Experimental research and application of tunnel transient electromagnetic leading detection remove noise method

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Abstract. In the construction process of underground space engineering such as tunnels, it often faces geological disasters such as water inrush and mud inrush. The transient electromagnetic method is based on the difference in electrical resistivity between surrounding rock and water-bearing structure, and can detect and locate the water-bearing structure in front of the tunnel face. However, due to the interference in the tunnel environment, the quality of the late data in the actual detection process is relatively poor and generally cannot be used. In this paper, uniform half-space model and three-layer classical model are designed to study the applicability of converting induced electromotive force detected by transient electromagnetic method into apparent resistivity. It is found that the late data conversion effect is good when there is no interference, and the late data conversion effect is poor in the case of strong interference. Using these two models, three filtering algorithms are compared respectively to improve the quality of late data, improve the detection depth of transient electromagnetic method. Through field experiments, after comparing the filtering algorithm with the traditional direct truncation method, it is found that the late data can be used, which effectively improves the depth of detection, and the early data imaging results are the same as the direct truncation mode imaging results, the filtering algorithm does not affect the early data.

1. Introduction

With the continuous demand of China's modernization development, a large number of underground projects such as tunnels and caverns have been accelerated. In engineering, it is often faced with complex and diverse geological hazards such as water inrush, mud inrush, and tunnel collapse. At present, traditional means such as on-site hydrogeological surveys and borehole surveys taken by the design unit during the survey and design phase are still unable to help on-site construction personnel to accurately recognize and predict the potential danger ahead of the tunnel face. In order to effectively promote the safe and smooth construction of engineering projects, geophysical exploration method is often used to carry out advance prediction of adverse geological disasters in the excavation process of underground space projects, so as to achieve the purpose of predicting the location and scale of abnormal structures such as water-bearing and mud-bearing in front of the tunnel face[1-3].

Transient electromagnetic method is an emerging geophysical exploration method based on low-frequency electromagnetic field. It is widely used because of its high resolution, good directionality and convenient operation in the field of geophysical near-surface detection, such as coal mine roadway adverse geological disaster prediction, groundwater exploration, geological exploration...
and mapping. For the calculation and interpretation of transient electromagnetic apparent resistivity in tunnels, Yang Haiyan et al. made a full-space apparent resistivity interpretation method for mine transient electromagnetic method, which can improve the apparent resistivity of the whole region[4]; Su Maoxin et al. used the method of interpreting the apparent longitudinal conductance of tunnel transient electromagnetic to improve the accuracy of geological prediction in advance of the tunnel[5]; Bai Denghai and MAXWELL A.M. gave the numerical calculation of the apparent resistivity of the whole process in the central mode of time domain transient electromagnetic method[6]; Qi Zhipeng et al.’s all-space and all-area apparent resistivity interpretation method can be used to calculate apparent resistivity of any measuring point on the tunnel face[7]. In a word, the calculation of apparent resistivity mainly focuses on the definition of the whole period, and there is little research on the correction of late apparent resistivity in the case of strong interference.

This paper mainly introduces the simulation and experiment of the transient electromagnetic method combined with the filtering algorithm response detection data processing and analysis method in the tunnel geological prediction, designing a uniform half-space model and a typical layered model, test the applicability of transient electromagnetic method response to detect the conversion of induced electromotive force into apparent resistivity. It is found that the effect of converting the induced electromotive force into apparent resistivity is significant in the absence of interference. In the case of strong interference, the late signal fluctuation seriously affects the value of apparent resistivity. In view of the fact that there are lots of interferences in the tunnel environment, the quality of the late stage data in the actual detection process is relatively poor, and it is generally unusable. The median filtering, arithmetic average filtering and rolling average filtering are used for the uniform half-space model and the typical layered model respectively, three kinds of filtering algorithms improves the quality of late data, improves the signal-to-noise ratio of late attenuation curve in strong interference environment of transient electromagnetic field, and improves the detection depth of transient electromagnetic method. Through the field test of Duijashan tunnel in Ankang city, Shaanxi province, it is found that the late data can be used by comparing the filtering algorithm with the traditional truncation method. The imaging results of the early data are the same as those of the direct truncation method, and the filtering algorithm does not affect the early data.

2. Tunnel transient electromagnetic filtering algorithm and numerical experiment

2.1. Tunnel transient electromagnetic principle

2.1.1. Fundamental. Due to the limited working space for underground projects such as tunnels and caverns, the traditional excitation method using large fixed source or magnetic dipole source as transient electromagnetic method is objectively restricted. Therefore, in the advance geological prediction of the tunnel face of transient electromagnetic tunnel, a multi-turn ungrounded return coil (return line source) with a certain current is used as an excitation source to emit a pulse field to the front of the tunnel face, as shown in fig.1. When the current in the transmission loop is suddenly switched off at a certain moment, the medium in front of the tunnel face will be excited into a ring-shaped penetrating response secondary eddy current field containing electrical information. The attenuation characteristics of the response secondary eddy current field are observed at the shut-off gap of the primary field, and the imaging interpretation of apparent resistivity is obtained by processing the response electromotive force, so that the targets of exploring the electrical property, scale and occurrence of surrounding rocks in front of the working face can be achieved, and the function of predicting geological anomalies with low resistance structures such as water-bearing and mud-bearing structures as targets can be achieved[8-10].
2.1.2. **Full-term apparent resistivity definition.** At present, the definition of apparent resistivity used in transient electromagnetic response detection is generally converted from the expression of transient electromagnetic field on a uniform half-space surface. However, because the relationship between transient electromagnetic field and earth resistivity is very complex, the definition of apparent resistivity in the early and late stages of transient electromagnetic field can only be derived by using the expression of transient electromagnetic field under limit conditions[11-15].

In view of the shortcomings of the above approximate interpretation, Qi Zhipeng et al. proposed a method of full-space apparent resistivity interpretation, which can calculate apparent resistivity at any measuring point on the tunnel face.

![Figure 2. Schematic diagram of loop decomposition into electric dipole](image)

As shown in figure 2, the coil is divided into each infinitesimal dl along the edge, R is the distance from P to infinitesimal dl, θ is the included angle between R and infinitesimal dl. From the calculus theory, it can be seen that the transient magnetic field response of point p with any spacing r in the loop plane can be regarded as the superposition of all microelement responses, and the uniform all-space parallel magnetic field component in the same plane is 0, only the vertical component, expressed as:

\[
\frac{\partial H_z}{\partial t} = \int \frac{I \, dl}{4\pi u_0 \sigma R^4} \sin \theta \sqrt{\frac{\mu}{\pi} u^5 e^{-u^2/2}}
\]

(1)

Where H\_z is the vertical magnetic field strength, t is the time, I is the current, μ0 is the medium permeability, σ is the medium conductivity, \( u = R \sqrt{\frac{u_0}{2\rho t}} \), \( \rho \) is the true resistivity of the medium, now order \( C_E = \int \frac{dl}{R^4} \sin \theta \sqrt{\frac{\mu}{\pi} u^5 e^{-u^2/2}} \), so:

\[
\frac{\partial H_z}{\partial t} = \frac{I}{4\pi \sigma} C_E
\]

(2)

The formula for calculating apparent resistivity \( \rho_s \) is:

\[
\rho_s = \frac{4\pi}{C_E} \frac{\partial H_z}{\partial t}
\]

(3)

Finally, the apparent depth is calculated by using the smoke ring propagation velocity formula in
the smoke ring principle.

2.1.3. Numerical Simulation. In order to test the applicability of transient electromagnetic method (TEM) in detecting the conversion of induced electromotive force into apparent resistivity, two models were designed to verify it. A uniform half-space model is used to verify the stability and effectiveness of the conversion of induced electromotive force into apparent resistivity for the uniform half-space model. A typical layered model is used to verify that the apparent resistivity definition method has a good identification effect on low-resistance abnormal structures. The emission source is 50m long. The geo-electrical parameters of the models are shown in Table 1. In the process of numerical simulation, the induced electromotive force attenuation changes of the two models with and without interference are calculated respectively as shown in fig. 3(a) and fig. 4(a), and the apparent resistivity curves of the two models are calculated and drawn by using the global apparent resistivity interpretation method as shown in fig. 3(b) and fig. 4(b).

| Model          | Uniform half space model | Layered model |
|----------------|--------------------------|---------------|
|                | Thickness (m) | Resistivity (Ω·m) | Thickness (m) | Resistivity (Ω·m) |
| First layer    | -               | 100           | 10             | 100            |
| Second layer   | -               | -             | 10             | 10             |
| Third layer    | -               | -             | -              | 100            |

Table 1. Geo-electrical parameters of models

Fig. 3. Uniform half-space model contrast curve
\( \rho_1 = 100 \Omega \cdot m, \quad h_1 = 10 m \)
\( \rho_3 = 100 \Omega \cdot m \)
\( \rho_2 = 10 \Omega \cdot m, \quad h_2 = 10 m \)

Compared with numerical simulation, it can be found that the comparison curve of uniform half-space model is shown in fig.3, under the condition of strong interference, the late data of induced electromotive force attenuation curve in fig.3(a) fluctuates greatly, and the late data of apparent resistivity curve in fig.3(b) jumps obviously; The contrast curve of layered model is shown in fig.4, under the condition of strong interference, the signal quality in the late stage of induced electromotive force attenuation curve in fig.4(a) is poor, and the data jitter in the late stage of apparent resistivity curve in fig.4(b) is significant. To sum up, under the condition of no interference, the effect of converting induced electromotive force into apparent resistivity by calculation is good, but under the condition of strong interference, the fluctuation of data severely reduces the signal-to-noise ratio in the process of apparent resistivity conversion.

2.2. De-noising filtering algorithm

Referring to digital filtering algorithms commonly used in electronic engineering, median filtering, arithmetic average filtering and rolling average filtering are applied to the data processing of tunnel advance geological prediction response detection.

2.2.1. Median filtering

For the tested parameters of the same attribute, continuously sample \( n \) times (generally \( n \) takes odd number), then queue the \( n \) sampling values from small to large or from large to small, taking the middle value of " queue" as the median value; If the sampling number \( n \) is even, the average value of the two values in the middle of the queue is taken as the median value. The median value is used to replace the maximum and minimum values in the queue respectively, and then the original sorting of the queue is restored.

Median filtering is more effective for filtering out pulse interference caused by fluctuation caused by accidental factors or error caused by instability of acquisition device.

2.2.2. Arithmetic average filtering

The general signal with random interference is filtered, and the arithmetic average filtering is considered, that is, an arithmetic average value is obtained, which is used to replace the highest and lowest “fluctuation” abnormal value caused by objective interference.

For \( N \) samples of continuous sampling, find an arithmetic mean \( y \) such that the sum of squares of the error \( b \) between \( y \) and each sampled value \( x_k \) is the smallest, which is:

\[
 b = \min \left[ \sum_{k=1}^{N} (y - x_k)^2 \right]
\]  

\[(4)\]
According to the limit principle of one-variable function, it can be obtained:

\[ y = \frac{1}{N} \sum_{k=1}^{N} x^{(k)} \]  

(5)

In this way, the filtering effect can be realized and the response amplitude caused by random factors can be reduced.

2.2.3. Rolling average filtering. Rolling average filtering is to form a sub-queue for every continuous \( n \) (\( n \) is not more than \( N \)) data among the continuously collected \( N \) data, thus forming a \((N-n+1)\) sub-queue. Starting from the first sub-queue, the arithmetic mean value \( \bar{x}^{(k)} \) \((k=1, 2, \ldots, N-n+1)\) of each sub-queue is calculated sequentially, and the highest and lowest “fluctuation” abnormal values in the sub-queue are replaced by the arithmetic mean value \( \bar{x}^{(k)} \). By the end of the calculation of the last sub-queue, the filtering of the data queue with a total amount of \( n \) is completed.

Rolling average filtering has a good suppression effect on periodic interference.

2.2.4. Filter Processing Composite Data Test. The uniform half-space model and classic three-layer model designed above are used for filtering, and the comparison curves of the models are shown in Figure 5 and Figure 6.

(a) Induced electromotive force attenuation curve    (b) Apparent resistivity curve

Figure 5. Uniform half-space model contrast curve

(a) Induced electromotive force attenuation curve    (b) Apparent resistivity curve

Figure 6. Layered model contrast curve
It is found that compared with the ideal attenuation curve under the condition of no interference in the numerical model, the fluctuation of induced electromotive force and apparent resistivity in the late period under strong interference is obvious, which seriously affects the calculation depth and accuracy; Three filtering methods of median filtering, arithmetic average filtering and rolling average filtering are used to correct the late data. It is found that the filtering has greatly corrected the overall situation of the de-noising attenuation curve and approaches the curve without interference\cite{16-20}.

3. Field Test

3.1. Geological overview of the tunnel area

Dujiashan Tunnel is located in Ankang City, Shaanxi Province. It is a single-hole two-track railway tunnel. The geological structure in this area is complex and the lithology of the strata varies, and there are different degrees of metamorphism. The relative elevation of mountain ranges from 500 to 800 meters. In the survey and design stage, the tunnel XDK223+950~XDK225+350 is designated as a strong water-rich section. The stratum is mainly limestone containing phyllite, and there are many faults passing through, the rock mass is affected by the structure, and joints and fissures are seriously developed, and the fissure water in the dissolution and fault zones is relatively developed. The tunnel passes through the fault fracture zone, fold structure zone and lithological contact zone where this section is located, and there may be risks of geological disasters such as water inrush and mud inrush.

3.2. Field data acquisition

Before the transient electromagnetic method is used to carry out the transient detection work at the entrance tunnel face XDK225+130 from the strong water-rich section of the Dujiashan Tunnel, the center loop device is used. The detection equipment uses ProTEM47 transient electromagnetic instrument, the emission current is 1A, the transmission fundamental frequency is 25Hz; the equivalent area of the receiving device coil is 31.4m², the turn-off time is set to 150μs, and the response data of 20 time channels is collected.

3.3. Data processing and analysis interpretation

During the detection process, the metal parts such as muck cars, formwork trolley, scaffoldings, etc., which are parked not far behind the tunnel face, and the noise generated by the on-site construction will cause different degrees of interference to the acquired transient electromagnetic response data. The vertical component induced electromotive force profile of the field data is drawn as shown in fig. 7, from this we can infer the late time channel data quality.

![Figure 7. Profile of the vertical component induced EMF](image)

Affected by existing tunnel transient electromagnetic theory and engineering site detection conditions, some of the unavoidable “fluctuations” often appear in response to late time channel data. In order to obtain more comprehensive geo-electric information in the apparent depth range in front of the tunnel face, the response electromotive force obtained by this detection is processed pertinently. The “fluctuation” data occurring in the late part of the response time channel are processed by
adopting truncation method and median filtering, arithmetic average filtering and rolling average filtering respectively to obtain reprocessed response data, and vertical component induced electromotive force profiles are drawn respectively, as shown in fig. 8.

![Profiles of the vertical component induced EMF](image)

Fig. 8(a) is a vertical component induced electromotive force cross-sectional view drawn with only the middle and early data retained. Fig. 8(b) is a vertical component induced electromotive force profile drawn after median filtering processing of “fluctuation” data in the part time channel of the late response period. Fig. 8(c) is a vertical component induced electromotive force profile drawn after performing arithmetic average filtering processing on “fluctuation” data in 6 time channels in the late response period. By filtering the abnormal data of general random interference, the response amplitude caused by random factors is reduced, thus weakening adverse interference. Fig. 8(d) is a vertical component induced electromotive force profile obtained by performing rolling average filtering processing on the “fluctuation” data in response of the late stage ten time channels. This filtering method suitable for high-frequency oscillation has good suppression effect on periodic interference and can effectively improve the smoothness of the whole data.

By processing the “fluctuation” data in response to the late period, the apparent resistivity contour sections as shown in Figure 9 are calculated and plotted respectively. It can be seen that the color scale changes show consistency. The results show that the geo-electric properties in front of the tunnel face can be roughly divided into three sections: the apparent resistivity within 5 meters from the apparent depth to the front of the tunnel face shows a low value, which indicates that there is a great possibility of water-bearing and mud-bearing abnormal structure in this section; the apparent depth is within 5~40 meters from the front of the tunnel face, and the apparent resistivity shows a high value, it is inferred that the surrounding rock condition is relatively complete and the possibility of large-scale water-bearing and mud-bearing abnormal structures is small; after the apparent depth is about 40 meters away from the front of the tunnel face, the apparent resistivity amplitude shows some electrical difference interfaces, which indicates that there may be a small-scale water-bearing and mud-bearing abnormal structure in this section.
Figure 9. Apparent resistivity contour profile

Figure 10. The water-inrush situations of drilling

Combined with the prediction and inference obtained from this geophysical exploration, field drilling verification is carried out. Drill in the middle position of the tunnel face and the left side of the middle. When the drill hits about 4 meters in front of the tunnel face, a small amount of water will start to appear in the hole, as shown in Figure 10; when drilling to 20m, there is no increase in water yield, the amount of water that continues to be drilled is basically unchanged, and the result of the water output in the front of the subsequent tunnel face is consistent with the drilling result. The drilling result is in good agreement with the visual depth of the geophysical inference, so the prediction conclusion can be proved to have practicality.

The data acquired by the tunnel detection is interfered by many factors on the engineering site. The induced electromagnetic field (secondary field) tends to “fluctuate” during the attenuation process. Due to the close correlation of the data, the unstable data is not properly processed and cause a reduction in the accuracy of the calculated apparent resistivity, which is one of the reasons that affect the reliability of the advanced geological prediction. Truncation can improve the conversion of response electromotive force into the color base filling standard of the apparent resistivity imaging process, thereby improving the resolution and accuracy of the overall apparent resistivity imaging, but affecting the depth of detection; after the filtering algorithm, the late data can be used. The detection depth is effectively improved, and the early data imaging results are the same as the direct truncation mode imaging results, and the filtering algorithm does not affect the early data.

4. Conclusions

By designing a uniform half-space model and a three-layer typical model, it is found that the effect of converting the induced electromotive force into apparent resistivity is good in the case of no
interference; In the case of strong interference, the low signal-to-noise ratio leads to large deviation in conversion to apparent resistivity. By using these two models and comparing three simple filtering algorithms to process the “jitter” data of late transient electromagnetic advanced detection, the signal-to-noise ratio of the advanced attenuation curve under strong transient electromagnetic interference environment can be improved, and the depth of transient electromagnetic detection can be increased. In the field test, the filtering algorithm is compared with the traditional direct truncation method, and it is found that the late data can more stably reflect the resistivity distribution of the rock mass, and the imaging result of the early data is the same as that of the direct truncation method.

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