GEOTHERMAL CHARACTERISTICS OF THE XIANSHUIHE FAULT ZONE AND THEIR ENGINEERING INFLUENCE ON TUNNEL CONSTRUCTION

by

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The Zheduo Mountain tunnel crosses the Xianshuihe fault zone in Kangding city. The Xianshuihe fault zone is composed of many large-scale faults and features a complex geological structure and strong geothermal activity. Based on geothermal drilling data, hydrogeological tests and the geothermal geological background of the study area obtained via hydrogeological surveys and hydrogeochemical methods in the process of tunnel surveying, this paper explores the exposure characteristics and distribution of geothermal water in the study area, analyses its hydrogeochemical and isotopic characteristics, and thoroughly studies the hydrogeological structure of the geothermal water to explore the genetic mechanism responsible for the formation of the geothermal water. The influence of the geothermal water and high ground temperatures on tunnel construction is further predicted, and practical and effective engineering treatment suggestions are proposed.

Key words*: Xianshuihe fault zone, geothermal water, hydrogeochemistry, geothermometry*

Introduction

The Xianshuihe fault zone (XFZ) is an active large-scale interpolate fault on the eastern margin of the Qinghai-Tibetan Plateau. Since the start of the Quaternary, the tectonic stress field in western Sichuan has changed to be mainly east-west, resulting in left-lateral strike-slip motion along the Xianshuihe fault [1]. The rock mass in the XFZ has suffered strong compression and shearing, making this area a good place for groundwater storage and deep groundwater circulation and migration [2]. The concentration and release of stress

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caused by fault activity can generate considerable thermal energy, and the fault structure can also become a heat conduction and heat storage channel [3, 4].

When the proposed tunnel crosses the XFZ at Zheduo Mountain, it may encounter problems such as high ground temperatures, abundant geothermal water and high pressure water. In particular, abundant geothermal water may become a restrictive factor for tunnel engineering [5-7]. Li *et al.* [8] preliminarily constructed a conceptual model of the geothermal system through hydrogeochemical analysis of the geothermal water in the XFZ. Some researchers [9-11] have used geophysical and geochemical methods to explain the genesis of geothermal springs in the Erdaoqiao and Yulingong geothermal areas of the XFZ. Yan *et al.* [12] studied the high temperature working environment of a long and deeply buried tunnel in western Sichuan, analysed the characteristics of the high temperatures and their impact on the project, and proposed a comprehensive 3-D cooling technique. However, there are few studies on geothermal water of the Zheduo Mountain area, and it is urgent to improve the research on the geothermal water in the tunnel site to reduce the adverse impact of high temperature hydrothermal activities on railway tunnel construction. Therefore, we investigated the exposure and distribution characteristics of geothermal water in the Zheduo Mountain tunnel site. The hydrogeochemical and isotopic geochemical characteristics of the project area and geothermal water around the tunnel are analysed. According to the measured ground temperature results from comprehensive well logging, the characteristics of the ground temperature distribution in the Zheduo tunnel site are analysed to explain the impact of high temperature geothermal conditions on tunnel engineering construction, which provides a scientific basis for the safe construction and operation of the tunnel.

Study area

The study area is located at the *Y* intersection of the Xianshuihe fault, Longmenshan fault and Xiaojiang fault, which are greatly affected by left-lateral strike-slip faulting. The main exposed strata include sedimentary strata and metamorphic strata, which are overlain by Quaternary sediments. The sedimentary strata are mainly composed of ancient Sinian, Silurian and Triassic strata. The metamorphic strata mainly include Devonian and Permian strata [8].

The hydrothermal activity area of the XFZ exhibits strong tectonic activity and widely developed faults. The XFZ with modern activities deeply cuts the crust, which has formed structural conditions conducive to forming a high temperature hydrothermal system, and the geothermal flow value in the area is higher than the average heat flow value for mainland China (approximately 65-75 mW/m^2) [13]. In addition, there have been many stages of magmatic activity along the fault zone, forming many important magmatic rock belts, which range in age from the Jinning period to the Himalayan period. Therefore, fault friction-induced heat generation, radioactive element decay-related heat release, residual magmatic heat and melting-related latent heat since 10 Ma are all important factors contributing to the hydrothermal activity in this area.

Characteristics of geothermal water exposure around the project area

The tunnel crosses Zheduo Mountain, which is the watershed of the Dadu River system and Jinsha River system. The XFZ is oriented NW-SE, crosses the project area, and influences the orientation of the strata, which are also distributed in the NW-SE direction. The hot springs near the Zheduo Mountain tunnel site are located from Daofu in the north to Hailuogou in the south. The hot springs and geothermal boreholes in Erdaoqiao, Yulingong, Zheduotang, Tangniba and other places are investigated in detail.

Outcrop characteristics of hot springs near Zheduo Mountain

The distribution of hot springs in the tunnel site is shown in fig. 1. Sixteen hot springs are exposed to the north of the tunnel site, including 11 hot springs (Q01~Q11) that are far from the tunnel and are mainly controlled by the Yala River fault. Most of the hot springs are 30~73 °C, and the exposed stratum is T_3z. The lowest temperature hot spring Q11 in the project area is also located in this area and has a temperature of only 10 °C; the exposed stratum is $\eta\gamma^3N_2$. The Tangniba hot springs (Q37 and Q38) are close to the tunnel and exposed along the F11 fault, and their temperatures are 55 °C and 90.3 °C, respectively. The Q38 is the hot spring with the highest temperature in the project area. There are nine hot springs exposed east of the #1 tunnel in Zheduo Mountain, and they are mainly controlled by the Yala River fault. The temperatures range from 13~42 °C, and the exposed strata are Dw^1, St^2, Z_2s, and Q, among others. There are ten hot springs exposed to the southeast of the #1 tunnel in Zheduo Mountain, and they are mainly controlled by the Selaha-Kangding fault and have temperatures of 45~88 °C.The exposed stratum of most spring points is Dw^1. There is one hot spring (Zheduotang hot spring) north of the exit of the #1 tunnel in Zheduo Mountain, and it is mainly controlled by the Zheduotang fault. Its temperature is 54 °C, and the exposed stratum is $\gamma\delta N_1$.

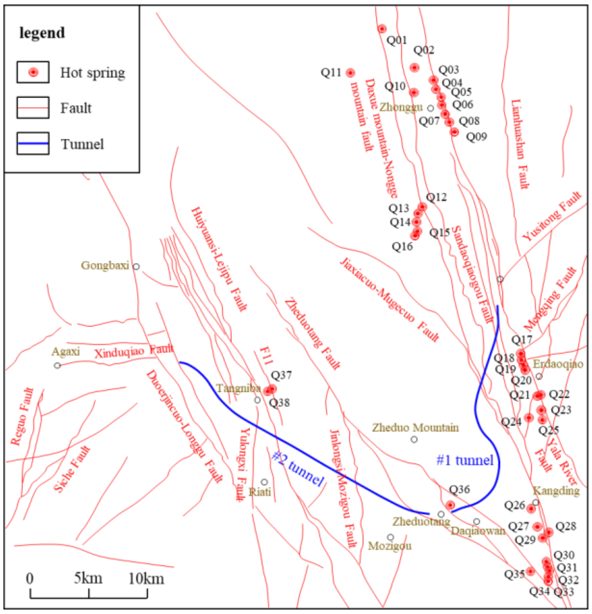

Figure 1. Distribution of hot springs around the project area

Geothermal characteristics revealed by deep holes/wells in the tunnel site

To understand the ground temperature in the tunnel site area, 28 boreholes/wells were arranged near the tunnel site area (including tunnel body holes and tunnel-adjacent holes), and a ground temperature test was carried out. The test results are shown in fig. 2.

The ground temperature gradient in 11 boreholes is greater than 3 °C per 100 m, indicating a high ground temperature gradient area, and these boreholes are mostly distributed in the Yala Ravine fault zone, Daxue Mountain-Nongge Mountain fault zone, Selaha-Kangding fault zone, *etc*. Among them, borehole DZ-17 is located in the Yala Ravine fault zone. The maximum ground temperature below the water level in this borehole is 43.97 °C, and the ground temperature gradient is anomalous (26.7 °C per 100 m), thus, this borehole may be affected by geothermal activity. There are negative geothermal gradient sections in borehole DZ-14 and borehole DZ-24, and it is speculated that there may be low temperature water inflow points nearby. In addition, the maximum stable ground temperature and ground temperature gradient near the Yala Ravine fault zone and Daxue Mountain-Nongge Mountain fault are higher than those near the Selaha-Kangding fault zone.

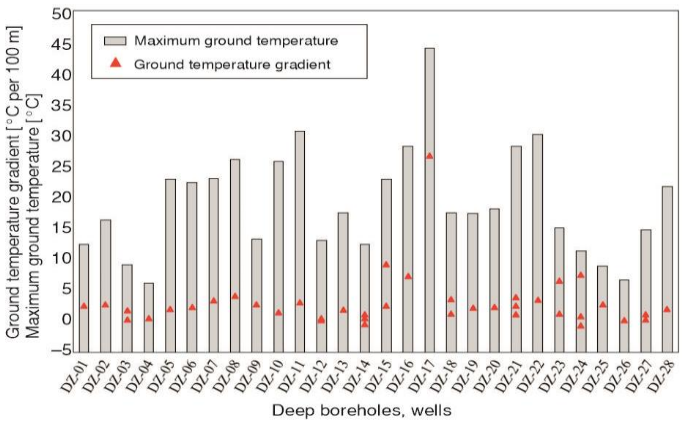

Figure 2. Ground temperature test results of tunnel site area

Analysis of the evolution mechanism of the geothermal water cycle around the project area

When the tunnel crosses the geothermal development area of the XFZ, to reasonably select an appropriate path and reduce the impact of geothermal activity on the tunnel, it is necessary to study the distribution, genetic mechanism and main controlling factors of geothermal development along the XFZ in the Zheduo Mountain section. The conventional hydro chemical analysis samples were collected in Yulingong, Zhonggu, Zheduotang, and other areas in Kangding city, including 16 groups of geothermal water, 2 groups of cold spring water and 2 groups of surface water.

Hydrochemical composition characteristics of geothermal water

The Piper plot analysis of the water samples shows that the main cations in the surface water and cold spring water are Ca^{2+} and Mg^{2+} and that the main anion is HCO_3^-. The main cation in the geothermal water is Na^+, and the main anion is HCO_3^-. The reasons for the great differences in hydrochemical type among the surface water, cold spring water and hot spring water are: deep underground hot water is often exposed as hot springs along faults after atmospheric infiltration and long-path migration, surface water is formed by the collection of atmospheric precipitation on the surface (including river or lake water and reservoir water), and the surface water system is an open water system, which is greatly affected by environmental and human factors. The overall hydrochemical types can be divided into the types $HCO_3{\cdot}Cl$–Na and HCO_3–Na. The hot springs in the Kangding, Zhonggu, and Zheduotang areas show obvious zoning differences.

Hydrogen and oxygen isotopic characteristics of the geothermal water

Geothermal water isotope samples and hydrochemical samples were collected at the same time. The CO_2 was measured by the equilibrium method, and H_2 was measured by the zinc method. The mass spectrometer used for analysis is a MAT251EM, and the analysis accuracy is ±0.12‰. A δD-$\delta^{18}O$ plot was drawn for the geothermal water in the study area, fig. 3. The results show that most of the hot spring water samples plot near the lower left of the atmospheric drawdown line [14], and the δD and $\delta^{18}O$ values of the underground hot water are lower than those of the surface water, indicating that the water samples originated in an area with a higher elevation and latitude. Hence, the recharge elevations of the underground hot water are higher than the elevations of the surface water sampling points. However, the hot spring samples near Erdaoqiao, the gully water samples and the river water samples in the study area plot near the upper right of the atmospheric precipitation line, indicating that these areas have relatively strong evaporation and relatively low-elevation and low-latitude origins and that the recharge elevations of the underground hot water are lower than the elevations of the surface water sampling points.

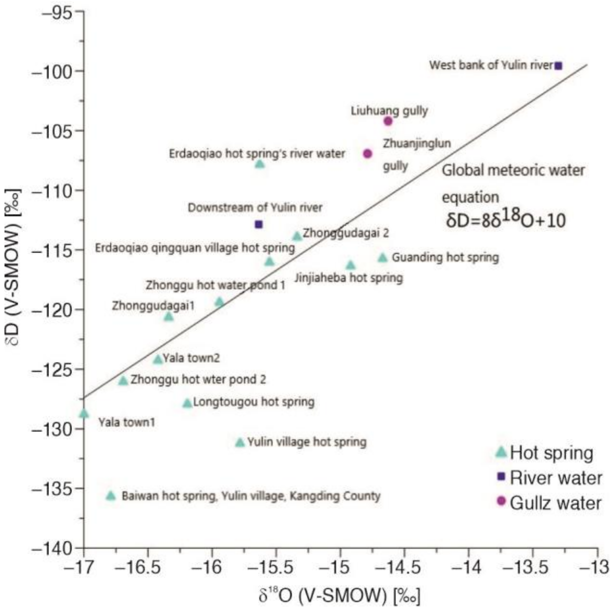

Figure 3. The δD-δ^{18}O plot of geothermal water samples around the study area

Genesis and controlling factors of geothermal water in Zheduo Mountain

One of the genetic models of the geothermal water in the Zheduo Mountain area involves the multi fault intersection zone; that is, the geothermal waters are related and come from a common heat source. Geothermal water is stored in a place with good water permeability and moves northwestward from the deep fault zone in Yulingong, Kangding. The thermal reservoir is generally a fractured aquifer, and some areas may be porous fractured aquifers. In the process of migration, the hot water rises along the secondary fault zone to form various hydrothermal systems.

The main fault controlling the development of geothermal water in the study area is the Yala River fault was followed by the Selahafault and Yulongxi fault. Geothermal water is mainly exposed in a bead-like distribution along the Yala River fault and is sporadically distributed on the Selahafault and Yulongxi fault. Therefore, the hydrothermal activity in the study area is the strongest along the Yala River fault, gradually weakening to the west, and there are no hot springs exposed to the east. The geological structure, hydrochemistry and hydrogen and oxygen isotopic analysis results show that the geothermal water circulation depth in the study area is large and the recharge range is high. The recharge area is the area above 4000 m height on the northern slope of Gongga Mountain. The recharge sources are mainly atmospheric precipitation, snowmelt water and shallow groundwater. The groundwater infiltrates and migrates in the northeast direction through the NE-SW tensile fracture and is heated at depths of 3000~4000 m in the Yala River fault zone to form high temperature geothermal water. Then, geothermal water rises along the intersection of faults and finally emerges at the surface to form hot springs. The water temperature of the hot springs belonging to this genetic model is generally controlled by the intersection depth of two groups of structural planes. The greater the depth is, the higher the water temperature and the more stable the flow. Most of the hot springs with an exposed temperature above 60 °C in the study area belong to this genetic model.

Analysis of thermal damage to the Zheduo Mountain tunnels

The impact of the water-rock interaction and significant hydrothermal activity on the mechanical properties of rock mass cannot be ignored [15]. The problem of thermal damage will seriously interfere with the progress of tunnel construction and the stability of tunnel structures. Therefore, it is necessary to study the potential harmful impact of the geothermal conditions on the tunnel.

The equation for the tunnel body temperature is given as [12]:

$$T = t + (H - h)g \tag{1}$$

where T is the temperature of the tunnel body, t – the temperature of the constant-temperature layer (we take 5 °C according to the deep hole data), H – the buried depth of the tunnel (the maximum buried depth of the tunnel is 1346 m), h – the thickness of the constant-temperature layer from the ground surface (we take 30 m in this area), and g – the ground temperature gradient in the tunnel area (the average ground temperature gradient of the tunnel should be calculated separately in different sections).

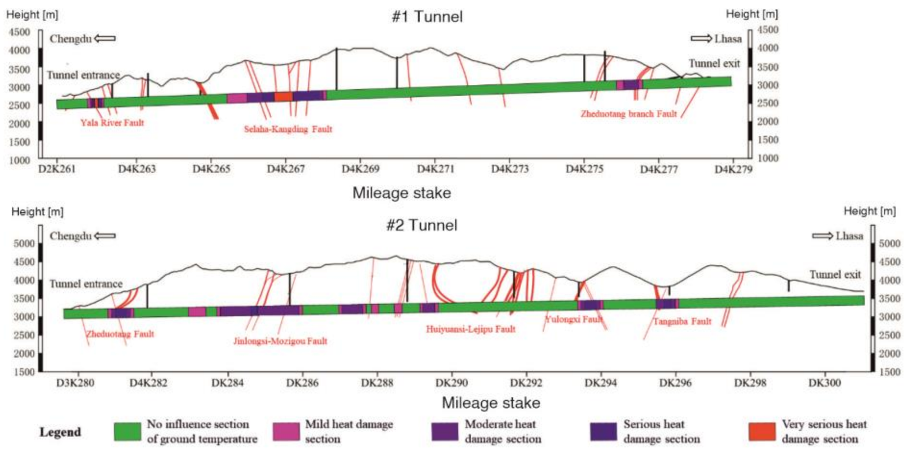

Figure 4. Heat damage degree in the Zheduo Mountain tunnels

The strata crossed by the proposed #1 tunnel and #2 tunnel in Zheduo Mountain mainly involve Triassic sandstone strata and Triassic metamorphic rock strata, respectively. The ground temperature distribution of the crossed-sections of the two tunnels can be further obtained by theoretical calculation. According to the ground temperature gradient and thermal infrared calculation results of comprehensive borehole logs, the high ground temperature section and ground temperature classification of the two tunnel bodies are predicted, as shown in fig. 4.

The two tunnels may experience serious heat damage at depth when crossing the fault, but the length of the heat damage section is short. For the #1 tunnel, the length of the mild heat damage section is 1125 m (accounting for 6.51%), that of the moderate heat damage section is 970 m (5.62%), that of the serious heat damage section is 1130 m (6.54%), and that of the very serious heat damage is 600 m (3.47%). For the #2 tunnel, the length of the section without heat damage is 14315 m (accounting for 69.0%), that of the mild heat damage section is 2280 m (11.0%), that of the moderate heat damage section is 3340 m (16.1%), and that of the serious heat damage section is 800 m (3.9%).

Conclusion

In this study, through field investigation, hydrogeochemical analysis and geothermal borehole temperature measurement, the geothermal characteristics, geothermal water genetic model and tunnel engineering impact of the XFZ in the Zheduo Mountain tunnel site are analysed. The hydrochemical types of the hot springs in the Zheduo Mountain tunnel site are mainly the $HCO_3·Cl–Na$ type and $HCO_3–Na$ type. The $HCO_3·Cl–Na$ hot springs are mainly distributed in the Kangding geothermal water area, and the $HCO_3–Na$ hot springs are mainly distributed in the Zhonggu and Zheduotang geothermal water areas. The heat damage of the #1 tunnel in Zheduo Mountain is highly concentrated along the Yala River fault and Selaha fault. The serious heat damage section is distributed in the area impacted by high temperatures near the Yala River fault and Selaha fault, and the heat damage in other sections is moderate or low. The serious heat damage in the #2 tunnel in Zheduo Mountain is distributed near the Zheduotang fault, Yulongxi fault, and Tangniba fault, while the heat damage in other sections is lower than moderate. During the construction of the Zheduo Mountain tunnels, they may pass through various types of geothermal areas. In addition to the problem of water inrush, the potential thermal damage also includes the corrosion of concrete materials by geothermal water. Therefore, the chemical corrosion resistance of concrete materials used in tunnel engineering is the key to ensuring their durability.

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