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Numerical Simulation Analysis of Electromagnetic Wave Transmission Characteristics in Open Hole Well

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Abstract

The study of the transmission characteristics of electromagnetic waves in the annular space of open hole well is of great significance for the application of electromagnetic wave wireless transmission technology in real-time monitoring of underground conditions in drilling engineering. Based on the in-depth study of the engineering electromagnetic field and electromagnetic wave, the finite element numerical simulation model of the stratum-drill pipe annular space is established. Through numerical simulation calculations, the attenuation law of electromagnetic wave signals in the annular space of open hole wells with increasing well depth was revealed. At the same time, the effects of the electromagnetic response parameters of the stratum, drill pipe, and filling medium on the attenuation rate of electromagnetic waves in the annular space were analyzed. The research results show that various factors may affect the attenuation rate of electromagnetic waves in the annular space of open hole wells, among which the change of stratum conductivity has a particularly significant impact on its attenuation rate. Therefore, in actual drilling engineering, the underground electromagnetic wave transmission scheme can be developed according to the electromagnetic response parameters of the stratum, drill pipe, and filling medium to reduce signal attenuation and improve data accuracy. The study provides important references for the application of electromagnetic wave wireless transmission technology in real-time monitoring of various underground data in drilling engineering.

Keywords

Stratum; Open Hole Well; Electromagnetic Wave; Transmission Characteristics.

1. Introduction

Oil exploration has been ongoing for a long time, and the demand for petroleum energy in various industries remains high, prompting continuous optimization and improvement of oil exploration technology. During oil and gas exploration, collecting various downhole data and analyzing them based on actual conditions are crucial for drilling safety. Therefore, better implementation of information transmission between the ground and downhole has always been a research focus in oil and gas exploration projects[1].

Currently, there are two commonly used methods for collecting underground data in engineering operations in China: wired and wireless methods[2] The wired method typically involves placing measurement instruments in the well, and the data measured by the instruments is transmitted to the ground through cables (or optical fibers). Then, the received data at the ground is analyzed to understand the current status of the underground work. This method has a rapid data transmission rate and convenient operation, but requires more cables in deep wells, and the wear on the cables (or optical fibers) inside the well is relatively severe, leading to high costs[3]. There are three types of wireless transmission methods: mud pulse propagation, acoustic wave transmission, and electromagnetic wave transmission[4]. The mud pulse transmission method uses mud pulse valves to convert drilling measurement information into mud pulse signals, which are then circulated to the ground through drilling fluid flow, thus achieving information transmission. This technology is relatively mature, but has a low transmission efficiency[5]. Acoustic wave-based data transmission methods are not limited by drilling fluid, have low manufacturing costs, but suffer from significant acoustic wave loss when the transmission distance is too long, and are easily affected by other interference[6]. Using electromagnetic waves for underground data transmission can effectively avoid the shortcomings of the other two data transmission methods. When electromagnetic waves are used for data transmission, they have high transmission efficiency, large data capacity, simple structure, and low cost. Therefore, it is necessary to study the electromagnetic wave transmission characteristics in open hole well. In addition, electromagnetic wave transmission has an irreplaceable role in some special drilling projects.

Electromagnetic transmission technology has become a hot topic of research today. By analyzing and comparing the downhole data acquisition methods used in oil drilling today, it is not difficult to see that electromagnetic wave transmission technology may become an important way to transmit data in oil production in the future. This article studies the simulation analysis of the transmission characteristics of electromagnetic waves in bare strata wells, which has guiding significance for designing and developing downhole working devices using electromagnetic waves as a medium, and provides theoretical support for using electromagnetic wave equipment for data transmission in practical engineering.

2. Theory and Method

The annular space formed by the stratum and drill pipe can be idealized as a coaxial waveguide system with a cross section of concentric circles. Within this system, electromagnetic waves can be classified as transverse electromagnetic waves (TEM, with no electric field or magnetic field components in the propagation direction), transverse electric waves (TE, with a magnetic field component but no electric field component in the propagation direction), and transverse magnetic waves (TM, with an electric field component but no magnetic field component in the propagation direction)[7].

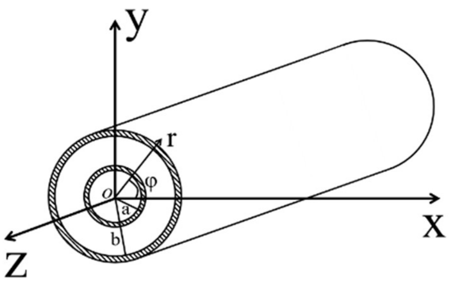

Figure 1. Coaxial waveguide system

In general, the coaxial waveguide system is analyzed using the cylindrical coordinate system (r, φ, z), and the electric field E and magnetic field H in the system can be described by Equation (1).

$$\begin{cases} \nabla_t^2 \boldsymbol{E}(r,\varphi) + k^2 \boldsymbol{E}(r,\varphi) = 0 \\ \nabla_t^2 \boldsymbol{H}(r,\varphi) + k^2 \boldsymbol{H}(r,\varphi) = 0 \end{cases} \tag{1}$$

In this equation, E is the electric field strength, V/m, E is the magnetic field strength, A/m, and k is the wave number, which is given by equation (2).

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$$k = \omega\sqrt{\mu\varepsilon} = \frac{\omega}{v} = \frac{2\pi}{\lambda} \tag{2}$$

In the formula, ω is the angular frequency of electromagnetic waves, rad/s; μ is the magnetic permeability of the electromagnetic wave transmission medium, H/m; ε is the dielectric constant of the electromagnetic wave transmission medium, F/m; v is the propagation velocity of electromagnetic waves in the medium, m/s; λ is the wavelength of electromagnetic waves with angular frequency ω in an ideal medium.

$$\begin{cases} \boldsymbol{E}(r,\varphi) = \boldsymbol{r}E_r(r,\varphi) + \boldsymbol{\varphi}E_\varphi(r,\varphi) + \boldsymbol{z}E_z(r,\varphi) \\ \boldsymbol{H}(r,\varphi) = \boldsymbol{r}H_r(r,\varphi) + \boldsymbol{\varphi}H_\varphi(r,\varphi) + \boldsymbol{z}H_z(r,\varphi) \end{cases} \tag{3}$$

In cylindrical coordinates, r, φ, and z represent the unit vectors along the radial (r), circumferential (φ), and z-axis positive directions, respectively.

Coaxial line waveguide systems belong to a dual conductor structure, resulting in the main mode of electromagnetic waves transmitted in the annular space formed by the stratum-drill pipe being TEM waves, while higher-order modes such as TE or TM waves may also exist. The transmission mode of electromagnetic waves is influenced by factors such as the size of the coaxial line, the filling medium between the inner and outer conductors, and the frequency of the electromagnetic waves[8].

When TEM waves propagate in coaxial waveguide systems, regardless of the frequency of the electromagnetic waves, they can propagate in the form of TEM waves. The TEM wavelength λg can be calculated using the following equation (4).

$$\lambda_{\mathrm{g}} = \frac{v_0}{f} \tag{4}$$

In this formula, v is the propagation speed of electromagnetic waves in the coaxial cable, and f is the frequency of electromagnetic waves in the coaxial cable.

When the wavelength λ of the electromagnetic wave within the coaxial line is less than the cut-off wavelength λTE of the lowest transverse electric wave mode, there is propagation of electromagnetic waves in the waveguide system in the transverse electric wave mode; when the wavelength λ of the electromagnetic wave within the coaxial line is less than the cut-off wavelength λTM of the lowest transverse magnetic wave mode, there is propagation of electromagnetic waves in the wavguide system in the transverse magnetic wave mode. The cut-off wavelength λTE of the lowest transverse electric wave mode and the cut-off wavelength λTM of the lowest transverse magnetic wave mode can be calculated using equation (5) and equation (6), respectively.

$$\lambda^{\mathrm{TE}} = \pi(a+b) \tag{5}$$

$$\lambda^{\mathrm{TM}} = 2(b-a) \tag{6}$$

In equations (5) and (6), a is the inner diameter of the annular space, b is the outer diameter of the annular space.

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Due to the non-ideal conductivity of the stratum and drill rod, and the presence of air, water vapor, and other media in the annular space, electromagnetic waves will experience energy attenuation during transmission.

When electromagnetic waves propagate in a waveguide, the attenuation caused by the waveguide wall and the attenuation caused by the filling medium are generally expressed in terms of loss power. In an ideal waveguide system, the guided wave amplitude of the electromagnetic wave is related to the distance from the transmission direction exponentially, which means that the transmission power decreases exponentially with the increase of the transmission distance (as shown in equation (7)).

$$P = P_0 e^{-2\alpha z} \tag{7}$$

In the formula, P0 is the transmitting power, W; z is the transmission distance, m; P is the transmitted power, W; and α is the electromagnetic wave attenuation coefficient, Np/m.

Derivative of equation (7) leads to the expression for the power loss of electromagnetic waves per unit transmission length as:

$$\Delta P = -2\alpha P \tag{8}$$

The theoretical calculation of coaxial waveguide systems is relatively complex and generally requires the use of Bessel functions and algorithms for analysis. Therefore, electromagnetic wave simulation software can be used to numerically analyze and solve the propagation of electromagnetic waves within the waveguide.

3. The Establishment of Finite Element Model

This article uses COMSOL Multiphysics simulation software to establish a model and perform numerical analysis. The "RF, electromagnetic waves, frequency domain" physical field interface is applied. Based on numerical mode analysis, the given frequency is inserted into the Helmholtz equation of the electric field, and then solved in the form of wave propagation direction.

The actual transmission distance of electromagnetic wave signals is affected by the on-site environment. When electromagnetic waves are used for signal transmission in underground engineering, the physical parameters of the stratum, metal, and filling media may have different degrees of influence on their intensity, which changes the transmission distance of electromagnetic waves in the shaft. This article mainly considers the influence of the electromagnetic response parameters of the stratum, drill rod, and filling media on the attenuation of electromagnetic waves. The electrical conductivity of the stratum is generally around 10 S/m, the relative magnetic permeability is generally around 1, and the relative permittivity can be 20 [10]; the electrical conductivity of the drill rod is generally around 106 S/m, the relative magnetic permeability is generally around 100, and the relative permittivity is generally 1 [11]; the filling medium between the stratum and the drill rod is generally air. Air, as a function of factors such as temperature and humidity, will produce certain changes in its electrical conductivity, relative magnetic permeability, and relative permittivity [12], which will affect the attenuation rate of electromagnetic waves.

cTaking the annular space composed of Φ244mm open hole well and Φ127mm drilling pipe as an example, the laws of electromagnetic wave transmission under the influence of multiple factors were studied and analyzed. Using the method of single factor analysis, the effects of electromagnetic response parameters of the stratum, drilling pipe, and filling medium on the attenuation of electromagnetic wave transmission were analyzed respectively. The reference values of each parameter are shown in Table 1.

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Table 1. Benchmarking parameters

parameters		value
stratum	conductivity S/m	10^1
	relative magnetic permeability	1
	relative dielectric constant	20
drill rod	conductivity S/m	10^6
	relative magnetic permeability	100
	relative dielectric constant	1
medium	conductivity S/m	0
	relative magnetic permeability	1
	relative dielectric constant	1

To establish a cuboid model for simulating the stratum, except for the top, the other five faces of the model establish infinite element domains to simulate the actual stratum space. The boundary conditions of the infinite element domains are set according to the physical properties of the stratum. When establishing the spatial model, the space formed by the stratum and the drill rod is equivalent to a hollow cylinder. A hollow cylinder is established at the center of the cuboid to simulate the annular space formed by the open hole and the drill rod. The axial line of the hollow cylinder coincides with the z axis, which is the longitudinal center axis of the cuboid. Taking into account various factors such as calculation time, resources, and grid independence, different parts of the grid are refined. A four-sided grid is used at the initial cross section of the open hole, and a sweep grid is used for multiple layers in the stratum, drill rod, air domain, and infinite element domain.

4. Results and Analysis

4.1 The Influence of Stratigraphic Electromagnetic Response Parameters on Electromagnetic Wave Transmission

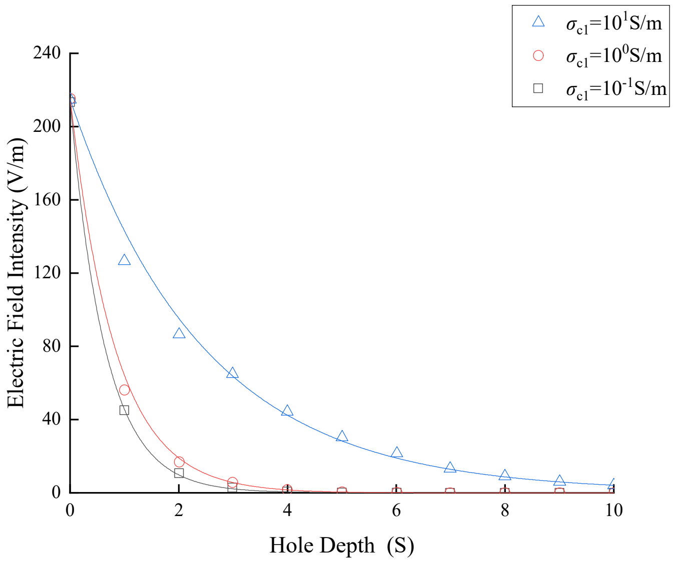

Figure 2. Relationship between E and D for different conductivities

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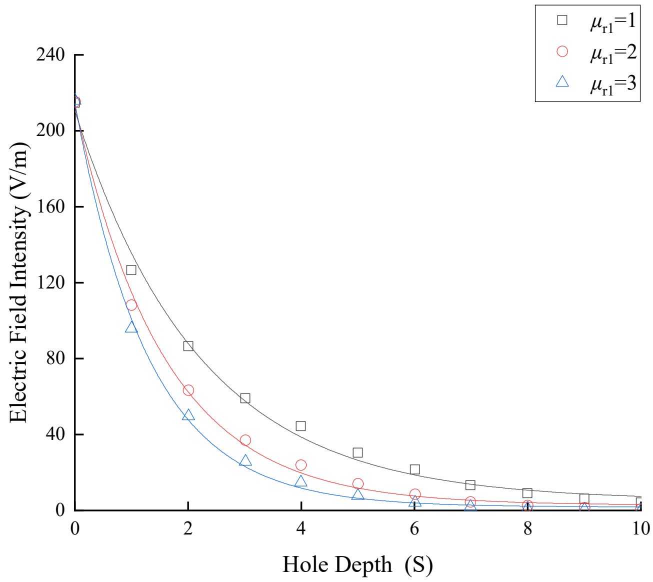

Figure 3. Relationship between E and D for different relative magnetic permeabilities

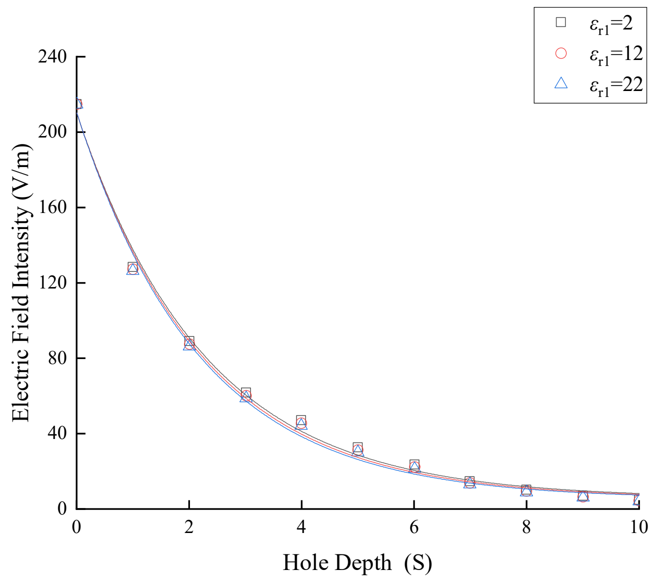

Figure 4. Relationship between E and D for different relative relative dielectric constant

When electromagnetic waves are transmitted in underground annular space, the electromagnetic response parameters of the strata have a certain impact on their transmission attenuation. When the composition and composition of the strata change, the electromagnetic response parameters of the strata will change accordingly, affecting the transmission attenuation rate of the electromagnetic waves. When the electrical conductivity of the strata is 10-1S/m, 100S/m, and 101S/m, the curve of electromagnetic wave intensity varying with well depth is shown in Figure 2. When the relative magnetic permeability of the strata is 1, 2, and 3, the curve of electromagnetic wave intensity varying with well depth is shown in Figure 3. When the relative permittivity of the strata is 2, 12, and 22, the curve of electromagnetic wave intensity varying with well depth is shown in Figure 4.

Analysis and fitting of the simulated electromagnetic wave intensity data show that: as the well depth increases, the intensity of electromagnetic wave signals decreases exponentially. The conductivity of the stratum has a significant effect on the electromagnetic wave attenuation rate, and the relative magnetic permeability of the stratum also affects the electromagnetic wave attenuation rate. In contrast, the relative permittivity of the stratum has no significant effect on the electromagnetic wave attenuation rate.

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4.2 The Influence of Electromagnetic Response Parameters of Drill Pipes on Electromagnetic Wave Transmission

The drill pipes used in engineering are generally made of carbon steel, and their electromagnetic response parameters vary with the type of drill pipe. When the electrical conductivity of the drill pipe is taken as 104S/m, 105S/m, and 106S/m according to the actual situation, the curve of the electromagnetic wave intensity varying with the depth of the well is shown in Figure 5. When the relative magnetic permeability of the drill pipe is taken as 50, 100, and 150, the curve of the electromagnetic wave intensity varying with the depth of the well is shown in Figure 6. When the relative dielectric constant of the drill pipe is taken as 1, 5, and 10, the curve of the electromagnetic wave intensity varying with the depth of the well is shown in Figure 7.

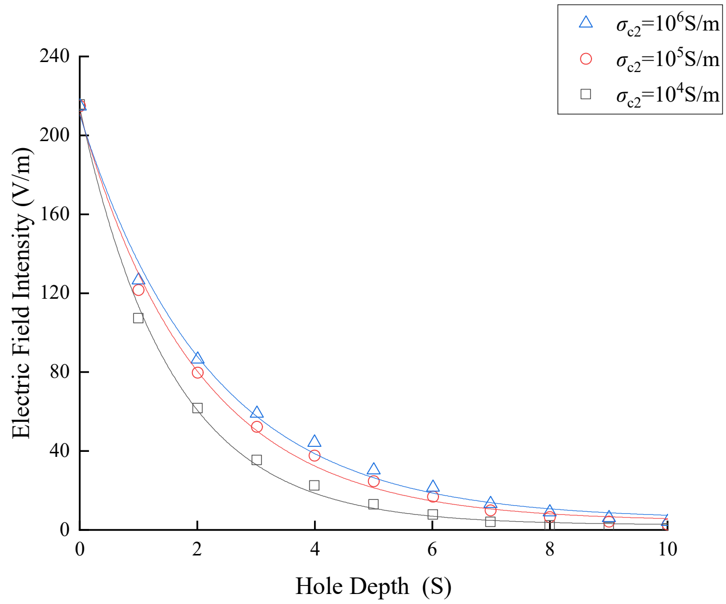

Figure 5. Relationship between E and D for different conductivities

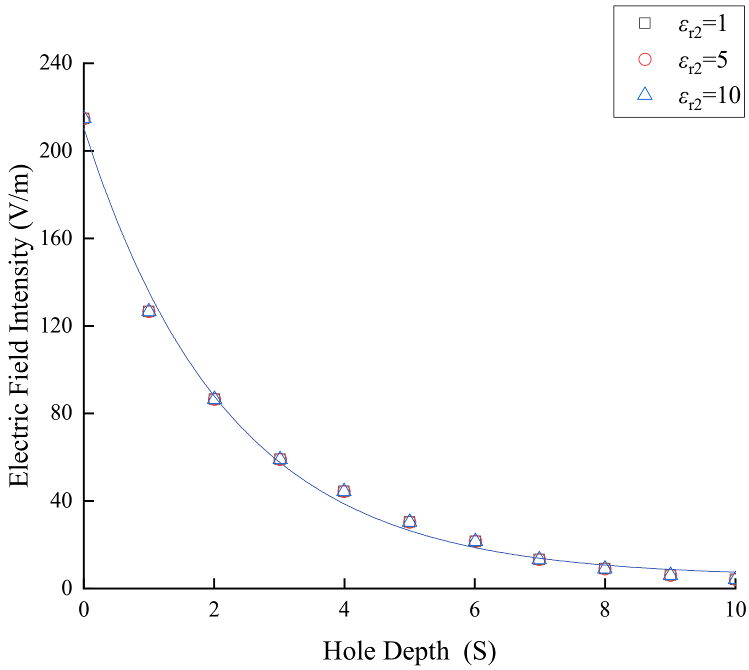

Figure 6. Relationship between E and D for different relative magnetic permeabilities

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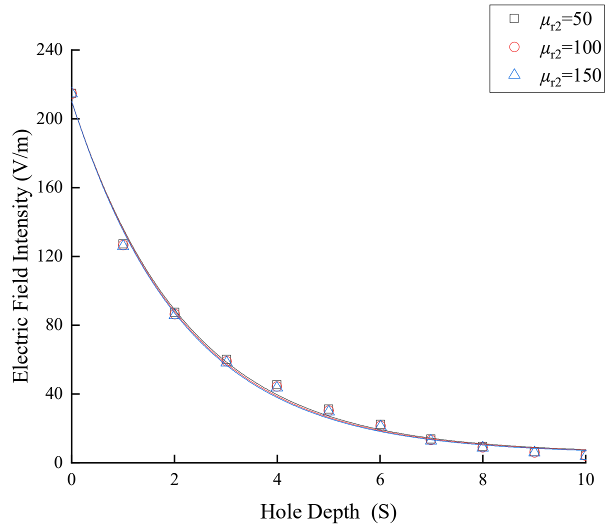

Figure 7. Relationship between E and D for different relative relative dielectric constant

The analysis and fitting of the simulated electromagnetic wave intensity data show that the electrical conductivity of the drill rod has a significant effect on the rate of electromagnetic wave attenuation. In contrast, within the range of parameter variations, the relative magnetic permeability and relative permittivity of the drill rod have no significant effect on the rate of electromagnetic wave attenuation in the well.

4.3 The Influence of Electromagnetic Response Parameters of the Medium on the Transmission of Electromagnetic Waves

The annulus inside the stratum and drill pipe is usually filled with a combination of air or nitrogen gas. Changes in temperature, humidity, and pressure in the environment may cause changes in the electrical conductivity, relative magnetic permeability, and relative permittivity of the gas, which in turn affect the rate of electromagnetic wave attenuation. When the electrical conductivity of the medium is 0S/m, 10-4S/m, and 10-3S/m, the curve of electromagnetic wave intensity varying with well depth is shown in Figure 8. When the relative magnetic permeability of the stratum is 0.9, 1.0, and 1.1, the curve of electromagnetic wave intensity varying with well depth is shown in Figure 9. When the relative permittivity of the stratum is 1.0000, 10005, and 1.0010, the curve of electromagnetic wave intensity varying with well depth is shown in Figure 10.

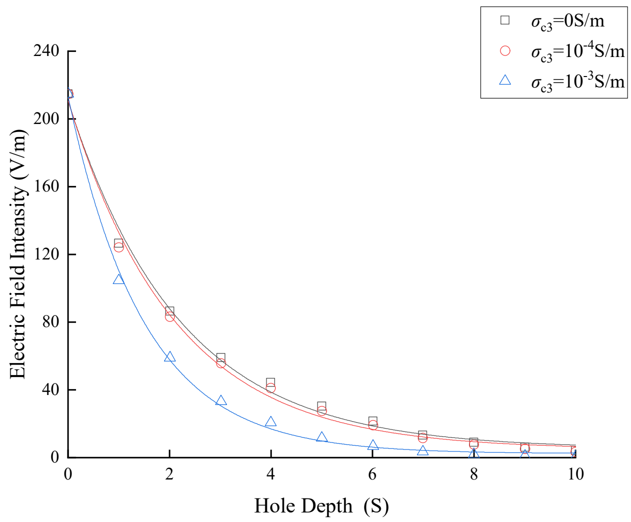

Figure 8. Relationship between E and D for different conductivities

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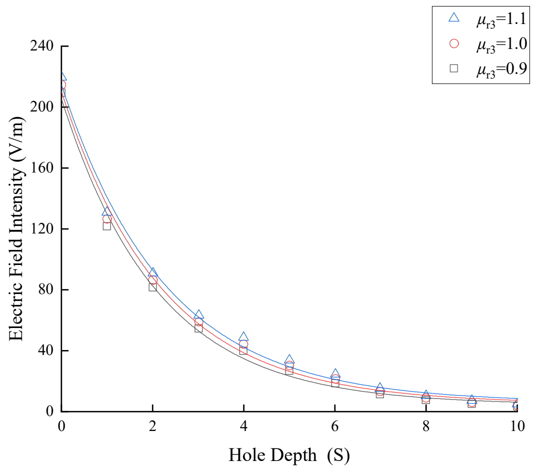

Figure 9. Relationship between E and D for different relative magnetic permeabilities

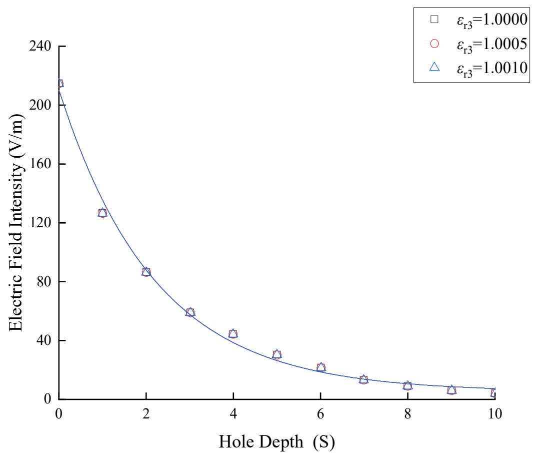

Figure 10. Relationship between E and D for different relative relative dielectric constant

The analysis and fitting of the simulated electromagnetic wave intensity data show that the conductivity of the filled medium in the annular space has a significant effect on the rate of electromagnetic wave attenuation. The relative magnetic permeability has a smaller effect, while the relative permittivity has no significant effect on the rate of electromagnetic wave attenuation in the well.

5. Conclusion

This article focuses on the propagation of electromagnetic waves and numerically simulates the propagation characteristics of electromagnetic waves in the open hole well model. Through numerical simulations, it is clear that the energy of electromagnetic waves decreases exponentially with the increase of well depth, and different factors in the well have different effects on the energy decay rate of electromagnetic waves. Using single-factor analysis to study the effects of stratum, drilling pipes, and medium electromagnetic response parameters on the energy decay rate of electromagnetic waves, it can be concluded that the change of stratum conductivity σ_{c1} has the most significant effect on the energy decay rate of electromagnetic waves, followed by stratum relative magnetic permeability μ_{r1}, drilling pipe conductivity σ_{c2}, medium conductivity σ_{c3}, and relative permittivity ε_{r3}. Other parameters do not have significant effects on the energy decay rate of electromagnetic waves within a certain range. Therefore, when using electromagnetic waves to transmit information in drilling engineering, the electromagnetic response parameters of the stratum, drilling pipes, and medium should be fully considered for possible errors in information transmission.

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