A metal interference correction method of tunnel transient electromagnetic advanced detection

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Abstract

Water inrush during tunnel excavation severally threatens the mining safety as blind water-bearing structures may develop in front of the working face. The transient electromagnetic method (TEM) has been widely applied in the advanced detection of tunnel water-bearing structures. However, the metal interference of both supports and tools in the tunnel has become a bottleneck that reduces the forecast accuracy of this method. In this paper, we analyse the effect of metal interference on TEM data and propose a novel set of an observation and correction method under metal interference based on the ratio of anomalous and background apparent resistivity. Flume mode experiments both with and without metal interference are carried out, showing that this interference can affect TEM measurements significantly and result in false anomalies, and that our proposed method can remove this ambient noise caused by metal interference appropriately. The practical application further proves that this method can effectively reduce low-resistivity interference introduced by the support and other metal tools inside the tunnel. By applying this correction method, the location of water-rich anomalies can be detected more precisely during the excavation process of the same tunnel, which is of high application value of reducing exploration difficulty and tunneling risk.

Keywords: transient electromagnetic method, advanced tunnel detection, metal interference, correction method

1. Introduction

Water inrush is a phenomenon where the water outflow from discharge aquifers suddenly increases during tunneling, which may cause severe losses of lives and property. Therefore, the prevention of water inrush is an essential topic in the guarantee of mining safety (Wu & Wang 2006; Przemyslaw 2011; Wu et al. 2018). It is believed that water-bearing porosities, water-transferring blind faults and karst structures together constitute the source of inrush water. In China, coal mines mainly deposit in the thick Middle Ordovician carbonate formation, which is rich in these geological structures, and thus the risk of a water hazard during tunneling is even greater (Li & Zhou 2006). Generally, water inrush occurs when the water pressure is higher than the strength of the seam footwall, and several models have been proposed to illustrate the process of this dynamic destabilising process (Bringemier 2012; Zhang et al. 2014; Yin et al. 2015). However, these theories focus on the principle of the reason of water inrush, and we need a more straightforward method in practical mine tunneling.
At present, geophysical prospecting methods, especially the direct current (DC) method, and the transient electromagnetic (TEM) method have become prevalent in evaluating the tunnel water hazard. This is because electromagnetic methods are sensitive to low-resistivity groundwater, with the advantages of convenient construction and straightforward interpretation (Miller 1986; Xue et al. 2007). The traditional DC method works well if the survey line is long enough. However, it should be noticed that this measurement requires a galvanic technique injecting current into the ground through a pair of transmitter electrodes, and its time and cost can often be prohibitively large (Marchant et al. 2013). Such approaches suffer from the drawback that they are more sensitive to side interfering bodies rather than water-bearing structures ahead of the working face under complex geological conditions (Qiang et al. 2011; LaMoreaux et al. 2014). In the late 2000s, several focused logging methods were introduced to improve the detection distance of DC advance detection and, among them, the BEAM (bore-tunneling electrical ahead monitoring) method is the most prominent (Kaus & Boening 2008). These methods make use of shield electrodes that are installed near the transmitting electrode. Therefore, electric currents are forced to flow toward the designated direction, and the detection distance extends from several meters to no more than 30 m.

The proposal of focused resistivity methods is a significant improvement compared with traditional DC methods. However, drawbacks do exist, and the alternative TEM method largely solves the problems of low positioning accuracy and difficult survey line layout (Zhao et al. 2019). The TEM method has been widely applied to both environmental and mineral investigations since the coupling between the transient field and mineral body was noticed (Wait 1951). At that time, modelling of the TEM method was usually performed in one dimension (Krivochieva & Chouteau 2002). Recently, the accurate solution of the TEM method has been continuously studied by the 3D finite-difference and finite-element simulation of Maxwell equations (Li et al. 2011; Wen et al. 2015). Several inversion methods, such as the pseudo-seismic imaging method, the nonlinear conjugate gradient method (NLCG) method and the Bayesian inversion method, have also been applied to TEM imaging and inversion (Newman & Commer 2005; Xue et al. 2016; Blatter et al. 2018). Part of these methods has also been applied to the tunnel environment in both modelling and inversion (Cheng et al. 2014; Li et al. 2019; Liu et al. 2019).

Nevertheless, the interpretation of 3D TEM datasets is numerically harsh, mostly because the model scale is usually extremely large with tens of thousands of parameters (Avdeev 2005). Therefore, an advanced detection method based on the interpretation of apparent resistivity is still highly necessary in fieldwork. The method has been studied from various aspects, including the maximum detection distance (no more than 120 meters), the layout of the transmitting and receiving system, and the mutual induction of the coil (Yu et al. 2007; Kolaj & Smith 2015; Yuan et al. 2018). In recent research, the TEM advanced detection method has been applied with a combination of magnetic resonance sounding methods, which provide decent detection performance (Shang et al. 2018).

In the practice of tunnel TEM advanced detection, one of the most challengeable issues we are facing is the electromagnetic interference problem. This is because the metal supports and metal tools arranged near the working face are generally not easy to remove when performing TEM measurements. The response of these metal bodies located near the TEM coil can easily conceal the low-resistivity abnormal response of the front water-bearing structures. This ‘low-resistivity pollution’ brings in the false anomaly, misleads data processing and thus further affects the accuracy of advanced geological interpretation. Understandably, the better the electrical conductivity of the metal interference is, and the shorter the distance between the body and the TEM coil is, the more severe the disturbance is (McNeill et al. 1984; Raiche & Gallagher 1985). The extraction of water-bearing body signals and the correction method for observation data under metal support interference are beneficial to improving the accuracy of TEM detection. However, researchers mostly pay their attention to the basic principle of TEM advanced detection, and the practical topic of metal interference during actual construction has not drawn much attention. Thus, how to effectively extract a low-resistivity anomaly signal in complicated interference situations needs to be studied further, and is of significant value of preventing water inrush hazards during the tunnel evacuation process.

In this paper, we propose an observation and correction method of TEM advanced tunnel detection based on practical experience. The flabellate observation system makes full use of the limited tunnel space, and three-dimensional data could be obtained by adjusting the normal direction of the transmitting coil. We use data that are not obviously impacted by metal interference as a reference, and thus the disturbed raw data could be effectively corrected. The structure of this paper is organised into three sections. In the first section, we introduce the basic theory of the whole-space TEM method, the acquisition method of tunnel field data and the correction method of metal interference. In the second section, a flume model experiment is carried out to verify the correctness and effectiveness of the correction method. In the final section, a field application example is presented showing the practical result of this correction method. Also, discussions and conclusions are proposed.
2. Methodology

The TEM method is an artificial source electromagnetic probing method based on electromagnetic induction theory. As the impulse primary (magnetic) field transmitted underground, the magnetic field generated by eddy current in the anomalous body of any moment can be regarded as an equivalent field generated by a horizontal annular line source, and the time-dependent ring-shaped distribution of inductive current process is widely known as the ‘smoke ring’ model (Nabighian 1979). After coupling with surrounding rocks, the secondary (magnetic) field generated by underground eddy current is observed by receiving coils. This kind of coupling between the surrounding rocks and the coil effectively guaranteed the detection of hidden water-bearing geological structures in the excavation direction. With the elapse of time, a decay curve of the secondary field is obtained, and advanced detection is further carried out by extracting and analysing the characteristics of observation data and the decay curve. A different pattern of the curve implies different resistivity distribution of the underground geological body (Kaufman & Keller 1983).

One of the most prominent differences between the ground TEM method and the tunnel TEM method is that during the process of TEM field transmission it spreads to the whole space. Thus, the observation data is an integrated response of the electrical property of rock-mass media within the entire space around the tunnel, which is called the ‘whole-space effect’. Specific to the tunnel environment, TEM probing has the following features. First, the observation space is highly limited. Therefore, the coil size is strictly limited by the area of tunnel working face. Second, many interference sources, such as complicated man-made noise, metal support, electricity facilities, electrical equipment, tunneling machines, rail tracks and locomotives, seriously influence the observation of TEM signal as shown in figure 1a (Hu et al. 2014). To address these difficulties in the actual application of TEM advanced tunnel detection, we develop a set comprising an observation method of tunnel field data and correction method under metal interference.

2.1. Correction method for metal interference

In this paper, the correction method of TEM metal interference uses signals that are not obviously affected by metal interference as a reference standard, and the polluted signals are corrected according to this standard. It is known that late-time apparent resistivity response generated by a TEM magnetic source takes the form of (Meju 1998)

$$\rho = \frac{\mu_0}{4\pi} \left[ \frac{2\mu_0 M q}{5tu(t)} \right]^{2/3},$$  \hspace{1cm} (1)

where $\mu_0$ is the vacuum permeability and $u(t)$ is the induced voltage at the moment of $t$. $M = I \times S_T$ represents the magnetic moment of transmitting coil, $I$ is the transmitting current.
current and $S_T$ is the area of the transmitting coil. $q = n \times S_R$ is the effective area of the receiving coil, $n$ is the turn number of the coil and $S_R$ is the area of the receiving coil. Therefore, for the different transmitting currents, the $S_T$ and $S_R$ are the constant if the TEM configuration is fixed.

Assuming that when the detection environment and acquisition parameter are the same the transmitting currents with and without metal interference are $I_a$ and $I_b$, the induced voltages are $u_a$ and $u_b$, and the calculated apparent resistivity are $\rho_a$ and $\rho_b$, respectively. Thus, the proportion between $\rho_a$ and $\rho_b$ can be represented as

$$\frac{\rho_a}{\rho_b} = \left(\frac{u_a/I_a}{u_b/I_b}\right)^{-2/3},$$

(2)

according to equation (1). Record $u_a/I_a$ and $u_b/I_b$ as $\bar{u}_a$ and $\bar{u}_b$, then equation (2) can be written as

$$\frac{\rho_a}{\rho_b} = \left(\frac{\bar{u}_a}{\bar{u}_b}\right)^{-2/3} = k,$$

(3)

where $k$ is the correction coefficient.

It can be seen that the correction coefficient obtained via the ratio between apparent resistivity is equivalent to that obtained via the ratio between $\bar{u}_a$ and $\bar{u}_b$. Notice that induced voltage and transmitting current are the raw data that we collect; the process outlined by equation (2) turns the correction of apparent resistivity into the correction of raw data, which is more convenient in fieldwork.

It should also be noted that the signals at early times usually exceed the maximum amplitude that the TEM receiver could record, while later time signals are concealed by environmental noises. Thus, it is natural that only several tens of time channels that compose the meaningful period of TEM response are analysed in this research as shown below. Meanwhile, by calculating the average value of $m$ groups of data that is not (obviously) affected by metal interference at each time channel, we can further reduce the measurement error and rationalise the correction processing by

$$\bar{u}_b(t_i) = \frac{1}{m} \sum_{i=1}^{m} \bar{u}_b(t_i),$$

(4)

where $i$ is the sequence number of selected correction reference standard and $s$ is the sequence number of the time channel. Dividing the observation data at each time channel to be corrected by the correction coefficient, we obtain the final result.

2.2. Data acquisition

In view of the above-mentioned correction method, the acquisition of the data both with and without metal support interference is the key issue of the whole advanced detection process. To interpret it, we shall first take a look at the observation system. Typically, the dipole–dipole device and coincident loop are the two major categories of field TEM device. The former device has the advantage of low mutual induction, while the latter benefits from a more significant secondary induction field. Considering the limited construction space underground and the convenience of practical measurement, the coincident loop is finally chosen.

Equation (1) indicates that under the same observation situation the larger the magnetic moment $M$ of the coil is, the higher the induced voltage we could record and the better signal-to-noise ratio we may achieve. It should be noted that the side length of the wireframe is usually less than 3 m, and the transmitting current should not exceed 6 A to achieve tunnel explosion-proof requirements. Therefore, the most realistic option to enlarge $M$ is to increase the coil area by increasing the number of turns, and thus multi-turn coil is applied in this study. The use of the multi-turn coil helps reduce the coil size, which further helps decrease the volume...
effect and improves the transverse resolution of advanced detection. However, the number of coil turns should not be too high so as to keep the low mutual induction and the high flexibility of the observation system.

As for advanced tunnel TEM detection, it is necessary to pay close attention to the whole surroundings, including the excavation front, the roof plate and the bottom plate. In this research, a flabellate observation system is adopted as shown in figure 1. By adjusting the direction of the electromagnetic field, that is, the normal direction of the transmitting coil and the receiving coil, multidirectional detection of the working front, roof, floor and side direction can be implemented. Therefore, we could utilise this flabellate observation method to detect the whole space in different orientations, and this set of three-dimensional data provides a more accurate criterion of the spatial position of abnormal bodies.

Certain construction specifications should also be followed to acquire high-quality data. Before entering the construction site, the types and quantities of metal supports are simplified as much as possible near the tunneling front face. In particular, large equipment such as road headers and scrapers should be withdrawn for at least 10 m. Also, electric facilities near the tunneling head are cut off to further reduce interference. When performing data collection, the wireframe of the multi-turn coil is fully expanded and flattened on the tunnel wall, and it should not be shaken when the transmitting current is switched on. Optimised measurement parameters, such as the number of overlays, the transmitting current, the signal amplification multiplier and so on, are also selected to enhance weak TEM signals.

Generally, metal supports are installed at the side and the roof of a tunnel, while the tunneling face is mostly bare rock.
Figure 4. (a) The satellite map of the experiment area. (b) The geographic map of the experiment area. The white background represents soft clastic rocks, the light yellow background represents hard clastic rocks, while the blue background represents the solid carbonate formation.

Figure 5. The configurations of transmitters and receivers in a tunnel.

3. Flume model experiment

To verify the feasibility of this correction method, we present an example of a flume model test. The indoor flume model (figure 2) is carried by a $200 \times 100 \times 80$ cm glass container, and a certain space of $80 \times 40 \times 55$ cm is separated to simulate the tunnel. The water injection height is 50 cm. In this experiment, we adopt an overlapping multi-turn small coil of $\phi$ 9 cm. The transmission coil has 12 turns, and the receive coil has 24 turns. A copper cylinder of $\phi$ 7.5 cm is chosen as the object abnormal body. As a simulator of the interfering metal support, fixed round steels of diameter $\phi$ 10 mm are placed at two sides of the tunnel (figure 2). The choice of this certain type of metal support is based on the fact that all kinds of supports result in a similar substantial uplift in the signal of the induced voltage. And thus, we believe that as the metal interference in this flume model experiment, round steel has a good case for representativeness. In this model test, the transmission frequency is 125 Hz, and the transmitting current remains at 2.6 A. Other measurement parameters are: a sampling rate of 1.25 MHz, number of overlaps is 1024, the number of time channel measurements is 120 and measuring time is from 500 to 2000 $\mu$s.

The simulation of both models with and without metal interference is carried out (figure 3). Since the evacuation front is what we are concerned about in this example, the flabellate observation system is applied with only one group. As shown in the multi-channel profiles of figure 3, the observation is performed every 15º. Thus, data of 13 directions are collected (figure 1). Considering further the time–depth relationship of the advanced TEM detection method, we could finally obtain the corresponding apparent resistivity profiles under different experimental conditions.

Without metal interference, the TEM response of the copper cylinder is remarkable as shown in figure 3a. The observation point-voltage profile presents a high-voltage characteristic, while the apparent resistivity section clearly shows the location of the low-resistivity copper cylinder. However, the observation point-voltage profile has the opposite feature
Figure 6. Contradistinction of the multi-channel profile before and after correcting metal support interference: (a) multi-channel profile of raw data and (b) multi-channel profile of corrected data.
Figure 7. Comparison of apparent resistivity before and after correction: (a) apparent resistivity before correction and (b) apparent resistivity after correction. The white circle denotes the low-resistivity body and the red line denotes the drilling result.
of high voltage at two sides and low voltage in the middle when the metal support is installed around the tunnel periphery, as shown in figure 3b. Meanwhile, the apparent resistivity section has the feature of high resistivity in the middle, which gives rise to the difficulty of distinguishing the abnormal body. In figure 3c, the corrected result is obtained using the correction method introduced in section 2.1. We note the calculation result that the metal interference at two sides of the tunnel working face is weakened, and the response of the metal anomaly body is highlighted.

4. A field application example

In this section, we further propose a fieldwork example that explores the development of a blind water-bearing structure in front of an excavation tunnel of a certain mine in China (figure 4). The configurations of transmitters and receivers in the real tunnel are shown in figure 5. In the advanced TEM detection method the corresponding flabellate observation system of 15 directions is used, in which we add two more measurements on both sides of the tunnel compared with the flume model experiment. Three groups of observation in the vertical direction are carried out to investigate the TEM response of the roof plate, tunneling direction and bottom plate. As shown in figure 6a, the response of the roof plate and a consequent landslide is obviously affected by I-beam steels and bolting supports. Figure 6b shows that our correction method can effectively suppress the influence of metal supports.

The correction of observation data is carried out further, and the apparent resistivity profiles of both raw data and corrected data are plotted in figure 5. Before correction (figure 7a), the two sides that are influenced by supports have low resistivity and the middle has relatively high resistivity. Correspondingly, the front low-resistivity body becomes visible after correction (figure 7b). The actual resistivity distribution is then objectively revealed by suppressing the support influence. With the combination of the corrected result and relative hydrogeology information, we deduce that a water-bearing structure exists in the front of the working face. As a confirmation, we drilled in this anomaly region. Water gushing occurred when drilling 57 m ($P_1$) ahead of the tunnel working face and the water inflow was $5\,\text{m}^3/\text{h}$. Water inflow increased to $10\,\text{m}^3/\text{h}$ and was stabilising at $25\,\text{m}^3/\text{h}$ at a drilling depth of 60 m ($P_2$). The verification conforms to the previous advanced detection result, proving the validity of our correction method.

5. Conclusions

Based on current TEM advanced detection technology, this paper analyses major metal interference sources in the tunnel environment. Combining with practical experiences, we propose a complete set of observation system and correction method making use of the signals that are not (obviously) impacted by metal interferences as a reference to correct signals that are severely polluted by tracks, metal supports and other tunneling machines. The probing system fully uses the limited tunnel space to provide three-dimensional profiles with relatively high resolution. The correction method combines the observation data near the middle of the tunneling front and the data before the installation of metal supports as a reference, which offers convincing correction results and is successful in model experiments and practical application.

The water flume experiment indicates that the anomaly response of low-resistivity target body can barely be observed when metal interference exists. After correction, the strong interference is effectively suppressed, and the possible location of the copper cylinder is clearly exhibited. The field experiment example further shows that the distribution characteristics of apparent electrical resistivity can be observed objectively using the correction method. And thus, we can propose a reasonable evaluation of the groundwater-bearing structures. Through these two examples, we conclude that the correction method proposed by this paper is effective in suppressing ‘low-resistivity pollution’ of tunneling metal supports and machines. The technique is of high application value because of its convenient construction and quick data processing, and the popularisation of this correction method can reduce the losses caused by water inrush hazards to a great extent.

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