express, Vol.12, No.2, 1–6

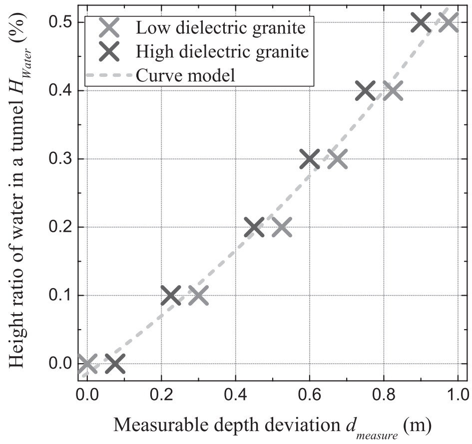

Fig. 3. Relations between the measurable depth deviation $d_{measure}$ and the height ratio of water in a tunnel H_{Water} by considering the low and high dielectric properties of granites and corresponding curve model.

Table II. Errors in the estimated water level (2.1 m $\times$ H_{Water}) in case of the medium dielectric granite

Maximum error ($H_{Water} = 0.2$)	Average error
0.068 m	0.044 m

If the measurable depth deviation $d_{measure}$ is small enough to be negligible, it is natural to conclude that the tunnel is empty. Otherwise, one may consider that the tunnel is partially filled with water. Then, the relation between the measurable depth deviation $d_{measure}$ and the corresponding height ratio of water in a tunnel H_{Water} is derived for the low and high dielectric properties of granite to cover the inhomogeneous granite. As shown in Fig. 3, the height ratio of water in a tunnel H_{Water} looks like exponentially increase depending on the measurable depth deviation $d_{measure}$ regardless the dielectric properties of the surrounding rocks. The curve model is formulated as:

$$H_{Water}(d_{measure}) = 0.601 \times \exp\left(\frac{d_{measure}}{1.527}\right) - 0.615. \tag{3}$$

The height of collected water inside an empty tunnel can be determined by multiplying obtained height ratio of water in a tunnel H_{Water} by total height of tunnel 2.1 m.

Finally, the validity of the proposed conversion procedure is confirmed by calculating errors in estimated water level (2.1 m $\times$ H_{Water}) in the case of the medium dielectric granite. As listed in Table II, the maximum error of 0.068 m corresponding to the height ratio of water in the tunnel H_{Water} of 0.2 is about 1.5 times the average error of 0.044 m. However, the maximum error is sufficiently small than the corresponding height of collected water, 0.420 m. Therefore, a partially water-filled tunnel can be explored by estimating the height of collected water in a tunnel regardless of the widely varied dielectric properties of granite in Korea.

DOI: 10.1587/elex.11.20141129
Received December 1, 2014
Accepted December 10, 2014
Publicized December 26, 2014
Copyedited January 25, 2015

4 Conclusion

Employing B-scan images of cross-borehole pulse radar for 6 different heights of collected water from the bottom to the half-height of a tunnel, a method to estimate the height of collected water inside a tunnel was developed. By considering the low and high dielectric properties of surrounding granite, the relation between the collected water level and the difference between depths corresponding to the fastest TOP and TOA was formulated into an exponential curve. The height of collected water inside a tunnel can be determined with average error of 0.044 m in the case of the medium dielectric property of granite. Therefore, the exponential curve will be helpful for detecting dormant intrusive tunnels in real operational site even though the tunnel is partially filled with water.

Acknowledgments

This research was supported by the Korea Institute of Science and Technology Institutional Program under Grant 2E24790.

DOI: 10.1587/elex.11.20141129
Received December 1, 2014
Accepted December 10, 2014
Publicized December 26, 2014
Copyedited January 25, 2015