Detection of Dysplasia Geological Structure of Highway Tunnel Based on High-Density Electric Method

HUANG Zheng-jun 1,2,* ZHANG Lei 1,2, LIANG Wei 1, LIU Yu 1,2, ZHANG Dong 1,2

1 School of Civil and Resource Engineering, University of Science & Technology Beijing, Beijing 100083, China
2 Beijing Key Laboratory of Urban Underground Space Engineering, USTB, Beijing 100083, China

* Corresponding author: huang_jun.0518@163.com

Abstract. Before the engineering design and construction of highway tunnels, it is necessary to carry out detailed investigations on the geographical layer distribution, dysplasia structural conditions, groundwater and other geological conditions in the engineering region, which can provide security for the engineering construction and service of the project. High-density electric method is an array type rapid exploration method. It has the advantages of measuring points easily setting, automatic data acquisition, rich information interpretation, short survey period and low cost. After more than 30 years of development and application, it is widely used and effective in engineering survey field. With the using AGI high-density resistivity imaging system, the geological conditions and poor structures of the Pine Mountain tunnel project of the 108 National Highway in the Jingxi Mountainous Area were investigated and implemented, and a variety of measuring devices were selected for comparative testing and data inversion analysis. By comparing the test results with the geological data and the situation on the site, it is inferred that more accurate information on stratigraphic structure and abnormal body distribution can make up for the serious shortage of engineering geological drilling points.

1. Introduction

With the development of social economy and urban construction, highway engineering construction has also entered a period of rapid development. In highway construction, tunnel construction is often required to improve the design of highways, especially highways. China is also a country with many mountainous terrains in the world. It has complex topography and geomorphology, varied geological conditions, and many unfavorable geological structures. It is easy to cause landslides, collapses, mudslides and other disasters. Therefore, in the engineering design and construction of highway tunnels, it is necessary to conduct detailed surveys on the geological conditions along the tunnel to fully identify the geological structure, groundwater burial conditions, stratum distribution and other conditions in the area where the project is located for the purpose of providing safety for construction and later use [1,2].

Conventional survey methods are mainly based on drilling. The effect is affected by the number and location of boreholes. It has long construction period and high cost, and there are shortcomings such as drilling difficulties and construction safety accidents. Therefore, it is especially important to use the rapid, efficient and safe exploration method to detect the hidden disaster distribution and geological conditions in the tunnel engineering area. After more than 30 years of development and application, high-density electrical method has achieved wide and effective application results in the
field of engineering survey. Many scholars and engineers at home and abroad have carried out a large number of applied researches, including poor geological body surveys of highway engineering, railway subgrade surveys, goaf detection, karst exploration, groundwater survey and other application fields. Combining with the basic principle and working characteristics of high-density electrical method, this paper applies to the investigation and exploration of the Pine Mountain tunnel project of 108 National Highway in the mountainous area of Beijing in the complex terrain and unfavorable geological conditions, which provides effective and reliable survey data for engineering design and construction to make up for the serious shortage of engineering geological drilling points.

2. Introduction to high-density electrical method

2.1 Working principle and characteristics

The high-density electrical method mainly refers to the DC high-density resistivity method. It is based on the electrical differences between different rock (mine) stones, which is an array of exploration methods solving various geological problems by observing and studying the underground distribution law and characteristics of artificial electric fields. The essence of this method is to establish an electric field in the ground through the grounding electrode, and observe the change of the surface electric field when different conductive geological bodies exist in the electric measuring instrument. So it can be inferred and explained the occurrence state of the underground geological body, and achieve the purpose of solving the geological problem.

The calculation of the earth resistivity in the uniform formation and the non-uniform formation is shown in the formula (2-1)~(2-2). In practical applications, the inhomogeneous medium layer is mainly considered in the formation.

\[
\rho = \frac{2\pi}{\frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} + \frac{1}{BN}} \times \frac{AU}{I} = K \frac{AU}{I} (\Omega \cdot m) \quad (2-1)
\]

Where \(\rho\) is the resistivity; \(\Delta U\) is the potential difference; \(I\) is the current.

\[
\rho_s = \frac{K}{I} E_{MN} \cdot MN = \frac{K}{I} j_{MN} \cdot \rho_{MN} \quad (2-2)
\]

Where \(\rho_s\) is the apparent resistivity; \(\rho_{MN}\) is the resistivity of any point between the measuring electrodes; \(j_{MN}\) is the current density component of the arbitrary direction between the electrodes in the MN direction.

The high-density electrical method has the following characteristics: 1) The electrode is arranged once, which can realize rapid and automatic measurement of field data; 2) It can effectively perform scanning measurement of various electrode arrangement modes, and obtain richer section geological information; 3) Data acquisition Automated or semi-automated, the acquisition speed is fast, avoiding the errors caused by manual operation; 4) pre-processing the data and displaying the profile curve shape, and automatically drawing and printing the result image after offline processing; 5) Compared with the traditional resistivity method, its low cost, high efficiency, more information, better interpretation, and significantly improved exploration capability.

2.2 Measurement method and workflow

High-density electrical measurements can be combined in a variety of arrays to form a variety of devices. According to the spatial position relationship between the power supply electrode and the measuring electrode, the two can be divided into two-pole device, single-sided three-pole device, heating device, dipole device and Schlumberg device etc., which were shown in Fig. 1 to 5. Different device types have their own advantages and disadvantages, as well as different application constraints. Therefore, in actual work, it should be based on solving the actual problem situation, the
test site geoelectric conditions and terrain conditions to select a more reasonable and effective device form for measurement.

![Fig. 1 Schematic diagram of the two-pole device](image1)

For example, since the electromagnetic coupling between the power supply circuit and the measurement circuit is good, the dipole device has been widely used and has hitherto been used in the detection of topographical factors. The dipole device is very sensitive to changes in resistivity in the horizontal direction, but is less sensitive to changes in resistivity in the vertical direction, meaning that the device works better when exploring longitudinal structures such as gullies and caves, exploring lateral structures such as rock beds and sediments. The layer effect is slightly worse. The Wenner device has the strongest signal strength. When the geoelectric interference is very strong, the Winner device is better. However, the data arrangement pattern of the Wenner device is trapezoidal. When the two-dimensional exploration is performed, the deeper the detection depth is, the smaller the horizontal coverage is. Therefore, if the pole pitch is larger, the effective detection width is narrower [13, 14].

Common high-density electrical instruments such as the AGI high-density resistivity imaging system are shown in Figure 6. The measurement process can be roughly divided into three independent steps: the first step is to design the measurement method according to the site geological conditions, as shown in Figure 7; the second step is setting wires and points and completion of measurement at the worksite; the third step is data processing and inversion calculation.
3. Road Tunnel Survey Engineering Application Example

3.1 Project Overview
The 108 National Highway Pine Mountain Tunnel is located in the mountainous area in the southwest of Beijing. The mountains are undulating and the altitude is mostly between 150 and 550m. It is dominated by low mountainous landforms, and there are alluvial terraces, river valleys and gully landforms. The terrain is complex and changeable, and it is a complex area with topography and landform. The slope is between 25 and 45 degrees, and the lithology is mainly composed of limestone, dolomite and metamorphic sandstone. The general feature of the landform is that the slope is gentle and the valley is wide. The "U"-shaped valley is more gently, and the longitudinal slope of the groove bed degree is mainly in 3~20°. The lengths of the left and right lines of the tunnel are 1302m and 1294m, respectively. The main purpose of the exploration is to find out the depth of burial of the bedrock along the tunnel, the geotechnical structure, the structural fracture zone, the location of the unfavorable geological structure (karst cave, fault, etc.) and its distribution regularity, and understand the relative water-rich degree of the fault and fracture zone on the tunnel axis, etc. That can provide suggestions for follow-up survey work and ensure the safe and smooth construction of the tunnel. The topography of the survey area is shown in Figure 8, and the survey line layout is shown in Figures 9-10.
Table 1 Rock resistivity parameters in the survey area

| No. | Rock type                  | Resistivity value | Remarks |
|-----|---------------------------|-------------------|---------|
| 1   | Limestone                 | $6 \times 10^{-2} - 5 \times 10^7$ |         |
| 2   | Dolomites                 | $5 \times 10^4 - 8 \times 10^5$ |         |
| 3   | Gray matter dolomite      | $1 \times 10^4 - 1 \times 10^8$ |         |
| 4   | Metamorphic sandstone     | $1 \times 10^3 - 1 \times 10^7$ |         |
| 5   | Clay                      | $1 - 2.5 \times 10^2$ |         |
| 6   | Gravel soil               | $3 \times 10 - 2 \times 10^7$ |         |

3.2 Electrical characteristics of stratigraphic rocks in the survey area

The hard layered carbonates in the area are widely distributed, and the rock types are mainly limestone, dolomite and gray dolomite. Its engineering mechanical characteristics are as follows: the rock is dense and hard, the strength is high, and the stability is good. However, after the dissolution, the continuity and integrity of the rock mass will be destroyed, the strength of the rock mass will decrease, and the water permeability will also increase. The main rock types of clastic rocks are metamorphic sandstones. The engineering mechanics are characterized by fine rock particles and high strength. The rock mass with structural planes or clay-like rock formations has poor mechanical strength. Clay and gravel soils are distributed in valleys, terraces (Hebei Town, Lujiautian), mainly composed of cohesive
soil and sand gravel. Their engineering mechanical properties are coarse particles and poor sorting. Table 1 shows the range of rock resistivity values for each layer in the survey area.

3.3 Inversion and analysis of detection results

Considering the site conditions and the survey design requirements, 20 short profile survey lines and 2 long profile survey lines are arranged in the area where the Pine Mountain tunnel is located. The detection poles are short and the long sections are 4m and 12m respectively. The measuring devices are compared with Winner and dipole-dipole devices, and the data inversion is analyzed by least squares method. Some of the typical profile inversion results are shown in Figures 11-13.

Figure 11 shows the test result of the line No. 8 on the right line. The total length of the line is 120m, which is perpendicular to the direction of the tunnel. The design position is 10m outside the hole. As can be seen from the figure (a), the range of resistivity varies from 108 to 10712 Ω·M, and the range is large. According to the analysis of the inversion results, the survey area is located in a paleo-valley stratum. The surface layer of the Quaternary is thicker, about 5~10m, and the hole is located in the Quaternary topsoil. Therefore, attention should be paid to the excavation. There is a high-resistance body on the right side of the hole. The surface appears as a huge rock mass, which is
inferred to be the high-resistance performance caused by the rock mass. The rock mass exists independently because it should be especially noticed during tunnel excavation.

Figure 12 shows the test result of line 7 of the left line hole. The total length of the line is 120m, perpendicular to the direction of the tunnel. The left side of the line is 57m from the center line of the left tunnel. The right side of the line is 57m from the center line of the left tunnel. Figure (a) shows that the resistivity of the section varies from 147 to 16331 Ω·M, and the formation resistivity changes more uniformly. The thickness of the top soil layer on the left side of the hole is about 5m. Combined with the surface topography, the left side of the hole is artificial slope protection. At the same time, trees are planted, so the surface is low-resistance. The right side of the hole is the valley area, which is formed by long-term erosion of rainwater. Therefore, the surface of the low-resistance body is thicker; the resistivity of the surface layer is higher than that of the body, and the resistivity changes uniformly, indicating that the rock layer is evenly distributed, and no obvious abnormal structure exists.

Figure 13 shows the test results of the section 1 of the vertical line of the left line of the tunnel. The line ZZ1 (because the length of the tunnel is long, the road passes through 108 times in the middle, the terrain is complex, so the detection section is segmented) is located in the middle of the left line. Segment, the length of the detection section is 524m, and the maximum depth is 197m, which meets the detection requirements. The profiling line intersects the original 108 national road at 446m (the culvert is there). The inversion graph shows that the resistivity ranges from 150 to 1000000 Ω·M, in which the of the Quaternary surface layer is less than the surface, and the rock mass is exposed. The inversion results in Fig. (a) show that there is a high-resistance anomaly at the 140m, 260m depth of the tunnel crossing area, which resistivity exceeds 100000Ω·M, and the high-resistance body is closed, so it is inferred that it may be a karst dissolution stratum. Key protection and monitoring should be carried out at this area during tunnel excavation. There is a certain difference in the resistivity between the left and right sides of the formation at 162m. In combination with the formation resistivity distribution and geological mapping data, it is inferred that there is a structure. In the range of 270m and depth of 250m, there is a small range of high-resistance anomalies in the formation, and the resistivity can reach 50,000 Ω·M, which can be inferred to be a high-resistance body caused by excessive pores of fractured rock mass or dissolved rock mass. At 350 m, the resistivity of the left and right sides of the
formation is significantly different, and it is inferred that there is a structure. From the surface appearance, it is a valley area at 380–440m, and a valley catchment area on the left side. Therefore, it shows a low-resistance body on the surface, and it intersects with the 108 national road. There are culverts on the surface, so in the detection inversion map. It is shown as a high-resistance body, which can be inferred to be caused by surface concrete culverts.

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The inversion results in Fig. (a) show that there is a high-resistance anomaly at a depth of 260m in the tunnel crossing area, the resistivity exceeds 100000Ω·M, and the high-resistance body is closed, so it is inferred that it may be a karst dissolution stratum. Key protection and monitoring should be carried out during tunnel excavation. There is a certain difference in the resistivity between the left and right sides of the formation at 162m. In combination with the formation resistivity distribution and geological mapping data, it is inferred that there is a structure. In the range of 270m and depth of 250m, there is a small range of high-resistance anomalies in the formation, and the resistivity can reach 50,000 Ω·M, which can be inferred to be a high-resistance body caused by excessive pores of fractured rock mass or dissolved rock mass. At 350 m, the resistivity of the left and right sides of the formation is significantly different, and it is inferred that there is a structure. From the surface appearance, it is a valley area at 380–440m, and a valley catchment area on the left side. Therefore, it shows a low-resistance body on the surface, and it intersects with the 108 national road. There are culverts on the surface, so in the detection inversion map. It is shown as a high-resistance body, which can be inferred to be caused by surface concrete culverts.

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4. Conclusion
Based on the working principle and characteristics of high-density electric method, the AGI high-density resistivity imaging system of American Laureate Company was used to analyze the geological survey of the Pine Mountain Tunnel of National Highway 108, and achieved good and effective application results. By comparing the test results with the geological data and the situation on the site, it is inferred that the information of the formation structure and the distribution of the anomaly are relatively accurate, and it has good consistency with the drilling data.

At the same time, the high-density electrical method mainly relies on the difference of formation resistivity for inversion and inference. The geoelectric model will have certain errors in the inversion process. Therefore, the distribution of the stratum and the location and range of the anomaly can only be qualitatively analyzed. The quantitative analysis has certain difficulties, and it is necessary to carry out further drilling and other means to assist in detailed investigation.

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