Study on the ability of transient electromagnetic method to identify low-resistance thin layer

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Abstract. Based on the different field source theory of transient electromagnetic method, the transient electromagnetic response expression of electric dipole is given, and the transient electromagnetic response of long-line source and loop line source is calculated by the superposition principle of electromagnetic field. Based on the definition of the whole area apparent resistivity, the apparent resistivity of the three-layer model was calculated by the binary search, and the apparent resistivity curve was plotted. By comparing the apparent resistivity curves of different models, the resolution limits of transient electromagnetic methods for low-resistance thin layers under different conditions are analysed and discussed. The identification and resolution of low-resistance thin layers by transient electromagnetic method are summarized. Transient electromagnetic working devices are of great significance.

1. Introduction
In recent decades, China's economy and various fields have developed rapidly. The demand for various mineral resources, energy and groundwater resources has increased rapidly. At the same time, many engineering problems are faced in various constructions, such as underground cavities encountered in highway construction, collapse columns encountered in coal mining, and water inrush problems during tunnel construction. To a certain extent, these problems are restricting the development of China's economy. Using geophysical methods to detect and forecast them will help to ensure the quality of the project, reduce economic losses, and speed up the progress of construction. Transient electromagnetic method is one of the important branches of geophysical exploration. According to the difference of electrical properties of underground rock mass or ore body, the spatial or temporal distribution law of electromagnetic field is studied to solve various geological problems. At present, although the transient electromagnetic method is widely used in energy exploration and engineering exploration, the data processing level of the transient electromagnetic method is not high. In this paper, long-line source and large loop are taken as examples to study the identification and resolution of low-resistance thin layer by transient electromagnetic method, to explore the detection ability of transient electromagnetic method, and to provide theoretical guidance for the selection of transient electromagnetic method working devices and interpretation of data processing.

On the research of transient electromagnetic detection capability: Zhijun Niu discussed the ability of transient electromagnetic method to detect conductive layer; Wei Li et al. combined adaptive shrinkage genetic algorithm with apparent longitudinal conductance differential imaging method to improve the ability of transient electromagnetic method to identify thin layer; Guoqiang Xue et al. used the one-
dimensional forward algorithm of transient electromagnetic method to compare the apparent resistivity curves of a series of geoelectric models with or without thin layers, and analysed the resolving power of transient electromagnetic method to thin layer structures with the relative error as the parameter.

2. Electromagnetic response of transient electromagnetic method

The time domain response of transient electromagnetics is equivalent to the time domain response superposition of many electric dipoles, so the TEM response of the long-line source and the loop source device can be calculated by superposition of the galvanic source transient electromagnetic response.

For horizontal electric dipole emission, the time domain vertical magnetic field at any point in the uniform half space is

\[ h_z(x,y) = \frac{I y}{4\pi r^3} \left[ 1 - \frac{3}{2u^2} \text{erf}(u) + \frac{3}{u\sqrt{\pi}} e^{-u^2} \right] \]  \hspace{1cm} (1)

In the formula (1), \( I \) is the current, \( A; \) \( dl \) is the electric dipole length, \( m; \) \( t \) is the sampling time, \( ms; \) \( u = [\mu_0 r^2/(4\pi t)]^{1/2}; \) \( \rho \) is the uniform earth resistivity; \( r = (x^2 + y^2)^{1/2}; \) \( x, y \) is the measuring point coordinate.

For a uniform half-space transient electromagnetic field, regardless of the shape of the device, as long as the device is considered to be a collection of multiple electric dipoles, the electromagnetic field at any point can be regarded as superposition of multiple electric dipoles at that point. Then the total magnetic field \( H \) at any point is

\[ H = \sum_{i=1}^{m} h_z(x,y)_i \]  \hspace{1cm} (2)

In the formula (2), \( m \) is the number of electric dipoles. \( h_z(x,y)_i \) Can be calculated from equation (1).

3. Binary search algorithm for the whole area apparent resistivity

For the measured magnetic field \( H_0(t) \) at time \( t \), it is necessary to find an apparent resistivity value \( \rho_a(t) \) at that moment. The theoretical magnetic field \( H(t) \) calculated by the apparent resistivity value \( \rho_a(t) \) and the equation (2) should be equal to the measured magnetic field \( H_0(t) \). Since the induced electromotive force monotonously decreases with increasing resistivity at any time. Therefore, using the characteristic of monotonic descent, an algorithm for obtaining the whole area apparent resistivity is designed. The basic idea is to halve the interval \([\rho_a, \rho_b]\) within the possible numerical range \([\rho_a, \rho_b]\) of the resistivity, and substitute the resistivity value of the point \( \rho_m = (\rho_a + \rho_b)/2 \) in the interval into the equation (2) to calculate the theoretical magnetic field \( H_m(t) \) at the midpoint. If the measured magnetic field \( H_0(t) \) is greater than the magnetic field \( H_m(t) \) at the theoretical midpoint, the apparent resistivity value should be in the interval \([\rho_a, \rho_m]\). This reduces the search range by half and increases the speed of calculation.

So the algorithm is named as a binary search algorithm. Specific steps are as follows: (1) The measured magnetic field at time \( t \) is \( H_0(t) \), and the apparent resistivity of the corresponding time \( t \) is \( \rho_a(t) \). To find \( \rho_a(t) \), it is assumed that the possible range of apparent resistivity is \([\rho_a, \rho_b]\); (2) Calculate the midpoint \( \rho_m = (\rho_a + \rho_b)/2 \) of the interval \([\rho_a, \rho_b]\), and substitute \( \rho_m \) as the value of the resistivity into the equation (2), and calculate the theoretical magnetic field \( H(t) \) at the time. (3) The theoretically calculated induced magnetic field \( H(t) \) is compared with the measured magnetic field \( H_0(t) \). If the relative error between the two is less than a given parameter \( \epsilon \), the \( \rho_m \) at this time is the true apparent resistivity corresponding to the measured magnetic field \( H_0(t) \). The calculation ends. Otherwise, go to the next step. (4) If \( H_0(t) > H(t) \), according to the fact that the induced electromotive force monotonically decreases with the increase of resistivity, it means that the \( \rho_m \) value is smaller than the true apparent resistivity, and the true apparent resistivity should be given to \( \rho_b \) in the \([\rho_a, \rho_m]\); otherwise, the true apparent resistance \( \rho_m \) should be assigned to \( \rho_a \) in the interval \([\rho_m, \rho_b]\). (5) Calculate
the length of the interval \([\rho_1, \rho_m]\), if it is less than the given precision, then end; otherwise, proceed to the next step. (6) Repeat steps (2), (3), (4), and (5).

4. Forward model calculation
The resolving power of the transient electromagnetic method to the subsurface target mainly depends on the electrical difference with the surrounding rock, the thickness, the depth of the buried depth, the minimum distinguishable signal in the field and the position of the observation point. Therefore, this paper mainly changes the depth, thickness and resistivity of the thin layer to judge the variation characteristics of apparent resistivity, and then determines the detection ability.

In the actual work in the field, the induced electromotive force is generally measured using an ungrounded loop line. It is generally considered that the magnitude of the induced electromotive force change is greater than 10%, and can be distinguished when it is greater than 15%. In this paper, it is considered that the variation range of resistivity is 10% is the resolution limit of the method, that is, when the magnitude of the change in resistivity is greater than 10%, the abnormality can be resolved, otherwise it cannot be resolved.

4.1. Resolution of long-line sources
In order to discuss the resolving power of the long-line source transient electromagnetic method, a three-layer geoelectric structure is taken as an example. Assume that the middle layer is a low-resistance layer, and the first layer and the third layer are high-resistance surrounding rocks. The model parameters are set as follows: the surrounding rock resistivity is 200 \(\Omega\cdot m\), the buried depth is 100 m, the long-line source is 1000 m, and the position is on the x-axis. The source is powered by 10 A and the observation time is 10^{-5}~1s. There are 30 sampling points and the observation point is located at (500, 900).

**Table 1. Abnormality of long-line source**

| Resistivity difference \(\rho_1/\rho_2 = 2\) | Buried depth ratio | 0.5 | 0.3 | 0.1 |
|---------------------------------------------|-------------------|-----|-----|-----|
| Abnormal difference                         |                   | 14.8| 10.2| 3.92|
| Abnormal difference                         |                   | 0.3 | 0.1 | 0.05|
| Abnormal difference                         |                   | 24.9| 10.8| 5.9 |
Figure 1. Long-line source apparent resistivity curve and abnormal difference curve. (1) The difference in resistivity is 2. (2) The difference in resistivity is 4.

Referring to Figure 1, the difference in resistivity is the same. The larger the ratio of buried depth is, the more obvious the apparent resistivity is. When the thickness ratio of buried depth is constant, the difference of resistivity is larger, and the apparent resistivity characteristic is more obvious. It is concluded from Table 1 that when the resistivity difference ratio is 2: the buried depth ratio is 0.3, the abnormal difference is slightly larger than 10%, the buried depth ratio is 0.1, and the abnormal difference is less than 10%. Therefore, the resolution at this time can be considered. The limit is slightly less than 0.3; when the resistivity difference ratio is 4: the buried depth ratio is 0.1, the abnormal difference is greater than 10%, the buried depth ratio is 0.05, the abnormal difference is less than 10%, and the resolution limit at this time is determined to be slightly less than 0.1.

4.2. Research on the detection capability of the return line source

Similarly, in order to study the resolving power of the return line source, this paper takes the three-layer geoelectric model as an example. Assume that the target layer is the low-resistance layer, and the first layer and the third layer are high-resistance surrounding rocks. In order to compare with the resolving power of the line source, the model parameters are as follows: the surrounding rock resistivity is 200Ω · m, and the buried depth is 100 m, the side length of the loop source is 1000 m, the power supply of the
source is 10A, and the observation time $10^{-5} \sim 1$ s has a total of 30 sampling points, and the observation point is located at (500, 900).

Table 2. Abnormality of the return line source

| Resistivity difference $\rho_1/\rho_2 = 2$ | Buried depth ratio | Abnormal difference |
|------------------------------------------|--------------------|---------------------|
|                                          | 0.5                | 15.5                |
|                                          | 0.3                | 10.7                |
|                                          | 0.1                | 4.12                |

| Abnormal difference $\rho_1/\rho_2 = 2$ | Buried depth ratio | Abnormal difference |
|------------------------------------------|--------------------|---------------------|
|                                          | 0.3                | 26.27               |
|                                          | 0.1                | 11.52               |
|                                          | 0.05               | 6.21                |

Figure 2. Return line source apparent resistivity curve and abnormal difference curve. (1) The difference in resistivity is 2. (2) The difference in resistivity is 4.

It can be seen from Fig. 2 that when the resistivity difference ratio is constant, the greater the buried thickness ratio, the stronger the resolution of the target layer. When the buried thickness ratio is uniform, the greater the resistivity difference ratio, the better the resolution of the target layer. Analysis Table 2 shows that when the resistivity difference ratio is 2; the buried depth ratio is 0.3, the abnormal difference is slightly more than 10%, the buried depth ratio is 0.1, and the abnormal difference is less than 10%. Therefore, the resolution at this time can be considered. The limit is slightly less than 0.3; when the
resistivity difference ratio is 4: the buried depth ratio is 0.1, the abnormal difference is greater than 10%, the buried depth ratio is 0.05, the abnormal difference is less than 10%, and the resolution limit at this time is determined to be slightly less than 0.1.

5. Conclusion
From the numerical simulation of transient electromagnetic method, the detection ability of the book layer is related to the thickness ratio of the buried layer of the thin layer and the difference ratio of the resistivity of the surrounding rock. In this paper, the three-layer geoelectric model is taken as an example to deeply investigate the resolving power of the transient electromagnetic method for the low-resistance thin layer, and the following conclusions are drawn:

(1) When the resistivity difference ratio is constant, the greater the buried thickness ratio, the stronger the resolution of the target layer. When the buried thickness ratio is uniform, the greater the resistivity difference ratio, the better the resolution of the target layer.

(2) Both the long-line source and the loop source can effectively identify the underground low-resistance thin layer. If the resolution capability is high, the return line source is used for measurement; in general, due to the topographical factors and work efficiency, the long-line source is selected to measure.

References
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