A Study on the Relationship Between the Detection Distance of Borehole Radar and the Resistivity of Background Medium

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Abstract. Borehole radar has been widely used in engineering, exploration and other fields, and the detection distance of borehole radar is an important indicator to measure its performance. The detection distance of borehole radar is affected by many factors, including the radar system, the physical properties of background medium, the borehole environment and so on. In this paper, the relationship between the detection distance of the borehole radar and the resistivity of background medium is studied by numerical simulation. The experimental results show that the detection distance of borehole radar increases with the increase of the resistivity of background medium, and the relationship between them is approximately linear. This kind of simulation is helpful to the theoretical study of the borehole radar.

1. Introduction

Ground penetrating radar (GPR) is a fast, non-destructive, and high-resolution detection method, which has been widely used to detect anomalies in subsurface [4,5,17]. However, the detection depth of surface GPR is limited, so borehole radar become crucial, because it can closely approach targets [6,13].

In Europe, America, Japan and other regions, the research and development of borehole radar system has been carried out since the early 1970s [3]. In 1978, Rubin et al. in Germany performed pulse radar experiments by means of single-hole measurement and cross-hole measurement respectively, and successfully identified underground rock formations. Since the 1990s, Tohoku University developed full-polarimetric borehole radar [10,12]. Wänstedt et al. [16] used borehole radar data combined with other geophysical data to realize the three-dimensional visualization of underground pollutants such as underground nuclear waste.

Domestic research on borehole radar started late, and most of the relevant articles are introductory [1,2,18]. China University of Mining and Technology first introduced borehole radar instruments from abroad [14]. In 2005, Liu et al. of Jilin University proved that it is feasible to detect fractures by borehole radar through physical experiments. Zhong Sheng et al. [19,20] obtained the borehole radar response characteristics of point adverse geological bodies through numerical simulation.

The above experts and scholars have made outstanding contributions to the practical application of domestic borehole radar and laid a solid foundation for the widespread application of borehole radar in China. In this paper, we use GPRMAX 3.0 [15] to carry out numerical simulations, and conduct a preliminary study on the relationship between the detection distance of borehole radar and the resistivity of background media.
2. Basic theory

At present, the measurement configuration of borehole radar is roughly divided into three types: single-hole reflection, cross-hole tomography and surface-borehole measurement. In this paper, we study the most widely used single-hole reflection measurement. Single-hole reflection measurement, as its name implies, is a continuous measurement with fixed distance between the transmitting antenna and the receiving antenna in a borehole.

The detection distance of borehole radar is mainly controlled by two parts, one is the gain index and dynamic range of the radar system, and the other is the resistivity and permittivity of the background media. The radar equation in lossy medium is

\[
\frac{p_r}{p_i} = \frac{G_r G_t \zeta_r \zeta_t \lambda \sigma}{(4\pi)^2 R^4} e^{-\alpha h},
\]

where \(G_r\) and \(G_t\) represent the gain of the receiving antenna and the transmitting antenna, respectively, \(\zeta_r\) and \(\zeta_t\) represent the propagation loss of antennas through the ground surface, respectively. Equation (1) is an approximate formula, because the attenuation constant \(\alpha\), antenna gain \(G\), target radar cross section (RCS) \(\sigma\), and surface loss \(\zeta\) are all functions of wavelength, and some of them even vary greatly with frequency. In practical applications, there is no analytical method for the strict calculation of the detection distance, and it can only be obtained by analyzing experimental data.

The dynamic range \(D\) of the borehole radar is defined as

\[
D = 20 \log_{10} \left( \frac{V_{\text{max}}}{V_{\text{min}}} \right),
\]

where \(V_{\text{max}}\) and \(V_{\text{min}}\) represent the maximum and the minimum voltage of the acceptable signals of the radar system, respectively.

Among them, the maximum acceptable signal should be satisfied so as not to overload the radar. Here we use the signal of the direct wave in the air as the maximum acceptable signal. In the impulse GPR system, a 16-bit ADC is mostly used, which can obtain a dynamic range of 96 dB. We can get the relationship between the minimum acceptable signal and the maximum acceptable signal by substituting the dynamic range of 96 dB into expression (2).

\[
V_{\text{min}} = \frac{V_{\text{max}}}{10^{4.8}},
\]

In the experiment, we first simulate the signal strength of the direct wave in the air and use it as the maximum signal that the radar system can receive. Then we calculate the minimum signal that the system can detect according to equation (3). Finally, the maximum detection distance corresponding to the minimum signal detected by the borehole radar system can be obtained.

3. Forward Modeling

In this paper, we mainly study the relationship between the detection distance of borehole radar and the resistivity of background medium. Therefore, we ignore the influence of the radar system in the numerical simulation. Generally, the relative permittivity of common underground rocks range between 2 and 9, so we set 5 as the relative permittivity of surrounding media in the simulation. In addition, the impact of borehole environment is not considered in the simulation because of its complexity and diversity.

GPRMAX 3.0 is used for numerical simulation. First, we design a three-dimensional air model (Figure 1) to simulate the signal strength of direct waves in the air. The length, width and depth of the model are 10m, 5m and 10m, respectively (the length, width and depth of all models in this paper correspond to the x, y and z directions of the model in the figure, respectively). The borehole is
located in the middle of the model \((x = 5 \text{ m}, y = 2.5 \text{ m})\), with a depth of 10 m. The entire model space is filled with air. The resistivity of air tends to be infinite. The center frequency of the antenna is 100 MHz. The distance between the transmitting and receiving antennas is 1 m. The wavelet is a Ricker wavelet. And the grid size is \(0.05 \text{ m} \times 0.05 \text{ m} \times 0.05 \text{ m}\). The simulation result is shown in Figure 2.

\[\text{Figure 1. The three-dimensional model for simulating direct wave in air.}\]

\[\text{Figure 2. The acquired of direct wave in air.}\]

It can be obtained that the amplitude of the maximum acceptable signal is 325.968292 V/m. The amplitude of the minimum acceptable signal is 0.005166 V/m by equation (3).

Then we design a model (as shown in Figure 3), and the length, width and depth of the model are 10 m, 5 m and 10 m, respectively. The borehole is located at \(x=1 \text{ m}, y=2.5 \text{ m}\), and the borehole depth is 10 m. The relative permittivity of the background medium is 5, and the resistivity is 100, 200, 250, 500, 800, 1000 and 2000, respectively (the unit is \(\Omega \cdot \text{m}\)). The thickness of the target layer is 2 m. The absorption boundary uses the PML absorption boundary, which occupies 10 grids (0.5 m) and not marked in the Figure. The target space is filled with air to enhance the permittivity contrast with the surrounding rocks.

\[\text{Figure 3. The three-dimensional model used to carry out the detection distance experiment of borehole radar.}\]

\[\text{Figure 4. Vertical profile of the model shown in Figure 3 (y = 2.5 \text{ m}).}\]

After the simulation is completed, we can get the magnitude of the reflected signal at the target layer, and then compare it with the minimum acceptable signal. If it is larger than amplitude of the minimum acceptable signal, increase the distance between the borehole and interface of the target
layer and continue the simulation; if it is smaller than the amplitude of the minimum acceptable signal, reduce that distance and continue the simulation. Until the magnitude of the reflected signal is equal to that of the minimum acceptable signal, then the distance between the target layer and the borehole is the maximum detectable distance.

The final results are shown in Table 1.

| Resistivity (ohm.m) | Detection distance (m) |
|--------------------|------------------------|
| 100                | 4.3                    |
| 200                | 8.4                    |
| 250                | 10.2                   |
| 500                | 19.1                   |
| 800                | 29.2                   |
| 1000               | 35.9                   |
| 2000               | 68.1                   |

It can be seen from the data in the Table 1 that the detection distance of borehole radar increases with the increase of the resistivity of background medium. By plotting the data in Table 1 (Figure 5), we can further obtain that the detection distance of borehole radar and the resistivity of background medium are approximately linear.

4. Conclusions

In this paper, we first design a three-dimensional air model. Then the signal strength of the direct wave in the air is obtained by numerical simulation, and it is regarded as the maximum acceptable signal that the radar system can receive. Then we calculate the minimum signal that the system can detect according to equation (3). Finally, the maximum detection distance corresponding to the minimum signal detected by the borehole radar system can be obtained. Through the results of numerical simulation, we can get that when the permittivity of the background medium is constant, the detection distance of borehole radar increases with the increase of the resistivity of background medium, and the relationship between them is approximately linear. This kind of simulation is helpful to the theoretical study of the borehole radar. However, the complexity of the actual underground medium was not
considered during the experiments in this article. Only a single homogeneous medium was tested, and the effect of borehole environment was not considered. Therefore, the experimental results are ideal and further research is needed.

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