Forward Simulation of Borehole Ground Penetrating Radar in Grouting Evaluation of Fault Fracture Zone

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Abstract

In the construction of underground engineering, fault fracture zones and other adverse geological problems are very common, which are likely to cause collapsing, water and mud bursting and other disasters. Grouting is often used to deal with the fault fracture zone. But after the grout is injected into the fault fracture zone, it's very difficult to evaluate the grouting quality, which leads to a poor grouting effect. The depth of the grouting into the rock is usually tens of meters, and after grouting the coring method is often used to evaluate the grouting effect, so that the borehole ground penetrating radar can be used to evaluate the grouting quality. Therefore, this paper makes forward models of different situations of grouting into a fault fracture zone. Borehole ground penetrating radar response characteristics of the fault fracture zone before, after grouting and with grouting defects can be obtained after executing forward simulations, which provides a theoretical basis for the evaluation of grouting quality in practical projects.

Keywords

Forward simulation; Borehole ground penetrating radar; Grouting evaluation; Fault fracture zone.

1. Introduction

At present, with the underground engineering construction environment becoming more and more complex, fault fracture zones and other adverse geological problems are very common, where the rock mass structure is broken and the self-bearing capacity is poor. It may form water channels, and is likely to cause collapsing, water and mud bursting and other disasters [1, 2], seriously endanger the safety of underground engineering construction

Therefore, in the construction of underground engineering, adverse geological bodies must be detected in advance. Ground penetrating radar (GPR) is a fast, non-destructive and high-resolution detection method, which has been widely used [3].

Projects show that grouting is an effective treatment for underground engineering geological disasters [4, 5, 6]. Therefore, in order to improve the self-bearing capacity of the surrounding rock, construct water-proof curtains and ensure the safety of the underground engineering construction and the stability of the operation process, grouting is often used to deal with the fault fracture zone.

But grouting is a concealing project, at present only some data such as the grouting time, the grouting pressure, the grouting volume can be relied on to control the grouting quality. The condition after the grout was injected into the rock can't be accurately identified, resulting in poor grouting effect. The depth of the grouting into the rock is usually tens of meters, and after grouting the coring method is often used to evaluate the grouting effect, so that the borehole GPR can be used to evaluate the grouting quality.

This paper makes forward models of different situations of grouting into a fault fracture zone. Borehole GPR response characteristics of the fault fracture zone before, after grouting and with grouting defects can be obtained after executing forward simulations, which provides a theoretical basis for the evaluation of grouting quality in practical projects.

2. Theory

The finite-difference time-domain (FDTD) method is a set of time domain equations obtained by differencing the Maxwell's equations. For 2-D GPR forward simulation, The Maxwell's equations [7, 8] for transverse magnetic (TM) waves can be written as:

$$\begin{cases} \dfrac{\partial E_z}{\partial y} = -\mu \dfrac{\partial H_x}{\partial t} - \sigma_m H_x \\ \dfrac{\partial E_Z}{\partial x} = \mu \dfrac{\partial H_y}{\partial t} + \sigma_m H_y \\ \dfrac{\partial H_y}{\partial x} - \dfrac{\partial H_x}{\partial y} = \varepsilon \dfrac{\partial E_z}{\partial t} + \sigma E_z \end{cases} \tag{1}$$

Where E is the electric field intensity (V/m), H is the magnetic field intensity (A/m), σ is the conductivity (S/m), σ_m is the magnetic conductivity (Ω/m), ε is the permittivity (F/m), μ is the permeability (H/m).

When the media is non-magnetic, there is $\sigma_m = 0$ and $\mu = 0$, therefore, only the impacts of σ and ε should be considered. The 2-D TM waves Maxwell's equations contain only three variables, H_x, H_y and E_z, which represent the *x*, *y* direction magnetic field intensity and the *z* direction electric field intensity respectively.

In the 2-D FDTD method, the space is divided into $a \times b$ grids (*a*, *b* are the long and wide mesh number). The smallest unit of the differential grid is Yee cell [7]. Each electric field component is surrounded by four magnetic field components, and each magnetic field component is surrounded by four electric field components. The electric field component and the magnetic field component are alternately sampled in the time sequence, which are different in time by half time step. Therefore, the FDTD equations [7, 8] of the 2-D TM waves can be obtained as follows:

$$\begin{cases} H_x^{n+1/2}(i, j+1/2) = CP \times H_x^{n-1/2}(i, j+1/2) - \\ CQ \times \dfrac{E_z^n(i, j+1) - E_z^n(i, j)}{\Delta y} \\ H_y^{n+1/2}(i+1/2, j) = CP \times H_x^{n-1/2}(i+1/2, j) + \\ CQ \times \dfrac{E_z^n(i+1, j) - E_z^n(i, j)}{\Delta x} \\ E_x^{n+1}(i, j) = CA \times E_x^n(i, j) + \\ CB \times \left[\dfrac{H_y^{n+1/2}(i+1/2, j) - H_y^{n+1/2}(i-1/2, j)}{\Delta y} - \right. \\ \left. \dfrac{H_x^{n+1/2}(i, j+1/2) - H_x^{n+1/2}(i, j-1/2)}{\Delta y} \right] \end{cases} \tag{2}$$

Where
$$\begin{cases} CA = \dfrac{2\varepsilon(i,j) - \sigma(i,j)\times\Delta t}{2\varepsilon(i,j) + \sigma(i,j)\times\Delta t} \\ CB = \dfrac{2\Delta t}{2\varepsilon(i,j) + \sigma(i,j)\times\Delta t} \\ CP = \dfrac{2\mu(i,j) - \sigma_m(i,j)\times\Delta t}{2\mu(i,j) + \sigma_m(i,j)\times\Delta t} \\ CQ = \dfrac{2\Delta t}{2\mu(i,j) + \sigma_m(i,j)\times\Delta t} \end{cases} \quad (3)$$

Where Δx and Δy are the x and y directions spatial step sizes of the Yee cell, Δt is the temporal step size.

3. Examples

Table 1 Electronic parameters table

Medium	ε (F/m)	σ (S/m)
Air	1	0
Rock	6	0.001
Totally dried grout	6.5	0.002
Water	81	0.01

The fault fracture zone model is shown in Fig. 1. The model size is 30m×10m. In the model, the gray color medium is rock. The black color area is the fault fracture zone, which is filled with broken rock mass. The typical electrical parameters [3] of these media are shown in Table 1. The borehole is located at the upper boundary of the model. The center frequency of the borehole radar antennas is 100MHz.

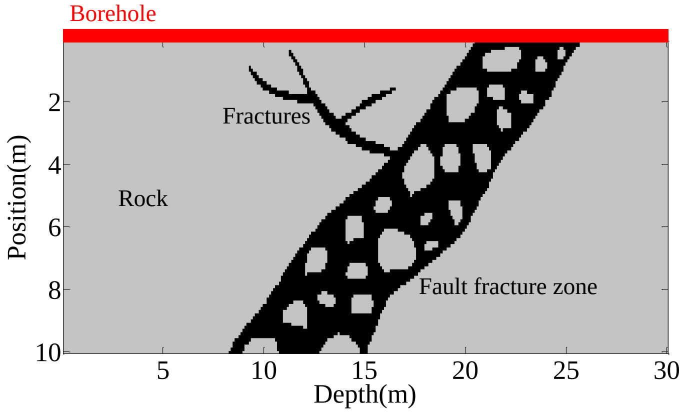

Fig. 1 The fault fracture zone model

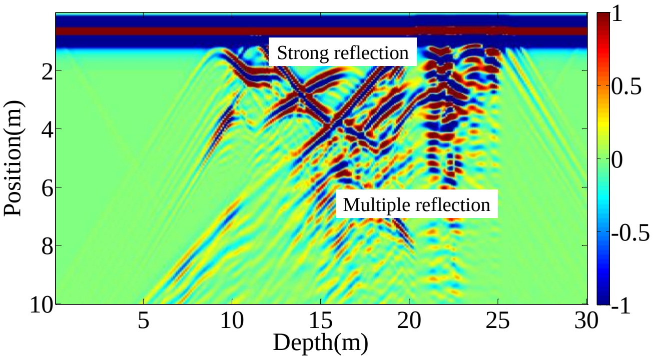

Fig. 2: The FDTD simulation result of the fault fracture zone model filled with air

When the fault fracture zone is filled with air, the FDTD simulation result is shown in Fig. 2. Strong reflections occur when the electromagnetic waves reach the fault fracture zone. The large number of broken rock mass result in disordered multiple reflections.

When the fault fracture zone is filled with water, the FDTD simulation result is shown in Fig. 3. Compared with Fig. 2, the phase of the reflected waves is reversed, and the amplitude enhances. The multiple reflections become more disordered.

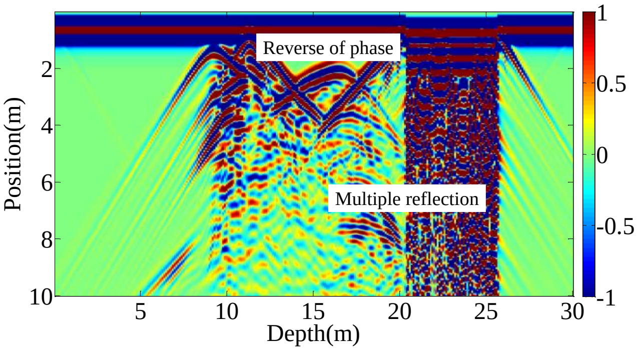

Fig. 3: The FDTD simulation result of the fault fracture zone model filled with water

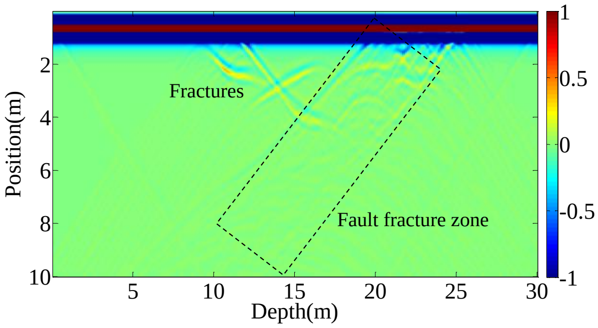

Fig. 4: The FDTD simulation result of the fault fracture zone model filled with grout

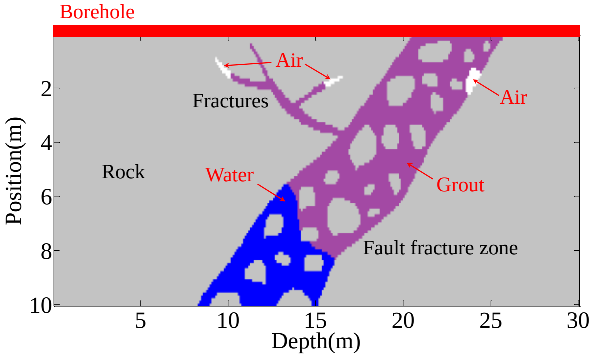

Fig. 5: The fault fracture zone model with grouting defects

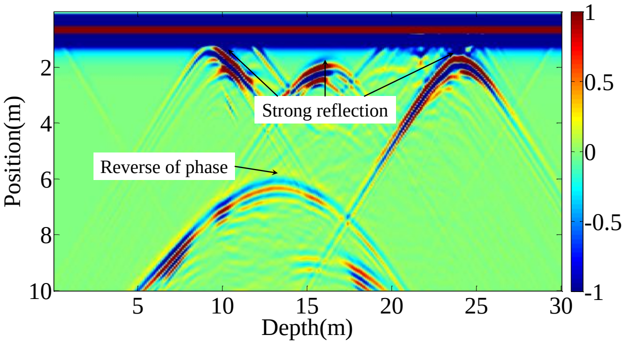

Fig. 6: The FDTD simulation result of the fault fracture zone model with grouting defects

After the grout has been injected and completely solidified, the FDTD simulation result is shown in Fig. 4. The fault fracture zone is filled with solidified grout, and only a small number of weak reflections are left.

When there are some defects after grouting, the fault fracture zone is not completely filled with grout. The model is shown in Fig. 5. The purple color medium is solidified grout, the white color medium is air, and the blue color medium is water. The FDTD simulation result is shown in Fig. 6. Where the fault fracture zone is filled with solidified grout, only a small number of weak reflections can be seen. However, hyperbolic shaped strong reflection occurs at the area with residual air and water. Compared to the reflection of air, the phase of water's reflection reverses. Therefore, whether there are defects after grouting into the fault fracture zone and the types of defects can be clearly identified from the FDTD simulation results.

4. Conclusion

This paper makes forward models of different situations of grouting into a fault fracture zone. Borehole GPR response characteristics of the fault fracture zone before, after grouting and with grouting defects can be obtained after executing forward simulations. Whether there are defects after grouting into the fault fracture zone and the types of defects can be clearly identified from the FDTD simulation results, which provides a theoretical basis for the evaluation of grouting quality in practical projects.

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