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Ground-penetrating radar for soil and underground pipelines using the forward modeling simulation method

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ABSTRACT

Ground-penetrating radar was simulated using the FDTD method with uniaxial anisotropic perfectly matched layers as absorbing boundary conditions. To study underground pipeline detection, the electromagnetic response properties of underground pipelines, under known soil conditions, were determined. Pipelines at different depths and with different diameters and different compositions were simulated and researched for their response. The simulation results were consistent with research and analysis, i.e., the deviation was in an acceptable range. This research is of great value to guide the detection of pipelines in cities and to explain the detection of materials underground.

1. Instruction

In recent years, GPR systems have been widely applied in both civilian and military uses as a high-resolution, high-accuracy, and nondestructive technique. For underground detection and identification of objects, in addition to research and improvements in the detection equipment, simulation and calculation in theory are the important factors in this domain [1].

Foreign scholars have conducted the majority of the research in GPR forward modeling. Domestically, Yue and He [2] applied super-absorption boundary conditions in GPR sectional forward modeling. Yu et al. [3] used complex geoelectricity GPR forward modeling with the FDTD method. Wang et al. [4], Casper et al. [5] and Roberts et al. [6] used the FDTD and a pseudospectral forward modeling algorithm to simulate the electromagnetic response characteristics of GPR in an isotropic media. In 2000, Wang et al. [7] examined the GPR numerical simulation of dispersive media using perfectly matched layer (PML) absorbing boundary conditions (ABCs) [8].

The GPR systems are now important tools to survey underground pipelines because a GPR system is lightweight, fast and accurate. However, little research has been conducted on the detection of underground pipelines using GPR systems because of the real-world complexity of geological structures. The objective of this article was to provide a theoretical foundation for the detection of underground pipelines by simulating the electromagnetic characteristics of an underground pipeline using the two-dimensional FDTD method with the uniaxial anisotropic perfectly matched layer (UPML) as ABCs [9,10].

2. FDTD method and the modeling of scattering field in soil

The FDTD method is advantageous for its efficiency and accuracy and because it can finish the calculation in one time unit when a transient pulse incident occurs [11,12].

The Maxwell curl equations are as follows:

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + J \tag{1}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} - \mathbf{J}_m \tag{2}$$

In isotropic linear media, following equations are used:

$$\mathbf{D} = \varepsilon \mathbf{E}, \quad \mathbf{B} = \mu \mathbf{H}, \quad \mathbf{J} = \sigma \mathbf{E}, \quad \text{and} \quad \mathbf{J}_m = \sigma_m \mathbf{H}.$$

where **E** is the electric field intensity, **D** is the electric flux density, **H** is the magnetic field intensity, **B** is the magnetic flux density, **J** is the electric current density, and $\mathbf{J}_m$ is the magnetic current density.

The detection system of the GPR was simplified so that the underground target was a two-dimensional problem, i.e., with a section perpendicular to the ground and research limited to the section area. The physical matters were not related to the z zone, or $\partial/\partial z = 0$. Conspicuously, the right-angle components of the

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electromagnetic field in two-dimensions can be divided into two groups, the TM wave and the TE wave. This paper used the TM wave as an example. The author used the FDTD method to separate and differentiate them. Written as a two-dimensional state of the TM wave, the equation is as follows [13,14,18]:

$$TM\begin{cases}\dfrac{\partial E_z}{\partial y} = -\mu\dfrac{\partial H_x}{\partial t} - \sigma_m H_x\\ \dfrac{\partial E_z}{\partial x} = \mu\dfrac{\partial H_y}{\partial t} + \sigma_m H_y\\ \dfrac{\partial H_y}{\partial x} - \dfrac{\partial H_x}{\partial y} = \varepsilon\dfrac{\partial E_z}{\partial t} + \sigma E_z\end{cases} \tag{3}$$

To separate and differentiate (3), considering $t = n\Delta t$, the equations are as follows:

$$H_x^{n+0.5}(i, j+0.5) = CP(m)\cdot H_x^{n-0.5}(i, j+0.5) - CQ(m)\cdot \frac{E_z^n(i, j+1) - E_z^n(i, j)}{\Delta y} \tag{4}$$

$$H_y^{n+0.5}(i+0.5, j) = CP(m)\cdot H_y^{n-0.5}(i+0.5, j) + CQ(m)\cdot \frac{E_z^n(i+1, j) - E_z^n(i, j)}{\Delta x} \tag{5}$$

$$E_z^{n+1}(i, j) = CA(m)\cdot E_z^n(i, j) + CB(m)\cdot\left[\frac{H_y^{n+0.5}(i+0.5, j) - H_y^{n+0.5}(i-0.5, j)}{\Delta x} - \frac{H_x^{n+0.5}(i, j+0.5) - H_x^{n+0.5}(i, j-0.5)}{\Delta y}\right] \tag{6}$$

In which,

$$CA(m) = \frac{1 - \frac{\sigma(m)\Delta t}{2\varepsilon(m)}}{1 + \frac{\sigma(m)\Delta t}{2\varepsilon(m)}} \tag{7}$$

$$CB(m) = \frac{1}{\frac{\varepsilon(m)}{\Delta t} + \frac{\sigma(m)}{2}} \tag{8}$$

$$CP(m) = \frac{1 - \frac{\sigma_m(m)\Delta t}{2\mu(m)}}{1 + \frac{\sigma_m(m)\Delta t}{2\mu(m)}} \tag{9}$$

$$CQ(m) = \frac{1}{\frac{\mu(m)}{\Delta t} + \frac{\sigma_m(m)}{2}} \tag{10}$$

The variable m in $CA(m)$, $CB(m)$, $CP(m)$ and $CQ(m)$ identifies one group of integers or half-integers.

The GPR system used the analysis area model shown in Fig. 1, which was also the model used for calculation and simulation in this article. The area considered was 30 cm × 50 cm, the upper portion of the model being air and the lower portion being topsoil. The parameters of the soil were as follows [1,15]: the relative dielectric constant was 4, and the conductivity was 0.005 S/m. The launch antenna was h_1 = 3 cm above the soil surface. The target detected underground was h_2 below the soil surface. To construct the model conveniently in Cartesian coordinates, a rectangle metal pipeline with a square section area was used. The effects of the pipeline depth, diameter, thickness and composition were determined.

First, the effects of the soil media on the electromagnetic signal under the conditions where the relative dielectric constant was 4 and the conductivity was 0.005 S/m were determined. Fig. 2 shows the electric field intensity wave of differential Gauss pulse waves 5 cm, 10 cm and 15 cm under the soil.

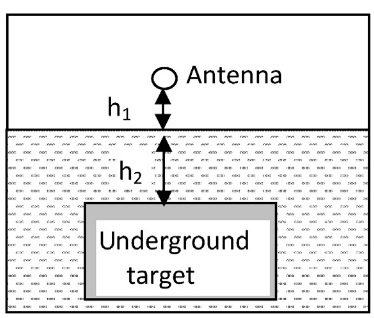

Fig. 1. The model of GPR detection and simulation.

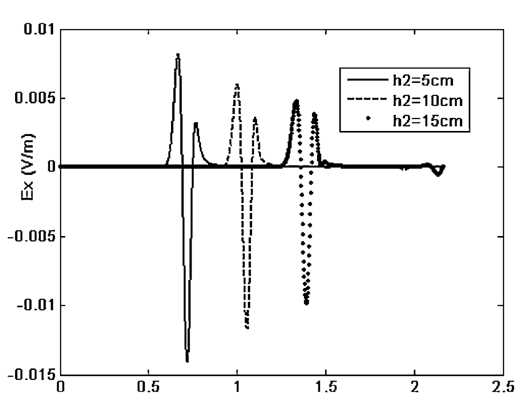

Fig. 2. The electric field intensity wave of differential Gauss pulse propagated into the soil in different depths.

As shown in Fig. 2, the pulse signal declined with the increase in the soil depth, and the forward motion of the pulse was slower and the width of the pulse was wider. This meant that the high-frequency component in the pulse signal became thinner sharply. Low-pass properties were observed in the high-frequency electromagnetic wave propagation in the soil. The resolution ability declined with the improvement in detecting depth.

The wave-forms decreased regularly along both axes in Fig. 2 because the depths calculated in Fig. 2 were related to time.

3. Analysis of the response characteristics of an underground pipeline

An underground pipeline is an important facility in a city and comprises the collection of pipelines and cables underground. Underground pipelines are categorized by the type of use for the pipe, such as water pipes, drainage pipes, gas pipes, heat pipes, electricity cable pipes, telecommunication pipes, and industrial pipes for oil and gas, and by the composition of the pipe, such as anti-corrosion steel pipe, cast iron pipe, steel mesh cement pipes, glass pipes, plastic pipes and ceramic pipes. The pipelines cross with each other and form a dense network, which ensures the daily operation of a modern city.

The Ministry of Construction of P.R. China passed a standard in June 2003 that stipulated that underground pipeline detection referred to the process of determining the properties and spatial position of the underground pipelines. The detection process included two basic components, the exploration of the underground pipeline and the mapping of the underground pipeline. To explore pipelines, the positions and depths of various underground pipelines were detected from images or with another method, and a viewpoint was set (called the pipeline point) on the ground. The mapping of underground pipelines required measurements of the