Detection Capability and Application Analysis of the Small-Loop Transient Electromagnetic Method

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Abstract. When working in the areas with strong interference and limited sites, such as cities, dams, and mountainous areas, using the conventional transient electromagnetic (TEM) devices is difficult to lay out large transmitter loops for conventional surveys. The small-loop transient electromagnetic method, which has the advantages of lightweight and high efficiency, is a new technology of current researches. First of all, A one-dimensional (1-D) layered model and a three-dimensional (3-D) homogeneous half-space model were established by using numerical simulation method. The research results show that the small-loop TEM devices can not only accurately reflect the anomaly information of deep targets, but also be more sensitive to the detection of shallow targets. By using high-current technology, the signal intensity and detection depth of multi-turn small-loop TEM devices and that of large loop device are the same. Finally, the accuracy and effectiveness of small-loop devices were verified through analysing the results of dam karst investigation. The research work provides a reference for the qualitative analysis of response characteristics and data interpretation of small-loop TEM.

1. Introduction

The transient electromagnetic (TEM) method is a near-surface geophysical method for investigating the distribution of underground resistivity [1]. At present, several widely used TEM configurations have been successfully applied in engineering exploration, mineral exploration, and shallow geophysical exploration. In the meantime, the theoretical aspect of this method has been studied and developed well, including Long off-set TEM, coincident loop, and large loop configurations, the down-hole TEM and Multi-transmitter electromagnetic surveys. Moreover, Multi-transmitter multi-receiver transient electromagnetic systems have been studied and developed in marine exploration [2-6]. However, there are few reports on the study of small-loop TEM configurations.

The TEM has the advantages of high efficiency, no grounding problems and high sensitivity to the low-resistance body. With the further development of urbanization and major infrastructure construction, the accidents caused by karsts, surface subsidence, and water diversion channels are becoming more and more serious at present. The conventional TEM exploration devices are central loop devices or large transmitter loops with a side length of several tens of meters or even several
hundred meters. When working in the areas with strong interference and limited sites, such as cities, dams, and mountainous areas, it is difficult to lay out large transmitter loops for surveys. Therefore, the small-loop TEM devices with anti-interference ability, high detection accuracy and strong adaptability to the site of construction have attracted the attention of scholars.

The small-loop transient electromagnetic method, which has the advantages of lightweight and high efficiency, is a new technology of current researches. At present, most of the theoretical researches on transient electromagnetic fields are concentrated on traditional transient electromagnetic devices, and their applications are focused on deep mineral resource exploration, coal mine water inrush and mud survey and geological survey [7-10]. However, researches on the small-loop transient electromagnetic method are relatively lagging behind. In view of the above problems, the small-loop space device model was established, and the spatial distribution characteristics of the electromagnetic field for small-loop was analyzed in this paper. Next, the response of a 1-D layered medium model and a 3-D half-space model was established and analyzed. Lastly, the data were collected with a small-loop transient electromagnetic system and conducted process and analysis.

2. Analysis of 1-D response characteristics of the TEM

It is assumed that the surface of the homogeneous half-space is a layered medium. The response from the surface caused by the circular loop in the frequency can be expressed as [11]

\[ H_1(\omega) = a I \int_0^{\infty} \frac{\lambda Z^{(1)}}{Z_0^{(1)} + Z_0} J_1(\lambda a) d\lambda \]  

(1)

Where \( I \) is the magnitude of the current in the loop, \( a \) is the radius of the circular loop, \( Z_0 \) is the surface impedance, \( Z^{(1)} \) is the total impedance of the earth, \( J_1 \) is the first-order Bessel function.

A two-layer model was established. The model parameters were set as \( \rho_1=10\Omega\cdot\text{m}, h_1=10\text{m}, \) and \( \rho_2=100\Omega\cdot\text{m} \), the thickness of the second layer of the medium was infinite. The response characteristics of different loop radius were compared. The radius of the transmitter coil was set as 10m, 50m, 100m to simulate the TEM response of the large loop, the radius of the transmitter coil was set as 1m, 2m, 5m to simulate the TEM response of the small-loop. All loop configurations used the same transmitted magnetic moment 10000Am\(^2\) (area times current). The corresponding coil radius and current parameters are shown in Table 1. The calculated results are illustrated in Figure 1, where the x-axis represents observation time, and the y-axis represents the vertical magnetic field component.

| device type         | r/m | I/A       |
|---------------------|-----|-----------|
| Large loop TEM      | 10  | 31.8310   |
|                     | 50  | 1.2732    |
|                     | 100 | 0.3183    |
| Small-loop TEM      | 1   | 3183.0988 |
|                     | 2   | 795.7747  |
|                     | 5   | 127.3240  |

Figure 1 (a) shows the vertical magnetic response decay curves corresponding to the radius of 1m, 2m, 5m, 10m, 50m, 100m; Figure 1 (b) shows the apparent resistivity curve corresponding to different radius of the transmitter coil. The apparent resistance calculation formula refers to the literature [4]. As can be seen from the figure: 1) Before 10\(\mu\)s, the response of the small-loop model is significantly stronger than that of the large loop model, which means that the configuration of the small-loop is more suitable for the detection of shallow targets (Figure 1 (a)); 2) In the late time, the responses of different radius are uniformly coincident, which means that the geological anomalous information detected by the small-loop device is the same as that detected by the large one; 3) In Figure 1 (b), the shallow resistivity distribution was accurately reflected by the small-loop device in early time. However, the detection results of a large-loop device have a large error. In summary, the small-loop TEM device can not only accurately reflect the deep anomaly information, but it is more sensitive and accurate for detecting shallow targets.
3. FDTD for transient electromagnetic field

In the following study, the 3-D homogeneous half-space model was established. The finite-difference time-domain method (FDTD) was carried out in this paper, which has been widely used in numerical simulation of the transient electromagnetic field in recent years. The Maxwell equation under quasi-static conditions is [12]:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2)$$

$$\nabla \times \mathbf{H} = \sigma \mathbf{E} \quad (3)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (4)$$

$$\nabla \cdot \mathbf{E} = 0 \quad (5)$$

Where $\mathbf{B}$ is the magnetic induction, $\mathbf{E}$ is the electric field intensity, $\mathbf{H}$ is the magnetic field intensity, and $\sigma$ is the conductivity of the medium. Because the displacement current is ignored, the time derivative term of the electric field is missing in (3). Therefore, it cannot be solved when using an explicit method that is required by finite-difference. Finally, the difference iteration formats of each component for the magnetic field in the x-direction, y-direction, and z-direction are derived as [13]:

$$B_{x}^{-1} i (i + \frac{1}{2}, j + \frac{1}{2}, k + \frac{1}{2}) = B_{x}^{-1} i (i, j, k) - \frac{\Delta \mathbf{E}_{x}}{2} 
\left[ E_{x}^{-1} (i, j + 1, k + \frac{1}{2}) - E_{x}^{-1} (i, j, k + \frac{1}{2}) \right] \Delta t_{x}$$

$$B_{y}^{-1} i (i + \frac{1}{2}, j, k + \frac{1}{2}) = B_{y}^{-1} i (i, j, k) - \frac{\Delta \mathbf{E}_{y}}{2} 
\left[ E_{y}^{-1} (i + \frac{1}{2}, j, k + 1) - E_{y}^{-1} (i + \frac{1}{2}, j, k) \right] \Delta t_{y}$$

$$B_{z}^{-1} i (i + \frac{1}{2}, j + \frac{1}{2}, k) = B_{z}^{-1} i (i, j + \frac{1}{2}, k + \frac{1}{2}) - \Delta \mathbf{E}_{z} 
\left[ B_{z}^{-1} (i + 1, j + \frac{1}{2}, k + 1) - B_{z}^{-1} (i, j + \frac{1}{2}, k + \frac{1}{2}) \right] \Delta t_{z}$$

3.1. Analysis of response characteristics of the homogeneous half-space model

![3-D model of homogeneous half-space](image-url)
In a rectangular coordinate system, the size of the 3-D homogeneous half-space medium was set as $300m \times 300m \times 300m$. The finite difference grid step size was 5, and the homogeneous half-space resistivity was $100\Omega\cdot m$. A small-loop source was performed as the excitation source. The radius was 1m, and the number of turns was 1, the transmitter current was set as 10A. The initial time was $1e^{-7}s$, and the number of iterations was 6000.

Figure 3. Contour map of magnetic field intensity in homogeneous half-space

Figure 4. Comparison of magnetic field intensity of multi-turn small-loop TEM

Figure 3 shows the contour map of the magnetic field intensity at different times in a homogeneous half-space after the emission current was turned off. The origin of the coordinates in the figure represents the center of the transmitter loop. Figure 3 shows a contour map of the vertical magnetic field intensity component. It can be concluded from the figure that at the initial moment, the transient electromagnetic field is mainly concentrated on shallow (Figure 3a). As time goes by, the electromagnetic field resulted from homogeneous half-space induction gradually spreads downward and outward, which shape is like a "smoke ring" (Figure 3c). The magnitude of the magnetic field intensity decreases as the observation time increases. The location of the maximum value of the magnetic field intensity shifts downward over time (Figure 3d). To explore whether the multi-turn small-loop TEM device can generate the same magnetic field magnitude as the large loop. An increased transmitted magnetic moment was adopted to improve the signal-to-noise ratio of the multi-turn small-loop. Figure 4 shows the change with depth in the magnetic field intensity of a multi-turn small-loop when the number of coil turns is constant and the transmitter current is different. From the analysis in Figure 4 (a), we can conclude that as the transmitter current increases, the maximum value of the magnetic field intensity increases linearly. It illustrates that both of the signal-to-noise ratio of
the multi-turn small-loop and the response of the detection target can be improved by increasing the transmitted magnetic moment. It can be seen from Figure 4(b) that when the number of coil turns is 10, and the transmitter current is 100A, the magnetic field intensity of the multi-turn small-loop is about 1.09 times as large as the large loop. Therefore, we can conclude that the multi-turn small-loop can also achieve a signal strength and detection depth comparable to the large loop by using the high-current transmission.

4. Application case analysis of the Small-loop TEM

A Dam Survey Hydraulic Engineering (DSHE) is located in a “V” shaped river valley at the junction of Yunnan and Guizhou province in China. The downstream of the river valley is a wide range of plain and a dissolution landform. The strata in the DSHE survey area are sandy mudstone in Devonian, limestone, and dolomite in Permian. To find out the structure of the stratum and the distribution of potentially unstable rock and concealed karst development area, the small-loop TEM survey was conducted in the region (Figure 5). In addition, the DSHE project involved drill core samples and geological interpretation. The TEM data were acquired along line length of 585m and the distance between each measurement point was 10 m. The following acquisition parameters were selected: the diameter of the coil was 1.2m, the current was 70A, the frequency was 16Hz, and the number of data iterations was 200.

![Figure 5. FCTEM60-1 transient electromagnetic system](image1)

![Figure 6. Apparent resistivity inverse results of the small-loop TEM](image2)

After the measured data was denoised and the apparent resistivity contour was obtained by inversion processing using EMIT Maxwell software (Figure 6). Combined with geological data, it can be analyzed from Figure 6 that: After the measured data was denoised and the apparent resistivity contour was obtained by inversion processing using EMIT Maxwell software (Figure 6a). Combined with geological data, it can be analyzed from Figure 6a that: It can be seen from the Figure that there is a low-resistivity zone (apparent resistivity is 50~500Ω·m) at the mileage of 140-240m and elevation of 1150-1210m. Based on the electrical exploration results, the borehole ZK1 location was selected adjacent to the location at 200m. The depth of the borehole is 160 m. The drilling results verify the existence of clay at the depth of 103m with the thickness of 2.1m (Figure 6a). In addition, the banded low-resistivity zone with an apparent dip of about 65 angles is shown at the mileage of 340-380m, which is speculated to be a response of the buried reverse fault F1. The accuracy and effectiveness of
the small-loop TEM were verified by comparing the karst investigation of the DSHE survey and geological drilling result, which shows that the small-loop TEM devices can detect large depths of geological structures by using high-current technology.

5. Conclusion
A 1-D layered model was established and the characteristics of the transient electromagnetic response of the small-loop and large loop were compared and analyzed. The research results show that the small-loop TEM devices can not only accurately reflect the anomaly information of deep targets, but also be more sensitive to the detection of shallow targets. Afterward, a 3-D homogeneous half-space model was established and the characteristics of transient electromagnetic response was analyzed. The research results show that by using high-current technology, the signal intensity and detection depth of multi-turn small-loop TEM devices and that of large loop devices are the same. Finally, the accuracy and effectiveness of small-loop devices were verified through analysis of the results of dam karst investigation.

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