Detection of water-rich fractured rock masses along proposed railway tunnel routes using three-dimensional aero-electromagnetic methods

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Abstract: Water inrush (gushing) is one of the primary hazards affecting the construction of underground engineering works, such as tunnels. The detection of water-rich fractured rock masses in the proposed routes of long trans-mountain tunnels is a significant engineering challenge. The traditional ground-based geophysical exploration methods are limited by rugged terrain. On the other hand, the aero-electromagnetic technique relies on differences in the resistivity of water-bearing and dry rocks to locate underground water. Using multi-dimensional geophysical data, this technique can improve the accuracy of exploration, locating masses of water-rich fractured rock along proposed routes of trans-mountain tunnels and guiding route selection. While promising, this technique is relatively young; thus, more research on their efficacy is required. In this study, aero-electromagnetic surveys of the Zheduoshan Tunnel of the Sichuan–Tibet Railway were conducted, and the feasibility and validity of the method were verified by directly collecting data from deep boreholes. The aero-electromagnetic technique is shown to have good application potential for improving the efficiency of geophysical exploration.

Key words: Three-dimensional aero-electromagnetic methods; Tunnelling engineering; Water-rich fractured rock mass; Sichuan–Tibet Railway

1. Introduction

Aero-electromagnetic geophysical surveys have a long history of development. Internationally, it is a robust technique based on mature technology; however, the research and development of aero-electromagnetic exploration systems is still in its infancy in China\textsuperscript{[1]}. The accelerated development of the western region of China requires the construction of long and deep railway tunnels, which is technologically challenging. If a tunnel passes through a
water-rich fractured zone, for example, major safety hazards, such as tunnel or ground collapse, and water or mud inrush will likely be encountered. Therefore, accurately determining the size and shape of water-rich fracture zones and other hazardous regions is necessary. Common geophysical exploration methods for mapping hazardous geologic bodies include ground-penetrating radar\cite{2,3}, elastic waves\cite{4,5}, ground conductivity\cite{6,7}, and transient electromagnetics. These techniques are mainly used for applications such as groundwater detection\cite{8-11}, mineral resource exploration\cite{12,13}, geological surveys and mapping\cite{14-15}, and detecting seawater intrusion\cite{16,17}. While they are robust, the complex geomorphology in the mountainous southwest regions of China, particularly the steep terrain along the Sichuan–Tibet Railway, poses problems to their application, because the traditional ground-based measurements are difficult to conduct in the rugged, high-altitude terrain.

In recent years, several studies have conducted theoretical and applied research on airborne geophysical exploration\cite{18-23}. The achievable detection depth has increased from less than 200 m to 2000 m, with a wider range. Studies have shown that aero-electromagnetic surveys are suitable for karst, fault, and lithology determination necessary for railway tunnel exploration\cite{24}. Airborne gravity and magnetic surveys, employed for exploration of geothermal water, have the advantages of wide scope, low cost, and fast data collection\cite{25}. Airborne transient electromagnetics have successfully been employed to locate the lead-zinc polymetallic ore reflected in the low resistivity of the Aqishan area of Xinjiang\cite{26}. Aero-electromagnetic surveys are being used for the first time in China for the exploration of long and deep tunnels for the Sichuan–Tibet Railway. Based on field tests and research, this study outlines the exploration of water-rich and fractured rock masses along the proposed routes of the railway tunnel using three-dimensional aeromagnetic surveys. This study aims to overcome the limitations of topography, improve the detection depth and scope, and allow for effective work, despite complex geological conditions.

2. Project overview

The proposed Zheduoshan Tunnel of the Sichuan–Tibet Railway is located in Kangding City, Sichuan Province. The tunnel entrance is located on the right bank of the Zhedu River on the west side of Zheduotang Village, Yulin Street, Kangding City, while the tunnel exit is located on the right bank of the Liqu River on the east side of Shuiqiao Village, Waze Township, Kangding City. The entrance mileage is CK279+825 m, the exit mileage is CK300+560 m, and the long chain is 12.86 m. The length of the tunnel is approximately 20,735 m, whereas the maximum depth of the tunnel is approximately 1219 m.

2.1. Topography

The area is located in the southwest margin of the transition between the Sichuan Basin and Qinghai–Tibet Plateau. As a result of strong erosion by the Minjiang River, the Dadu River, and other water systems, the terrain has high relief, dense gully networks, and intersecting mountains. The climate is warm, with typical subtropical warm and wet valley characteristics, such as dense vegetation. A watershed is present between the Dadu River and Yalong River in the area of Zhedu Mountain and Dapao Mountain. The surface elevation is 3460–4730 m, and the primary external forces are ice-water erosion, freezing and thawing, and biological weathering, which
is typical for a plateau landform. The entrance of the tunnel is located on the west half slope of Zheduotang. National Highway G318 is on the other side of the river, and thus, traffic conditions of rural access roads are good. The exit of the tunnel is located near National Highway G318 and Shuiqiao Village, Waze Township, with average traffic conditions.

2.2. Formation lithology
The area strata belong to the Jinchuan Yajiang units from Kangding to Xinlong. The Quaternary Holocene colluvium (Q4col) exposed in the tunnel area mainly comprises fine breccia, coarse breccia, gravely, and block stone soil. An alluvial/proluvial layer (Q4al+pl) comprises silty clay, coarse-grained soil, and pebbly soil. Slope eluvium (Q4dl+el) comprises silty clay (with breccia inclusions), coarse-to-fine breccia soil, and gravelly soil (with breccia inclusions). The Quaternary Pleistocene moraine layer (Q2fgl) is composed of powdery clay, coarse-to-fine breccia soil, gravelly soil, and block stone soil. The underlying bedrock is interbedded quartz sandstone and slate from the upper Triassic to Jurassic (T3zw), interbedded quartz metasandstone and calcareous quartz metasandstone of the Zagunao formation (T3z), and the Neogene fine-to-coarse biotite monzogranite and granodiorite (γδN1).

![Figure 1. Topographic map of Zheduoshan Tunnel](image)

2.3. Geological structure
Zhedu Mountain is located on the west side of the junction of the Yangtze block and the Qiangtang–Sanjiang orogenic system. The east side is the Kangdian basement complex belt of the Yangtze block, and the west side is the Yajiang residual basin of the Qiangtang–Sanjiang orogenic system. Zhedu Mountain is also located in a region affected by three deep active fault zones: Xianshuihe, Longmen Mountain, and the Anning River. Numerous active faults are present in series along the mountain trend. From east to west, the four branch faults of the Xianshuihe Fault Zone are as follows: the Yalahe Fault, Seraha Kangding Fault, Zheduotang Fault, and Yulongxi Fault. Numerous fractures are present throughout the tunnel site, such as the Zheduotang Fault, Jinlongsi–Mozigou Fault, Huiyuansi–Lejipu Fault, Yulongxi Fault, and
In addition, several other local features exist that have been interpreted as faults from geophysical and remote sensing data.

3. Aero-electromagnetic exploration

3.1. Basic principles

Aero-electromagnetic methods categorize the underlying rock based on differences in electrical resistance. Varying degrees of fracture, weakness, karst development, and water content affect the resistivity of rock. Based on the magnitude and distribution of electrical resistance, this property is used to determine the spatial distribution of underground geological bodies. The main factors affecting resistivity are mineral composition, rock structure, geologic structure, and water content.

| Formation lithology                                                                 | Inversion resistivity, $\rho$ (Ω.m) |
|-----------------------------------------------------------------------------------|-------------------------------------|
| Extremely fractured, weak, strongly developed karst, or water-rich                 | $\leq 500$                           |
| Weak or water-bearing, with medium development of fractures and karst              | 500–1600                            |
| Somewhat or partially fractured, weak, or weakly developed karst                   | $\geq 1600$                         |

The detection depth of airborne transient electromagnetics can reach 400–600 m with high resolution, while the detection depth of airborne natural field electromagnetics can reach 2000 m, but with lower resolution. Therefore, the proposed solution is to combine the airborne transient electromagnetics and airborne magnetotellurics, and
perform three-dimensional joint inversion of the data from the two methods. To adequately account for large changes in the depth of the Sichuan–Tibet Railway tunnel, ensure the reliability of geophysical data, and maximize the efficiency of the exploration work, this geophysical survey uses a combination of airborne transient electromagnetics and airborne magnetotelluric and aeromagnetic measurements. The main instruments used in the study were a versatile time domain electromagnetic (VTEM) system (Vtemlite), a Z-axis tipper electromagnetic (ZTEM) system developed by Geotech, Aurora, Ontario, Canada, and a G822A magnetometer sourced from the United States. When only a single electromagnetic method is used for the detection of mineral resources, it is usually transient electromagnetics. However, this method alone does not reach the detection depth required for planning a deep railway tunnel section. On the other hand, if only airborne natural field electromagnetics are used, no high-frequency data is obtained, and thus, shallow tunnel sections appear blank. Therefore, to survey a tunnel with varying depth, multiple aeromagnetic methods must be employed. When both airborne transient electromagnetics and airborne natural field electromagnetics are used, three-dimensional joint inversion of the datasets allows for the adequate mapping of both deep and shallow sections of the proposed railway tunnel. Water-rich fracture zones located by airborne geophysical exploration can be subsequently verified by drilling boreholes. This eliminates potential errors from multiple solutions of the geophysical data. After drilling, comprehensive logging can be performed to determine the rock integrity and groundwater development at varying depths. Furthermore, water abundance within a rock mass can be evaluated by pumping tests.

3.2. Principles of survey line layout
Data must be collected along multiple survey lines to effectively explore the geological conditions of the railway line, ensure the reliability of the geophysical data, and maximize the efficiency of the exploration project. Li Jian and others summarized the research and experience of the aero-electromagnetic methods of Geotech company in Canada. To ensure that entire area of the proposed Sichuan–Tibet Railway tunnel is mapped and that the data remain reliable at the edges, the survey lines extended 3 km beyond the tunnel length and the width of the exploration area was 2.1 km. Exploration lines include a central line through the center of the proposed route, a left line group, and right line group, arranged to the left and right of the central line. Each group comprises five additional parallel survey lines, which are symmetrically arranged with respect to the central line. The distances between the lines on each side increase with increasing distance from the central line, and the distance between the outermost edge lines is twice the tunnel exploration width. The length of each line extends 3 km outward from both tunnel ends.

3.3. Test design
According to the layout principle of Li Jian described above, one survey line was arranged along the center line of section CK279+000–CK291+000 m, and then, five parallel survey lines were set both its sides. They were symmetrically arranged with respect to the central line, and the horizontal distances between them were 50, 100, 200, 300, and 400 m, i.e., there were 10 survey lines parallel to the central line in total, and located 50, 150, 350, 650, and 1050 m from the center line (Figure 4). The transverse width between the lines (the distance between the outermost two lines) was 2.1 km. See Figure 5 for additional illustration of the layout of the aero-electromagnetic survey lines of the Zheduoshan Tunnel.

![Figure 4. Layout of aero-electromagnetic survey lines for the Zheduoshan Tunnel](image)

(1: proposed railway center line; 2:– survey lines at 50 m horizontal distance from the central line; 3: survey lines at 100 m horizontal distance from the central line; 4: survey lines at 200 m horizontal distance from the central line; 5: survey lines at 300 m horizontal distance from the central line; 6: survey lines at 400 m horizontal distance from the central line)
Figure 5. Survey lines for aero-electromagnetic exploration of the Zheduoshan Tunnel

The total length of all 11 survey lines is 396 km (Table 2 and Figure 4). ZTEM_MT3Dinv software was employed to perform a three-dimensional inversion of the data from the 11 lines, using the terrain elevation and the height of the electromagnetic receiving coil as constraints. The results of inverting the VTEM data (resistivity depth imaging (RDI)) were used as the initial model of the shallow ZTEM data. Subsequently, a joint inversion with the middle and deep ZTEM data was performed. The inversion center area (the size of the vertical grid) geometrically increased with the depth. The real and imaginary parts of the X and Y components in the frequency range of tilter parameters involved in inversion were in the 37–600 Hz range. The initial resistivity was set to 1000 Ω·m, and the resistivity range was 1–10^6 Ω·m. The relative error was set to 20%, and the tilter noise to 1%. The three-dimensional joint inversion resistivity section map, combining data from all 11 lines, was obtained from 20 stacking iterations, and formed the basis for the subsequent data interpretation.

Table 2. Layout of aero-electromagnetic survey lines for the Zheduoshan Tunnel

| Geophysical method | Start mileage | End mileage | Line length (km) | Number of lines | Total length (km) |
|--------------------|---------------|-------------|------------------|-----------------|------------------|
| VTEM               | CK279+000 m   | CK291+000 m | 18               | 11              | 198              |
| ZTEM               | CK279+000 m   | CK291+000 m | 18               | 11              | 198              |
4. Test data analysis

4.1. Data processing and geological interpretation

Geosoft Oasis montaj V7.1 software, combined with data processing software developed by Geotech, was employed to process the aero-electromagnetic data to obtain the three-dimensional joint inversion resistivity map, as shown in Figure 6.

![Figure 6. Crosssection of apparent resistivity retrieved by combining ZTEM and VTEM data](image)

The resistivity profile and geological data (Figure 6) demonstrate that sections CK291+000–CK287+000 m and CK283+000–CK279+000 m have low resistance. In section CK291+000–CK287+000 m, the inversion resistivity isoline has irregular low resistance, such as eyeball, belt, or irregular tree. The inversion resistivity values are less than 1000 Ω·m for section CK291+000–CK287+000 m. Section CK283+000–CK279+000 m is generally characterized by medium resistance, with low resistance regions of some parts. In the middle of the tunnel route, section CK287+000–CK283+000 m is mainly characterized by heterogeneous high resistance, such as lumpy or flaky.

![Figure 7. Apparent susceptibility crosssection of aeromagnetic inversion](image)

From the aeromagnetic inversion crosssection (Figure 7), the overall apparent susceptibility is relatively low. Apparent resistivity isolines with a dense gradient, bends, and discontinuities appear at positions CK290+000 m, CK289+550 m, CK288+200 m, CK287+300 m, CK285+000 m, and CK283+000 m of the crosssection. The inversion resistivities of sections CK288+850–CK288+700 m, CK282+150–CK282+400 m, and CK280+900–CK280+750 m are reduced, implying a low-resistivity rock block, with an apparent resistivity below 500 Ω·m.
The calculated apparent resistivity and the real coordinates of the survey area were used to obtain the contour map shown in Figure 8. The results of geophysical exploration reported in this section and geological data suggest that section CK291+000–CK287+000 m comprises quartz metasandstone and calcareous metaquartz sandstone. The lithology of section CK287+000–CK283+000 m is mainly adamellite, while the lithology of section CK283+000–CK279+000 m is mainly granodiorite.

Figure 9. Comprehensive results

The geophysical and geological data suggest that the gradient-dense zone of apparent resistivity at positions CK290+000 m, CK289+550 m, CK288+200 m, CK287+300 m, CK285+000 m, and CK283+000 m results from a fault. Positions CK290+000 m and CK289+550 m are on the Huiyuansi–Lejeep Fault, which has a determined displacement at the known fault position.

The resistivity characteristics suggest that the low-resistivity anomalies in sections CK288+850–CK288+700 m, CK282+150–CK282+400 m, and CK280+900–CK280+750 m are class V geophysical anomalies, indicating extremely fractured, weak, or water-rich bodies.
To test the accuracy of the aerial surveys, geological drilling was subsequently performed in the abnormal area.

4.2. Verification by geological drilling

Data from borehole DZ-Zheduoshan-shen-2-1 suggest that the fault zone (generally fractured) is below 595 m and that the upper part 17 sections are sandwiched by 2–10 m wide structural fracture zones. Water gushing starts at a depth of 293.7 m, and the water inflow rate is 310.5 m$^3$ per day. The borehole exhibited a closed water-rich structure, forming a channel. The high head difference and high fissure rate produced a concentrated overflow of water.

Figure 10. Photos of cores from borehole DZ-Zheduoshan-shen-2-1

Borehole DZ-Zheduoshan-shen-2-2 revealed fault breccia at depths of 412–434 m, 451–557 m, and 600–628 m, fault gouge at a depth of 644.6–654.5 m, and 14 m of structural fractures in the upper and lower strata, 2–10 m wide. Water gushing starts at a depth of 287.15 m, at a rate of 304.3 m$^3$ per day, and water leakage was observed to 888 m. The borehole exposed a closed water-rich structure forming a channel, and the high head difference and high fissure rate lead to concentrated overflow of water. Geophysical exploration demonstrated that the abnormal zone is about 200 m thick. The rock mass is somewhat fractured, and the excavation process may lead to the collapse of the arch crown, flooding, major deformation, and other
similar problems.

Figure 11. Photos of cores from borehole DZ-Zheduoshan-shen-2-2

The confined water revealed by boreholes in the Zheduoshan area suggests two possibilities. One is that underground water moves downward along fractures, eventually becoming confined by the granite. Another is that the confined water derives from precipitation in the high-altitude Zheduoshan terrain and is confined by sandstone. The groundwater flows along the fractures in sandstone and slate in the Triassic strata after being recharged by precipitation. Either way, the high pressure of the confined water will undoubtedly cause construction difficulties when the tunnel works are undertaken. This highlights the necessity of accurate geological understanding and mapping for construction planning.

5. Conclusions
The detection depth of airborne transient electromagnetics is generally about 400 m, which allows for shallow layer detection with high data resolution. The detection depth of airborne natural field electromagnetics, however, is about 2000 m, allowing for medium to deep layer detection with high macroscopic data resolution. A combination of these two methods can be used to accurately survey proposed routes for railway tunnels with highly variable depths.
This aero-electromagnetic technique was applied for the Zhedoushan Tunnel of the Sichuan–Tibet Railway, revealing the spatial positions and sizes of water-rich fractured rock masses, which were subsequently verified by boreholes. The technique can improve the accuracy of tunnel exploration in comparison to the traditional geophysical methods, which are limited by surface conditions, such as topography. Moreover, this technique allows for higher efficiency of railway engineering exploration and is very promising for guiding route selection.

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