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Theoretical Channel Model and Characteristics Analysis of EM-MWD in the Underground Coal Mine

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ABSTRACT The measurement while drilling (MWD) system in underground coal mine currently uses wire for signal transmission. However, it has shortcomings such as strict technical requirements for cable drill pipe processing and high cost of use. Electromagnetic measurement while drilling (EM-MWD) is a new technology has a high rate of information transmission with fast measurement speed and low cost and is not affected by the drilling media. Hence, it is necessary to investigate a reliable electromagnetic transmission channel which is suitable for underground coal mine. This study selects the excitation method through comparison and conducts theoretical research on this basis. Based on the classical electromagnetic theory, the equivalent transmission line method is adopted to calculate and analyze the channel characteristics, while the electrical properties of the coal seam and the surrounding rock are considered. The results demonstrate that the formation resistivity, drill pipe resistivity, and the emission frequency are the main factors affecting signal transmission. On the basis of the uniform equivalent transmission line model, the theoretical model is established by combining the segmented uniform transmission line theory. The layered equivalent transmission line model can be better used to evaluate the regional applicability of the EM-MWD system.

INDEX TERMS EM-MWD, equivalent transmission line, channel model, attenuation properties.

I. INTRODUCTION

With the development of coal mining technology and the application of coal mining automation, the production scale and efficiency of coal mines have been greatly improved. The directional drilling technology of near-horizontal Measurement while drilling (MWD) in underground coal mines can realize long-hole directional drilling and precise control of the drilling trajectory, ensuring the drilling trajectory is effectively extended in the target layer, and can be used for multi-branch hole construction, with the advantages of high drilling efficiency, multiple uses in one hole, and centralized extraction [1]. It has been used in underground coal mine gas extraction, water control, geological structure, abnormal body exploration, etc [2], [3].

According to the transmission medium, the MWD can be divided into wired MWD and wireless MWD. One of the most commonly used and accepted wired MWD systems used in coal mines is the DDM MECCA directional drilling monitoring system from Australia VLD Company. After many years, four series of wired MWD systems have been successfully developed, which are used in connection with the central cable drill pipe. They have been promoted and applied in more than 30 mining areas [4]. Due to the strict technical requirements and high cost of central cable drill pipe processing, and the severe signal attenuation and poor reliability during long-distance transmission, wireless MWD has become an effective way to solve the above problems [5].

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MWD is a technology that continuously measures various parameters in real time while drilling [6]. The application of the technology of transmitting real-time data from the sensor at the drill bit to the surface in the MWD system can minimize downtime and improve work efficiency [7]. Signal transmission is the key to the development of MWD technology. The wireless MWD system mainly has five transmission methods including mud pulse, electromagnetic wave, acoustic wave [8], smart drill pipe [9], and optical fiber [10]. The disadvantages of acoustic transmission are large signal attenuation and serious interference from the drilling environment. Smart drill pipes are expensive and their reliability decreases after repeated use. Optical fiber transmission is still in the stage of theoretical research.

For now, mud pulse and electromagnetic wave technology are currently more mature in application [11]. The working voltage and current of the mud pulse MWD system are large, and the coal safety design is difficult. Compared with the electromagnetic wave transmission method, its transmission rate is slow and the transmission efficiency ratio is low. The increase in the transmission time and frequent replacement of the battery pack will reduce the drilling efficiencys [12]. At present, electromagnetic wave MWD is mainly based on the purchase of foreign products, and domestic technology is still in the development stage. The development of electromagnetic wave MWD suitable for underground coal mines will greatly improve the level of downhole near-horizontal directional drilling technology.

Electromagnetic measurement while drilling (EM-MWD) is a new technology that emerged in the last century. It has a high rate of information transmission with fast measurement speed and low cost and is not affected by the drilling media [13]. During drilling, the drill pipe, well wall, and stratum constitute a transmission channel for electromagnetic waves, as shown in Fig. 1. The electromagnetic wave radiates from the emission source to the surroundings and is received by the surface antenna [14]. It does not need mud as a carrier for the signal and requires less drilling fluid and drilling pumps. It has better adaptability to underbalanced wells. The instrument is divided into two parts: transmitter and receiver. The transmitter is located near the downhole drill bit and is used to collect bit attitude parameters (including tool face angle, dip angle, azimuth angle), temperature, pressure, battery voltage, and other parameters, and then send to the receiver. After the receiver completes the signal processing, it will be transmitted to the host for display. It is convenient for drillers to understand the attitude of the drill bit and adjust the drilling position.

The EM-MWD technology has its shortcomings: the resistivity of the formation will affect electromagnetic signals propagated in the formation and the effective transmission depth will be subject to certain restrictions [15], [16], which limits the large-scale application of electromagnetic drilling technology. In order to improve the reliability of the system, we establish the theoretical model of the electromagnetic wave transmission channel while drilling, and analyze the main factors affecting the transmission through calculation and simulation, and helps the instrument research and development to determine the technical indicators and related parameter ranges.

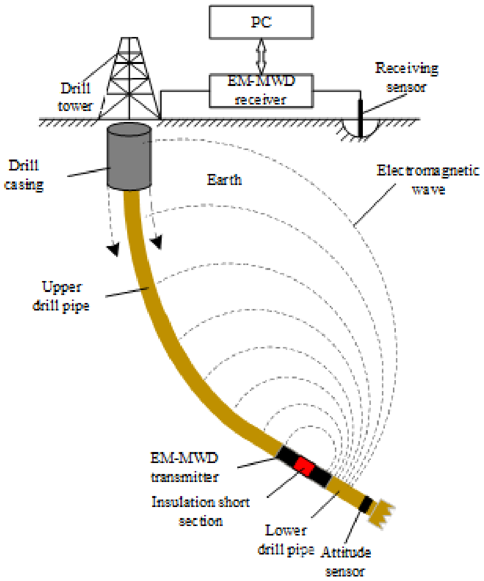

FIGURE 1. Schematic of the EM-MWD.

Up to now, the equivalent transmission line method [17], [18], electrode method [19], moment method [20], and finite element method [21] are generally used to establish ground EM-MWD electromagnetic transmission channel model. *Hill* and *Wait* first studied the signal transmission from the loop coil at the bottom of the drill pipe to the ground. They predicted that the optimal signal frequency range when the transmission depth reaches several kilometers is 10 to 100 Hz [16]. *Liu* equates the characteristics of the electromagnetic channel as a combination of capacitance and resistance to calculate the attenuation of electromagnetic waves [22]. *Carcione* and *Poletto* adopted telegraph equations, based on ladder networks or coaxial cables instead of drill pipes, and achieved good results [23]. *Li* and *Nie* use numerical pattern matching NMM based on the method of moments to obtain accurate simulation results [24]. *Zeng* uses the electric field integral equation (EFIE) and the method of moments (MoM) to obtain a linear system for the axial current distribution on the drill string [25].

However, there is few research describe the modeling process of downhole EM-MWD electromagnetic transmission channel in details. For the downhole EM-MWD electromagnetic transmission channel, due to the complicated boundary conditions of the excitation device in the hole, the concern is the extremely low frequency near the field, and it is difficult to strictly solve the field equation. The schematic diagram of downhole system is shown in the Fig. 2. At present, the common modeling and numerical analysis methods of EM-MWD electromagnetic signals can be divided into two categories: 1) the equivalent transmission line method based on the

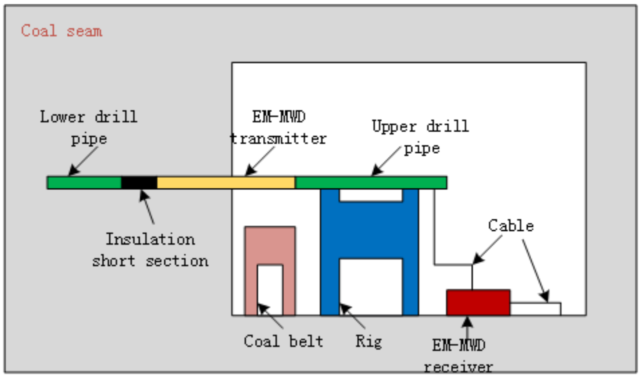

FIGURE 2. Schematic diagram of underground transmission in coal mine.

concept of path; 2) solve the field equation boundary value problem.

The surface EM-MWD electromagnetic transmission channel and the downhole EM-MWD electromagnetic transmission channel belong to the half-space problem and the full-space problem respectively [26]. Because of the complex boundary conditions of the excitation device in the borehole and the extremely low frequency near the field, the downhole EM-MWD is more difficult to strictly solve the field equation. Moreover, since the downhole EM-MWD has significant circuit characteristics, it is easy to obtain simple and practical analysis results by using the approximate equivalent transmission line method or electrode method. Therefore, this paper proposes a theoretical channel model and analyzes the characteristics of EM-MWD in the underground coal mine. The contributions of the paper consist of the following points:

1) The approximate equivalent transmission line method is adopted to establish the underground EM-MWD electromagnetic transmission channel model in coal mines;
2) The segmented uniform transmission line theory is employed to establish a theoretical model considering stratification;
3) The influence of formation resistivity, drill pipe resistivity, launch frequency, and lower drill pipe length on the transmission depth of EM-MWD signals are analyzed;
4) An EM-MWD system is developed and tested in the actual underground coal mine to identify the effectiveness of the theoretical calculations.

II. FORMATION ATTENUATION CHARACTERISTICS OF ELECTROMAGNETIC WAVES

Theoretically, air is the medium with the largest resistivity and smallest permittivity in nature, with the highest electromagnetic wave speed and the smallest attenuation. Water is the medium with the largest dielectric constant and the lowest electromagnetic wave speed. The electromagnetic parameters of dry rock, soil, and concrete are not much different, most of them belong to a high-resistance medium. Due to the different porosity and degree of saturation of various types of rock and soil, there is a large difference in electromagnetic properties. These differences are manifested in dielectric constant and electrical conductivity, which determine that different lithologies correspond to different wave speeds and different attenuations. If the rock is filled with water, the electromagnetic properties of the water-filled medium will be affected by the water. The dielectric constant is between water and rock and soil, and the conductivity will also increase significantly [27].

Generally, when electromagnetic waves enter the rock, due to the heat loss of the eddy current, the intensity of electromagnetic waves attenuates as the distance increases. Electromagnetic waves propagate in rock formation. The lower the resistivity of the rock formation, the higher the conductivity and the faster the attenuation [28]. According to the electromagnetic characteristic parameters of some rocks, the resistivity of the rock formations drilled by geological drilling is generally large, which is a good channel for electromagnetic signal transmission. The application of the EM-MWD system to solid mineral deposit exploration and drilling can give full play to the advantages of EM-MWD.

III. ELECTROMAGNETIC WAVE SIGNAL EXCITATION METHOD

In a drilling system, the drill pipe itself can be regarded as a very long metal conductor, and the drill pipe is generally used as a transmitting antenna. The four common electromagnetic wave excitation methods are horizontal electric excitation, vertical electric excitation, horizontal magnetic excitation and vertical magnetic excitation. Limited by the drilling space, the most suitable way of excitation in the well is to excite the axial current guided along the drill pipe, that is, vertical electrical excitation.

The common structure is shown in Fig. 3. The first method is to divide the drill pipe into two electrically insulated parts through an insulating short section to form an asymmetric dipole antenna, and add voltage excitation at both ends of the insulating section. The second method uses the drill rod as a support to wind a coil that is consistent with the axis of the drill rod, and add current excitation to the coil. The last one

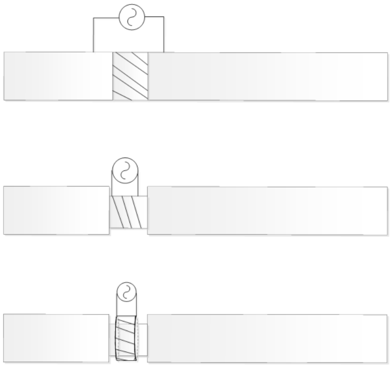

FIGURE 3. Three structural forms.

is to install a spiral ring with a magnetic core on the drill pipe and add current excitation to the coil.

At present, most people adopt the first method, which is easy to implement and analyze. The drill pipe is divided into upper and lower sections with an insulating short section. The two sections must meet the mechanical strength required for electrical insulation and drilling construction. The insulator must be able to withstand very high torque and pressure, and it needs to be made of special materials. The second method does not need to divide the drill rod into two sections, but due to the influence of the drill rod, the effective area of the coil becomes smaller and the excitation effect is weakened. The third method is affected by factors such as the size of the magnetic core, the permeability, the number of coil turns, and the excitation frequency. It is not as direct and efficient as the first method. Therefore, the system adopts the first excitation method.

IV. UNIFORM EQUIVALENT TRANSMISSION LINE MODEL

The actual coal mine underground EM-MWD transmission channel is mainly composed of drill string, mud, casing, and stratum. If the casing is not considered and the stratum is a homogeneous medium, the model can be established as shown in Fig. 4.

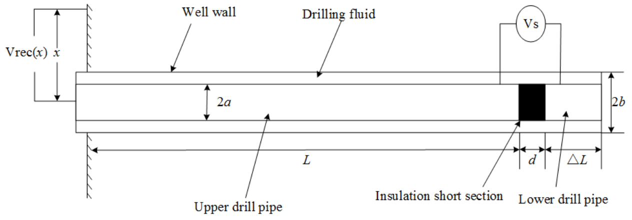

FIGURE 4. **Schematic diagram of uniform equivalent transmission line model.**

The drill pipe radius is a, b is the borehole radius, $a - b$ is the thickness of the mud layer, L is the length of the upper drill pipe, ΔL is the length of the lower drill pipe, d is the equivalent radius of the upper drill pipe transmission line, Δd is the equivalent radius of the lower drill pipe transmission line. The per unit length of the transmission line of series resistance r and series inductance l, parallel conductance g and capacitance c can be expressed as:

$$r_1 = r_2 = \frac{1}{2\pi a \sigma_m \tau \left(1 - \frac{\tau}{2a}\right)} \tag{1}$$

$$g_{1k} = \frac{2\pi \sigma_k}{\ln\left(b_{0k}/b_k\right)} \tag{2}$$

$$g_{2k} = \frac{2\pi \sigma_k}{\ln\left(\Delta b_{0k}/b_k\right)} \tag{3}$$

$$l_1 = \frac{\mu_0}{2\pi} \ln \frac{d}{a} \tag{4}$$

$$l_2 = \frac{\mu_0}{2\pi} \ln \frac{\Delta d}{a} \tag{5}$$

$$c_{1k} = \frac{2\pi \varepsilon_0 \varepsilon_r}{\ln\left(b_{0k}/b_k\right)} \tag{6}$$

$$c_{2k} = \frac{2\pi \varepsilon_0 \varepsilon_r}{\ln\left(\Delta b_{0k}/b_k\right)} \tag{7}$$

where, the subscripts 1, 2 respectively represent the upper and lower drill pipes, τ is the wall thickness of the drill pipe, σ_k is the conductivity of the k-layer medium, b_{0k} is the outer conductor radius of the upper drill pipe, Δb_{0k} is the outer conductor radius of the lower drill pipe, b_k is the outer radius of the k-layer medium, and $k = 1, 2$ represent the mud layer and the stratum. d is the equivalent radius of the upper transmission line, Δd is the equivalent radius of the lower transmission line. σ_m is the conductivity of the drill pipe. μ_0 is the permeability of the formation, assuming that its value is equal to the permeability of the vacuum. ε_0 is the free space permittivity and ε_r is the relative permittivity of the formation. When the total parallel conductance of the transmission line is equal to the conductance between the drill pipe and infinity, the equivalent radius of the transmission line can be calculated using the long spheroid model, there are:

$$d = L \tag{8}$$

$$\Delta d = \Delta L \tag{9}$$

The series impedance per unit length of the transmission line is denoted as Z, which is expressed as:

$$Z_i = r_i + j\omega l_i \tag{10}$$

where, ω is the excitation frequency, j is the unit of imaginary number, and the subscripts $i = 1, 2$ respectively represent the upper drill pipe and the lower drill pipe.

The parallel admittance per unit length of the transmission line is:

$$\frac{1}{Y_i} = \frac{1}{g_{i1} + j\omega c_{i1}} + \frac{1}{g_{i2} + j\omega c_{i2}} \tag{11}$$

The characteristic impedance of the coaxial line formed by the drill pipe and the formation is:

$$Z_{0i} = \sqrt{\frac{Z_i}{Y_i}} = \sqrt{\left(r_i + j\omega l_i\right)\left(\frac{1}{g_{i1} + j\omega c_{i1}} + \frac{1}{g_{i2} + j\omega c_{i2}}\right)} \tag{12}$$

The propagation constant is:

$$\gamma_{0i} = \sqrt{Z_i \cdot Y_i} = \sqrt{\left(r_i + j\omega l_i\right) / \left(\frac{1}{g_{i1} + j\omega c_{i1}} + \frac{1}{g_{i2} + j\omega c_{i2}}\right)} \tag{13}$$

According to the transmission equation of the transmission line, the current and voltage distribution on the drill pipe can be expressed as:

$$V(x) = A_1 e^{-\gamma_{01} x} + A_2 e^{\gamma_{01} x} \tag{14}$$

$$I(x) = \frac{A_1}{Z_{01}} e^{-\gamma_{01} x} - \frac{A_2}{Z_{01}} e^{\gamma_{01} x} \tag{15}$$

where, A_1 and A_2 can be determined by boundary conditions. When the receiving end of the EM-MWD system is approximately open, the excitation end and end conditions are

$I(0) = V_s/Z_T = I_0$, Z_T is the impedance of the transmitting antenna, $I(L) = 0$.

Then, we can get:

$$A_1 = \frac{I_0 Z_{01}}{1 - e^{-2\gamma_{01}L}} \tag{16}$$

$$A_2 = \frac{I_0 Z_{01} e^{-2\gamma_{01}L}}{1 - e^{-2\gamma_{01}L}} \tag{17}$$

Hence, there are:

$$I\left(x\right) = \frac{I_0}{1 - e^{-2\gamma_{01}L}} \left(e^{-\gamma_{01}x} - e^{\gamma_{01}(x-2L)}\right) \tag{18}$$

$$V\left(x\right) = \frac{I_0 Z_{01}}{1 - e^{-2\gamma_{01}L}} \left(e^{\gamma_{01}(x-2L)} + e^{-\gamma_{01}x}\right) \tag{19}$$

When the receiving end is open, the impedance of the transmission line formed by the upper drill pipe and the stratum is recorded as Z_1, and the impedance of the transmission line formed by the lower drill pipe and the stratum is recorded as Z_2, and $Z_T = Z_1 + Z_2$. According to the transmission line theory, there are:

$$Z_1 = Z_{01} \coth\left(\gamma_{01} L\right) \tag{20}$$

$$Z_2 = Z_{02} \coth\left(\gamma_{02} \Delta L\right) \tag{21}$$

and

$$I_0 = \frac{V_S}{Z_1 + Z_2} \tag{22}$$

Therefore, we can obtain:

$$I\left(x\right) = \frac{V_S}{\left(Z_1 + Z_2\right)\left(1 - e^{-2\gamma_{01}L}\right)} \left(e^{-\gamma_{01}x} - e^{\gamma_{01}(x-2L)}\right) \tag{23}$$

$$V\left(x\right) = \frac{V_S Z_{01}}{\left(Z_1 + Z_2\right)\left(1 - e^{-2\gamma_{01}L}\right)} \left(e^{\gamma_{01}(x-2L)} + e^{-\gamma_{01}x}\right) \tag{24}$$

The receiving electrode is arranged at a distance n from the orifice. When $n \ll L$, the receiving voltage between n and infinity mainly depends on the receiving voltage between the orifice and the point at infinity. So, the receiving voltage between the orifice and the receiving electrode n point is:

$$V'(n) = V(L)\frac{\ln(n/a)}{\ln(L/a)} \tag{25}$$

V. SEGMENTED EQUIVALENT TRANSMISSION LINE MODEL

The uniform equivalent transmission line model does not consider the heterogeneity of casing and formation, and cannot predict and evaluate the applicability of the system block based on the block formation resistivity and the system's technical indicators. Therefore, on the basis of the previous uniform equivalent transmission line model, the segmented transmission line theory can be used to consider the heterogeneity of the formation to establish a segmented equivalent transmission line model.

As shown in Fig. 5, the formation model is divided into $N+1$ layers, the last $N+1$ layer is infinitely thick, the drill pipe radius is a, the borehole radius is b, the upper drill pipe length is L, and the lower drill pipe length is ΔL.

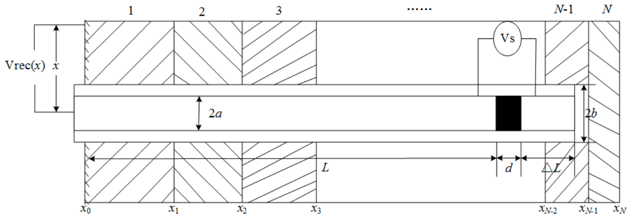

FIGURE 5. Schematic diagram of segmented uniform equivalent transmission line model.

Each layered stratum, drill string and mud form a uniformly equivalent transmission line, and the distribution parameters of the transmission line are calculated by Eq. (1) to (7). According to the theory of uniform equivalent transmission line, the equations of each segment of the transmission line can be obtained, and the connection relationship is as follows:

$$Z_{(m+1)L} = Z_{mi} \tag{26}$$

$$I_{m+1}\left(x_m\right) = I_m\left(x_m\right) \tag{27}$$

$$V_{m+1}\left(x_m\right) = V_m(x_m) \tag{28}$$

Equation (26) indicates that the input impedance of the m section of the transmission line is the load impedance of the $m+1$ section of the transmission line; Eq. (27) and (28) are the current continuous and voltage continuous conditions, respectively. By establishing a uniform equivalent transmission line equation for each segment and using the connection relationship between the segments, we can calculate the current and voltage distribution on the drill pipe.

VI. CALCULATION AND ANALYSIS

In the calculation, the magnetic permeability $\mu_0 = 4\pi \times 10^{-7}$ H/m, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m, the relative permittivity of mud and formation is 10, the parameters of the drill pipe used in the electromagnetic wave while drilling system of the underground coal mine are: drill pipe radius $a = 36.5$ mm, the outer radius of the borehole is 0.05 m, drill pipe wall thickness $\tau = 5$ mm, lower drill pipe length $\Delta L = 5$ m, the orifice receiving electrode spacing $n = 50$ m, the excitation voltage $V_s = 12$ V, the excitation frequency is 10Hz, the drill pipe resistivity is $2.5 \times 10\text{-}7\ \Omega \cdot m$, the formation resistivity is $10\ \Omega \cdot m$, the mud conductivity is 1.0 S/m, and the formation conductivity is 0.1 S/m.

Figure 6 shows the change of signal with transmission depth at different frequencies. It can be seen that the frequency decreases and the attenuation of signal transmission becomes smaller. When the wellhead receiving voltage is constant, the system transmission depth increases.To increase the transmission depth of the system, a transmission frequency within 20 Hz is a better choice.Since other factors affecting transmission are inherently difficult to change,

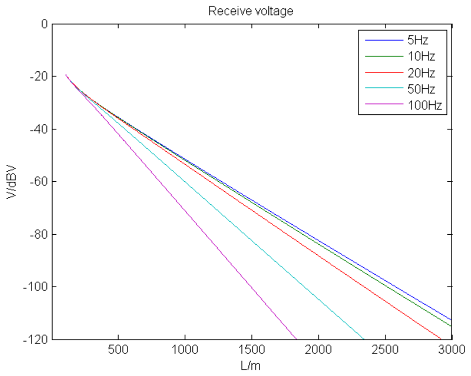

FIGURE 6. Signal attenuation at different frequencies.

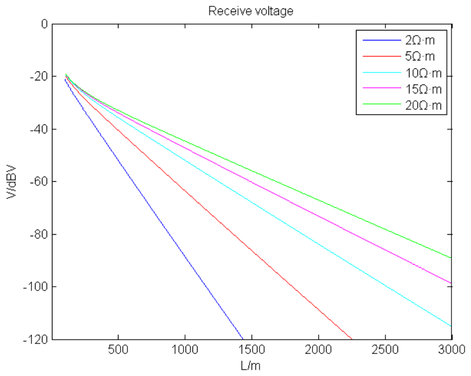

FIGURE 7. Signal attenuation at different formation resistivity.

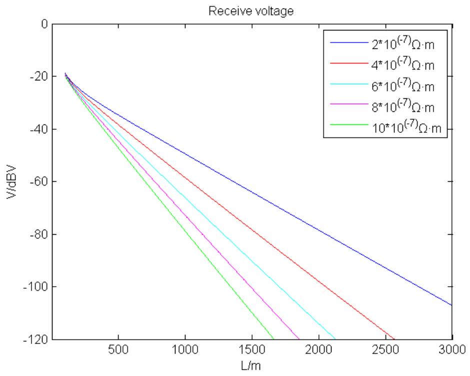

FIGURE 8. Signal attenuation at different drill pipe resistivity.

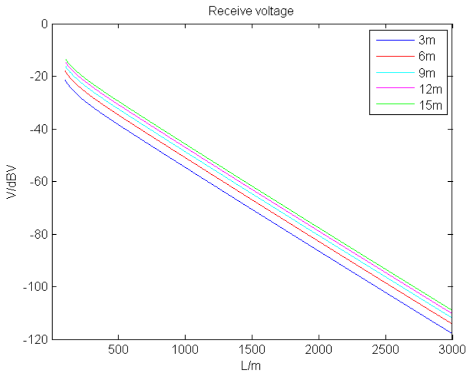

FIGURE 9. Signal attenuation at different lower drill rod lengths.

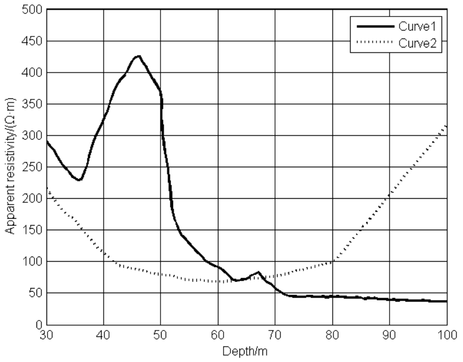

FIGURE 10. Theoretical simulation results when strata are stratified.

the EM-MWD system generally reduces the frequency to increase the transmission depth.

Figure 7 is the change of signal with transmission depth under different formation resistivity. It can be seen that the signal attenuation is greatly affected by the resistivity of the formation, and it decreases with the increase of the resistivity of the formation.In actual applications, the formation resistivity of different blocks is quite different. Therefore, the signal transmission of the EM-MWD system has certain regional applicability.

Figure 8 shows that the drill pipe resistivity has an effect on signal transmission. When the resistance becomes larger, the conductivity of the drill pipe becomes worse, and the signal transmission depth becomes smaller. It can be seen that the lower the resistivity of the drill pipe, the greater the increase in signal transmission depth.

Figure 9 shows the influence of different lower drill rod lengths on signal transmission. As the length of the lower drill rod increases, the signal transmission depth also increases. Therefore, if conditions permit, we can increase the length of the lower drill rod to improve signal transmission depth.

According to literature [29], there is a graph of the measured apparent resistivity in two coal seams in a certain mining area, as shown in Fig. 10. For curve 1, the apparent resistivity first decreases and then increases. The apparent resistivity decreases normally in the 30-70 m section, and the apparent resistivity rises significantly around 80 m, which is caused by faults in the coal seam.The apparent resistivity of curve 2 presents a trend of change from high to low, then increases and decreases at last.The apparent resistivity is attenuated normally at 30-35 m, and then obviously uplifted at about 37 m because of the fault in coal seam. It can be seen that the fault will cause the apparent resistivity to increase significantly. Fig. 11 is the theoretical simulation result when the 30-100 m stratum is stratified. The value of the simulated

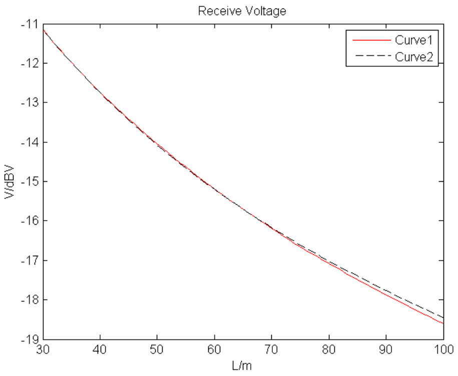

FIGURE 11. Theoretical simulation results when strata are stratified.

FIGURE 12. In-hole launch probe tube.

formation resistivity is shown in Fig. 10. Since the depth is shallow at this time, the difference in voltage attenuation is small.Before 60 m, the wellhead receiving voltage of curve 1 was slightly higher than that of curve 2. After that, the wellhead receiving voltage of curve 2 overtook curve 1. Compared with the uniform transmission line, the simulation result during stratification can better reflect the signal attenuation affected by the resistivity of the formation.

In order to verify the correctness of the theoretical calculations, we developed an MWD system for actual transmission tests. The transmitter in the system hole is shown in Fig. 12, and the receiver is installed in the explosion-proof computer, as shown in Fig. 13.

The comparison results are shown in Fig. 14 and Fig. 15. Fig. 14 is a comparison diagram of the measurement results and calculation results of Well 3341 in Yangquan, China, and

FIGURE 13. Explosion-proof computer with receiver.

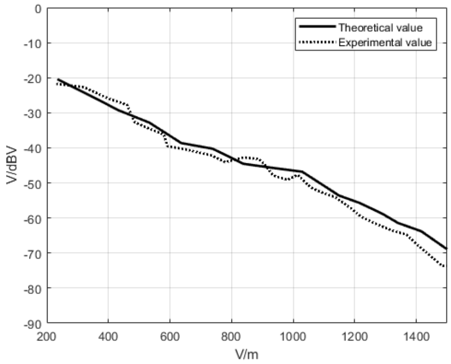

FIGURE 14. Comparison of calculation results and experimental measurement results of Well 3341 in Yangquan, China.

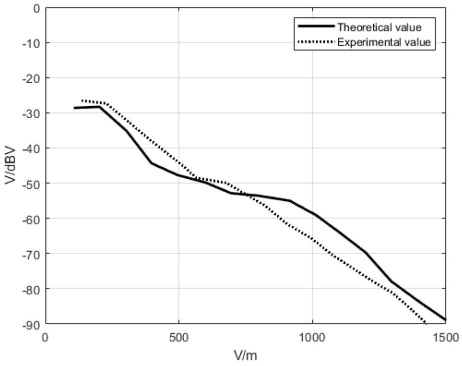

FIGURE 15. Comparison of calculation results and experimental measurement results of Well 2 in Huangling, China.

Fig. 15 is a comparison diagram of the measurement results and calculation results of Well 2 in Huangling, China. It can be seen from the figure that the calculation result and the experimental measurement result signal changes with depth in accordance with the same trend, and the calculated value and the measured value at the same depth point are not much different, which verifies the correctness and applicability of the model. The deviation between the calculated value and the measured value at the same depth point is mainly caused by two factors: one is the simplified processing of the stratum by the model, and the other is that the parameters in the model cannot be accurately obtained, and only approximate values can be used to participate in the calculation.

VII. CONCLUSION

In this study, the approximate equivalent transmission line method is employed to establish the underground EM-MWD electromagnetic transmission channel model, and on this basis, combined with the segmented uniform transmission line theory to establish a theoretical model considering stratification. The main contributions are as follows:

1) The EM-MWD channel simulation analysis is carried out using the equivalent transmission line model. The analysis shows that the formation resistivity, drill pipe resistivity, and transmission frequency are the main factors affecting signal transmission. The signal attenuation increases with the increase of well depth, drill pipe resistivity and transmission frequency, and decreases as the resistivity of the formation increases. Since formation resistivity and drill string resistivity are uncontrollable factors, in actual operation, the transmission frequency is generally reduced to increase the depth of EM-MWD. The most suitable working frequency of EM-MWD is 5 Hz to 15 Hz.
2) Extending the lower transmitting antenna (increasing the length of the drill string below the insulating short section) is beneficial to reduce signal attenuation and increase the signal strength received on the ground, thereby increasing the transmission depth of EM-MWD.
3) The layered transmission line needs to be analyzed in combination with the actual formation resistivity distribution, and the layered equivalent transmission line model can be better used for the evaluation of the regional applicability of the EM-MWD system.

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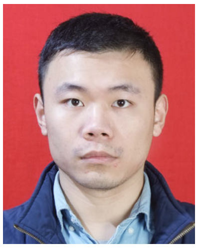

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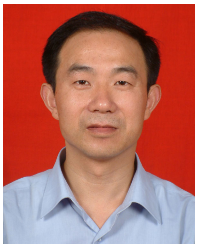

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