Study on Application of Electromagnetic Tomography Advanced Geological Prediction in Tunnel Construction

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Abstract—With the large-scale construction and rapid development of underground engineering, wide application of advanced geological prediction technologies is needed in order to ensure construction safety and avoid such accidents, the geological conditions and rock mass in front of working face must be done before the excavation. To ensure construction safety and avoid such accidents, the geological conditions and rock mass in front of working face must be done before the excavation.

Geological prediction in tunnel construction is a leading international topic and problem all over the world [18-24]. The tunnel geological prediction becomes a difficult problem with high demand and difficult technology for complicated geological conditions and frequent engineering accident of tunnel. Advanced geological forecast methods includes geological analysis, advanced drilling method, the seismic reflection wave method, geological radar method, transient electromagnetic method, land sonar method, seismic wave tomographic imaging method and so on [25-28]. At the current stage, tunnel prediction is mainly based on seismic reflections, assisted by geological radar. In order to effectively predict geological problems in the front of tunnel face using the seismic reflection signals, special prediction technologies such as negative apparent velocity, Horizontal Seismic Profile, Tunnel Seismic Prediction, True Reflection Tomography, and Tunnel Seismic Tomography have been developed using different observation patterns and data processing techniques [29-38]. Electromagnetic tomography is used to surveying in the underground engineering as a mature technology.

In this paper we provide a general formulation with complete solution for electromagnetic tomography interacting under the tunnel construction. The paper discusses the issues in computed tomography reconstruction process under the conditions of incomplete projection based on the electromagnetic wave computed tomography, which is frequently used in the tunnel by means of numerical models and project cases. Meanwhile, this paper finds good stability of the horizontal projection matrix, proposes safe mining mechanisms based on trend...
projection matrixes in combination with the mining process in tunnel, and further expounds the mechanisms in detail using project cases.

II. PROJECT SUMMARY AND GEOLOGICAL CONDITIONS

A. Project Summary

Huangzhuang tunnel is a highway tunnel, the starting pile number is k145+030, the tunnel at the end of the pile number is k145+958, its total length is 0.928 km. The road standard is secondary and the design speed is 40 km/h. The clear height is 5m, and the width is 9m. Tunnel portal design is for terminal wall. The tunnel is shallow, buried from K145+256 to k145+418 and the buried depth from 18.5 to 31.3 m.

B. Geological Conditions

Tunnel hole body is mainly through the late yanshanian granite and the import section is mainly cretaceous andesite. The exposed rock from the new to old is \( Q_4^{el+al}, Q_4^{el+pl} \) and Ptn.

III. ELECTROMAGNETIC WAVE THEORY AND MODEL

The size of tunnel is relatively narrow and long. Normally, the strike length of tunnel is 928 m, and the width is about 150m. The basic principle of using electromagnetic wave computed tomography to detect the internal structure of tunnel in a rock is as follows: When the electromagnetic wave propagates in the underground rock strata, owing to differences physical properties between coal and rock, there are certain differences in their absorption for electromagnetic wave energy. Therefore, the attenuation of electromagnetic wave energy on the direction along electromagnetic wave ray contains geological information on the direction along this ray. In the rock’s tunnel, we can use the received electromagnetic wave energy to rebuild the geological uncertain areas within the coverage range of the rays.

It can be shown in Fig. 1 that the numerical model is 928 m long and 150m wide. It is supposed that there is a four faults. The arrangement mode of ray coverage is a standard observation system as the radio-wave imaging method used in a rock. One side emits the electromagnetic signal, and the opposite side receives the signals in approximate fan shape. In this observation system, the observation system is an incomplete projection, and the formed linear equation is highly sparse and pathologically ill-posed problem with serious rank-defect. The iterative method with constraints is the only way to solve this problem. However, the computed results depend heavily on the initial value, size of grid dividing and iteration number. This model is most typical in the current tunnel computed tomography analyses. However, the solution in the reconstruction process has the most severe distortion. Through the analysis of this model, the author will discuss in detail the characteristics and problems when the electromagnetic wave computed tomography is used. These computed tomography data can be used to discover stable quantity and to guarantee safety in the process of tunneling.

IV. ANALYSIS OF ELECTROMAGNETIC WAVE COMPUTED TOMOGRAPHY ALGORITHM

A. Transmission of Electromagnetic Waves

The physical parameters of coal are different from roof to floor (such as conductivity \( \sigma \), magnetic conductivity \( \mu \) and dielectric constant \( \varepsilon \) ) in a coal mine, they have different capacities to assimilate electromagnetic wave energy when the electromagnetic wave traverses the tunnel. The low-resistance strata has a strong absorption capacity of electromagnetic waves and when the electromagnetic wave meets the interface with fracture structure in its advancing direction, the reflection and refraction of electromagnetic wave occur and this depletes the energy. Therefore, when the electromagnetic wave of the emission source transmits through the tunnel and meets with four faults, fractured aquifer, tunnel

Figure 1. Standard rays arrangement applied in an electromagnetic wave, 928 m long and 150 m wide numerical tunnel model with faults
thinning area or other structures, the energy information of the electromagnetic wave reveals the geological information along the path it transmits through. The transmission electromagnetic wave with fixed-frequency can therefore be used. The change of the medium electromagnetic property and wave impedance along the ray path of the electromagnetic wave may cause change of the electromagnetic field intensity. By analyzing the electromagnetic field intensity, the change of physical properties of the medium in the testing zone can be predicted. In the end, we find that the internal structure of the tunnel face and the variation of tunnel thickness can be estimated by the variation of physical properties of the rock stratum.

The field intensity expression of the electromagnetic wave which transmits through the tunnel at any point of the medium is as follows:

\[ E = E_0 \frac{e^{-\beta r}}{r} f(\theta) \sin \theta \]  

(1)

where:

- \( E \): The actual measured field intensity of a certain point of the medium;
- \( E_0 \): The initial radiation field intensity that determines the emission power and surrounding media;
- \( r \): The distance between the transmitter and the receiver;
- \( f(\theta) \sin \theta \): The direction factor; \( \theta \) is the included angle between the dipole axis and the direction of the measured point; generally, \( f(\theta) = \cos\left(\frac{\pi}{2} \cos \theta\right) \sin \theta \) is applied for the calculation. Since the largest change of \( \theta \) ranges from 76° to 90° in the observation system of electromagnetic wave computed tomography in the tunnel of rock, it is approximately considered that \( f(\theta) = 1 \).
- \( \beta \): When the electromagnetic wave transmits in the medium, it is certain that part of the electromagnetic energy is absorbed with the increase of the distance. \( \beta \) refers to the attenuation amount of the unit distance field intensity and it is labeled absorption coefficient. \( \beta \) is determined by the medium absorption coefficients of parameters such as operation frequency, resistivity of the medium, magnetic conductivity of the medium and dielectric constant. It is generally expressed with the following expression:

\[ \beta = \omega \sqrt{\mu \varepsilon} \cdot \sqrt{1/2[1 + \sigma^2/(\sigma^2 \varepsilon^2 + 1)]} \]  

(2)

From Eq. (2) it can be seen that under conditions with fixed frequency \( (\omega = 2\pi f) \), the value of \( \beta \) is the function of dielectric constant \( \varepsilon \), conductivity \( \sigma \) and magnetic conductivity \( \mu \) of the rock. Since there are large differences between the dielectric constants of the tunnel and of the rock and the change of magnetic conductivity \( \mu \) is small, there is an obvious change in the values of \( \beta \) and \( E \). Moreover, since the tunnel is another kind of waveguide medium relating to the rock stratum, when its thickness changes, the wave impedance will change. This also leads to the change of the values of \( \beta \) and \( E \).

From Eq. (1) it can be seen that the value of the field intensity of a certain point is determined by four parameters. When the radiation condition does not change with time, \( E_0 \) is a constant and we regard the initial field intensities of the same emission points are the same. The absorption coefficient \( \beta \) is the main parameter that affects the amplitude value of the field intensity; since the field intensity attenuates with the distance exponentially, the larger the value of \( \beta \), the faster the field intensity will attenuate. After taking the logarithm of Eq. (1), we get:

\[ \ln(E) = \ln(E_0) - \beta r - \ln(r) \]  

(3)

Considering that \( \beta \) and \( r \) may have linear correlation, a relevancy formula can be defined as

\[ \eta = \frac{\ln(r_{\text{max}})}{\ln(r_{\text{min}})} \]  

(4)

It can be shown in Fig. 2 that the average length of the tunnel face ranges from 220 m to 330 m, the electromagnetic wave computed tomography can form an approximate sectorial observation system in the tunnel. Therefore, the transmission distance of the electromagnetic wave ray changes with the length of the tunnel from the nearest 220 m to the farthest 330 m. Here we take into consideration the tunnel under two extreme conditions with the smallest width as 220 m and the largest length as 330 m. Taking the tunnel with the largest transmission distance as 220 m long as an example, from Eq. (4) it can be seen that the corresponding change of \( \ln(r) \) ranges from 5.2983 to 5.3287 and the relevancy is 99.43%. When calculating for the tunnel with a length of 300 m, the corresponding change of \( \ln(r) \) ranges from 5.7038 to 5.7183 and the relevancy is 99.75%. Therefore, Eq. (3) can be approximately regarded as being straight with a slope of
\( \beta \) and \( \ln(E) \) and \( r \) is regarded to have a linear correlation. As a result, \( \ln(E) \) and \( r \) can be used to build linear equation to get the distribution condition of \( \beta \) in the tunnel.

B. Electromagnetic Wave Computed Tomography

In the tunnel the electromagnetic wave computed tomography technology is widely used to detect the geological structure. The means of data interpretation is developing from single manual approach to geophysical tomography technology. The algorithms at present are mainly based on the Back Projection Technique, algebraic reconstruction technique, simultaneous iterative reconstruction technique), and least squares qr-factorization of direct rays. The image-forming of electromagnetic wave computed tomography is to conduct inversion for the absorption capacity of the electromagnetic wave of the medium in the tunnel based on the actual measured data. Absorption capacity of the electromagnetic wave can demarcated the internal structure of tunnel face.

The electromagnetic wave transmitter is placed in one of the roadways of tunnel. On the other opposite roadway, an electromagnetic wave antenna is placed every 10 m in a sectorial manner (as shown in Figs. 2). Based on the field intensity \( E_k \) of electromagnetic wave received at each receiving point, inversion of the absorption coefficient \( \beta(x, y) \) is conducted. Supposing the intensity of the electromagnetic wave received of the \( k \) electromagnetic wave along the propagation path \( L_k \) is \( E_k \), then,

\[
E_k = \int L_k \beta(x, y) d\beta
\]  

Eq. (5) is a curvilinear integral; \( d\beta \) is arc length infinitesimal. Under the effect of different media underground, the transmission path of the electromagnetic wave is generally a curve. However, since the transmission path of the electromagnetic is short inside the tunnel, all the ray paths are regarded to be straight when building the computed tomography model. The discrete picture and reconstructed image can be acquired.

In this case, a square grid discrete tunnel is applied. The amount of the cells after the discretization in the reconstructed area is \( N \), which amount is the product of the line number i and column number j in the discrete area. The absorption coefficient of the electromagnetic wave of each grid is denoted as \( \beta_{ij} \), where, i is the line number of the discrete tunnel and j is the column number of the tunnel after discretization. Then, the field intensity \( E_k \) received by the \( k \) th electromagnetic wave ray can be expressed as:

\[
E_k = \sum_{n=1}^{N} \alpha_{in} \beta_{kn}
\]  

where, \( \alpha_{in} \) is the length that the \( k \) th ray passes through the \( n \) th grid. When \( k \) rays passes through the inversion area, Eq. (6) can be written in a matrix form as follows:

\[
A\beta = E
\]  

where, \( A \) is distance matrix; \( E \) is the magnetic field intensity matrix each ray receives; \( \beta \) is the absorption coefficient matrix. It is noteworthy that in the image-forming process of electromagnetic wave computed tomography, since matrix \( A \) is a large-scale sparse matrix, iteration method is applied for the solution. The iteration algorithm frequently used at present is back projection technique, algebraic reconstruction technique, simultaneous iterative reconstruction technique and least squares qr-factorization. Since the observation system of the electromagnetic wave computed tomography can only be placed in the roadway, the features of the coefficient matrix it forms is highly-sparse and the coverage of the limited angle can at most be \( 28^\circ \). Therefore, based on the theory at present, it is difficult to reconstruct the abnormal area completely (Fig. 4). Because the size structure of tunnel face is unique and trend length is 5-15 times more than width length in the tunnel, a stable indicating value must be discovered to guide safe production in combination with the computed tomography inversion result.

V. RELIABILITY ANALYSIS OF THE TREND PROJECTION MATRIX

Under these circumstances, the tomography is an ill-posed problem with serious rank defects because of the observation system’s characteristic. This leads to problems such as obscure image boundary, low resolution ratio, obvious boundary effects and serious distortion of the results. Based on the theoretical analysis and practice of predecessors, a better resolution result of the image can be achieved through addition of constraint conditions. But this result is restricted to complete and measurable solution set of \( \beta \) as the constraint. In the computed tomography detection of tunnel the absorption coefficient of the tunnel of electromagnetic wave cannot be achieved accurately. The absorption coefficient of electromagnetic waves near the fault revealed by the mining roadway can
not also be achieved accurately. This leads to a problem that the result of the inversion by applying constraint regularization relies more on the reliability of the constraint conditions. It has some guiding significance in reality.

In order to guide safety in production, the computed tomography solution result had better to be analyzed from another perspective. Due to the particularity of the size of the tunnel, the strike length of the tunnel is far larger than the width of the tunnel. In actual productive process, if there is a stable and high-resolution index for the quantization and comparison of the geological abnormalities along the strike direction to give alarm in the excavation process, it is meaningful for safe production. Through numerical computed tomography modeling and inversion, it can be discovered that the abnormalities along the advancing direction of the tunnel are in a stable form whether or not the inversion result converges to true value. Namely:

$$M_p = \lim_{k \to \infty} \left[ \sum_{m=1}^{m} X_{m1} \sum_{m=1}^{m} X_{m2} \ldots \sum_{m=1}^{m} X_{mn} \right]$$

(8)

where, \(m\) is the number of lines after gridding; \(n\) is the number of columns after the gridding; \(M_p\) converges to a constant value. Since this matrix has a strong stability and guiding significance along the mining direction of tunnel, it is named as a confidence matrix \(M_p\) along the mining direction of the tunnel in the incomplete projection computed tomography. The stable features will be explained in the following modeling and inversion of electromagnetic wave computed tomography, even if authors does not offer the stability of the matrix theoretically.

It can be shown in Fig. 5 that the properties of trend projection matrix with incomplete projection of the data are studied by the numerical model. The area to be measured in the model simulation is a 150 m long and 150 m wide square. The area is divided into 225 grids with 15 lines and 15 columns. The black area is simulated anomalous area where the electromagnetic wave absorption coefficient is supposed to be 2 and the electromagnetic wave absorption coefficient in other areas is supposed to be 1.

Fig. 5 indicates that the observation system of the numerical model is successively complete projection, limited angle projection and cross projection just like electromagnetic wave computed tomography. From this, a set of complete projection data and two sets of incomplete projection data are acquired. The three sets of data are used respectively for the computed tomography inversion image-forming of the numerical model. Through comparison and analysis of the computed tomography inversion image-formation and trend projection curve under the condition with coverage of rays as shown in Fig. 5, it can be seen that when the projection data are complete, the computed tomography inversion can completely reconstruct the original drawing. When there is limited angle projection for the observation system, there are obvious differences between the final inversion result and the real situation.

However, through comparison of the trend projection curve (Fig. 6), it is discovered that the projection curves of the three situations are in conformity with the actual situation. With the decrease of projection data, the projection curve does not change greatly overall and it has good stability as well as indicating value.

We also can use the numerical model (Fig. 7) to make the result more contrastive and illustrative.

Through analysis of the projection curve with different iterations in the 10x10 grid, it is discovered that the projection curves with 200 iterations, 400 iterations, 600 iterations, 800 iterations and 1,000 iterations tend to remain consistent. This indicates that the projection matrix is slightly affected by the iterations and has good stability and convergence.

The model is divided into a 15mx15m grid, 30mx30 m grid and 60mx60 m grid. 1,000 iterations are conducted for original data to compare the variation of the projection matrix with the same iteration number of different grids, as is shown in Fig. 8.
It can be shown in Fig. 8 that in the gridding process, the solution result may fluctuate if the number of the grids is too large, in other words, the number of the unknown is larger than the equation number. If the number of the grids is too small, the calculating result is largely affected by the initial value. Only when the number of the grids is appropriate can we obtain the optimal solution. For the solution result under conditions with the same iteration number and different grids, the total trend is consistent. This indicates that the curve form of the projection matrix has good stability and will not change with iterations and gridding fluctuations.

VI. CONCLUSIONS

The electromagnetic tomography was used for Huangzhuang tunnel and it worked well. The forecast results proved that by using the image method, the geological conditions of the area in front of the working face of the tunnel could be well known timely, and also the forecast result could be sent timely. There is still much work to be done in the study of guarantees for safety in tunneling. At present, the theoretical study of linear equation solutions constituted by large-scale sparse matrixes still cannot eliminate the artifacts in the reconstruction process of anomalous areas, and it is still unable to be compared with computed tomography results under complete projection in the aspect of the precision in the process of guiding safety production. Meanwhile the applicable procedures of electromagnetic tomography method were so simple that it was possible to carry on the forecast work without the influence on the tunnel construction. With the electromagnetic tomography, the basis could be provided to the tunnel construction and parameter adjustments to guarantee the construction safety.
The horizontal projection matrix of the tunnel was analyzed through theory and numerical value simulation. As for the computed results under conditions with the same iteration number and different grids, their overall trends still tend to toward consistency, indicating that the curve of the projection matrix is stable, and does not change with the change of iteration number and grid partition. Due to the particularity of the rock tunnel structure, however, the coefficient matrix formed by the tunnel is highly sparse, and the maximum coverage of the limited angle is only 30°. So, under these conditions with the current theories, achieving the complete reconstruction of anomalous areas is impossible.

Tunnel electromagnetic tomography can effectively and safely guide the excavation of the tunnel section working surface in combination with reconstructed images and excavation technology.

REFERENCES


