Numerical simulation of ground penetrating radar based on advanced prediction of adverse geological bodies

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Abstract. The geological conditions of the unfavorable geological bodies and the monitoring environment are characterized by diversity and complexity. It is still very difficult to use ground penetrating radar (GPR) to detect and interpret later. In this paper, the finite-difference time-domain method is used to simulate the propagation process of electromagnetic wave of GPR in the models of water-filled, mud-filled and fractured zones formed by cavities, faults and faults, and the response characteristics of electromagnetic wave under different conditions are analyzed. The results show that the simulation results coincide with the model design data, which proves that the numerical simulation results can provide a reference for the graphic interpretation of the actual exploration results. The A-Scan diagram shows that when the electromagnetic wave enters the medium with large dielectric constant from the medium with small dielectric constant, the phase of the wave will change, and the greater the difference of relative dielectric constant is, the stronger the radar reflection signal will be. At the same time, the model results show that the energy of electromagnetic wave will decay sharply under water-bearing conditions, and multiple waves will be formed below, which can provide a reference for ground penetrating radar in the actual detection of water-bearing cracks.

1. Introduction

Ground penetrating radar (GPR) is a physical detection method for the propagation of ultra-high frequency short pulse (106-109 Hz) electromagnetic wave in underground media. It uses non-grounding measurement to perform fast and continuous detection, and the detection object is non-destructive, which makes the ground penetrating radar widely used in many fields such as engineering geological exploration, disaster geological survey, highway engineering quality inspection [1]. However, due to the complex environment of unfavourable geological bodies, there are many factors affecting the detection effect of ground penetrating radar, and the experience of accurate interpretation of ground penetrating radar images for adverse geological exploration is insufficient. The numerical simulation results are helpful to improve the understanding of the characteristics of the target reflection profile and provide the basis for the interpretation of the detection data.

Numerical simulation technology has been widely used in various industries due to its flexibility, convenience and cost-saving [2]. At present, the commonly used forward numerical simulation methods of ground penetrating radar include finite element method (FEM), boundary element method (BEM), moment method (MOM) and finite difference time domain method (FDTD) [3]. Lubowiecka [4] used GPR and finite element analysis (FEM) to analyse Masonry Bridges and to study the causes of structural damage. Tajdini M [5] simulated the scattering effect of reinforcing bars in a layered bridge by Green's function and moment method to interpret the ground penetrating radar images.
Kosmas [6] combined with FDTD simulation to detect buried objects in the actual dispersion map, and the results were in good agreement with the GPR experimental data. Wang [7] based on GPR detection characteristics, simulated the underground coal mine fire profile with finite difference time domain method. The numerical results show that the method is correct and feasible. Using numerical simulation method to simulate the detection environment has become a very feasible means to supplement the actual observation of GPR.

This paper analyzes the adverse geological bodies such as underground water-bearing cavities and faults, and combines MATLAB and other software to analyze the propagation and reflection of electromagnetic waves emitted by ground-penetrating radars under different adverse geological bodies. The research results can help to improve the recognition experience of the detection images of adverse bad geological bodies, and provide reliable interpretation experience for the application of GPR in the detection of adverse geological bodies.

2. Simulation of finite difference time domain method

GPR is a geophysical method of imaging underground by radar pulse electromagnetic wave. On the macro scale, all electromagnetic phenomena can be described by Maxwell’s equations, in order to obtain stable solutions of the equations on a finite space-time scale. K S Yee put forward the Finite Difference Time Domain(FDTD) in 1966 [8]. The theory of FDTD replaces the differential equation in Maxwell’s curl equation of time domain with the finite difference equation, which makes the continuous problem discrete and obtains the difference equation system about the field component, and then uses the spatial grid with the same electric parameter to simulate the object under study.

\[
\nabla \times H = J + \frac{\partial D}{\partial t}
\]

\[
\nabla \times E = -\frac{\partial B}{\partial t}
\]

\[
\nabla \cdot B = 0
\]

\[
\nabla \cdot D = \rho
\]

Where: \(H\) is the magnetic field strength (A/m), \(E\) is the electric field strength (V/m), \(B\) is the magnetic induction (Wb/m²), \(D\) is the electric displacement vector (C/m²), and \(\rho\) is the charge density (C/m³), \(J\) is the current density of the applied power supply (A/m²).

![Figure 1. Yee’s grid](image)

The FDTD method is used in the data storage space of computer to simulate the propagation process of continuous actual electromagnetic wave in time and space is simulated. In the radiation and scattering problems of electromagnetic field, the boundary is always open and the electromagnetic field will occupy infinite space, but the memory of the computer is limited, so it can only simulate the finite space. In order to simulate the propagation of wave in infinite space, it is an effective method to set boundary conditions at the truncation so that the wave transmitted to the truncation is absorbed by the boundary without reflecting.
In the time domain finite difference theory, the time increment $\Delta t$ and the spatial increments $\Delta x$, $\Delta y$, $\Delta z$ are not independent of each other, they must satisfy the formula (2) relationship to avoid the numerical results from being unstable. As required, the spatial eigenvalue spectral domain must be fully included in the stabilization interval to ensure that all digital wave models in the algorithm are stable.

$$\Delta t \leq C \left[ \frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2} \right]^{-1/2}$$

(2)

Where: $\Delta t$ is the time increment, $C$ is the propagation velocity of electromagnetic wave, and $\Delta x$, $\Delta y$, $\Delta z$ is the discrete components in the directions of $x$, $y$ and $z$, respectively.

3. Numerical simulation of typical bad geological bodies

3.1. Parameter set of dielectric structure model

According to the actual detection calculation and the computer simulation space size, the size of the adverse geological body in mixed media is calculated, and the antenna frequency is determined according to the depth and accuracy requirements of the test detection. The underground medium model of the area to be detected is established, and the model is built according to the mixed medium model, and the corresponding dielectric constant, conductivity and other parameters are selected. The discrete grid step sizes $\Delta x$, $\Delta y$ and $\Delta z$ and the time step $\Delta t$ are divided according to the theoretical and stable conditions of the solution to determine the time window size. GPR simulation frequency is 800 MHz, iteration calculation, output results. Specific parameters are shown in Table 1 [9].

| Medium type       | Dielectric constant | Conductivity     | Relative permeability |
|-------------------|---------------------|------------------|----------------------|
| Air               | 1                   | 0                | 1                    |
| Water             | 81                  | $1\times10^{-5}$-$3\times10^{-2}$ | 1                   |
| Fracture zone     | 25                  | $3\times10^{-3}$ | 1                    |
| Clay              | 8-12                | $10^{-3}$-$1$    | 1                    |
| Mud               | 10                  | $10^{-3}$-$10^{-2}$ | 1                   |

3.2. Forward modeling of underground cavity

Underground rivers and underground holes have great safety effects on engineering construction. Water-bearing karst caves and underground rivers are the main disaster-causing factors of geological disasters such as water inrush and mud inrush. Therefore, it is necessary to forecast and detect adverse geological bodies such as underground rivers and underground holes in advance by ground penetrating radar detection. For this reason, this paper designs a model of underground long strip and square voids and other adverse geological bodies (figure 2). The model simulates the non-uniform medium filled with air and water respectively, which is used to explore the influence of shape and water on the signal.
3.3. Numerical simulation of adverse geological bodies caused by faults

Fault is the most common adverse geological phenomenon in engineering construction, and it is a very common structural form. It destroys the integrity and continuity of rock mass in varying degrees, greatly reduces the strength of surrounding rock, and causes the development of fractures on both sides of rock strata, resulting in serious fragmentation of rock mass. Fracture surface constitutes groundwater passage, which enhances the water conductivity and water-rich of surrounding rock, and is the main cause of geological hazards in construction. For this purpose, two models of faults and cracks caused by faults are designed (figure 3). In the model, the faults are simulated at 0.5–1m in the lateral direction, causing the stratum to be discontinuous. The cracks were filled with media such as mud, water and broken rock mass, and finally the fault models in five different cases were obtained.

4. Numerical simulation results analysis

The forward simulation results of the square cavity model and the strip model are shown in figure 4. The results obtained by simulation in an inhomogeneous medium are more realistic; from the analysis of the results of the model simulation, it can be seen that the position recognition of the anomalous geological body by GPR is very accurate. Figure 4-a and 4-b are the results obtained when the rectangular voids are filled with air and water respectively. Figure 4-c and 4-d are filled with square voids filled with air and water.
In the forward figure 4-a of strip cavity, it can be seen that there is strong reflection wave at the time depth of 0.4-0.6m. Because of the multiple reflection of electromagnetic wave in the relatively narrow space of the cavity, it is shown that the image is continuous on the same phase axis and the position corresponds to the position on the forward simulated image. Figure 3-c also reflects the reflection occurring in the cavity. Because of the detection principle, the figure is shown as a hyperbolic shape, and strong diffraction occurs on both sides of the wall, which is a typical feature of square voids.

The attenuation of electromagnetic wave in liquid (such as water) is faster than that in general solid. The higher the frequency, the faster the attenuation. From figure 4-b and figure 4-d, we can see that the signal intensity of the waveform is significantly different. In water environment, the energy of electromagnetic wave decays rapidly.

Figure 5 is a single channel data (A-scan waveform data) extracted from figures 4-a, 4-b, 4-c and 4-d. In figure 5, we can see that the phase of electromagnetic wave will change when it meets the reflection from the interface of unfavorable geological body. The phase of electromagnetic wave will change from positive to negative when it enters the medium with large dielectric constant from the medium with small dielectric constant.

Figure 6. Fault and crack model results

(a. Fault, b. crack, c. muddy crack, d. water-bearing crack, e. crush zone)
The image of forward modeling of fracture (crack, muddy crack, water-bearing crack and crush zone) caused by fracture is shown in figure 6 below. It can be clearly seen that in the experiment of simulating faults in different layered topography, the fault event axis is clearly displayed, and the thickness of the layered topography is clearly reflected.

From figure 6, as a whole, it is possible to obtain a strong reflected wave at a depth corresponding to the design depth of the model. Since the entire side of the fracture occurs at 0.5m, the entire phase is not continuous, and the waveform is clearly reflected on the forward image.

Figure 6-a corresponds to figure 6-b, figure 6-a has discontinuous coaxial axes but no missing axes. In figure 6-b, it can be clearly seen that the coaxial missing occurs at 0.4-0.5m transversely, which is consistent with the cracks produced by the faults designed by the model. This proves the practicability of ground penetrating radar in the investigation between geological faults and ground fissures caused by faults.

It can be obtained from figure 6-a that the radar profile appears at a lateral depth of 0.5 to 1.2 m at a depth of 0.5 m, which does not correspond to other reflected waves, and is judged as a reflection surface formed by the backfill after the fault sinks. In the case of 0.35m, 0.5m, 0.6m, 0.73m, 0.8m, and 0.9m, the in-phase axis is discontinuous at a lateral position of 0.6m. According to the judgment conditions of the fault, it is analyzed to appear in the lateral direction of 0.6m. For the fault, the resulting interlayer thickness is consistent with the actual model design thickness.

In comparison with figure 6-a and figure 6-b, it is found that in figure 6-b, the in-phase axis discontinuity occurs at a depth of 0.35m and 0.5m, respectively, but the lateral position is missing at 0.52–0.62m, and Correspondingly, in the 0.6m, 0.73m, 0.8m, and 0.9m, the in-phase axis is missing at the lateral position of 0.53–0.63m and 0.54–0.64m, respectively, and there is a significant parabolic curve in the same phase axis, which is judged in a sloping geological crack at a lateral position of 0.52–0.65m.

From the comparison of figures 6-b, 6-c, 6-d and 6-e, it can be found that the radar maps of ground fissures caused by fault dislocation have little difference due to the formation of mud-filled, water-filled and fractured zones in different environments. Judging that the reason is mud filling, water filling and fragmentation zone are water-rich substances, and the dielectric constant is not very different. Comparing figure 6-b with figure 6-c, 6-d and 6-e, it can be found that there are obvious stripe textures at the transverse position of 0.6m, the principle is to analyze other media filled in cracks caused by fault dislocation, in the water environment, the dielectric constant of the surrounding medium varies greatly, and the diffraction phenomenon caused by the propagation of electromagnetic wave between two substances with large difference in dielectric constant.

5. Project practical application

In field measurement, the center frequency of radar antenna is 450MHz, the separation distance of antenna is 0.25m, the moving step is 0.02m, and the recording time window is 30ns.

From the measured data shown in figure 7, it can be seen that hyperbolic reflection occurs at the depth of 0.15m, the distance from the starting point of 0.45m and 0.71m. According to the experience of ground penetrating radar image interpretation, these two places are pipelines. In the range of 0.6–0.8m in depth and 0.4–0.7m away from the starting point, there are obvious multiple reflections and strong electromagnetic wave energy, which are basically consistent with the void simulation results of the model designed in figure 3-c in this paper. Combining with engineering geological data, it is inferred that there are voids in this range. After the later construction and excavation verification, there are small holes in this area, which basically coincide with the results of advance prediction and forward modeling, and achieve the effect of advance prediction in engineering.
In the process of engineering construction, geological hazards are often caused by the influence of bad geological bodies. Because of the development of fractures caused by faults, water channels with higher water content are formed when rainwater and other media are filled.

The project is located in the active fault area, and the underground structure is complex. The center frequency of radar antenna is 100MHz and the antenna spacing is 1m. The sampling time window is 450ns. As shown in figure 8, at depths of 4m and 7-10m, there are two distinct coaxial axes, and the waveforms around the coaxial axes are quite disordered. There are passages at 55m and 61m horizontally, which are similar to the forward results of the model of muddy fractured zone in this paper. Combining with engineering geological data, it is inferred that there may be fault fractured zone and downward fractured water passage in this area. Later excavation proves that there are muddy filled passages and small fractured zones, which are in good agreement with the results of radar advanced prediction and forward simulation, and achieve the effect of engineering advanced prediction.

6. Conclusion

In this paper, through the discrete processing of three-dimensional FDTD mesh, the bad geological body model is established and the forward profile image is obtained. The results show that:

1. The numerical simulation can provide an effective reference for the actual detection results.
2. When the electromagnetic wave enters the medium with large dielectric constant from the medium with small dielectric constant, the phase of the wave will change. On the contrary, when the material with large dielectric constant enters the material with small dielectric constant, the corresponding phase of the wave will not change. The bigger the difference of relative dielectric constant is, the stronger the reflected signal will be.
3. By simulating the crack filling different materials, the respective ground penetrating radar images are obtained, and it is found that the water has a great influence on the electromagnetic wave signal, and the electromagnetic wave energy is sharply attenuated under the water condition, and multiple waves are formed below; with the increase of depth, the electromagnetic energy decreases gradually, and the reflected signal of the target decreases accordingly.

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