Comparative Analysis and Research on Electromagnetic Detection Technology of Tunnel Groundwater

Guicai Cao, Guangyi Gao, Lichao Nie

Prospecting, Survey & Design Institute of China Railway Tunnel Group Co., Ltd., Shandong University

Abstract. The electrical method is a sensitive technique for groundwater detection. As the tunnel develops in a deep direction, the groundwater problem becomes prominent. Thus, tunnel groundwater forecasting is particularly important. Through the advanced water exploration prediction practice in the complex geology of Gaoligongshan Tunnel, the water detection sensitivity of the complex frequency conductance (CFC) technology and the time-domain transient electromagnetic method (TEM) are compared. The advantages and disadvantages of the two methods are discussed, and the CFC technology is obtained. In accordance with the conditions of use of the time-domain transient electromagnetic method, the processing data of the CFC and the TEM method are compared with the actual excavation to reveal the groundwater development and establish a correlation.

1. Introduction
The mountain tunnels that have been built or planned to be built in China are generally long, large, and deep, whereas other tunnels have complex geological conditions [1]. As the tunnel develop deep into the ground, the problem of groundwater becomes prominent. At present, the electrical method is considered a relatively sensitive technical means for groundwater detection. Many experts and scholars at home and abroad have conducted considerable amounts of exploratory work. The high-density electrical method followed the idea of electrical exploration introduced in the late 1970s. After their mature development, software and instruments have been constantly updated. At the end of the 20th century, for shallow exploration, the first-arrival refraction-wave method has been used to find rock hills, etc., whereas the electrical method has been used to test groundwater from the surface down. For the purpose of finding water and detecting aquifers, the electrical method technology is relatively mature [2-5]. However, the geophysical advanced geological detection technology during tunnel construction involves the complex transplantation or transformation of the surface geophysical exploration technology [6-9]. Given the particularity of the electrical test principle, the application of the electrical method to tunnel detection is often limited by the environment of the measurement point layout.
Essentially, the advanced geological prediction technology for tunnel construction is an innovation of traditional geophysical exploration technology. This paper compares the exploration sensitivity of the complex frequency conductance (CFC) technology with the time-domain transient electromagnetic method (TEM) through the practice of advanced water exploration prediction in Gaoligongshan Tunnel. The improvement of forecasting technology provides a reference.
2. Forecast Principle

2.1 CFC
CFC is a new electromagnetic-wave water detection technology. CFC technology is based on the conductivity and permittivity of the water-bearing rock mass and the reduction of wave impedance. Electromagnetic waves in the frequency band of 100 KHz to 10 MHz are used for detection. Electromagnetic waves are reflected in the contact zone between the water-bearing and dry rock masses, and the water content of the surrounding rock in front of the palm face is predicted based on the coherent characteristics of electromagnetic waves at the receiving point [10]. The frequency band used for detection must be reasonably selected to effectively solve the problem of advanced water exploration in tunnels. The selection of electromagnetic-wave frequency bands complies with the following principles: ① effectively distinguishing dry rock masses from water-bearing rock masses; ② using an electromagnetic-wave propagation distance that can cover the predicted distance.

Rock mass is a complex frequency conductive medium with electrical conductivity and permittivity. The conductivity of a complex frequency increases after the water is contained, whereas the intrinsic impedance decreases. Electromagnetic waves show reflectance when they meet at the interface where the intrinsic impedance changes. CFC uses electromagnetic waves in the mid-band of 100 KHz to 10 MHz, the center frequency is 1 MHz, the wavelength of the electromagnetic wave is between 10 and 500 m, and the wavelength is equivalent to the detection distance. At this point, the incident and reflected electromagnetic waves interfere with each other in space and time. For a certain reflection interface, the coherence frequency of different receiving points differs. The strongest record is obtained at the antinode, and the coherent frequency is obtained. Using the 1/4 wavelength principle of frequency-distance, the reflected wave coherent frequency method is established. The location of the water-bearing body can be obtained based on the observed frequency spectrum, the magnitude of the coherent amplitude, and the intensity of the reflected wave are both related to the water content.

2.2 TEM
TEM belongs to time-domain electromagnetic methods. This method follows the principle of electromagnetic induction. A non-grounded loop for transmitting a pulsed magnetic field to the ground and a receiving coil for measuring the underground from the ground during a pulsed magnetic field interval is adopted when conducting TEM detection. A method for induced secondary magnetic field caused by the medium detects the apparent resistivity of underground medium [11-12]. When the transient electromagnetic test is carried out in the tunnel, the excavated part of the tunnel is extremely small relative to the surrounding underground space, and the detection process can be regarded as being carried out in the entire underground space. The full-space transient secondary electromagnetic induction eddy current field, with the transmitting coil as the center, propagates and attenuates outward along the plane of the transmitting coil [13] and reaches different depths and ranges at varied times.

The performance of the secondary vortex field is related to the electrical properties of the underground medium. Compared with similar rock layers, the apparent resistivity is relatively high when the rock layer is relatively complete, resulting in a weak eddy current field. When the rock layer is rich in water, the apparent resistivity is relatively low, resulting in a strong vortex field. Therefore, by observing the secondary electromagnetic field, the secondary eddy current field can grasp the distribution of the apparent resistivity of the underground medium to infer the location of the corresponding medium.

3. Collection Processing Forecast System

3.1 CFC
(1) Collection method
CFC water detection technology is achieved by transmitting and receiving electromagnetic waves and determining the coherent frequency. A dipole antenna is used to transmit and receive electromagnetic waves, and the antenna uses the electrodes buried on both sides of the tunnel.
One group transmits, and three groups receive. The transmitting and receiving antennas are arranged in an array-observation mode. The purpose of array reception is to improve the directionality of the observation system, thereby enhancing the signal in front of the palm face and suppressing the lateral signal. The directivity of imaging increases with the increase in the receiving electrodes. The electrode is buried in the surrounding rock and is in close contact with the surrounding rock to ensure that the conduction and displacement currents act simultaneously, which is different from that in traditional radar antenna. One pair of electrodes transmits, the position remains unchanged, and the other pair of electrodes moves to receive electromagnetic waves. During each transmission, the receiving electrode moves once. Combining multiple transmissions and receptions form a complete array. The transmitting and receiving electrodes are distributed in the surrounding rock, which effectively reduces various interferences in the tunnel and improves the signal-to-noise ratio.

Figure 1 shows the specific layout of the CFC observation system scheme:
① Three (3) pairs of receiving electrodes, namely, M1N1, M2N2, and M3N3, are arranged on two side walls, with three electrodes on each side, a spacing of 10 m, and an electrode depth of 1.8 m; ② one (1) pair of transmitting electrodes AB is arranged on both sides of the tunnel, with one electrode on each side placed 10 m away from the receiving electrode and buried at a depth of 1.8 m; ③ the length of transmitting electrode and receiving electrode is >2 m; ④ the transmitting electrode and receiving electrode need to be well coupled with the surrounding rock.

(2) Transmitting and receiving equipment
The transmitter frequency band of CFC detection system is 100 KHz to 20 MHz, the highest emission peak voltage is 6 kV, and the emission current can reach 120 A. The electromagnetic-wave digital acquisition instrument is dual channel, the sampling rate is 400 MHz/ch, with dynamic 16 bits, and the transmission current and receiving pole voltage are recorded simultaneously. Figure 2 shows the instrument.
Figure 2. CFC excitation and receiving instruments

(3) Data processing
Figure 3 shows a record of the transmitter electrode current and receiver electrode voltage collected by the engineering example. The data acquisition length is 100 µs, and the sampling frequency is 100 MHz. The waveform indicates a broadband recording of the pulse envelope.

Figure 3. CFC signal record

The CFC shift images are obtained through the process of record selection, data preprocessing, geometric position editing of observation system, frequency spectrum normalization, CFC electromagnetic-wave speed scanning, CFC synthetic aperture shift imaging calculation, etc.

Figure 4. CFC offset image

3.2 TEM
(1) Collection method
With the direction of the palm face as the reference zero point, in the horizontal direction, the transmitting coil shifts from 45° to 45° from the right, and every 15° offset is a set of data, resulting in
seven data sets. In each data set, the transmitter coil is tilted from $45^\circ$ to $45^\circ$ downwards, and each offset of $15^\circ$ is one data set, reaching a total of seven data sets. The test method obtains a total of 49 data sets (Figure 5).

![Figure 5. Tunnel TEM method](image)

(2) Transmitting and receiving equipment
Instrument selection involves the PROTEM 47HP transient electromagnetic instrument. The test device uses a parallel dipole device (Figure 6) to reduce the mutual inductance effect of the coil. The transmitting coil is a $2 \times 2$ m2 wire frame, the number of turns is 64, and the supply current is 1 A; the equivalent area of the receiving coil is 31.4 m². The following parameters are used to improve the signal-to-noise ratio and ensure the reliability of the original data: transmitting frequency of the transmitting host: 6.25 Hz; off time: 150 µs; integration time: 15 s; the number of acquisition gates: 30; gain multiple: 4.

![Figure 6. Arrangement of transient electromagnetic coils in the tunnel](image)

(3) Data processing
Transient electromagnetic detection data include going through “file format conversion” → “data preprocessing” → “generate profile file” → “time-depth conversion” → “depth correction” → “advance detection coordinate conversion” → “whitening” → “section The process flow of drawing” → “Generating apparent resistivity profile,” obtaining a total of seven two-dimensional plan views of apparent resistivity.

“Time-depth conversion” is completed by inversion calculation. The depth after inversion is the apparent depth and needs to be corrected; “depth correction” parameters are generally determined by field experiments and geological data.
4. Excavation Reveal Comparison and Analysis

4.1 Excavation reveal comparison

The Gaoligong Mountain Tunnel has a special geographic location and extremely complex geological structures. The engineering geological conditions include “three highs” (high geothermal, high in-situ stress, and high seismic intensity) and “four actives” (active new tectonic movement, active geothermal water environment; the characteristics of active external dynamic geological conditions and active bank slope shallow-surface reconstruction process). Tunnel #1 inclined shaft construction area mainly passes through the stratigraphic lithology of Cambrian Shahechang Formation slate, siltstone with limestone and marl, and Cambrian Baoshan Formation Section 1 (∈ [3] b (1)) slate. Sandstone is mixed with argillaceous limestone, the second member of Gongyang River Group (∈ gn (2)) schist, slate, phyllite with quartzite, and metamorphic sandstone. The Zhengdong cave passes through two synclines and three faults. The Bangmai–Shaojiazhai fault and Bangmai–Shaojiazhai secondary fault are thermally conductive faults. The horizontal guide passes through two synclines and two faults; the secondary faults of Bangmai–Shaojiazhai are thermally conductive faults.

The inclined shaft of Gaoligongshan Tunnel revealed from XJ1ZK1+183 indicates that the surrounding rock is limestone and slate, with developed joint fractures, broken and partially broken rock mass, and formation of block stone and gravel-like structure. The groundwater is developed, the palm surface is seepage, the vault arch waist is linear, and the small strand is effluent. The mileage XJ1ZK1 + 183, XJ1ZK1 + 103, XJ1ZK1 + 045, XJ1ZK0 + 963, XJ1ZK0 + 883, and XJ1ZK0 + 803 are used during CFC and transient electromagnetic synchronous implementation to ensure the safety of tunnel construction and reduce the risk of mud inrush and to obtain the effectiveness of groundwater electromagnetic detection technology, and the forecast results and actual excavation findings are used for comparison. Figure 8 and Table 1 show the implementation and revealing comparison, respectively.

Figure 7. Results of tunnel transient electromagnetic detection

Figure 8. CFC and transient electromagnetic implementation
### Table 1. Comparison between CFC and TEM and actual application

| Forecast mileage | CFC detection results | Transient electromagnetic detection results | Actually reveal the situation |
|------------------|-----------------------|---------------------------------------------|------------------------------|
| XJ1ZK1+183 ~     | Groundwater is dominated by fissure water, which is generally linear to strand flow | Development of a small amount of water seepage | Groundwater is not developed |
| XJ1ZK1+160 ~     | Groundwater development mainly from linear to strand water | | Groundwater, mainly linear water and strand water, development, with a maximum influx of 60 m³/h |
| XJ1ZK1+083 ~     | Groundwater, which is mainly fissure water, is more developed and generally follows a linear flow | Groundwater is developed and mainly includes linear effluent and seepage. |
| XJ1ZK1+045 ~     | Partial water, mainly dripping and seepage | Groundwater is developed; local linear water | Groundwater is weakly developed; mainly dripping water |
| XJ1ZK1+008 ~     | It is in a weak water-bearing state, where the reflected wave intensity near +980 is strong, the groundwater is speculated to be nearby, and the remaining groundwater is weakly developed | Weak development, local drip seepage | Groundwater is weakly developed; mainly drip seepage water, and local linear water |
| XJ1ZK0+980 ~     | Weak development, local drip seepage | Groundwater is weakly developed, and with partial strand water |
| XJ1ZK0+930 ~     | The surrounding rock has a large water content and is affected by fissures. The palm surface is generally linear and strand-shaped. | Groundwater is more developed and presumably linear water |
| XJ1ZK0+855 ~     | The groundwater is not developed; linear effluent and seepage may be present | Groundwater is not developed, and local seepage exists |
| XJ1ZK0+834 ~     | Groundwater is not developed, and local seepage exists | Groundwater is more developed, mainly as seepage and linear water |
| XJ1ZK0+781 ~     | Groundwater is developed, and it is generally linear and seepage. | Groundwater is more developed, from linear to strand water |
| XJ1ZK0+723 ~     | Groundwater is not developed, and local seepage exists | Groundwater is weakly developed, and mainly drip seepage water, and local linear water |

#### 4.2 Analysis of forecast results

The offset image obtained by CFC technology reflects the distribution of the coherent energy of the reflected wave. Red and yellow stripes indicate the strong coherent energy, respectively, the reflected wave strength, the interface with large water content, followed by green, less blue water content. The TEM mainly detects the resistivity distribution, and its purpose is to find the abnormal resistivity distribution under the background resistivity distribution and to judge the water content of the surrounding rock through the comparison of resistivity. According to the statistical findings of the forecast results and actual excavation, the comparative analysis of the forecast results of the CFC technology and the TEM is as follows:

1. CFC technology and TEM have certain sensitivity to groundwater. With the stranded effluent at XJ1ZK1 + 108 as an example, both procedures can accurately respond to the section with large water influx.
(2) The TEM is prone to be affected by the water environment, resulting in deviations in the forecast results, whereas the CFC technology is less disturbed. Given XJ1ZK1+045–XJ1ZK1+008 as an example, the development of groundwater in the mileage section during the implementation caused a certain deviation to the prediction results of transient electromagnetics.

(3) Quantitative interpretation of groundwater using CFC technology and TEM is difficult to accomplish, but transient electromagnetic method can predict the spatial location of groundwater development. With XJ1ZK1 + 108 strand effluent as an example, TEM can guide drilling to find water accurately.

Through multiple verifications on the construction site, the accuracy of groundwater detection by the two electromagnetic methods is relatively high. The accuracy of CFC technology is 78.0%, and that of TEM is 75.2%, which can meet the requirements of on-site safety production.

5. Advantages and Disadvantages of the Two Methods in Water Exploration
CFC technology and TEM differ in terms of acquisition, data processing, and interpretation of results. The CFC technology requires a borehole layout observation system for acquisition and does not require treatment of surrounding metals. The TEM only needs to ensure that the surrounding environment is free of metal interference. The acquisition time of CFC technology is shorter than that of TEM, but the data processing time of both methods is short. CFC technology judges the water content by shifting the image response to the distribution of reflected wave coherent energy, whereas the TEM mainly detects the resistivity distribution and judges the water content of the surrounding rock by comparing the resistivity.

From the theoretical basis, layout of the observation system, prediction results, and practical experience but limited spatial conditions of the working surface in the tunnel and observation mode of the anomaly ahead, the advantages and disadvantages of the two prediction methods are mainly manifested as follows:

| Serial number | Forecasting method | Applicable environment | main feature | Pros and cons |
|---------------|--------------------|------------------------|--------------|---------------|
| 1             | CFC technology     | Drilling and blasting method, TBM construction | Based on the characteristics of the conductivity and permittivity of the water-bearing rock mass and the reduction of the wave impedance, electromagnetic waves in the frequency band of 100 KHz to 10 MHz are used for detection. An ungrounded loop is used to transmit a pulsed magnetic field to the ground, and during the interval of a pulsed magnetic field, the receiving coil is used to observe the secondary induced magnetic field caused by the underground medium. | The forecast distance is long, and the interference from the space environment is small. The frequency band most sensitive to the water-bearing body can only be determined qualitatively when water is present, which barely affects the construction. |
| 2             | TEM                | Drilling and blasting | | The forecast distance is far, the requirements for the construction space environment are high, the groundwater can be judged semi-quantitatively, and the accuracy is high. |
6. Conclusions and Recommendations
(1) CFC technology is sensitive to aquifers, but it can only qualitatively analyze the development of groundwater and requires verification with advanced drilling (CFC requires less space environment than TEM. Tunnels that cannot be implemented can be used).
(2) TEM is not only sensitive to groundwater but also has a certain degree of response to joint cracks and undesirable structural planes. The complex geological and water-rich formations use better transient electromagnetic effects and can guide drilling to find water.
(3) CFC technology or both methods can be used to detect groundwater in the water environment to reduce the deviation of forecast results caused by environmental interference.
(4) CFC technology and TEM have certain sensitivity to groundwater development degree, and the signal spectrum of the data processing process should be related to the groundwater development morphology and water content to establish a unified relationship.

References
[1] QIAN Qihu. Challenges faced by underground projects construction safety and countermeasures[J]. Chinese Journal of Rock Mechanics and Engineering, 2012, 31(10): 1 945 ~ 1 956.(in Chinese)
[2] Mao Zhuoliang. Discuss the current situation and development prospect of engineering geophysical prospecting in China [J]. Low Carbon World, 2014, (03). (in Chinese)
[3] Zhi Zhenghua. Prospective role of geophysical methods in geotechnical engineering survey [J]. City Survey, 2009 (02). (in Chinese)
[4] Wang Xingtai. New method and technology of engineering and environmental geophysical prospecting [M]. Beijing: China Geological Publishing House, 2006.(in Chinese)
[5] Zhu Debing. A review of the current status of engineering geophysical methods and technologies [J]. Progress in Geophysics, 2002, 17 (1): 163-170. (in Chinese)
[6] Alimoradi, A., Moradzadeh, A., Naderi, R., Salehi, M.Z., Etemadi, A., 2008. Prediction of geological hazardous zones in front of a tunnel face using TSP-203 and artificial neural networks. Tunn. Undergr. Space Technol. 23 (6), 711–717.
[7] Ashida, Y., 2001. Seismic imaging ahead of a tunnel face with three-component geophones. Int. J. Rock Mech. Min. Sci. 38 (6), 823–831.
[8] Liu, B., Li, S.C., Li, S.C., Zhang, Q.S., Xue, Y.G., Zhong, S.H., 2009. Study of application of complex signal analysis to predicting karst-fractured ground water with GPR. Yantu Lixue/rock & Soil Mech. 30 (7), 2191–2196
[9] Liu, B., Li, S.C., Zhang, Q.S., Li, S.C., Xue, Y.G., 2009b. Study of the prediction of karst-fractured groundwater in prediction and early warning system of tunnel geologic hazards. J. Shandong Univ. 39 (3), 115–121
[10] Application of complex frequency conductivity technology in detecting water in tunnel. Yangtze River, 2015, 46(21) ;50-24.
[11] Li Xiu. Theory and Application of Transient Electromagnetic Sounding [M]. Xi’an: Shaanxi Science and Technology Press, 2002.(in Chinese)
[12] Niu Zhilian. Principle of Time Domain Electromagnetic Method [M]. Changsha: Central South University Press, 2007.(in Chinese)
[13] Tan Daiming, Qi Taiyue, Liu Chuanli. Research and Application of Transient Electromagnetic Response of Tunnel in Full Space [J]. Hydrogeology and Engineering Geology, 2009,14 (3): 111-116.(in Chinese)