

# Construction Technology for Highway Tunnels Crossing Fault Fracture Zones

Hai-Feng Zhang\*

Yunnan Maxi Expressway Co., Ltd., Wenshan, Yunnan 663501, China

\*Correspondence to: Hai-Feng Zhang, Yunnan Maxi Expressway Co., Ltd., Wenshan, Yunnan 663501, China, E-mail: [1565934556@qq.com](mailto:1565934556@qq.com)

**Abstract:** With the expansion of highway engineering into mountainous regions, tunnels crossing fault fracture zones have become increasingly common. Such geological conditions are highly complex and prone to hazards such as collapse and water or mud inrush, posing serious threats to construction safety, quality, and progress. Based on engineering practice, this paper systematically analyzes the geological characteristics of fault fracture zones and their impacts on tunnel construction. It elaborates on pre-construction preparations, including geological investigation, scheme design, material and equipment preparation, and personnel training. Emphasis is placed on key technologies such as excavation, support, grouting reinforcement, and drainage. Monitoring contents, methods, and data processing essentials are reviewed, and targeted control measures are proposed. Key experiences are summarized to provide guidance for highway tunnel construction through fault fracture zones, ensuring construction and quality safety and supporting the development of highway engineering.

**Keywords:** highway engineering; tunnel construction; fault fracture zone; construction technology

## Introduction

Highway tunnels are critical structures for crossing complex terrain and shortening travel distances. Their construction quality and safety directly affect the overall operational efficiency and service life of highways. In mountainous highway tunnel construction, fault fracture zones are common complex geological sections, characterized by weak rock masses, loose structures, and abundant groundwater. Construction in such zones is prone to problems such as surrounding rock collapse, water and mud inrush, and support deformation, which increase construction difficulty and cost and may even lead to safety accidents. Although highway tunnel construction

technologies in China have developed in recent years, challenges remain when dealing with complex fault fracture zone geology, including insufficient adaptability of technologies and inadequate risk prevention and control. This paper discusses relevant construction technologies from three aspects, aiming to provide references for similar projects.

## 1. Geological Characteristics of Fault Fracture Zones and Their Impacts on Tunnel Construction

### 1.1 Geological Characteristics of Fault Fracture Zones

Fault fracture zones are geological regions formed by



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the fracturing and displacement of rock masses under tectonic stress during crustal movement. Their core geological characteristics are manifested by highly fractured rock masses, loose structures, and strong heterogeneity. These zones are mainly composed of fragmented rock masses, fault gouge, breccia, and various filling materials, featuring poor rock mass integrity, high porosity, and weak physical and mechanical properties. Their compressive and shear strengths are significantly lower than those of intact rock masses. The distribution range and degree of fragmentation of fault fracture zones vary considerably. In some areas, the fracture zone is relatively narrow and the rock mass exhibits better cementation, whereas in other areas the width may reach tens of meters, with extremely loose rock masses. In addition, fault fracture zones are often associated with groundwater enrichment. Groundwater mainly exists in the form of pore water and fissure water, which can easily form water inflow channels, increasing the risk of water and mud inrush during construction. Meanwhile, groundwater further softens the rock mass and reduces the stability of the surrounding rock. After excavation, stress in the surrounding rock is rapidly released, making large deformations such as face extrusion, crown settlement, and sidewall convergence more likely to occur, posing severe challenges to tunnel construction.

### **1.2 Impacts of Fault Fracture Zones on Tunnel Construction**

The complex geological conditions of fault fracture zones have significant adverse impacts on the safety, quality, and progress of highway tunnel construction, making them key areas requiring strict control during tunneling. In terms of construction safety, the poor stability of fractured rock masses makes surrounding rock collapse and block falling likely during excavation. When combined with abundant groundwater, water and mud inrush accidents may occur, threatening the personal safety of construction personnel and the integrity of construction equipment. In terms of engineering quality, fractured rock masses are unable to provide a stable load-bearing foundation for support structures, which easily leads to deformation and cracking of support systems. During lining construction, quality defects such as honeycombing, surface roughness, and leakage are

prone to occur, adversely affecting the service life of the tunnel <sup>[1]</sup>. Regarding construction progress, to cope with complex geological conditions, additional procedures such as enhanced geological investigation, advance support, and grouting reinforcement are often required, along with adjustments to construction schemes and parameters. These measures reduce construction efficiency and may lead to schedule delays. At the same time, construction costs inevitably increase, further intensifying the difficulty of project implementation.

## **2. Pre-Construction Preparations for Highway Tunnels Crossing Fault Fracture Zones**

### **2.1 Geological Investigation and Advance Forecasting**

Geological investigation and advance forecasting prior to construction constitute the fundamental prerequisites for tunnel construction through fault fracture zones. The core objective is to accurately identify the geological conditions of the fault fracture zone, thereby providing a scientific basis for the formulation of construction schemes. Geological investigation generally adopts a combination of methods, including geological drilling, geophysical exploration, and ground-penetrating radar (GPR). The investigation focuses on identifying key parameters such as the spatial distribution and extent of the fault fracture zone, degree of fragmentation, physical and mechanical properties of the rock mass, groundwater distribution, and potential water inflow volume, based on which a detailed geological investigation report is compiled.

Advance forecasting is mainly aimed at identifying the geological conditions ahead of the tunnel face. Techniques such as advance drilling and geological radar detection are employed to predict in advance the boundary position, internal structure, and groundwater conditions of the fault fracture zone. Potential geological hazards can thus be detected in a timely manner, and the forecast range and accuracy can be clearly defined. This provides prompt and reliable geological information for optimizing construction schemes and adjusting construction procedures, effectively avoiding blind or unsafe construction operations.

### **2.2 Design and Optimization of Construction Schemes**

Based on the results of geological investigation and

advance forecasting, targeted construction schemes should be formulated and scientifically optimized to ensure feasibility, safety, and economic efficiency. The construction scheme should clearly define key aspects such as excavation methods, support types, grouting reinforcement parameters, drainage measures, and construction schedule. In accordance with the geological characteristics of fault fracture zones, excavation methods that minimize disturbance to the surrounding rock should be preferentially selected. Support structures and grouting parameters should be reasonably designed, and comprehensive drainage measures should be established. During scheme design, full consideration should be given to the complexity and variability of geological conditions, with sufficient flexibility reserved for scheme adjustment. Professional technical personnel should be organized to conduct scheme demonstration and review, with particular emphasis on verifying safety and feasibility. For geological hazards identified during investigation, construction procedures should be optimized and specific preventive and control measures should be defined. This ensures that the construction scheme can effectively address various problems encountered during tunneling in fault fracture zones and provide reliable guidance for orderly construction implementation.

### **2.3 Preparation of Construction Materials and Equipment**

The quality of construction materials and equipment directly affects construction effectiveness and must be carefully prepared in advance to ensure that project requirements are fully met. With respect to construction materials, priority should be given to products with high strength, good durability, and suitability for construction in fault fracture zones. These mainly include rock bolts, steel arch frames, shotcrete, grouting materials, and drainage pipes. Strict quality inspections should be carried out before materials enter the site, with thorough verification of material specifications, performance parameters, and conformity certificates, so as to prevent unqualified materials from being used in construction. Regarding construction equipment, machinery and devices compatible with the construction scheme should be provided, including excavation equipment, support installation equipment, grouting equipment, drainage systems, and monitoring

instruments. Particular attention should be paid to checking equipment performance and integrity. On-site commissioning and trial operation should be conducted to ensure that all equipment can operate normally and reliably during construction <sup>[2]</sup>.

### **2.4 Training of Construction Personnel and Safety Education**

Construction in fault fracture zones is characterized by high difficulty and significant risk, placing stringent requirements on the professional skills and safety awareness of construction personnel. Therefore, systematic training and safety education should be carried out in advance. Professional skills training should focus on key construction technologies, construction processes, operational specifications, and emergency response measures specific to fault fracture zone tunneling. Construction personnel should be organized to study the construction scheme and relevant technical standards, and experienced technical experts should be invited to provide on-site guidance. Through these measures, the operational skills and emergency response capabilities of construction personnel can be effectively enhanced. At the same time, clear safety responsibilities should be assigned to each position, safety responsibility agreements should be signed, and non-compliant operations should be strictly prohibited, thereby ensuring construction safety throughout the tunneling process.

## **3. Core Construction Technologies for Highway Tunnels Crossing Fault Fracture Zones**

### **3.1 Excavation Technology**

When a tunnel passes through fault fracture zones, lithological contact zones, or soft-hard rock interfaces, the core objective of excavation technology is to minimize disturbance to the surrounding rock and control the risk of collapse. Prior to excavation, advance exploratory drilling should be carried out to detect geological conditions and groundwater conditions ahead of the tunnel face. Based on the results of advance geological forecasting, advance curtain grouting or advance small-pipe grouting should first be adopted as auxiliary construction measures to achieve water sealing and reinforcement of the surrounding rock in the contact zone. If confined groundwater is identified, a full-section advance curtain

grouting scheme should be implemented for water cutoff, and a certain number of drainage holes should be arranged along the tunnel perimeter after excavation. In contact zone sections, the reserved core soil method combined with the three-bench excavation method should be adopted. During construction, excavation cycle footage must be strictly controlled, and the cycle length should be reasonably determined according to the degree of rock mass fragmentation, so as to avoid surrounding rock instability caused by excessive one-time excavation. During excavation, mechanical excavation should be the primary method in soil sections, supplemented by small-scale weak blasting where necessary. In rock sections, controlled blasting technology should be applied for the upper bench excavation to reduce blasting-induced disturbance to the surrounding rock, ensure a smooth excavation profile, and control overbreak and underbreak. After excavation, the tunnel face should be promptly cleaned, and initial support should be rapidly installed to shorten the exposure time of the surrounding rock and prevent collapse caused by weathering and softening. Meanwhile, on-site construction management should be strengthened during excavation. Deformation of the surrounding rock and groundwater conditions should be continuously observed, and construction should be suspended immediately if abnormalities are detected, with emergency measures taken before resuming work.

### 3.2 Support Technology

Support technology is a key measure for controlling deformation of surrounding rock and preventing collapse in fault fracture zones. A composite support system consisting of “advance support + initial support + secondary lining” should be adopted to ensure timely and effective support. Advance support should preferentially use pipe-roof support and small-pipe grouting support to reinforce the surrounding rock ahead of the tunnel face in advance, forming a protective support layer and reducing the risk of collapse during excavation. Initial support should adopt a combined support system of shotcrete, rock bolts, and steel arch frames. Immediately after excavation, shotcrete should be sprayed to seal the surrounding rock, followed by the installation of reinforcing mesh, erection of steel arch frames, and installation of rock bolts to ensure that the initial support can rapidly bear the pressure of the surrounding rock<sup>[3]</sup>. Secondary

lining should be constructed after deformation of the initial support has stabilized. Cast-in-place concrete lining should be used, with strict control over lining thickness and casting quality. Close bonding between the secondary lining and the initial support should be ensured to form an integrated support system, thereby enhancing the overall stability and impermeability of the tunnel.

### 3.3 Grouting Reinforcement Technology

Grouting reinforcement technology is mainly applied to improve the properties of rock masses in fault fracture zones, enhance the stability of the surrounding rock, and seal groundwater flow channels, thereby reducing the risk of water inrush. It is a key auxiliary technology in the construction of tunnels through fault fracture zones. According to geological conditions and construction requirements, appropriate grouting materials and methods should be selected. Commonly used grouting materials include cement grout and cement–sand grout, while grouting methods mainly comprise advance grouting, peripheral grouting, and backfill grouting. Advance grouting is used to reinforce the surrounding rock ahead of the tunnel face, peripheral grouting is applied to strengthen the rock mass around the tunnel, and backfill grouting is used to fill voids between the support structure and the surrounding rock. During construction, grouting parameters—including grouting pressure, grouting volume, and grouting rate—must be strictly controlled to ensure uniform and dense grouting. After completion, the effectiveness of grouting should be inspected, and supplementary grouting should be carried out in areas where the results fail to meet requirements, ensuring that the reinforcement effect satisfies construction demands.

### 3.4 Drainage Technology

In view of the characteristics of groundwater enrichment in fault fracture zones, a drainage strategy combining water sealing and drainage, adapted to local conditions, should be adopted to effectively control groundwater and prevent water and mud inrush accidents. Drainage technology mainly includes two aspects: advance water sealing and in-tunnel drainage. Advance water sealing is achieved through grouting to block groundwater flow channels and reduce groundwater inflow into the tunnel. In-

tunnel drainage involves the installation of drainage ditches, sump pits, and drainage pipelines to promptly discharge accumulated water within the tunnel. During construction, drainage facilities should be reasonably arranged according to the magnitude of water inflow, and appropriate drainage equipment should be selected to ensure that drainage capacity meets construction requirements. Groundwater monitoring should be strengthened to continuously track changes in groundwater level and inflow volume, and drainage schemes should be adjusted in a timely manner. If excessive water inflow is anticipated or observed, advance grouting measures should be implemented in advance to control groundwater ingress and ensure smooth construction progress.

## **4. Construction Monitoring and Control for Highway Tunnels Crossing Fault Fracture Zones**

### **4.1 Monitoring Contents and Methods**

Construction monitoring is an important means of understanding surrounding rock deformation and the stress state of support structures, as well as timely identifying potential construction hazards. The main monitoring contents include surrounding rock settlement, surrounding rock convergence, stress in support structures, groundwater level, and water inflow volume. Surrounding rock settlement and convergence are monitored using instruments such as levels and convergence meters, with monitoring points arranged on the tunnel lining and data collected at regular intervals. Stress monitoring of support structures is carried out using stress meters installed on rock bolts, steel arch frames, and linings to track changes in structural stress. Groundwater monitoring employs water level gauges and flow meters to continuously monitor variations in groundwater level and inflow. Monitoring methods combine automated monitoring with manual measurements to ensure the accuracy and timeliness of data. Monitoring frequency is reasonably adjusted according to construction progress and the degree of surrounding rock deformation.

### **4.2 Processing and Analysis of Monitoring Data**

The core of monitoring data processing and analysis lies in organizing and interpreting the collected data to determine trends in surrounding rock deformation and support structure stress, thereby identifying

potential construction risks in a timely manner. During construction, dedicated personnel are assigned to collect and organize monitoring data. The collected data are screened and verified, with abnormal data eliminated to ensure authenticity and accuracy. Professional data analysis software is used to conduct trend and comparative analyses, and monitoring curves are plotted to clarify deformation rates of the surrounding rock and stress variation patterns of support structures. This enables assessment of surrounding rock stability and support structure safety. If abnormal monitoring data are identified, the causes are promptly analyzed to determine whether risks such as surrounding rock instability or support structure deformation exist, providing a reliable data basis for formulating construction control measures<sup>[4]</sup>.

### **4.3 Construction Control Measures**

Based on monitoring data and on-site construction conditions, targeted construction control measures should be formulated to ensure construction safety and quality. In cases of excessive surrounding rock deformation, excavation cycle footage should be adjusted in a timely manner, exposure time of surrounding rock should be reduced, and advance support and initial support should be strengthened. Measures may include increasing the density of steel arch frames, adding more rock bolts, and, when necessary, implementing secondary grouting reinforcement to control deformation.

When abnormal stress is detected in support structures, the installation quality of the support system should be inspected, and reinforcement measures should be taken promptly. Support parameters should be adjusted to ensure that the support structures can safely bear the surrounding rock pressure. For abnormal groundwater inflow, drainage efforts should be intensified, additional drainage facilities should be installed, and advance grouting measures should be adopted to block groundwater channels and control water ingress.

## **Conclusion**

The construction of highway tunnels crossing fault fracture zones is a complex and demanding task involving geology, construction techniques, and monitoring and control. Through thorough pre-construction preparations—including accurate

geological investigation and advance forecasting, as well as scientifically designed and optimized construction schemes—a solid foundation can be established for safe and efficient construction. In the future, with continuous technological advancement, further research and development of new construction technologies and materials are needed to improve construction efficiency and quality, thereby promoting the advancement of highway tunnel engineering to a higher level.

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