

Article

Evaluation of the Capabilities of Grounded-Wire Source Surface-Borehole Transient Electromagnetic Detection in Complex Geological Settings

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Abstract: The surface-borehole transient electromagnetic method exhibits significant advantages in identifying deep targets, as its closer distance to subsurface targets results in more pronounced effective anomalies when compared to surface-based techniques. The grounded-wire source TEM demonstrates enhanced capabilities for deep exploration, featuring increased penetration depth, enhanced signal response, superior resolution, and minimized volume effects, which render it especially effective for examining intricate deep reservoirs. This study utilizes a time-domain finite-element method with unstructured tetrahedral grids to conduct three-dimensional numerical simulations of grounded-wire source SBTEM in complex terrains, capitalizing on the flexibility and precision of this method for modeling detailed geological structures. A comparative analysis of electromagnetic field responses between conductive and high-resistivity targets indicates that the detection capability of magnetic field components decreases more markedly than that of the vertical electric field E_z as the burial depth of the target increases. The grounded-wire source SBTEM exhibits enhanced sensitivity and better identification capabilities for conductive targets when compared to high-resistivity alternatives. The present research represents a detailed analysis of the impact of complex terrain on the detection capabilities of grounded-wire source SBTEM, utilizing electromagnetic response simulations of typical three-dimensional complex geological models. The results provide robust theoretical backing and empirical evidence for an enhanced understanding of subsurface resource exploration.

Keywords: surface-borehole transient electromagnetic method; grounded-wire source; complex geological settings



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1. Introduction

The surface-borehole transient electromagnetic method (SBTEM) was developed in the 1970s and encountered significant advancements in the 1980s, influenced by two main factors. Initially, the substantial borehole resources gathered from mining activities in prominent domestic mining regions offered unparalleled opportunities for SBTEM observation and investigation. The introduction of advanced foreign instrumentation and the optimization of observation environments has led to a significant increase in theoretical, methodological, and applied studies of SBTEM. Recent developments have significantly driven the extremely rapid progress of domestic SBTEM technologies [1–3]. The combined impact of accumulated domestic engineering experience and imported technological innovations significantly improved the technical complexity and practical use of this exploration method.

The SBTEM has proven to be more effective in identifying deep conductive targets, as shown in the foundational study by Dyck and West [4]. Further studies broadened its applications: Spies and Greaves confirmed the high-resolution monitoring capabilities of SBTEM for dynamic oil reservoirs by conducting numerical simulations of the Holt Sand in situ combustion oil reservoir [5]. West et al. utilized a direct integral equation method to analyze borehole TEM responses within realistic geological models, revealing that anomalies arise from complex interactions between eddy currents in the targets and dipole currents [6]. Significant progress in comprehending interference mechanisms was achieved in subsequent decades. Buselli et al. emphasized the significant influence of electromagnetic coupling between conductive layers above and targets on TEM responses [7]. Zhou et al. conducted a numerical investigation into the transient fields induced by magnetic dipoles in roadway anomaly models, uncovering notable early-stage contour distortion in “smoke-ring” fields adjacent to conductive bodies [8]. Recent advancements feature the creation of a 3D finite-element forward-modeling algorithm based on octree meshing [9]. This algorithm methodically assesses borehole effects on electromagnetic responses to tackle the challenges posed by sparse borehole distribution during inversion processes. These milestones highlight SBTEM’s advancing technical capabilities and its essential function in tackling intricate subsurface exploration challenges.

Transient electromagnetic methods are classified into loop-source TEM and grounded-wire source TEM according to the configurations of the transmitters [10,11]. The implementation of loop-source systems presents challenges in mountainous or swampy areas, while grounded-wire source TEM illustrates greater penetration depth and improved adaptability to topographic variations. In recent years, there has been a growing scholarly focus on the advantages of grounded-wire source SBTEM. Chen et al. performed one-dimensional simulations to assess the detection capabilities of grounded-wire source SBTEM, revealing sign reversal phenomena in the E_z and H_x components during subsurface electromagnetic diffusion [12]. Simultaneously, Wu et al. examined the response characteristics and full-domain apparent resistivity of grounded-wire source SBTEM, effectively identifying water-bearing goaf zones in coal mines [13]. Wang et al. advanced computational techniques by developing a three-dimensional forward-modeling algorithm for SBTEM, utilizing a non-structured mesh vector finite-element method [14]. Their studies confirmed the accuracy of algorithms by comparing them to one-dimensional analytical solutions and conducted a systematic analysis of the mechanisms and origins of zero-value zones in E_x and dBy/dt components. These studies collectively demonstrate the evolving technical sophistication and practical versatility of grounded-wire source SBTEM in addressing complex geological exploration challenges. The current issue is that previous research models are relatively simple, mostly one-dimensional, and there is still insufficient understanding of the characteristics of SBTEM responses under complex models.

SBTEM faces particular challenges in data interpretation since conventional surface TEM theoretical models are not applicable in an intuitive way. Current methodologies primarily depend on the qualitative analysis of multi-measurement transient response profiles to estimate the spatial distribution of subsurface anomalies [4,15]. Zhi et al. highlighted the effectiveness of multi-channel response plots for inverting subsurface electrical parameters and identifying geological targets [16]. They demonstrated the practical value of these plots in mineral exploration and groundwater detection using anomaly-derived estimations to determine the position, scale, and burial depth of ore bodies. Xue et al. conducted a systematic investigation into characteristic response curve patterns across various geoelectric models and their relationships with subsurface medium parameters [17]. Their findings underscore the essential role of multi-channel transient profiles in the interpretation of TEM data, supported by both theoretical simulations and field validations. This context

emphasizes that a thorough examination of the grounded-wire source SBTEM response characteristics is essential for precise data interpretation and serves as a fundamental basis for understanding the method's core behavior.

This study employs three-dimensional forward-modeling of grounded-wire source SBTEM in intricate geological settings through a time-domain finite-element method utilizing unstructured tetrahedral grids, capitalizing on their adaptability and precision for heterogeneous subsurface simulations. After validating the algorithm, a systematic analysis of three-dimensional electromagnetic responses from various complex geological models reveals the influence patterns induced by the terrain on the observed SBTEM responses. This research provides a solid foundation for improving detection methods and increasing interpretative precision in challenging exploration scenarios.

2. Forward-Modeling Using FETD Method

The propagation of transient electromagnetic fields induced by grounded-wire sources is governed by Maxwell's equations:

$$\begin{cases} \nabla \times E(r, t) = -\frac{\partial B(r, t)}{\partial t}; \\ \nabla \times H(r, t) = J(r, t) + J_s(r, t). \end{cases} \quad (1)$$

where r denotes the position vector; $E(r, t)$, $B(r, t)$, $H(r, t)$, and $J(r, t)$ represent the electric field intensity, magnetic flux density, magnetic field intensity, and conduction current density at position r and time t , respectively; and $J_s(r, t)$ corresponds to the external source current density at r and t . The relationships that define the current density and magnetic field are expressed as follows:

$$\begin{cases} J = \hat{\sigma} E; \\ B = \mu H. \end{cases} \quad (2)$$

Here, $\hat{\sigma}$ is the anisotropic conductivity tensor; $\mu = \mu_0 \mu_r$ is the permeability; μ_r is the relative permeability; and $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$. Equation (2) is the first behavior differential form of Ohm's law, which is the basic relationship between the second behavior B and H . Equations (1) and (2) can eliminate the magnetic field and obtain the diffusion equation of the electric field in the time domain:

$$\nabla \times \left[\frac{1}{\mu} \nabla \times E(r, t) \right] + \hat{\sigma} \frac{\partial E(r, t)}{\partial t} + \frac{\partial J_s(r, t)}{\partial t} = 0. \quad (3)$$

By transforming Equation (3) into an approximate time-domain finite-element formulation, the residual vector $R(r, t)$ is defined. The computational domain is divided into tetrahedral finite elements, and a weighted residual integration method is utilized to ensure that the residual vector within each element equals zero. The formulation of the weighted residual integral across the computational domain Ω is presented as follows:

$$\int \int \int_{\Omega} W(r) \cdot R(r, t) dV = 0. \quad (4)$$

where $W(r)$ is the weighting coefficient. Its significance is to minimize the inner product of $W(r)$ and $R(r, t)$, that is, $W(r)$ and $R(r, t)$ are orthogonal, to find the optimal solution. Derived from the first vector Green's theorem, the following can be applied:

$$\int \int \int_{\Omega} W(r) \cdot \nabla \times \left[\frac{1}{\mu} \nabla \times E(r, t) \right] dV = \frac{1}{\mu} \int \int \int_{\Omega} (\nabla \times W(r)) \cdot (\nabla \times E(r, t)) dV - \frac{1}{\mu} \int_{\Gamma} W(r) \times (\nabla \times E(r, t)) \cdot ndS. \quad (5)$$

The computational domain is divided into discrete elements utilizing unstructured tetrahedral meshes. This study utilizes vector basis functions to approximate the linearly distributed electric field within the elements, ensuring the automatic enforcement of tangential continuity and divergence-free conditions of the electric field. The electric field at any location within a tetrahedral element can be represented as follows:

$$\begin{cases} 2\Delta t J^{(i+2)}(t) = 3J^{(i+2)}(t) - 4J^{(i+1)}(t) + J^{(i)}(t); \\ (3M + 2\Delta t S)E^{(i+2)}(t) = M[4E^{(i+1)}(t) - \\ E^{(i)}(t)] - 2\Delta t J^{(i+2)}(t). \end{cases} \quad (6)$$

From the first row of Equation (6), the current source term for arbitrary transmitter current waveforms can be derived, while the second row is simplified as follows:

$$KE = b \quad (7)$$

where K denotes the coefficient matrix, E represents the edge-based unknown electric field, and b corresponds to the known source term.

This research utilizes a step-off excitation technique for conducting three-dimensional numerical simulations of grounded-wire source transient electromagnetic phenomena. The initial electric field $E(r, 0)$ is composed of two components: the internal electric field $E_1(r)$ generated by the elongated wire source, and the steady-state DC electric field $E_2(r)$ formed between the positive and negative electrodes at the wire terminals:

$$E(r, 0) = E_1(r) + E_2(r) \quad (8)$$

In computational practice, the electric field within the internal wire is often neglected. However, the steady-state DC electric field $E_2(r)$, produced by subsurface current injection via the positive and negative electrodes, results in a potential gradient. The calculation of this field component can be derived from the negative gradient of the electric potential $\varphi(r)$:

$$E_2(r) = -\nabla\varphi(r). \quad (9)$$

The point source is located at $r_s = (x_s, y_s, z_s)$, and the current intensity is I . Based on Ohm's law and the continuity of the electric field in the differential form in Equation (2), the following results can be obtained:

$$\nabla \cdot J(r) = I\delta(r - r_s). \quad (10)$$

Here, $J(r)$ denotes the current density at position r , and δ represents the impulse function.

The Poisson equation, which describes the electric field generated by positive and negative point sources, can be derived by reapplying the differential form of Ohm's law:

$$\nabla \cdot (\sigma \nabla \varphi(r)) = -I\delta(r - r_s). \quad (11)$$

Finally, to maintain consistency in boundary conditions between the DC and time-domain electric fields, both fields are calculated using the same tetrahedral mesh discretization and integrated through a total-field formulation. Considering that the truncation boundaries of the computational domain are placed at a considerable distance from the transmitter source, the external boundaries Γ are consistently applied with Dirichlet boundary conditions in the numerical simulations:

$$\begin{cases} \varphi|_{\Gamma} = 0; \\ (n \times E)|_{\Gamma} = 0. \end{cases} \quad (12)$$

A homogeneous half-space model (Figure 1) was constructed to verify the accuracy of the proposed algorithm. The transmitter source, oriented along the x-axis, measured 200 m in length, was positioned at the coordinates $(-2000 \text{ m}, 0 \text{ m}, 0 \text{ m})$, and operated with a current intensity of 1 A. The air layer resistivity was set to $10^8 \Omega \cdot \text{m}$, while the homogeneous subsurface resistivity was $10 \Omega \cdot \text{m}$. The receiver was positioned at the origin $(0 \text{ m}, 0 \text{ m}, 0 \text{ m})$. Figure 2 illustrates the comparative analysis between the ex-field data computed using the proposed algorithm and the results obtained from the open-source software CSEM1D [18]. The two datasets exhibit strong consistency, with a maximum relative error under 3%, effectively confirming the reliability and accuracy of the developed algorithm.

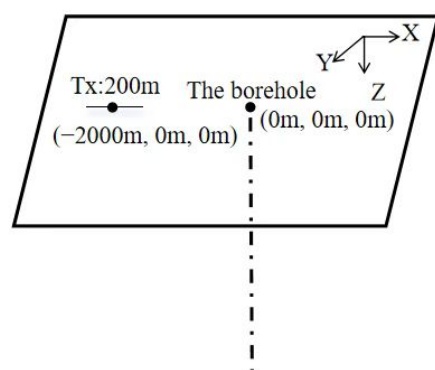


Figure 1. Schematic diagram of a homogeneous half-space model.

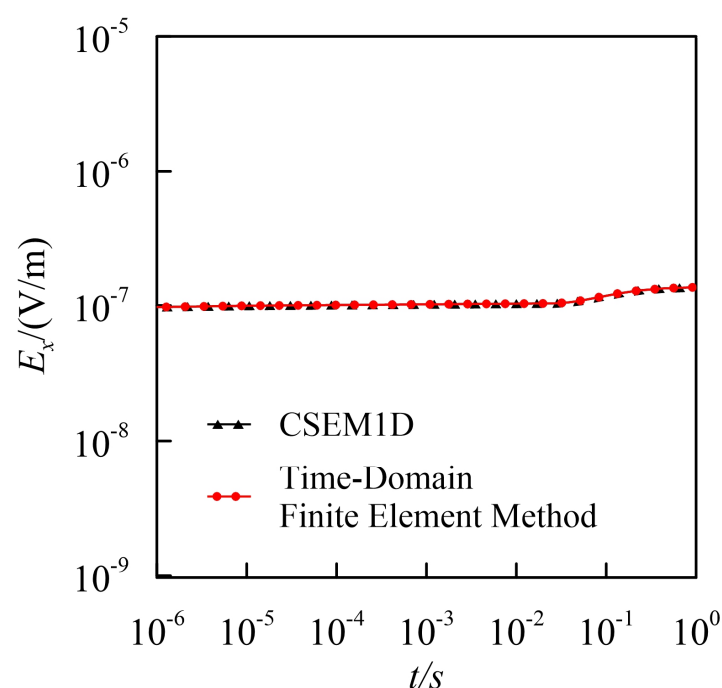


Figure 2. The results of the accuracy verification.

3. Analysis of the Sounding Capability of Grounded-Wire Source SBTEM

In order to assess the depth-resolving capabilities of the grounded-wire source SBTEM for targets located at different burial depths, a three-dimensional geoelectric model was created for forward-modeling purposes. The configuration of the model parameters is explained as follows: A long-wire transmitter Tx with a 400 m length was deployed along the x-axis, centered at $(0 \text{ m}, -1200 \text{ m}, 0 \text{ m})$, and energized with a 1 A current. The air layer resistivity was set to $10^8 \Omega \cdot \text{m}$, while the bedrock resistivity was $100 \Omega \cdot \text{m}$. A target with dimensions of $200 \text{ m} \times 200 \text{ m} \times 100 \text{ m}$ was located at depths of 1000 m and 2000 m,

respectively. Observation boreholes were drilled to depths of 1500 m and 2500 m, with measurement points positioned at 50 m intervals. The transient responses of E_z , dBx/dt , dBy/dt , and dBz/dt fields were analyzed across three time channels to characterize their spatial–temporal evolution patterns.

3.1. Conductive Target

Figure 3 presents the computational outcomes. Panels (a) and (d) illustrate the E_z field response curves without a conductive target, whereas panels (b) and (e) show the E_z responses with targets located at depths of 1000 m and 2000 m, respectively. The comparative analysis shows that the response curve morphologies for both burial scenarios are nearly identical. In the specified depth intervals, the field amplitudes show a marked decrease, along with noticeable waveform distortions which feature single-peak anomalies, which indicate target positions at depths of 950–1050 m and 1950–2050 m. Furthermore, the extremal points in the E_z response curves are in close alignment with the upper and lower boundaries of the target.

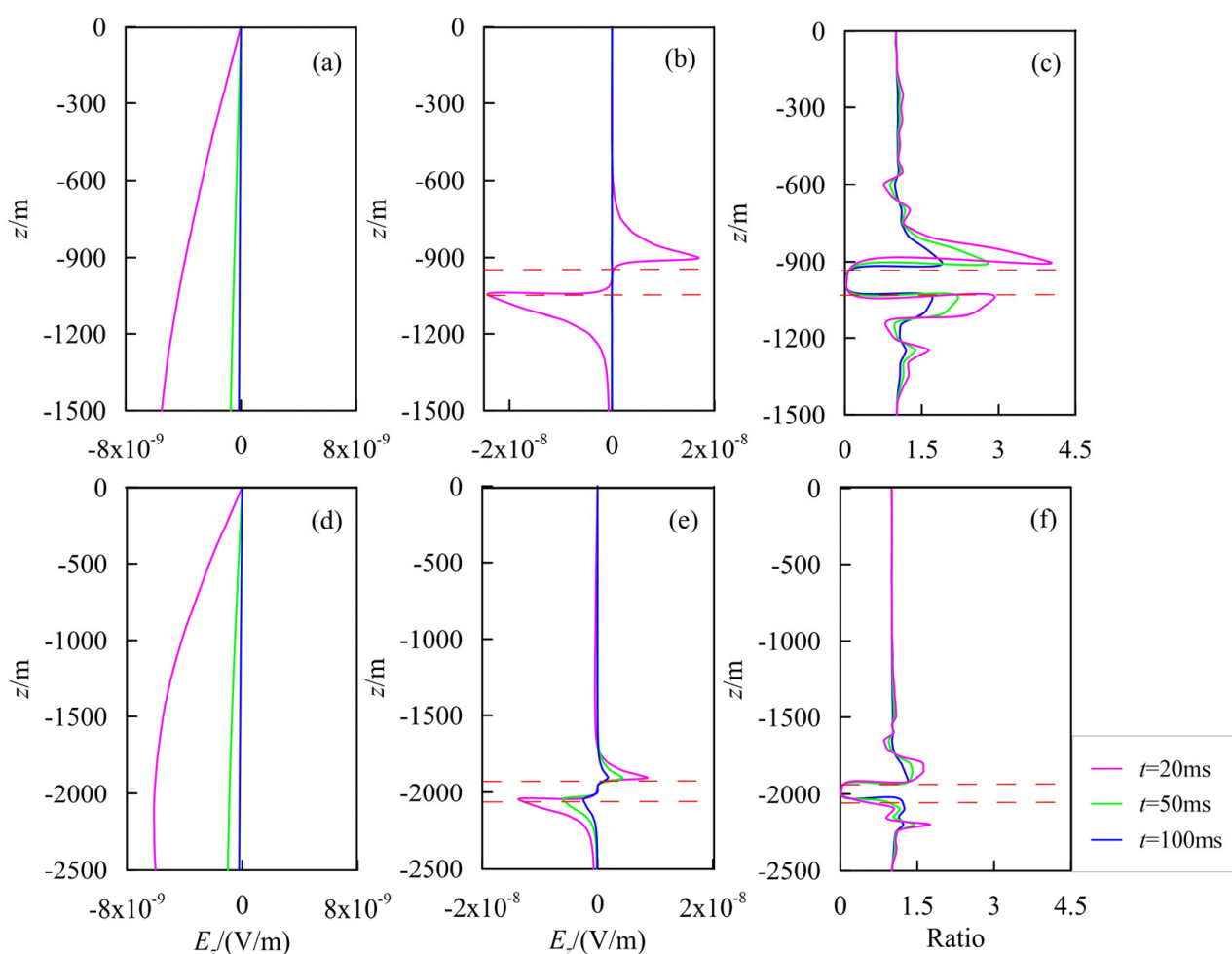


Figure 3. E_z response curves of conductive targets at different burial depths: (a,d) E_z responses of the uniform half-space; (b,e) E_z responses with target bodies buried at 1000 m and 2000 m depths, respectively; and (c,f) ratios between responses with and without target bodies at 1000 m and 2000 m burial depths, respectively.

To interpret the anomalies systematically induced by the target, the total field was normalized by calculating the ratio between scenarios with the target and those without, as illustrated in the relative anomaly curves in Figure 3c,f. The curves demonstrate significant

distortions at designated locations, where extreme values align with target boundaries, facilitating accurate target localization. In the case of a 1000 m burial depth, the relative anomalies of the E_z field are observed to be a maximum of 2.99 and a minimum of 0.02. At a burial depth of 2000 m, the values decrease to 1.75 and 0.014. This shows that, as the target depth increases, the extremal range of E_z relative anomalies decreases, suggesting a reduction in resolution; however, the magnitudes of the residual anomalies continue to be substantial. The results validate the robust discriminative ability of the E_z field for conductive targets, maintaining a high detection accuracy even at considerable depths.

Figure 4 displays the computational results. Panels (a) and (d) display the dBx/dt field response curves without a conductive target, whereas panels (b) and (e) depict the dBx/dt responses for targets located at depths of 1000 m and 2000 m, respectively. The comparative analysis shows that the response curve morphologies for both burial scenarios are nearly identical. In the late-stage decay, the amplitude of the magnetic field decreases gradually, with the response curves mainly indicating the characteristics of the background field. This phenomenon is due to the temporal influence being more significant than the spatial dependence in late-time transient electromagnetic signals. With an increase in target burial depth, the dBx/dt field magnitude progressively strengthens; however, within the specified target depth intervals, field amplitudes significantly diminish, accompanied by clear waveform distortions that distinctly indicate target positions at depths of 950–1050 m and 1950–2050 m. The extrema in the dBx/dt response curves are in close alignment with the upper and lower boundaries of the target.

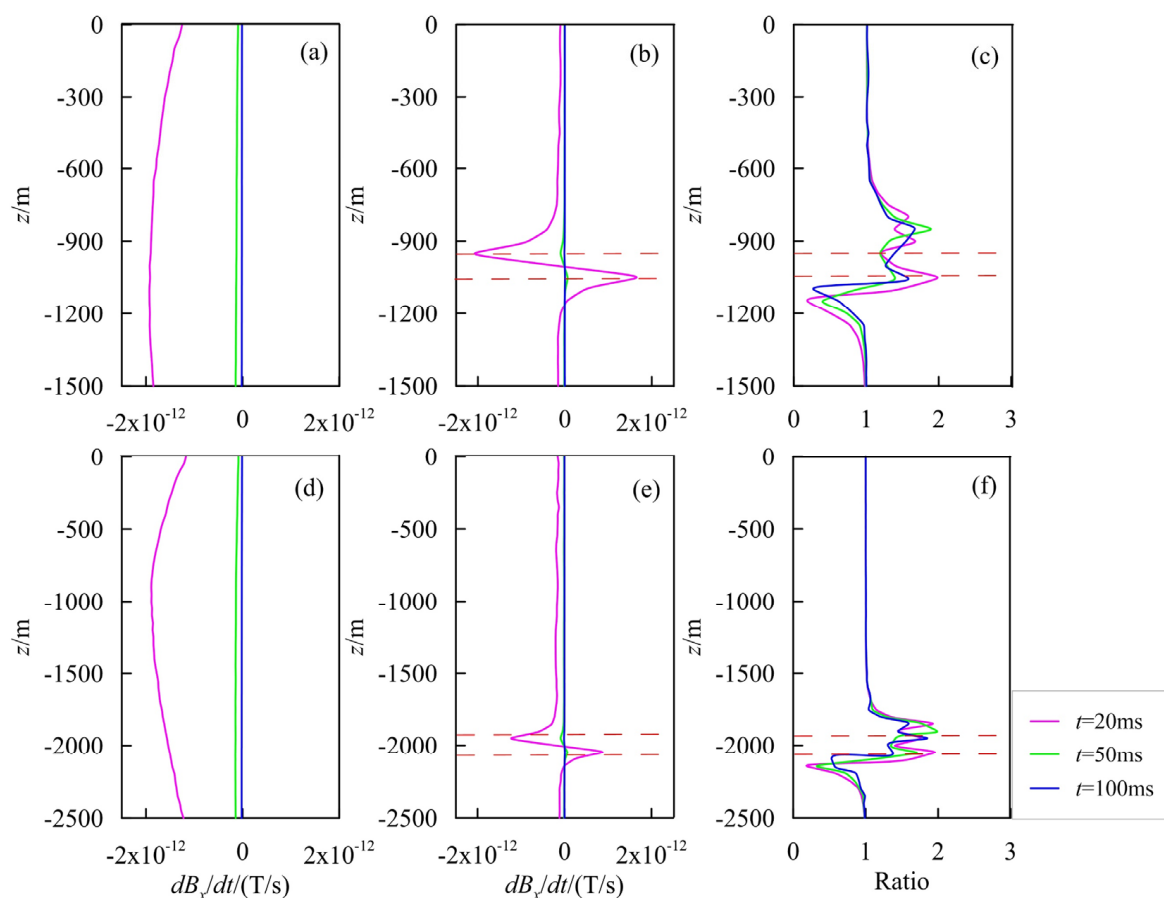


Figure 4. dBx/dt response curves of conductive targets at different burial depths: (a,d) dBx/dt responses of the uniform half-space; (b,e) dBx/dt responses with target bodies buried at 1000 m and 2000 m depths, respectively; and (c,f) ratios between responses with and without target bodies at 1000 m and 2000 m burial depths, respectively.

Figure 4c,f demonstrate significant distortions in the dBx/dt relative anomaly curves at target locations. For the 1000 m burial depth, the maximum and minimum relative anomalies of the dBx/dt field are 1.98 and 0.19, respectively. The values decrease to 1.95 and 0.19 for the 2000 m burial scenario, suggesting a gradual contraction in the extremal range of relative anomalies and a corresponding decline in resolution as the target depth increases. In comparison to the Ez component, the dBx/dt field shows a reduced ability to discriminate conductive targets, especially in the detection of deeper anomalies.

The computational results are illustrated in Figure 5. Panels (a) and (d) depict the dBy/dt field response curves in the absence of a conductive target, while panels (b) and (e) present the dBy/dt responses for targets buried at 1000 m and 2000 m depths, respectively. As observation time and burial depth increase, the dBy/dt anomaly response gradually attenuates. In the late-stage decay phase, the response curves primarily indicate the characteristics of the background field. The curves within the specified depth intervals show notable distortions, featuring distinct extremal points that indicate target positions at depths of 950–1050 m and 1950–2050 m. The extremal points are closely aligned with the central position of the targets.

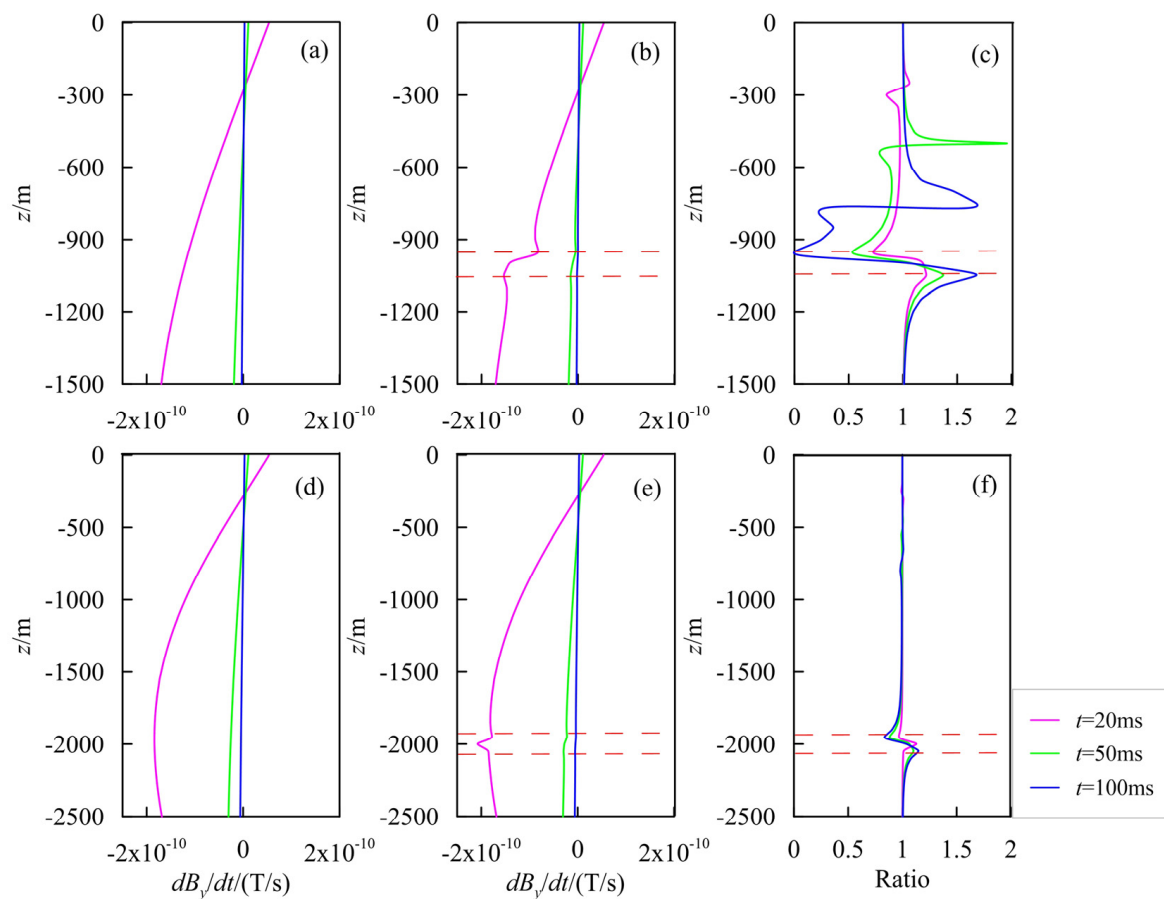


Figure 5. dBy/dt response curves of conductive targets at different burial depths: (a,d) dBy/dt responses of the uniform half-space; (b,e) dBy/dt responses with target bodies buried at 1000 m and 2000 m depths, respectively; and (c,f) ratios between responses with and without target bodies at 1000 m and 2000 m burial depths, respectively.

Figure 5c,f indicate that, at a burial depth of 1000 m, the relative anomalies of the dBy/dt field reach a maximum of 1.95 and a minimum of 0.005. As the burial depth reaches 2000 m, the corresponding values diminish to 1.13 and 0.83. This shows a significant decrease in the extremal range of dBy/dt relative anomalies and a related reduction in

resolution as the target depth increases. The findings indicate that the burial depth of conductive targets has a significant effect on the detection capability of the dBz/dt field, which shows reduced discriminative performance, especially in identifying deeper anomalies.

The computational results are presented in Figure 6. Panels (a) and (d) display the dBz/dt field response curves in the absence of a conductive target, while panels (b) and (e) illustrate the dBz/dt responses for targets buried at 1000 m and 2000 m depths, respectively. The anomaly responses, similar to the dBx/dt and dBz/dt response curves, are primarily concentrated in the initial stages, exhibiting weaker anomalies in the later stages, where the curves mainly represent background field data. The response curves within the specified depth intervals show notable distortions, featuring distinct extremal points that indicate target positions at depths of 950–1050 m and 1950–2050 m. The extremal points are closely aligned with the central position of the targets.

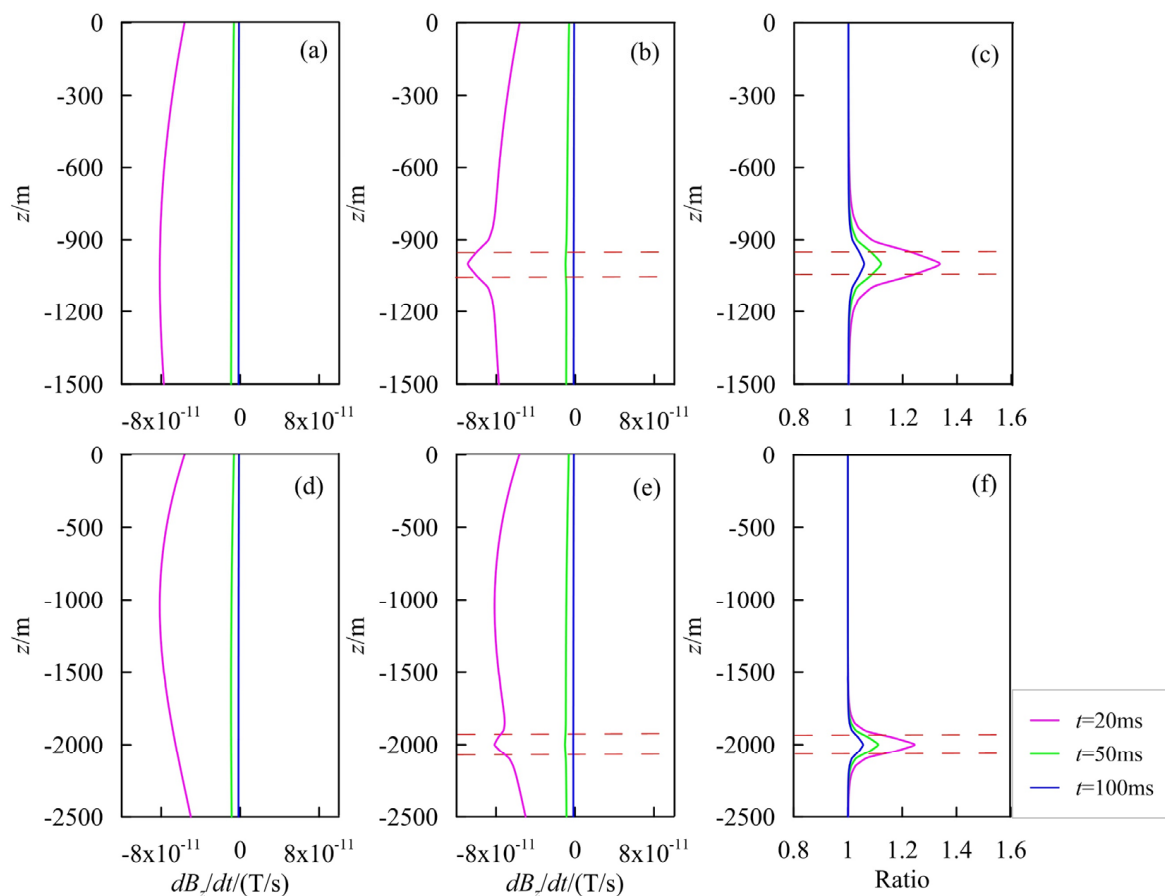


Figure 6. dBz/dt response curves of conductive targets at different burial depths: (a,d) dBz/dt responses of the uniform half-space; (b,e) dBz/dt responses with target bodies buried at 1000 m and 2000 m depths, respectively; and (c,f) ratios between responses with and without target bodies at 1000 m and 2000 m burial depths, respectively.

Figure 6c,f indicate that, at a burial depth of 1000 m, the relative anomalies of the dBz/dt field reach a maximum of 1.34 and a minimum of 0.99. As the burial depth reaches 2000 m, the corresponding values diminish to 1.25 and 0.99. This indicates a notable reduction in the extremal range of dBz/dt relative anomalies and a corresponding decline in resolution with increasing target depth. The dBz/dt field shows a reduced ability to discriminate conductive targets in comparison to the Ez component, especially in the detection of deeper anomalies.

The burial depth of conductive targets affects the depth-resolving capabilities of all magnetic field components (dBx/dt , dBz/dt , dBz/dt), which are notably less effective

compared to the vertical electric field E_z . This indicates that the E_z field could provide enhanced resolution and detection capabilities in SBTEM applications for investigating deeper reservoirs.

3.2. High-Resistivity Target

In order to assess the depth-resolving capabilities of various SBTEM field components, the conductive target was substituted with a high-resistivity target, maintaining its resistivity at $1000 \Omega\cdot\text{m}$ while all other parameters remained constant. The responses of the electromagnetic anomaly in the SBTEM fields were examined for high-resistivity targets located at depths of 1000 m and 2000 m, respectively.

Figure 7 illustrates the computational results. Panels (a) and (d) illustrate the E_z field response curves without a high-resistivity target, whereas panels (b) and (e) show the E_z responses for targets located at depths of 1000 m and 2000 m, respectively. The comparative analysis shows that the response curve morphologies and characteristics for both burial scenarios are nearly identical. With an increase in burial depth, the response curves show notable distortions within the specified target depth intervals, marked by distinct single-peak anomalies which effectively indicate target positions at depths of 950–1050 m and 1950–2050 m. Furthermore, the E_z response curves exhibit two extremal points on one side of the target depth, which closely align with the upper and lower boundaries of the target.

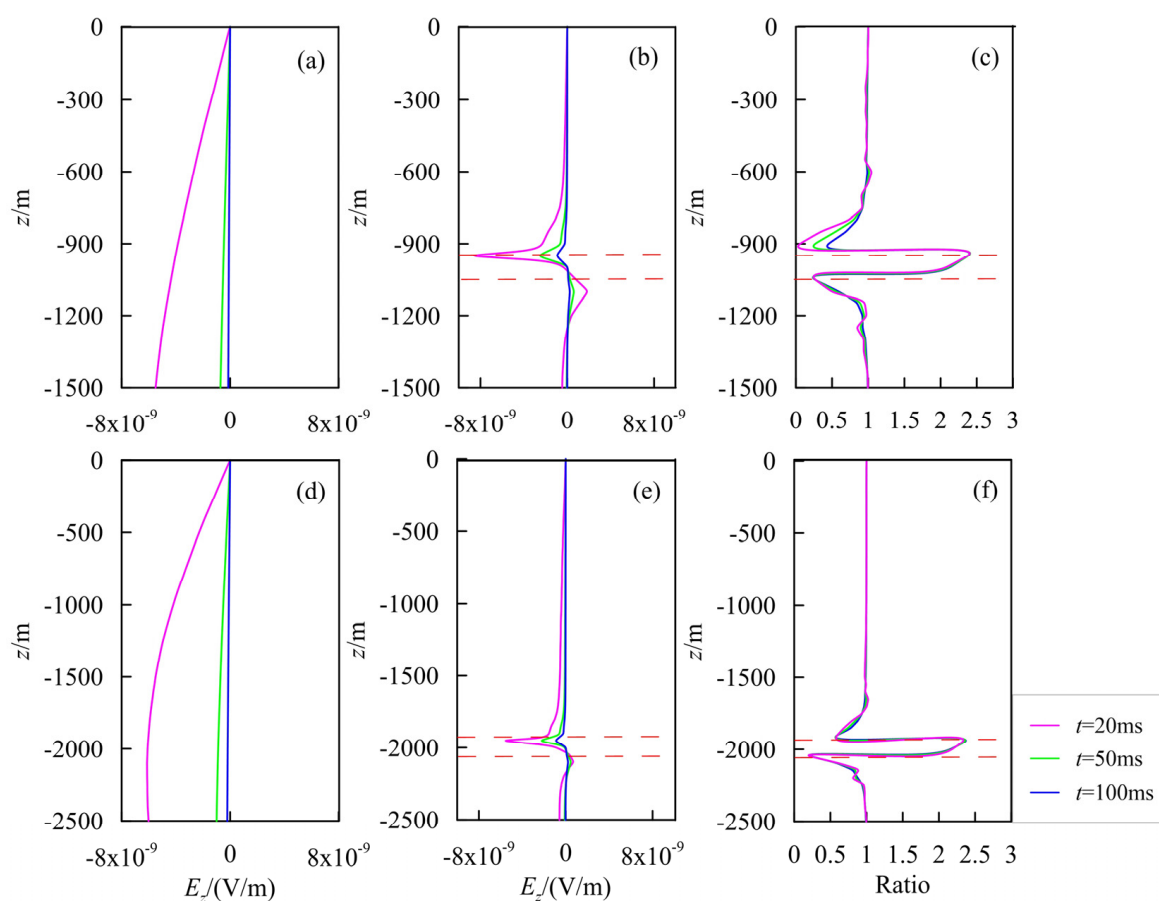


Figure 7. E_z response curves of high-resistivity targets at different burial depths: (a,d) E_z responses of the uniform half-space; (b,e) E_z responses with target bodies buried at 1000 m and 2000 m depths, respectively; and (c,f) ratios between responses with and without target bodies at 1000 m and 2000 m burial depths, respectively.

Figure 7c,f illustrate significant distortions in the E_z relative anomaly curves at target locations, with extremal points closely aligned with the target boundaries, facilitating accurate target identification. The relative anomalies of the E_z field at a burial depth of 1000 m are observed to be a maximum of 2.39 and a minimum of 0.005. Conversely, at a burial depth of 2000 m, the values change to 2.34 and 0.59. This shows a gradual decrease in the extremal range of E_z relative anomalies and a related reduction in resolution as the target depth increases. However, the overall anomaly magnitudes remain substantial, highlighting the robust discriminative ability of the E_z field for high-resistivity targets, even at increased depths.

The computational results are presented in Figure 8. Panels (a) and (d) present the dB_x/dt field response curves without a high-resistivity target, whereas panels (b) and (e) depict the dB_x/dt responses for targets located at depths of 1000 m and 2000 m, respectively. With increasing burial depth, the dB_x/dt field magnitude progressively strengthens, and the response curves show notable distortions within the specified target depth intervals, clearly indicating target locations at depths of 950–1050 m and 1950–2050 m. Figure 8c,f demonstrate significant distortions in the dB_x/dt relative anomaly curves at target locations, with extremal points nearly coinciding with the target boundaries, thereby offering a solid foundation for the precise identification of target edges.

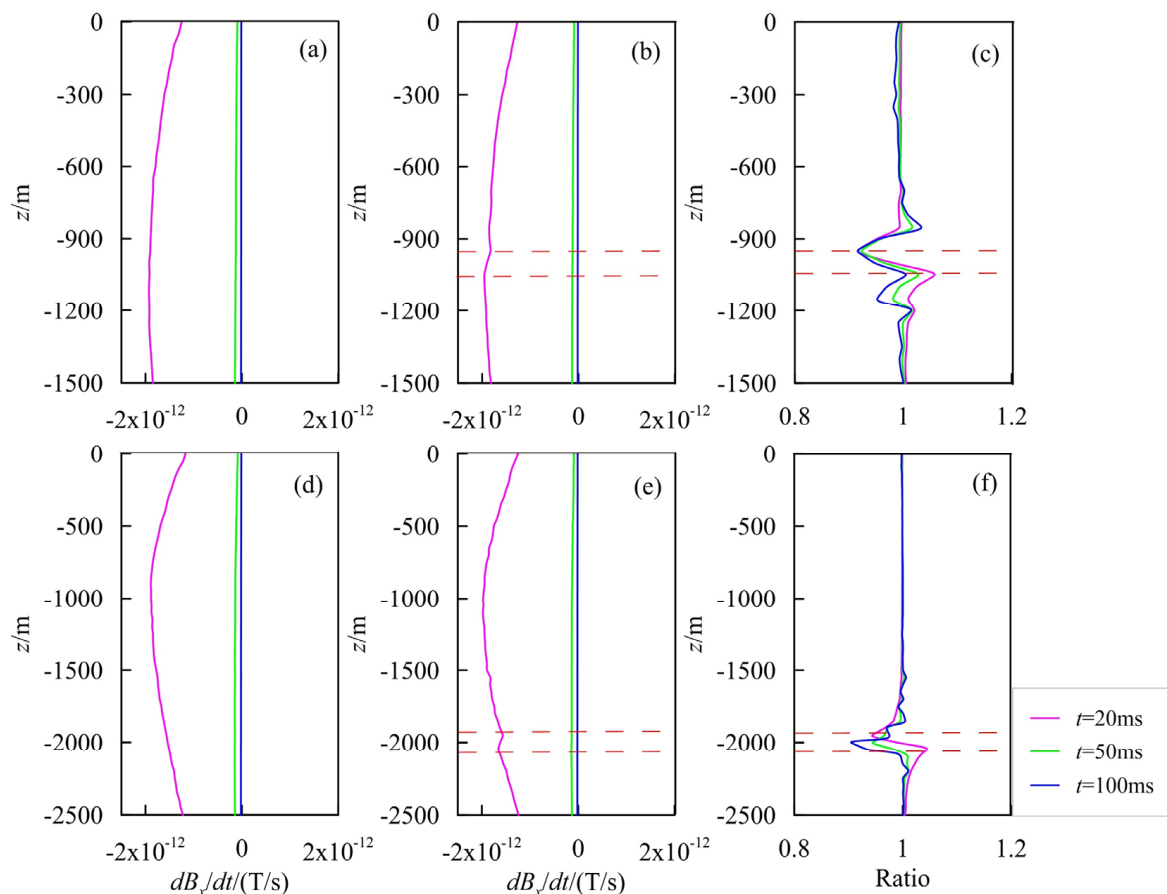


Figure 8. dB_x/dt response curves of high-resistivity targets at different burial depths: (a,d) dB_x/dt responses of the uniform half-space; (b,e) dB_x/dt responses with target bodies buried at 1000 m and 2000 m depths, respectively; and (c,f) ratios between responses with and without target bodies at 1000 m and 2000 m burial depths, respectively.

The maximum and minimum relative anomalies of the dB_x/dt field at a burial depth of 1000 m are 1.04 and 0.91, respectively. Conversely, as the burial depth reaches 2000 m, the values adjust to 1.02 and 0.91. This shows a gradual decrease in the extremal range of dB_x/dt

relative anomalies, along with a corresponding reduction in resolution as target depth increases. The dBx/dt field demonstrates a reduced ability to discriminate high-resistivity targets in comparison to the Ez field, especially in the detection of deeper anomalies.

Figure 9 illustrates the computational results. Panels (a) and (d) explain the dBy/dt field response curves without a high-resistivity target, whereas panels (b) and (e) show the dBy/dt responses for targets located at depths of 1000 m and 2000 m, respectively. With an increase in the observation time and burial depth, the anomaly response diminishes progressively. The response curves from later stages and deeper boreholes mainly indicate background field data. Within the specified depth intervals, the response curves show negligible distortions, which complicates the clear identification of the target.

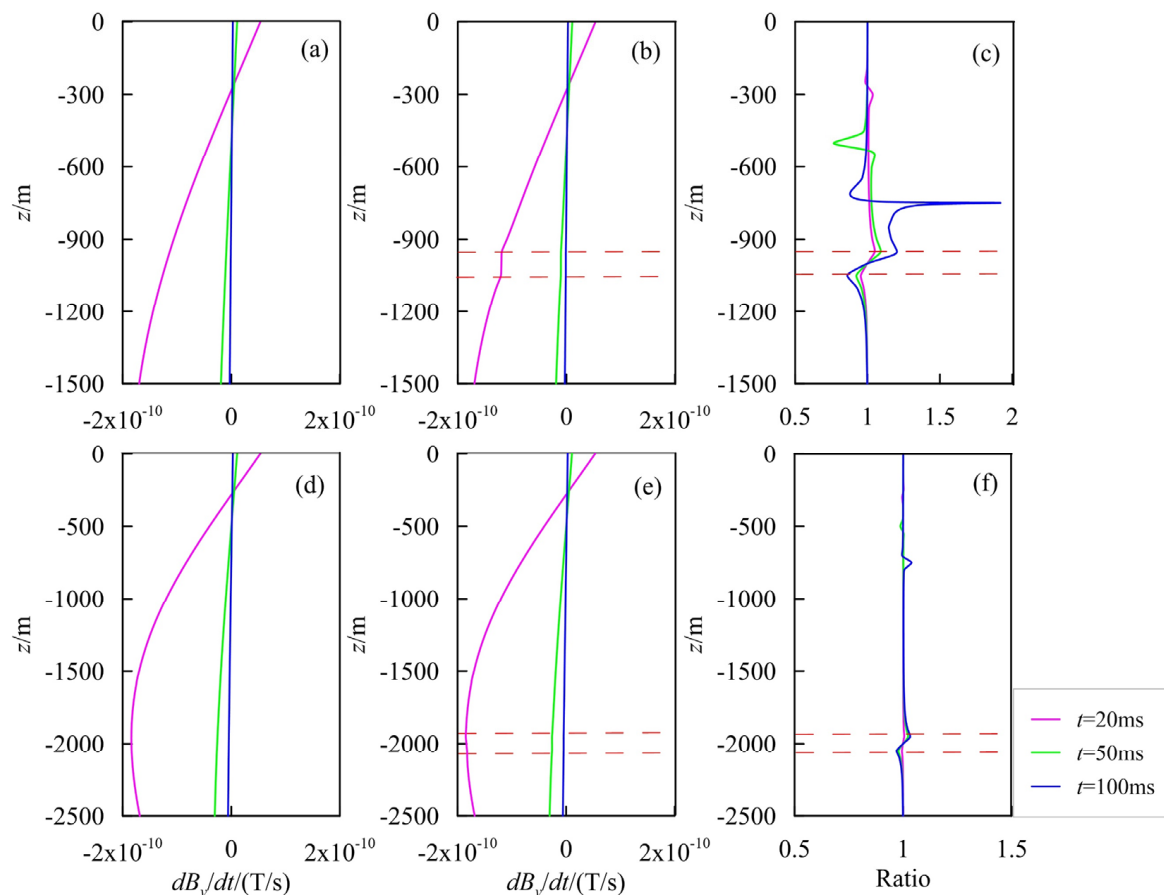


Figure 9. dBy/dt response curves of high-resistivity targets at different burial depths: (a,d) dBy/dt responses of the uniform half-space; (b,e) dBy/dt responses with target bodies buried at 1000 m and 2000 m depths, respectively; and (c,f) ratios between responses with and without target bodies at 1000 m and 2000 m burial depths, respectively.

Figure 9c,f indicate that, at a burial depth of 1000 m, the dBy/dt field exhibits maximum and minimum relative anomalies of 1.91 and 0.86, respectively. Conversely, as the burial depth reaches 2000 m, the values diminish to 1.04 and 0.96. This indicates a significant decrease in the extremal range of dBy/dt relative anomalies, along with a related drop in resolution as the target depth increases. The findings indicate that the burial depth of the target significantly affects the depth-resolving capability of the dBy/dt field, which shows reduced discriminative performance for high-resistivity targets, especially in the detection of deeper anomalies.

The computational results are presented in Figure 10. Panels (a) and (d) present the dBz/dt field response curves without a high-resistivity target, whereas panels (b) and (e)

depict the dBz/dt responses for targets located at depths of 1000 m and 2000 m, respectively. The anomaly responses, akin to the dBx/dt and DBy/dt response curves, are primarily concentrated in the initial stages, exhibiting weaker anomalies in the later stages, where the curves mainly represent background field data.

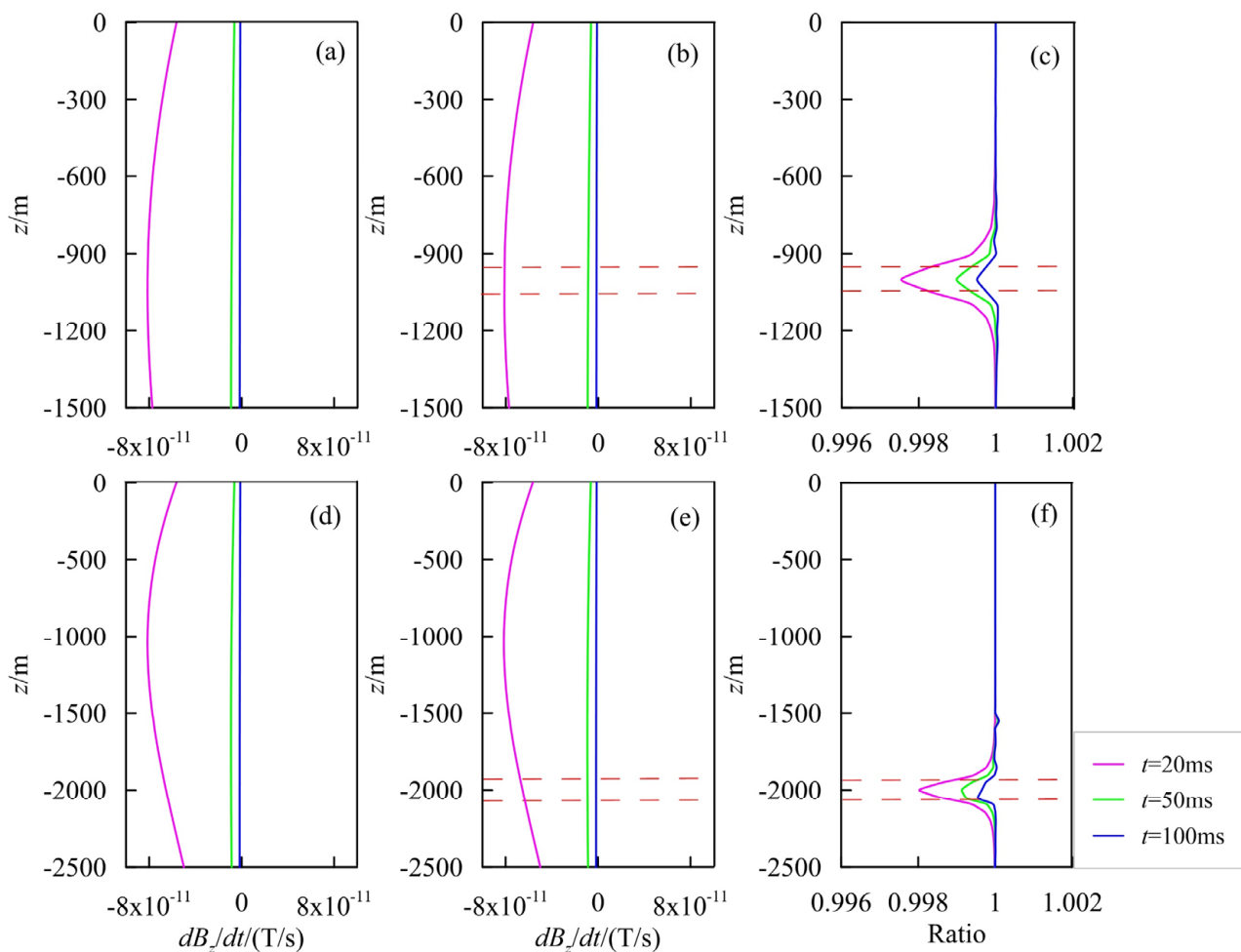


Figure 10. dBz/dt response curves of high-resistivity targets at different burial depths. (a,d) dBz/dt responses of the uniform half-space; (b,e) dBz/dt responses with target bodies buried at 1000 m and 2000 m depths, respectively; and (c,f) ratios between responses with and without target bodies at 1000 m and 2000 m burial depths, respectively.

Figure 10c,f indicate that, at a burial depth of 1000 m, the maximum and minimum relative anomalies of the dBz/dt field are 1.01 and 0.997, respectively. Conversely, at a burial depth of 2000 m, the values adjust to 1.01 and 0.998. This shows a minor decrease in the extremal range of dBz/dt relative anomalies as the target depth increases. However, the changes are minimal, and the magnitudes of the anomalies continue to be very small. In comparison to the Ez field, the dBz/dt field shows a reduced ability to discriminate high-resistivity targets, especially when identifying deeper anomalies.

In general, the burial depth of high-resistivity targets affects the depth-resolving capabilities of all magnetic field components (dBx/dt , DBy/dt , dBz/dt), which are notably less effective compared to the vertical electric field Ez . This indicates that the Ez field could provide enhanced resolution and detection capabilities when investigating deeper reservoirs.

4. Analysis of Response Characteristics of the SBTEM in Complex Terrain Conditions

4.1. Conductive Metal Ore Target

A three-dimensional geoelectric model was designed to investigate the electromagnetic response characteristics of the grounded-wire source SBTEM in complex deep reservoir exploration, as illustrated in Figures 11 and 12. The transmitter measured 400 m in length and was positioned at the coordinates (0 m, −1200 m, 0 m), with a current of 1 A flowing through it. The resistivity of the air was established at $10^8 \Omega \cdot \text{m}$, whereas the resistivity of the bedrock was measured at $500 \Omega \cdot \text{m}$. The second sedimentary layer exhibited a resistivity of $333.3 \Omega \cdot \text{m}$ and encompassed an irregular conductive metal ore characterized by a resistivity of $1 \Omega \cdot \text{m}$. The third layer, made up of mudstone, exhibited a resistivity of $100 \Omega \cdot \text{m}$, while the upper sedimentary layer showed a resistivity of $200 \Omega \cdot \text{m}$. The dimensions of the metal ore were 1200 m in the x-direction, 600 m in the y-direction, and 500 m in the z-direction, with the center located at the coordinates (0 m, 0 m, −600 m). To analyze the electromagnetic response characteristics of the anomaly in boreholes positioned at varying horizontal distances, seven boreholes were strategically placed at $x = 0 \text{ m}$, $x = \pm 200 \text{ m}$, $x = \pm 400 \text{ m}$, and $x = \pm 600 \text{ m}$, arranged sequentially along the x-axis.

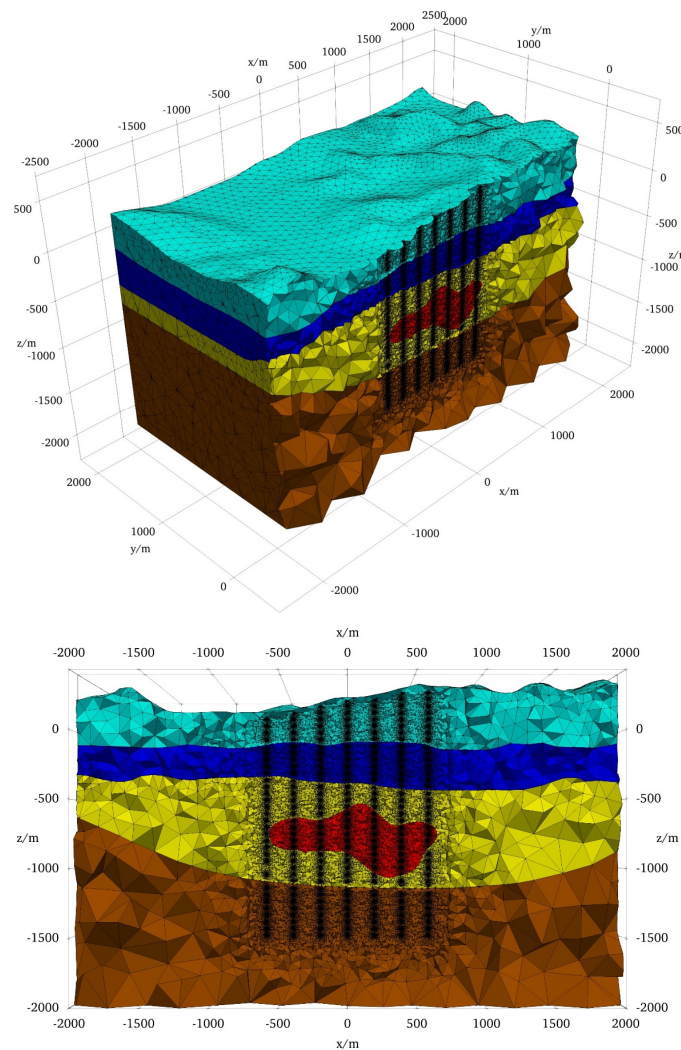


Figure 11. Complex deep reservoir model diagram. The cyan represents the air layer with a resistivity of $10^8 \Omega \cdot \text{m}$; the blue represents the bedrock with a resistivity of $500 \Omega \cdot \text{m}$; the yellow represents the sedimentary layer with a resistivity of $333.3 \Omega \cdot \text{m}$; the brown represents the bedrock with a resistivity of $100 \Omega \cdot \text{m}$; the red represents the conductive metal ore with a resistivity of $1 \Omega \cdot \text{m}$.

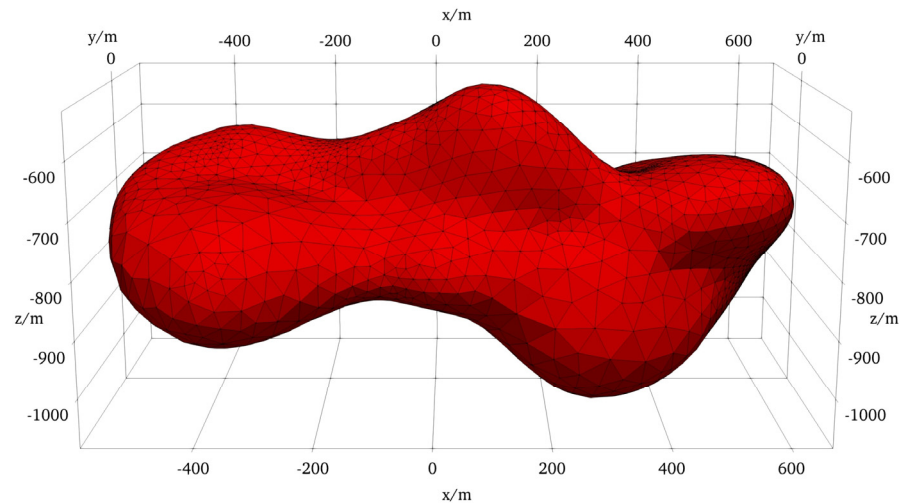


Figure 12. Complex irregular anomalous body diagrams.

Figure 13 presents the computational results, illustrating the E_z field response curves across various boreholes within the complex deep reservoir model which includes the metal ore. The E_z response curves display unique shapes that correspond to changes in formation resistivity, clearly outlining the locations of various strata. The most significant curve inflection corresponds to the location of the metal ore, while the extremal points indicate the boundaries of the ore, effectively delineating its presence. The maximum relative anomaly of the E_z field is 15. When the borehole intersects a reduced volume of the metal ore or moves further away from it, the amplitude of the E_z response curve decreases, leading to a gradual decline in resolution.

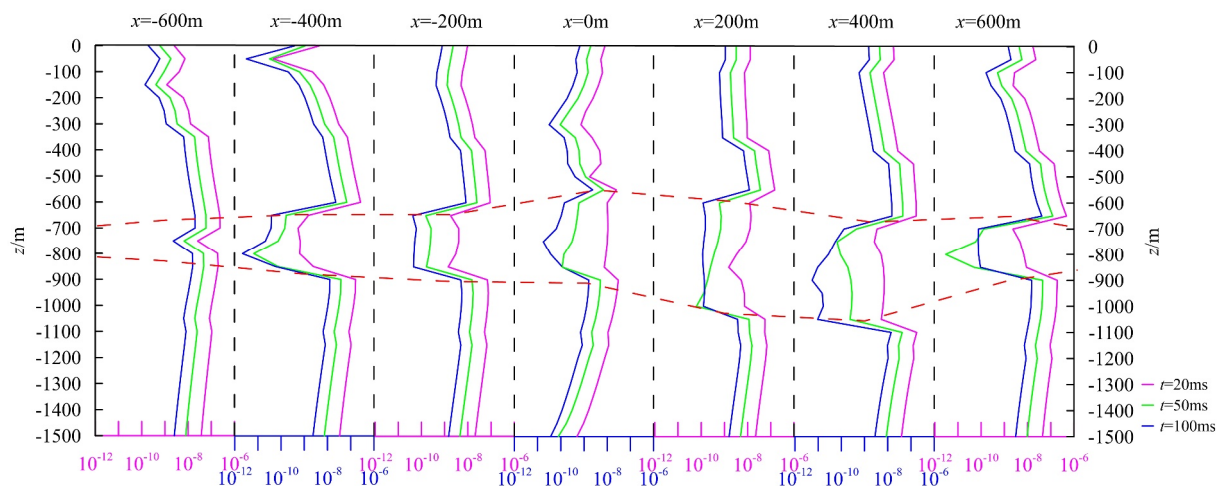


Figure 13. The response curve of the E_z field in different drill holes when the complex deep reservoir model contains metallic minerals.

Figures 14–16 illustrate the dBx/dt , dBy/dt , and dBz/dt field response curves across various boreholes for the model which includes the metal ore. Boreholes that intersect the metal ore show distinct anomaly responses. The maximum relative anomalies of the dBx/dt field, dBy/dt field, and dBz/dt field are 12.4, 6.8, and 9.3, respectively, demonstrating a high level of sensitivity. In areas beyond the metal ore, the dBy/dt and dBz/dt response curves exhibit minimal variations, with the anomaly signals nearly hidden by the background field. Overall, out of all the components of the electromagnetic field, the dBx/dt and E_z fields exhibit the most pronounced discriminative abilities, aligning with the response traits of conductive targets in flat terrain scenarios.

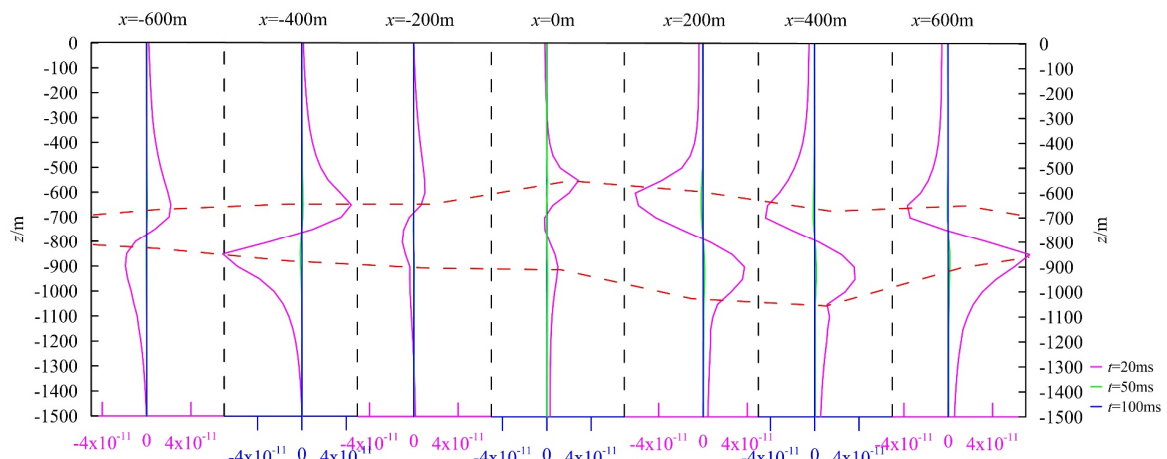


Figure 14. The response curve of the dBx/dt field in several drill holes when the sophisticated deep reservoir model incorporates metallic materials.

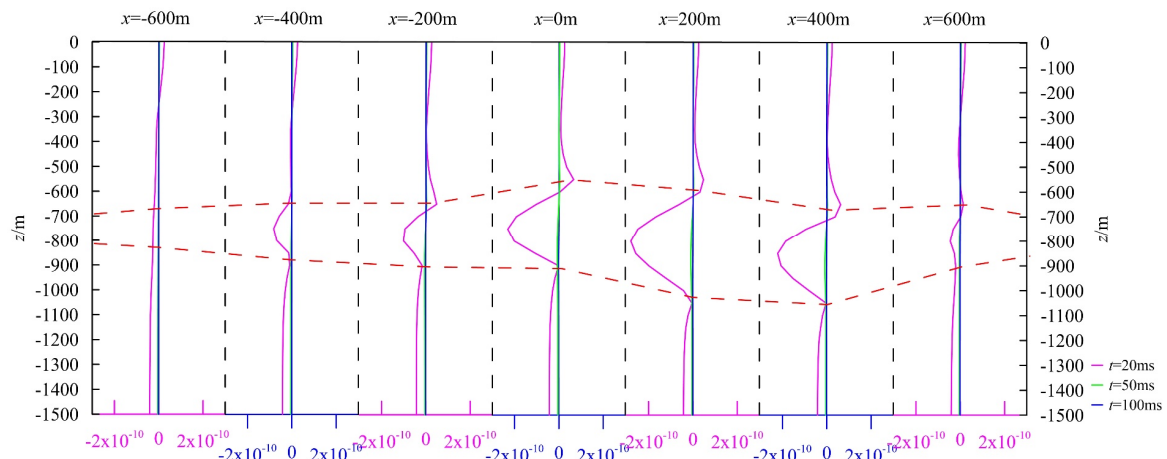


Figure 15. The response curve of the dBx/dt field across various drill holes in the context of a complex deep reservoir model that includes metallic minerals.

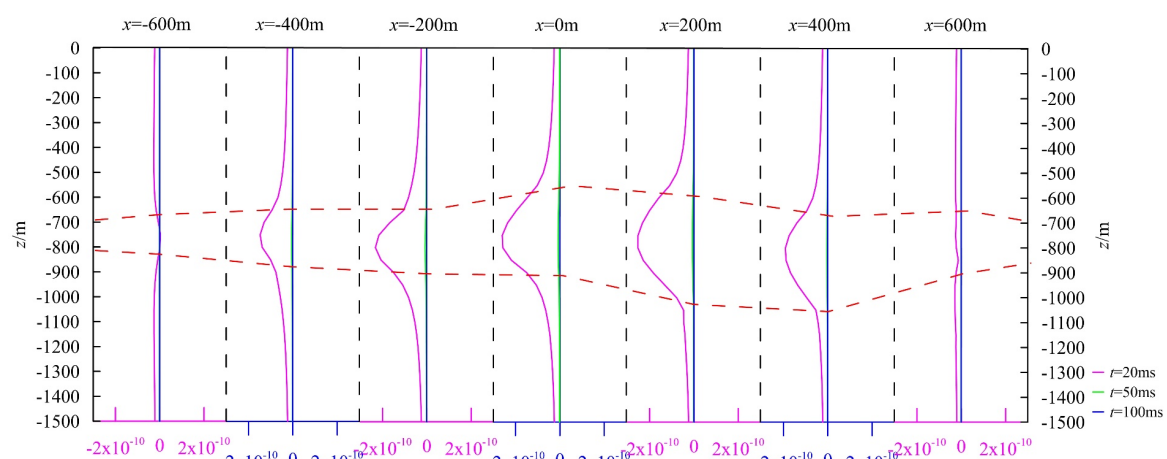


Figure 16. The response curve of the dBz/dt field in different drill holes when the complex deep reservoir model contains metallic minerals.

4.2. High-Resistivity Oil Reservoir Target

In order to examine the electromagnetic response characteristics of the grounded-wire source SBTEM for hydrocarbon reservoirs within intricate deep geological formations,

the resistivity of the anomaly depicted in Figure 17 was established at $1000 \Omega \cdot \text{m}$, with all other parameters held constant. The response characteristics of the E_z , dBx/dt , dBy/dt , and dBz/dt fields were analyzed systematically under these conditions.

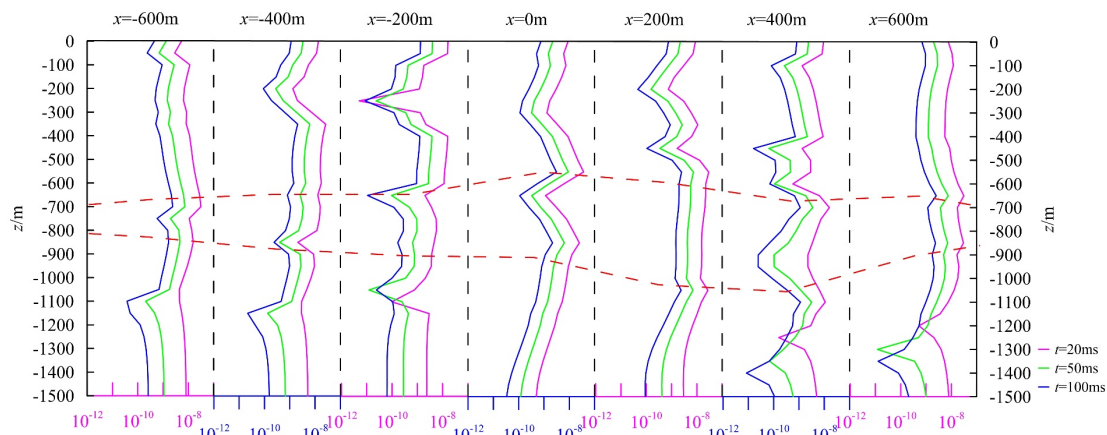


Figure 17. The response curve of the E_z field in different boreholes when the complex deep reservoir model contains oil and gas reservoirs.

Figure 17 illustrates the computational results, displaying the E_z field response curves across various boreholes for the complex deep reservoir model that includes a hydrocarbon reservoir. The E_z response curves display distinctive patterns that correspond to changes in formation resistivity, clearly demonstrating the locations of various strata. In contrast to conductive metal ores, the E_z field response curves exhibit challenges in consistently detecting the hydrocarbon reservoir. This difficulty arises due to the significant influence of complex terrain and the overwhelming presence of the background field on the signal. The maximum relative anomaly of the E_z field is only 4.5.

Figures 18–20 present the dBx/dt , dBy/dt , and dBz/dt field response curves across various boreholes for the model that includes the hydrocarbon reservoir. The data illustrate that those boreholes intersecting the hydrocarbon reservoir do not display any notable anomaly responses, suggesting a lack of sensitivity. The maximum relative anomalies of the dBx/dt field, dBy/dt field, and dBz/dt field are 3.2, 1.7, and 1.4, respectively. The overall fluctuations are minimal, and due to the influence of complex terrain, the response signals from the hydrocarbon reservoir are nearly completely obscured by the background field.

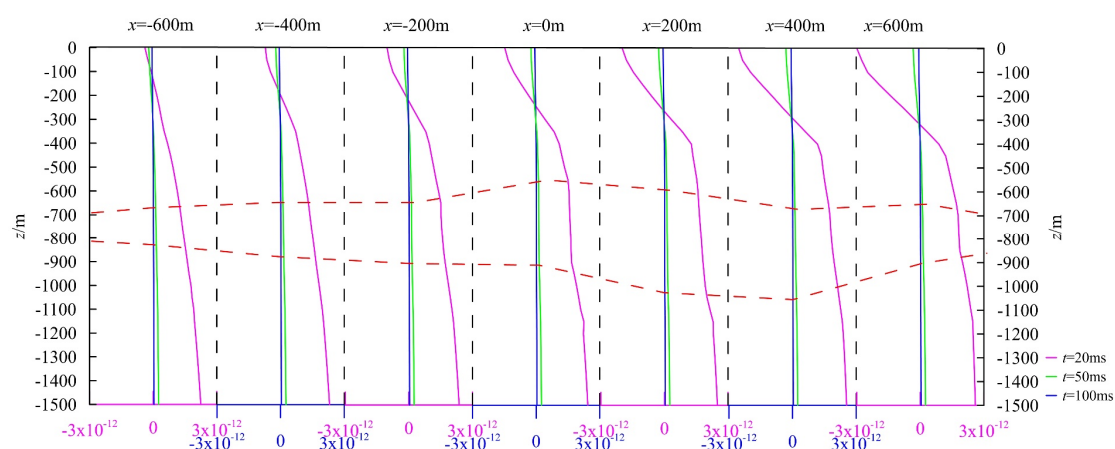


Figure 18. The response curve of the dBx/dt field in different boreholes when the complex deep reservoir model contains oil and gas reservoirs.

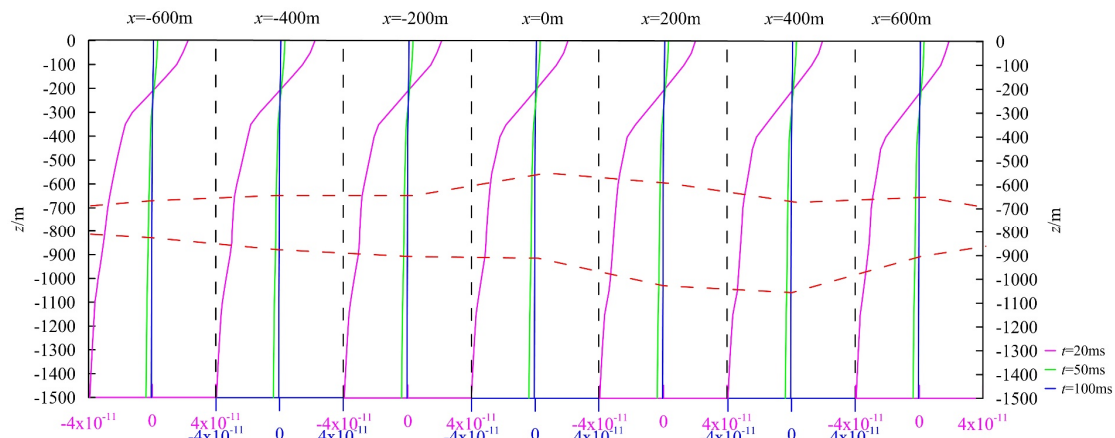


Figure 19. The response curve of the dB_y/dt field in different boreholes when the complex deep reservoir model contains oil and gas reservoirs.

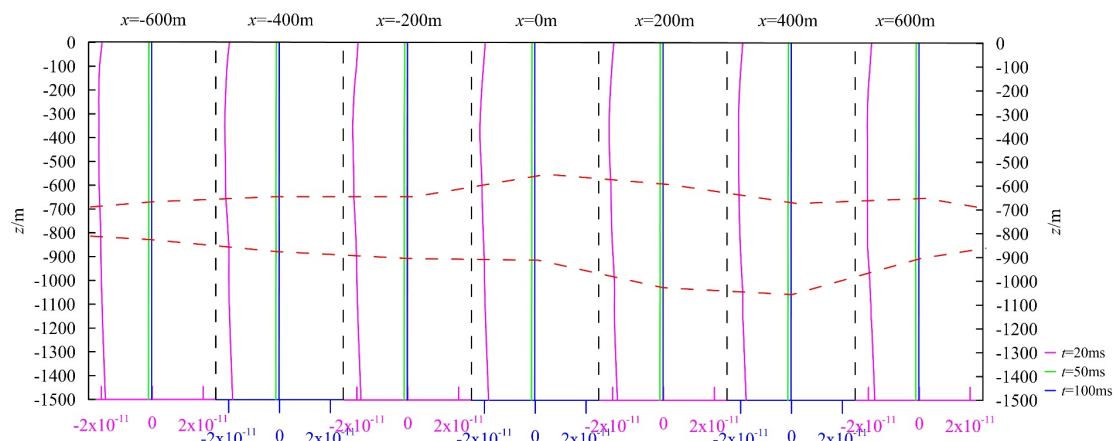


Figure 20. The response curve of the dB_z/dt field in different boreholes when the complex deep reservoir model contains oil and gas reservoirs.

5. Conclusions

This study utilized the time-domain finite-element method, leveraging the flexibility of unstructured tetrahedral meshes to develop a three-dimensional SBTEM that effectively represents complex terrain conditions and reflects real geological settings. Based on comprehensive numerical simulations, the subsequent conclusions were derived:

The detection capabilities of the various components of the grounded-wire source SBTEM for conductive targets exhibit minimal influence from the terrain, enabling the precise identification of conductive target locations with enhanced sensitivity. The method exhibits lower detection capabilities for high-resistivity targets, which complicates reliable identification.

The detection performance of the grounded-wire source SBTEM is significantly affected by complex terrain. This not only complicates the morphology of field response curves but may also introduce spurious anomalies, thereby increasing the difficulty in data processing and interpretation.

With an increase in the burial depth of low- or high-resistivity targets, the depth-resolving capabilities of the magnetic field components in grounded-wire source SBTEM are notably less effective compared to those of the vertical electric field E_z . This indicates that the E_z field could provide enhanced resolution and detection capabilities when investigating deeper reservoirs. Furthermore, the E_z field demonstrates strong layering capabilities and displays significant sensitivity to variations in resistivity.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Dang, B.; Liu, C.; Yang, L.; Wang, G.; Wang, M.; Ren, Z.; Dang, R. EMD-based borehole TEM array signal denoising and baseline wander correction for NDT of downhole casings. *IEEE Access* **2020**, *8*, 150213–150224.
2. Tao, F.; Zhipeng, Q.; Bin, Y.; Zhao, Z.; Bingchun, W.; Xianxin, S.; Lei, L.; Rui, Z.; Jikuang, W.; Bofan, L.; et al. Full waveform inversions of borehole transient electromagnetic virtual wave fields and potential applications. *J. Environ. Eng. Geophys.* **2020**, *25*, 211–222. [[CrossRef](#)]
3. Yang, Y.; Peng, S.; Shan, H.; Peng, Q. Numerical simulation of water-bearing coal goaf using ground-borehole TEM—A case study of Tongxin Coal Mine, Shanxi Province, China. *Front. Earth Sci.* **2024**, *12*, 1289469. [[CrossRef](#)]
4. Dyck, A.V.; West, G.F. The role of simple computer models in interpretations of wide-band, drill-hole electromagnetic surveys in mineral exploration. *Geophysics* **1984**, *49*, 957–980. [[CrossRef](#)]
5. Spies, B.R. Depth of investigation in electromagnetic sounding methods. *Geophysics* **1989**, *54*, 872–888.
6. West, R.C.; Ward, S.H. The borehole transient electromagnetic response of a three-dimensional fracture zone in a conductive half-space. *Geophysics* **1988**, *53*, 1469–1478. [[CrossRef](#)]
7. Buselli, G.; McCracken, K.G.; Thorburn, M. Transient electromagnetic response of the Teutonic Bore orebody. *Geophysics* **2012**, *51*, 957–963.
8. Zhou, J.; Liu, W.; Li, X.; Qi, Y.; Qi, Z. 3-D full-time TEM modeling using shift-and-invert Krylov subspace method. *IEEE Trans. Geosci. Remote Sens.* **2020**, *58*, 7096–7104.
9. Qin, C.; Li, H.; Li, H.; Zhao, N. High-order finite-element forward-modeling algorithm for the 3D borehole-to-surface electromagnetic method using octree meshes. *Geophysics* **2024**, *89*, F61–F75.
10. Skokan, C.K.; Andersen, H.T. Deep long-offset transient electromagnetic surveys for crustal studies in the USA. *Phys. Earth Planet. Inter.* **1991**, *66*, 39–50. [[CrossRef](#)]
11. Strack, K.M. *Exploration with Deep Transient Electromagnetics*; Elsevier: Amsterdam, The Netherlands, 1992.
12. Chen, W.; Han, S.; Xue, G. Analysis on the full-component response and detectability of electric source surface-to-borehole TEM method. *Chin. J. Geophys.* **2019**, *62*, 1969–1980. (In Chinese)
13. Wu, J.; Li, X.; Zhi, Q.; Deng, X.; Guo, J. Full field apparent resistivity definition of Borehole TEM with electric source. *Chin. J. Geophys.* **2017**, *60*, 1595–1605. (In Chinese)
14. Wang, L.; Yin, C.; Liu, Y.; Su, Y.; Ren, X.; Hui, Z.; Zhang, B.; Xiong, B. Three-dimensional forward modeling for the SBTEM method using an unstructured finite-element method. *Appl. Geophys.* **2021**, *18*, 101–116.
15. Chen, W.; Han, S.; Khan, M.Y.; Chen, W.; He, Y.; Zhang, L.; Hou, D.; Xue, G. A Surface-to-Borehole TEM system based on grounded-wire sources: Synthetic modeling and data inversion. *Pure Appl. Geophys.* **2020**, *177*, 4207–4216.
16. Zhi, Q.; Wu, J.; Wang, X.; Deng, X. Deep anomaly localization using surface-borehole TEM and its application in the Wulong Gold deposit. *J. Appl. Geophys.* **2025**, *232*, 105577.
17. Xue, G.; Chen, W.; Zhou, N.; Li, H. Short-offset TEM technique with a grounded wire source for deep sounding. *Chin. J. Geophys.* **2013**, *56*, 255–261. (In Chinese)
18. Key, K. Is the fast Hankel transform faster than quadrature. *Geophysics* **2012**, *77*, F21–F30.

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