Underground Anomaly Detection by Electromagnetic Shock Waves

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***Abstract*—A method for the detection of underground anomalies by electromagnetic (EM) shock waves was described in [IEEE Trans. Ant. Prop. vol. 59, no. 1, pp. 149-153, January 2011]. Following Grischkowsky *et al.* [Phys. Rev. Lett., vol. 59, pp. 1663-1666, 1987], an EM shock wave will develop in a dielectric medium by exciting a pulse which leaks into the dielectric bulk from a transmission line. A shock wave occurs when the group velocity in the line exceeds the phase velocity in the dielectric. This mechanism is similar to Cherenkov radiation. The transmission and reception of the EM shock wave between two identical leaky transmission lines is introduced. For underground detection, the two lines are placed in boreholes and are made in a manner in which the speed of propagation in the line is faster than the speed of propagation in the ground. The effect on the shock wave by an underground anomaly such as a dielectric or metallic pipeline located between the two boreholes is studied. The anomaly scatters the shock wave, resulting in a detectable disturbance in the received signal. The time delay of this disturbance, with respect to the time when the pulse was transmitted, is correlated with the location of the object. Numerical examples are presented by using a two-dimensional finite-difference time-domain algorithm.**

I. Introduction

Detection and ranging of underground anomalies is important for a variety of applications such as finding underground ores, unmapped infrastructure pipelines, and removal of mines. While numerous methods for underground detection exist, practical considerations such as resolution, speed of detection, attenuation through the ground, and system size determine which method or combination of methods should be used.

The method described in this paper [1] uses the transmission of an EM shock wave from one borehole to another. It relies on the phenomenon that when an EM pulse is injected into a leaky transmission line (TL) placed along a dielectric bulk, an EM shock wave will be radiated inside the bulk if the velocity of the signal inside the leaky TL exceeds the phase velocity in the bulk [2]. This radiation is similar to Cherenkov radiation.

Fig. 1 shows a vertical cross section of the ground with two boreholes. A leaky TL, also known as a distributed antenna, is placed along each borehole. A transmitter is connected to one of the lines and a receiver is connected to the other line. The transmitter generates an electric pulse that propagates along the leaky TL. Since the line is leaky, the signal radiates outside while propagating. The type of the line is chosen so that the propagation through the line is faster than the propagation through the ground. Thus, similar to [2], a Cherenkov-like EM radiation shock wave forms inside the medium while the electric pulse propagates along the TL. This shock wave propagates conically, scans the ground around the transmitting TL, and part of it couples to the receiving TL. In the receiving TL some of the signal will propagate downstream, and some of it upstream towards the receiver. If the ground has an anomaly such as a metallic pipeline between the two boreholes, it will scatter the shock wave. In this case the received signal will be perturbed according to the shape and location of the anomaly.

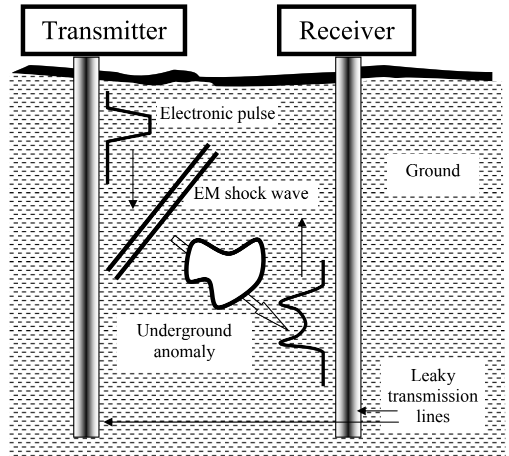

Fig. 1. Scheme of anomaly detection by EM shock wave.

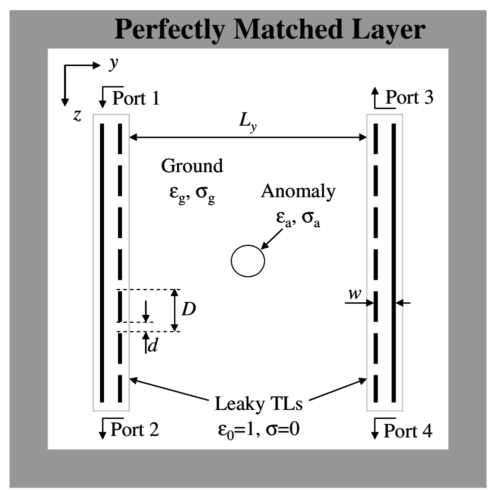

Fig. 2. FDTD setup. Each leaky TL is represented by two parallel plates where the plate facing the anomaly is slotted. The pulse is injected to the input port, Port 1. The received signal is measured in Ports 3 and 4.

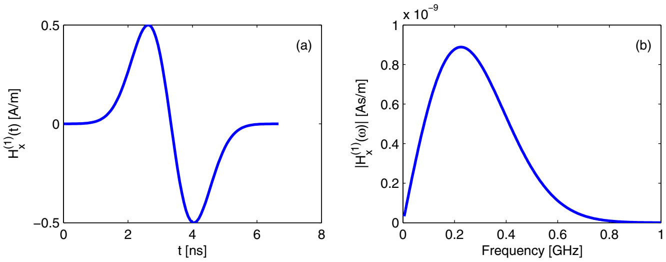

Fig. 3. Magnetic field component of the bipolar Gaussian pulse injected to Port 1, $H_x^{(1)}$, as shown by Eq. (1b) (a) and its Fourier spectrum (b).

II. FDTD FORMULATION

A 2D model for simulating the concept illustrated in Fig. 1 is shown in Fig. 2. The z direction is down into the ground. The setup is infinite along the x direction. The excitation was injected in the input port, Port 1, of the transmitting line. The received pulse was measured at the upper end of the receiving line, Port 3. The finite-difference time-domain (FDTD) formulation was used by central differencing of the TE$_x$ polarized Maxwell equations, where the EM field components were H_x, E_y, and E_z.

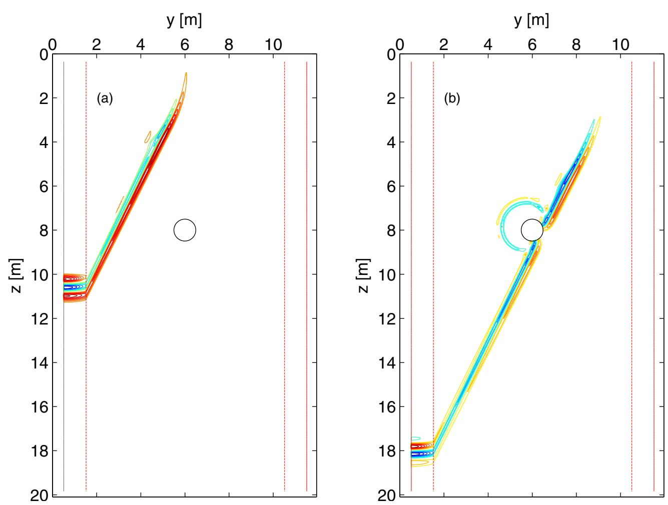

Fig. 4. Contour plot of H_x at 37.3 ns (a) and at 62.3 ns (b).

III. NUMERICAL EXAMPLE

A numerical example of anomaly detection by EM shock wave is presented in this section. The ground relative permittivity was $\varepsilon_{rg} = 5$ and its conductivity was $\sigma_g = 10^{-3}$ S/m. In order to study underground wave scattering by a good conductor, a circular anomaly with $\sigma_a = 58 \times 10^6$ S/m, $\varepsilon_{ra} = 1$, and with a diameter of 1 m was centered between the transmission lines at a depth of 8 m.

A transverse-EM bipolar Gaussian pulse was injected at Port 1. This pulse is shown in Fig. 3(a). Its Fourier spectrum, $H_x^{(1)}(\omega) = \int H(t)e^{-j\omega t}\,dt$, is presented in Fig. 3(b).

A contour plot of H_x at 37.3 ns and at 62.3 ns is shown in Figs. 4(a) and 4(b), respectively. As shown in Fig. 4(a), when

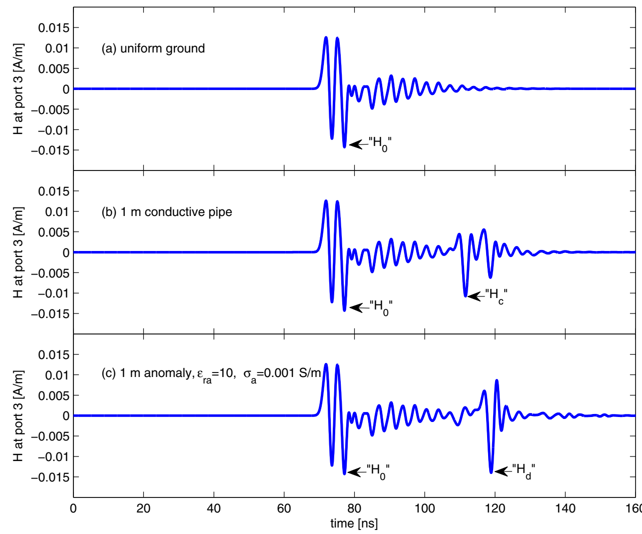

Fig. 5. Signal received in Port 3 when there was no anomaly in the simulation area (a), for a conductive anomaly (b), and for a dielectric anomaly, $\varepsilon_{ra} = 10$ (c).

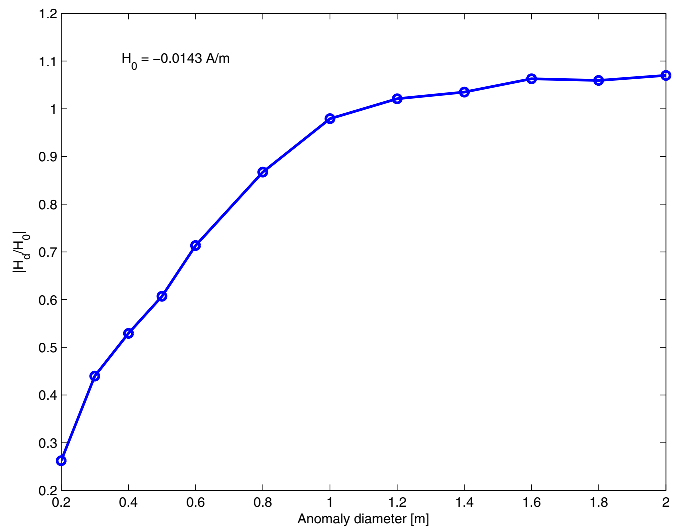

Fig. 6. Peak field in Port 3, $|H_d|$, relative to $|H_0|$, where $H_0 = -14.3$ mA/m, for various dielectric anomaly diameters.

the signal propagated along the transmitting line a shock wave was formed in the ground. The shock propagated at an angle of $\sim$ 63 degrees with respect to the z axis. This angle is in agreement with the Cherenkov angle of $\cos^{-1}(1/\sqrt{\varepsilon_{rg}}) = 63.4$ degrees. The wave was then scattered by the circular anomaly, as seen in Fig. 4(b).

The signal received in Port 3 is shown in Fig. 5 for three cases: (a) when there was no anomaly in the simulation area, i.e. $\varepsilon_{ra} = \varepsilon_{rg}$, and $\sigma_a = \sigma_g$; (b) for a conductive anomaly, $\varepsilon_{ra} = 1$, and $\sigma_a = 58 \times 10^6$ S/m; (c) for a dielectric anomaly, $\varepsilon_{ra} = 10$ and $\sigma_a = \sigma_g$. In these plots all of the signals had the same shape up to a time of about 100 ns, where between 70 and 80 ns the shock wave was reconstructed, with some dispersion, back into the original electric signal.

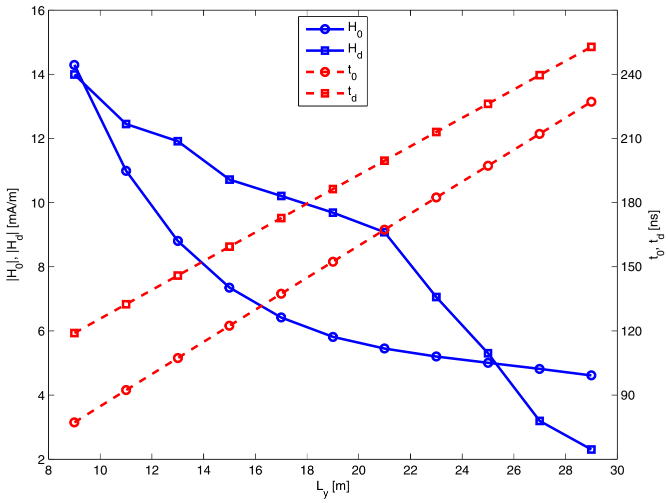

Fig. 7. Peak fields in Port 3 by the reconstructed shock wave and by the 1-m dielectric anomaly, $|H_0|$ (solid line with circles) and $|H_d|$ (solid line with squares), respectively, vs. the distance between the lines, L_y. The anomaly was located symmetrically between the lines at a depth of 8 m. The time of arrival of these peak fields, t_0 (dashed line with circles) and t_d (dashed line with squares), respectively, are shown with respect to the right axis.

The reconstructed shock wave in these plots is denoted by "H_0". The peaks by the conductive anomaly and the dielectric anomaly in Figs. 5(b) and 5(c) are denoted by "H_c" and "H_d", respectively.

The peak field in Port 3, $|H_d|$, for various dielectric anomaly diameters (all with $\epsilon_{ra} = 10, \sigma_a = 0.001$ S/m) is shown in Fig. 6. In this plot the field was calculated relative to $|H_0|$, where $H_0 = -14.3$ mA/m (see Fig. 5c). Clear relative signal was obtained for anomalies with diameters as small as 0.2 m. This resolution is in agreement with the pulse length in the ground.

The effect of the distance between the transmitting and receiving lines, L_y, on the peak signals in Port 3 by the shock wave and by the anomaly are shown in Fig. 7. The anomaly properties were $\epsilon_{ra} = 10$ and $\sigma_a = 0.001$ S/m. The anomaly was placed symmetrically at equal distances between the lines, and at a depth of 8 m. In this figure the peak value by the reconstructed shock wave, $|H_0|$ (solid line with circles), and by the 1-m dielectric anomaly, $|H_d|$ (solid line with squares), are plotted with respect to the left axis. The time of arrival of these peak fields, t_0 (dashed line with circles) and t_d (dashed line with squares), respectively, are shown with respect to the right axis.

IV. Discussion

The transmission and reception of EM shockwave was demonstrated. The shock wave was transmitted and received by leaky transmission lines in a way which resembles Cherenkov radiation. Underground anomaly detection by this scheme was provided.

The choice of the FDTD simulation parameters was according to the following guidelines. The grid resolution, Δ, was determined by the ground permittivity and by the pulse frequency spectrum shown in Fig. 3. High frequencies (by pulses with a short rise time) are required for better resolution where the anomaly minimum size should be on the order of the shortest wavelength. As explained in the introduction, high ground conductivity will degrade the resolution and decrease the penetration range since the attenuation increases with frequency. The TL periodicity, D, has to be small, i.e. a portion of the pulse length, in order to allow the electric pulse to generate a smooth shock wave. However, a too small value of D would result in an unnecessarily denser mesh and a longer simulation time. The ratio d/D should be chosen in a way as to allow sufficient out-coupling of the pulse energy into radiation while maintaining enough peak power in the electric pulse while it propagates along the entire length of the transmission line.

The time it took the wave to appear in Port 3 (Fig. 5, ~ 70 ns), was related to the distance between the two TLs, namely $L_y/c\sqrt{\varepsilon_{rg}}$. The time it took for the anomaly signal to appear (~ 110 ns) was longer, determined by the path-length downwards the transmitting TL and the Cherenkov angle through the ground towards the anomaly, and then to the receiving TL (see Fig. 7 and analysis below). The localization of the anomaly could be determined, for example, by analyzing the above data together with data in which Port 2 is used as an input port.

In Fig. 7 the slope of the reconstructed shock wave time is $c\Delta t_0/\Delta L_y = \sqrt{\epsilon_{rg}}$, as expected from the propagation through the ground. The slope of the anomaly time agrees with $c\Delta t_d/\Delta L_y = \sqrt{\epsilon_{rg} - 1}$, as it should. This can be explained by examining the time it took the shock wave to arrive to the anomaly, $c^{-1}(L_z + 0.5 L_y\sqrt{\epsilon_{rg} - 1})$, where $L_z = 8$ m is the depth of the anomaly. From symmetry and reciprocity considerations the time t_d is twice this value. This indicates that the receiving line operated as a Cherenkov radiation like antenna, in a similar manner to the transmitting line.

References

[1] A. S. Kesar, "Underground anomaly detection by electromagnetic shock waves," *IEEE Trans. Ant. Prop.*, vol. 59, pp. 149–153, 2011; and references therein.

[2] D. Grischkowsky, I. N. Duling, III, J. C. Chen, and C. -C. Chi, "Electromagnetic shock waves from transmission lines," *Phys. Rev. Lett.*, vol. 59, pp. 1663–1666, 1987.