Building Technology and Solutions for Railway Tunnels under Complex Geological Conditions

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Abstract: Based on the experience of existing railway tunnel engineering and in view of the typical complex geological conditions such as large deformation of soft rock with high crustal stress, rock burst, active fault zone, high ground temperature, and high-pressure water-rich fault, this paper analyzes the characteristics of railway tunnel and puts forward the technical solutions for construction. Relevant technical solutions for construction are of referential value for Sichuan-Tibet Railway tunnel construction.

Keywords: Sichuan-Tibet Railway; high crustal stress; soft rock; rock burst; high ground temperature; active fault zone; high-pressure water-rich fault; building technology

1 Introduction

In recent years, the railway tunnel building technologies have been improving gradually with the constant increase and expansion for the quantities and scales of railway tunnel construction, with which China has become a great and strong power in tunnel construction in real sense[1]. Deformation mechanism of railway tunnel with large deformation in soft rock together with the addressing measures have been put forward by Zhao Yong, et al[2-3] through the engineering tests and the site practices and studies with successful applications in the Tianpingshan Tunnel of the Guiyang-Guangzhou Railway. Dynamic construction technologies for preventing and addressing rock burst have been determined by Han Kai, et al[4] in analyzing the typical characteristics of rock burst by relying on the Bayu Tunnel of the Lhasa-Linzhi Railway. Engineering countermeasures have been worked out from multiple aspects by Lei Junfeng[5] for his researches starting from the causes and features of high ground temperature exerting from the typical geothermal Jiwoxiga Tunnel on Lhasa-Shigatse Railway. Researches on the tunnel response characteristics and preventive measures for the tunnel crossing the active fault zone have been carried out by Geng Ping, et al[6-7] through numeric calculation and engineering tests. Good results have been achieved

(This paper is selected from *China Railway*)

by Zhang Jinfu, et al[8] in the researches on addressing problems of water-rich and high-pressure faults and determining the technical measures of grouting reinforcement and water plugging for the Dazhushan Tunnel on the Dali-Ruili Railway.

Summaries on the adverse geological problems existing in recent-year tunnel construction have been made and five kinds of characteristics for complex geological conditions centering on large deformation of high-crustal stress soft rock, rock burst, active fault zone, high ground temperature, and water-rich fracture zone have been analyzed with respective technical countermeasures and suggestions being put forward.

2 Tunnel Building Technology of Large Deformation in Soft Rock with High Crustal Stress

2.1 Characteristics of large deformation in soft rock with high crustal stress

Tunnel construction is liable to large deformation when coming across the high-crustal stress soft rock stratum, for which it is characterized by large amount of deformation, high rate, long duration, and even the initial support steel frame distortion, overrun and other phenomena, bringing about extremely great difficulties to the construction. The deformation failure of the surrounding rock depends on the nature of surrounding rock, environmental conditions (magnitude of crustal stress, development and distribution of groundwater, etc.), and support parameters. The large-deformation mechanism of surrounding rock can be summed up into following four aspects[9-13].

(1) Soft rock creep and plastic deformation. Tunnel excavation will surely cause readjustments to the stress of the surrounding rock and the stress adjustment will cause expansion, creep and plastic deformation of surrounding rock, enabling the surrounding rock to bring about greater convergent displacement[9].

(2) Bending deformation of tabular formation. Generally, it is easy to occur in the thin-layered to extremely thin-layered structure rock mass and the unloading caused by tunnel excavation makes the layered rock layer bend and deform in the form of plate. The bending deformation can be subdivided into longitudinal bending and transverse bending, for which the longitudinal bending is perpendicular to the force of the layer to play the dominant role, while the transverse bending is parallel to the force of the layer to play the dominant role. For some layered soft rock in particular, there would be often the occurrence of structural weakening[9-10] (refer to Fig. 1).

(3) Cataclastic texture deformation. Local stress concentration caused by excavation and unloading due to surrounding rock fragmentation and joint fissures makes the originally closed joint fissures open and expand, which easily leads to collapse and bedding sliding. But there is still a part of relatively complete surrounding rock along the layered bending and buckling failure, and the performance of the tunnel failure at this time is in the combined forms of bending, buckling, bedding sliding, collapse, etc.[9-10] (refer to Fig. 2).

(4) Granular compaction structure. The surrounding rock is extremely broken and loose. Under the action of high crustal stress, the surrounding rock becomes compact and loose immediately after the tunnel excavation. The deformation and failure mode of the surrounding rock is characterized by progressive expansion of the loose ring. Due to the different directions of the principal stress, the plastic zone can appear in different parts of the hole, which leads to large deformation in these parts[9-10] (refer to Fig. 3).

2.2 Technical countermeasures

Large deformation of soft surrounding rock with high ground stress is one of the prominent problems in deep buried tunnel and poor treatment will cause collapse or support overrun. Deformation control criteria for tunnel construction of high ground stress soft surrounding rock must be set up to bring into full play and make use of the self-bearing capacity, take effective pre-reinforcement measures, select appropriate working methods, rational modes of support as well as lining opportunity, control the total amount of deformation, and ensure safety and reliability of tunnel structure[3,9-15].

(1) Conducting active reinforcement of surrounding rock, limiting development of the plastic zone, and bringing into play the self-bearing capacity of surrounding rock. Active reinforcement of surrounding rock is conducted by using long and short bolts, anchor cables and grouting with the provision of supporting machines and equipment to improve the con-

(a) Larger intensity before disturbance

(b) Intensity weakening after excavation and disturbance

Fig. 1 Schematic diagram of structural weakening and bending deformation of layered soft rock

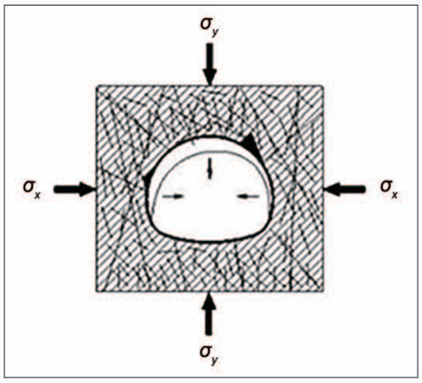


Fig. 2 Cataclastic texture

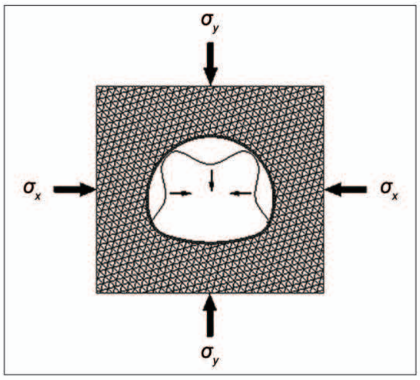


Fig. 3 Granular structure

struction efficiency. Advanced anchoring techniques are employed to bring into play the anchoring role in time.

(2) Making rational determination of the excavation section and footage. Excavation part and footage should be rationally selected according to the features and deformation law of the surrounding rock stress adjustment in soft rock tunnel construction of high ground stress.

(3) Optimizing the working methods with division of steps as less as possible to realize large-section excavation and close the inverted arch into ring as early as possible. Excavation steps are minimized and construction steps are simplified to adopt large-section excavation as more as possible, close the inverted arch into ring as early as possible and achieve the safe and rapid construction of tunnel under the prerequisite of securing stability of the surrounding rock.

(4) Optimizing the construction techniques. Importance is attached to advance support and advance reinforcement based on the conditions of surrounding rock stability, and longitudinal connection of steel frame is enhanced to increase the overall deformation-resistant capacity of steel frame.

(5) Supporting of mechanization. For the realization of safe and rapid construction for tunnels of soft surrounding rock with high ground stress, it is imperative to realize supporting of mechanization, reduce immensely the time occupied for a single working procedure, and decrease the quantity of the site working staff.

3 Tunnel Building Technology of Rock Burst in Hard Rock with High Crustal Stress

3.1 Rock burst characteristics

The main characteristics of rock burst lie in the irregularity and randomness at the time of occurrence, for which it is difficult to make accurate predictions and have great impact on the construction safety and working efficiency. The law is initially summed up based on the statistics of the rock burst cases that have taken place as follows: (1) Rock burst takes place mostly in the deep part of the tunnel (with the depth of over 700 m); (2) Rock burst occurs mostly in the strata with greater intensity, homogenization and better integrity of surrounding rock; (3) Brittle rocks are often cracked and ejected (flaky), slabbing often occurs in strata with well-developed bedding, while fracturing, loosening and block dropping often occur in strata with well-developed joint; (4) The rock burst position is mostly concentrated in the range of 1 to 3 times of tunnel diameter from the tunnel face, which can occur in the tunnel wall (arch, wall, tunnel bottom), and can also occur in the excavation face (front); and (5) It is the most serious within 2 to 3 hours after excavation, with many times and high intensity, but it will occur intermittently within 1 to 2 days, and there will be slow rock burst phenomenon such as slabbing and block dropping after 2 days.

3.2 Technical countermeasures

3.2.1 Rock burst micro-seismic monitoring and prediction and early warning

The site monitoring results are transmitted to the management platform for timely analysis and feedback[9] (refer to Fig. 4).

3.2.2 Corresponding technical measures

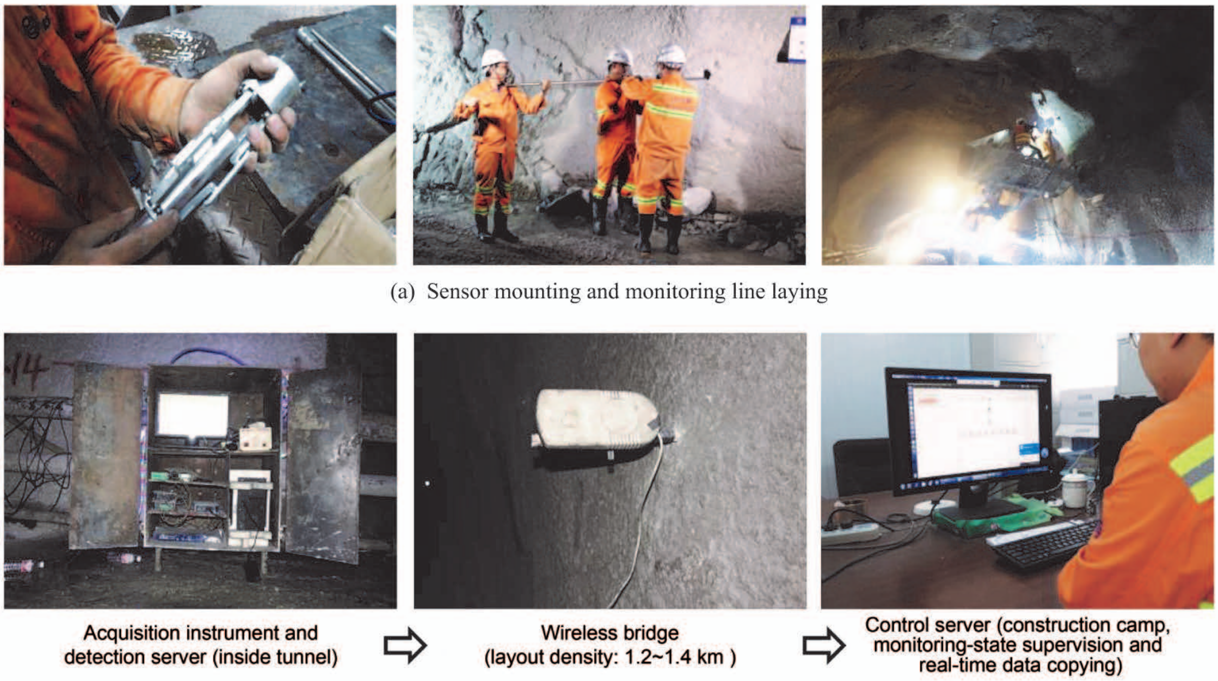
Comprehensive analyses on the factors such as lithologic characteristics, physical and mechanical properties, characteristics of crustal stress as well as excavation and blasting methods of the hard rock section are carried out in construction to determine the rock burst grades. Different measures for excavation and support are taken for different rock burst grades through the adjustment of rock burst grade by crustal stress test and prediction and early warnings, for which the common measures are as follows[9,11]:

(1) Light rock burst. Each digging footage shall not exceed 3 m and full-face excavation shall be carried out as far as possible, forming at one time, so as to reduce the disturbance to surrounding rock. High-pressure water is sprayed on the tunnel face and tunnel wall in time to reduce the stress of surrounding rock. The arch wall shall be laid with mortar anchor rod and shotcreting support with anchor net.

(2) Moderate rock burst. The digging footage shall be controlled within 2.5 m. Steel-fiber concrete shall be sprayed initially in time and the expansion-shell type pre-stressed hollow anchor rod shall be driven, with others being the same as above.

(3) Severe rock burst. The digging footage shall be controlled within 2 m. Steel-fiber concrete shall be sprayed initially in time and the φ76 mm advance stress hole shall be applied to release stress ahead of time. Steel arch frame shall be erected for the advance anchor rod and the expansion-shell type pre-stressed hollow anchor rod with respraying of C25 concrete.

(4) Crack burst. Should there be



(a) Sensor mounting and monitoring line laying

(b) Erection of real-time monitoring and wireless monitoring systems

Fig. 4 Physical diagram of rock burst micro-seismic monitoring and prediction and early warning system

occurrence of crack burst, special research is required according to the site conditions with measures of special treatment being taken.

3.2.3 Construction protection

Mesh reinforcement shields shall be set up in driver's cabs of loader, excavator, three-arm drilling jumbo as well as muck car to protect safety of the working staff (refer to Fig. 5).

4 Building Technology of Tunnel with High Ground Temperature

4.1 Characteristics of high ground temperature

High ground temperature is characterized by deterioration of operational environment and decrease of productivity and mainly classified into two categories, i.e. high rock temperature and high water temperature. Conditions for forming high ground temperature include mainly heat source, water source, heat reservoir layer, structure, etc. Formation of geothermal heat can be classified into three major categories according to different heat sources, i.e. heat source of earth's mantle convection, heat source of volcanic magma pool as well as fission heat source of radioactive element.

4.2 Technical countermeasures

4.2.1 Excavation and blasting

The selection of blasting materials and detonating methods for tunnels in high ground temperature areas shall be based on different grades of high ground temperatures, i. e. high-strength detonating tube and detonating cord resistant to 80 ℃ can be used for normal connection and detonation if 50 ℃≤ borehole rock temperature < 70 ℃; whereas high-strength detonating tube and detonating cord resistant to high temperature of 120 ℃ can be used with the improvement of the charge structure and wrapping of explosive[9-11] by a heat insulation film in case of borehole rock temperature ≥ 70 ℃.

4.2.2 Cooling by ventilation

(1) Sending cold air and increasing the wind speed inside the tunnel as much as possible. For sending cold air, the local climatic conditions can be used, or equipment can be adopted to make inlet air cooling.

(2) Relay fans can be added in the tunnel to strengthen ventilation inside during construction on the basis of high-power ventilation scheme so as to reduce the temperature in the tunnel, quicken the velocity of air flow, increase the oxygen content inside and improve the workers' comfort.

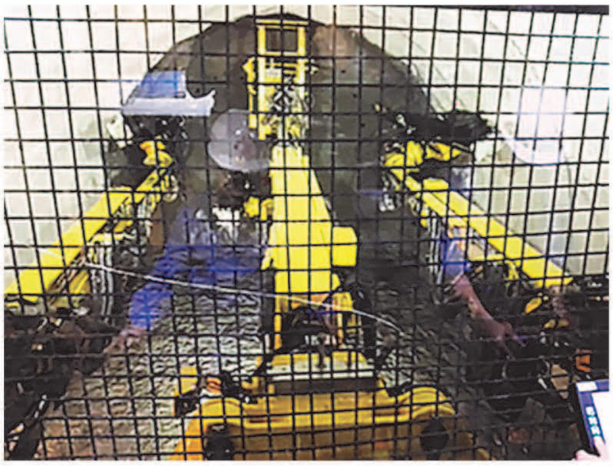
(3) Enhancing the local ventilation intensity of important parts in the tunnel to add, for instance, ventilators or local fans, etc.[11] on the tunnel face.

4.2.3 Cooling by water sprinkling

Due to the influence of high ground temperature inside, the ambient temperature in the tunnel is high, while the water temperature outside the tunnel is low, to which cold water outside the tunnel can be used for cooling by water sprinkling inside the tunnel.

4.2.4 Cooling by refrigeration

(1) Cooling by ice-block refrigeration. The practice of cooling by ice-block refrigeration is to place the ice blocks that have been prepared beforehand outside the tunnel at the places with relatively concentrated working staff, thus reducing the ambient tem-



(a) Protective mesh reinforcement mounting to three-arm drilling jumbo

(b) Protective mesh reinforcement mounting to dump truck

(c) Protective mesh reinforcement mounting to excavator

(d) Protective mesh reinforcement mounting to loader

Fig. 5 Mesh reinforcement shields

perature to certain extent and improving the construction environment and operational conditions[11] (refer to Fig. 6).

(2) Cooling by mechanical refrigeration. Cooling by mechanical refrigeration can be adopted when the ground temperature is high and with poor effect of the conventional measures. In combination with the characteristics of high ground temperature for railway tunnel engineering, it is

Fig. 6 Cooling by ice block in the tunnel

generally recommended to adopt the independent and mobile refrigeration equipment, i.e. the way of implementing local refrigeration for different work faces, which is advantageous for flexibility and small one-time investment. If the section of high ground temperature is long, refrigeration with large surface mounted refrigerating machine can be adopted with however larger one-time investment[9].

4.2.5 Labor protection measures

(1) Preventing scald by high-temperature water. During construction of advance geological drilling, workers shall wear high-temperature steam protective suits to prevent personal injury caused by hot water and steam gushing during drilling.

(2) Setting up mobile lounge in the tunnel. It can help the working staff have rest and timely recovery of physical strength (refer to Fig. 7).

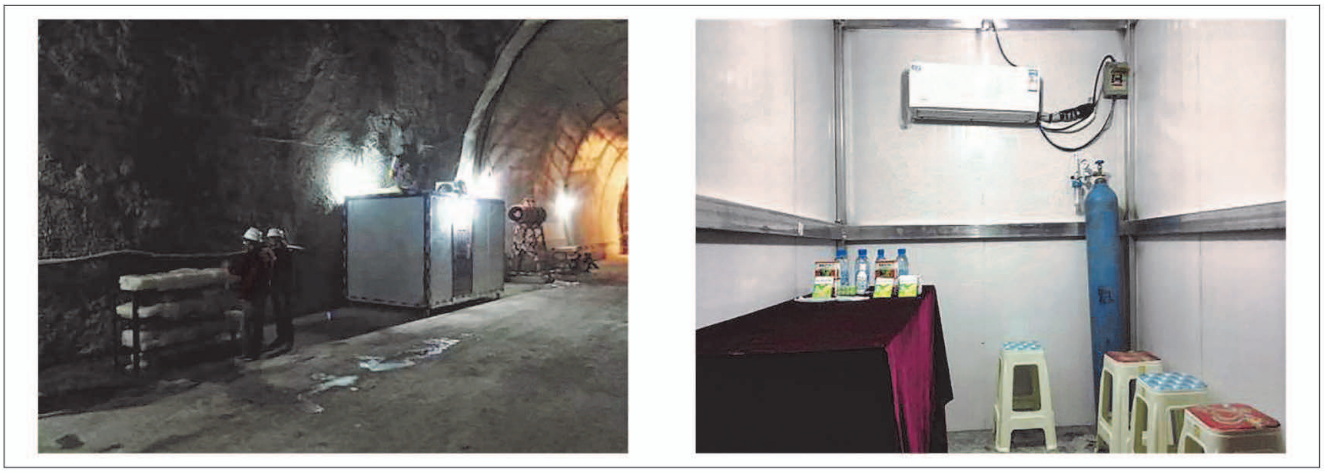


Fig. 7 Mobile lounge and interior arrangement

(3) Enhancing healthcare control of personnel. The working hours shall be duly shortened with the increase of construction shifts and strengthening of health examination based on the ambient temperature the tunnel.

5 Tunnel Building Technology of Active Fault Zone

5.1 Characteristics of active fault zone

The active faults are classified into translation fault (strike-slip), reverse fault and normal fault according to tectonic stress state and the nature of relative displacement of the two walls. Among them, the strike-slip is the most common one. The engineering characteristics for active fault zone are as follows[9]:

(1) Poor engineering and geological conditions and extremely great difficulties in construction. Due to the recent activation of active fault zone, the strata are often severely compressed, the surrounding rock is weak and broken, and the original crustal stress is high or water-rich. It is extremely liable to landslide, water and mud inrush, or large deformation of soft rock during construction, bringing about great risks in safety to construction.

(2) Direct failure caused to structure due to fault zone dislocation. Fault zone dislocation might cause shearing displacement to surrounding rock and likewise result in shearing failure to the tunnel structure.

5.2 Technical countermeasures

For tunnel construction in active fault zone, structural system of "large-rigidity ring lining + reserved deformation and reinforcement spaces + combined wide deformation joint" is generally adopted, i. e. taking measures of optimizing structural shapes, reserving deformation and reinforcement spaces, minimizing the length of structural segment, combining wide deformation joint, energy dissipation by isolation, reinforcing surrounding rock, and selecting type of rail structure adapting to deformation based on the factors such as dislocation features of active fault zone, fault material composition, etc. So as to achieve the goals[9] of structural reliability and operational safety.

(1) Reserving deformation and reinforcement spaces. Reserving of deformation and reinforcement spaces shawill be achieved through expanding the size of tunnel clearance section according to the possible dislocation quantity and dislocation mode of the active fault.

(2) Minimizing the length of structural segment. The length of concrete placed in each slab in the longitudinal direction of the tunnel shall be minimized as far as possible to keep the fault zone and the segments at both sides of the fault zone within certain range be relatively independent (refer to Fig. 8).

(3) Combining deformation joint. Wide deformation joint shall be adopted within the range of active fault lining to realize the design of "large-rigidity ring lining + combined deformation joint". The width of the wide deformation joint is 5 ~ 8 times of the width of the conventional deformation joint.

(4) Measures of energy dissipation by isolation. Flexible materials shall be filled back between the primary support and the secondary lin-

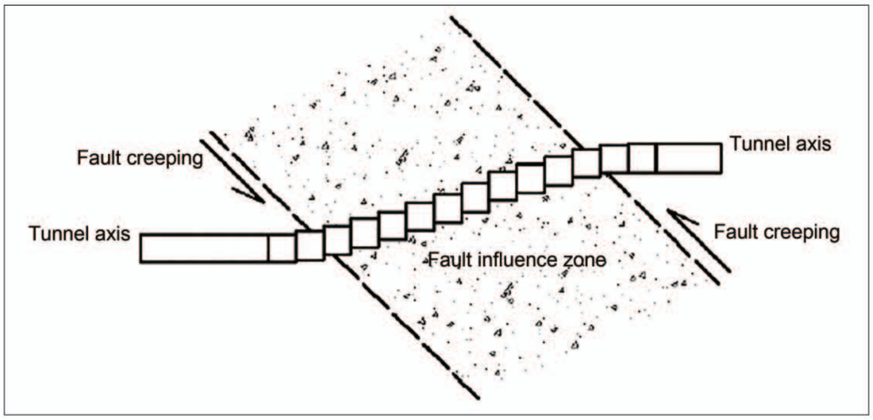


Fig. 8 Sub-segmental design

ing and the displacement caused by stratum creep and earthquake is absorbed and digested on the primary support and intermediate buffer layer as much as possible so as not to affect the normal use function of the secondary lining (refer to Fig. 9).

(5) Optimizing shape of lining structure. The stress condition of circular or nearly circular lining is more reasonable than that of horseshoe lining, so the stress condition of lining structure can be improved by changing the contour shape of lining.

(6) Reinforcing surrounding rock. The broken zone surrounding rock shall be reinforced through grouting and other means to strengthen the integrity of surrounding rock, improve the construction safety and at the same time enhance the earthquake-resistant capacity of surrounding rock itself so as to improve the overall seismic capacity of the support structures.

(7) Selecting type of rail structure adapting to deformation. The design of ballasted bed is generally adopted for crossing the active fault zone.

6 Tunnel Building Technology of High-pressure and Water-rich Fault

6.1 Characteristics of high-pressure and water-rich fault

Fault is the most common adverse geological phenomenon in the process of tunnel excavation. The fault fracture zone is one of the most unstable sections of tunnel surrounding rock, which is liable to collapse during construction. Fault and its fracture zone are the main storage places of karst water, underground river and silt in karst development area, and are the main sources of water and mud inrush in tunnel construction. The faults, fracture zones and small faults with good sealing conditions are also the main gas accumulation spaces in coal measures strata. Therefore, the fault and its fracture zone are one of the main causes for the geological disasters of tunnel construction[9-11].

The fault is a water conducting structure, and the stability of the surrounding rock is very poor once the high-pressure groundwater is enriched. When a tunnel passes through a high-pressure and water-rich fault, safety accidents of water and mud inrush will easily occur and the construction difficulty and safety risk are extremely great if insufficient attention or improper engineering measures are taken.

6.2 Technical countermeasures[9-11,14-15]

6.2.1 Accurate prediction of fault properties by advance drilling with combined far and near distances

Middle- and long-distance (100 ~ 150 m) boreholes are adopted to monitor the water pressure of fault; and short-distance (20 ~ 30 m) advance borehole is adopted to determine the engineering characteristics and revise and improve the countermeasures.

6.2.2 Pilot heading advance dewatering and drainage

(1) Parallel heading. In general, parallel headings are set in karst development areas and water-rich areas and therefore the functions of advance water exploration and drainage of parallel heading can be fully utilized to reduce the water volume and water pressure of main tunnel construction and ensure the safety of main tunnel construction.

(2) Roundabout heading. In the section without parallel heading, when the water volume and water pressure of the fault are large, local roundabout headings can be added for advance drainage and pressure relief. The roundabout heading can be set at high position. Taking the case of Liangshan Tunnel on the Xiamen-Shenzhen Railway for example, for which it is 9 888 m long and confronting with mud and water inrush in L7 fault fracture zone, high-level roundabout heading is used to drain water in advance and reduce the groundwa-

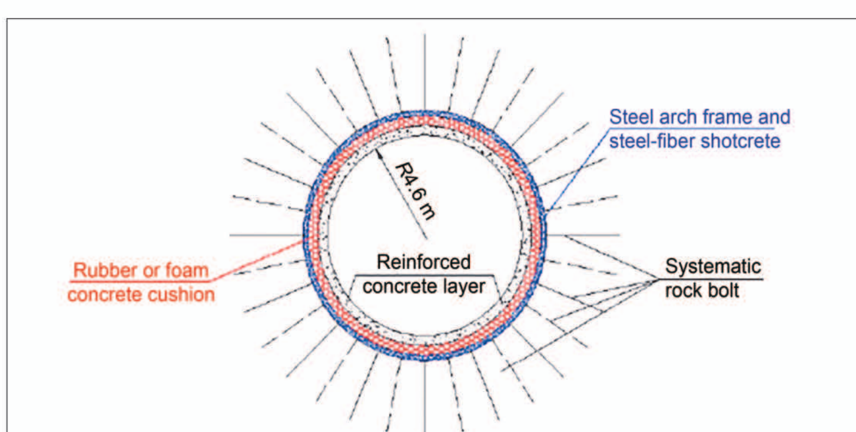


Fig. 9 Design of energy dissipation by isolation

ter level, thus ensuring the grouting reinforcement effect[11] of the main tunnel. The schematic diagram of high-level water discharge tunnel for Liangshan Tunnel is shown in Fig. 10.

(3) Advance drainage of work face. Drain holes with a length of more than 30 m shall be drilled at the excavation face by using the advance diving drill. Before the tunnel is excavated, the confined water in front of e tunnel is discharged in advance through the drainage hole, so that the water quantity of the tunnel face is reduced or no water exists, thereby reducing the difficulty of excavation operation.

(4) Advance stratum pre-reinforcement. Advance stratum pre-reinforcement is the effective auxiliary measure for construction of tunnel with soft surrounding rock and moreover the necessary technical measure for construction of tunnel with high-pressure and water-rich fault. The most common method of advance reinforcement used is the grouting reinforcement, for which horizontal jet grouting for reinforcement can be used in the case of sand layer, and freezing method can also be used in the case of qualified tunnel.

(5) Enhancing support and closing as soon as possible. The primary support and secondary lining of fault section are strengthened and the way of short-step quick excavation, quick support and quick closure is adopted to ensure the construction safety.

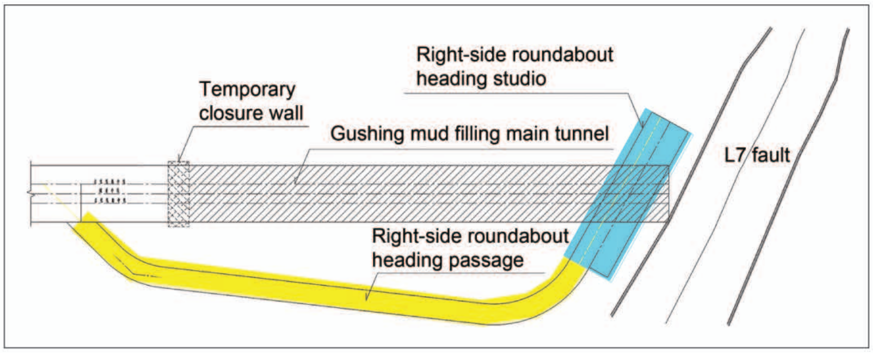


Fig. 10 High-position roundabout heading of Liangshan Tunnel on the Xiamen-Shenzhen Railway

7 Conclusions and Suggestions

(1) Soft rock of high crustal stress is characterized by the large deformation of surrounding rock, high deformation rate and long duration for deformation, for which the main countermeasures are active control of surrounding rock deformation, mechanized construction, optimized techniques and methods, and fast closed ring forming[17-19];

(2) Rock burst is characterized by more difficulties for rock burst prediction, and great influence on construction safety and working efficiency, for which the main countermeasures are micro-seismic monitoring, release of crustal stress, enhanced support, and equipment and personnel protection;

(3) High ground temperature is characterized by deterioration of operational environment and decrease of working efficiency, for which the main countermeasures are the measures of temperature decrease such as water sprinkling, strengthened ventilation, ice-block or mechanical refrigeration, etc. according to the temperature grading;

(4) Active fault zone is characterized by geological crushing, and direct failure caused to structure due to fault zone dislocation, for which the main countermeasures are large-rigidity ring lining, reserved deformation and reinforcement spaces, combined wide deformation joint, etc.; and

(5) High-pressure and water-rich fault is characterized by easy production of mud and water inrush, for which the main countermeasures are the enhanced advance prediction, advance drainage, reinforced stratum and strengthened support.

For complex geological conditions, especially plateau railway tunnel, great importance should be attached to geological investigation, with advanced and comprehensive investigation means being adopted, geological conditions being found out, and special design and dynamic design being carried out. The study on deformation mechanism of soft rock tunnel with high crustal stress should be strengthened, especially under the condition of super-large buried depth, and the quantitative relationships among the physical and mechanical indices of surrounding rock, crustal stress, rock structure, support parameters and support deformation should be found out as far as possible. Study on mechanism of rock burst in high crustal stress hard rock tunnel should be strengthened. Prediction of rock burst should be strengthened to grasp the time, position and grade of rock burst. Research and application on mobile air conditioning system in tunnel with high ground temperature should be enhanced. The study on prediction and forecast technologies and disaster mechanism of high-pressure and water-rich fault should be strengthened.

(Translated by Zheng Mingda)

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