

# Deformation and failure of a tunnel in the restraining bend of a strike–slip fault zone: an example from Hengshan Mountain, Shanxi Province, China

Daming Lin<sup>1</sup> · Renmao Yuan<sup>2</sup> · Yanjun Shang<sup>3</sup> · Weixing Bao<sup>3</sup> · Kaiyang Wang<sup>3</sup> · Zhongjian Zhang<sup>4</sup> · Kun Li<sup>3</sup> · Wantong He<sup>3</sup>

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**Abstract** The Yanmenguan Tunnel runs through Hengshan Mountain in Shanxi Province, China. The mountain is mainly composed of metamorphic rock cut by a well-developed strike–slip fault system. As a result of the local geological setting, significant deformation and mud bursting occurred during excavation of the tunnel. In this paper, a representative 170-m-long section of the tunnel (from Sta. 118 K + 30.0 to Sta. 118 K + 200.0), which is located in the restraining bend area of the strike-slip fault system, is chosen as a case study to investigate the influence of such a fault on tunnel stability. The characteristics of strike-slip faults and asymmetrical pressure are then investigated, in conjunction with monitoring stress and displacement in the tunnel. The results of the analysis suggest that the strike-slip fault complicates the geological condition and decreases the quality of the rock masses. Different rock mass classifications for the surrounding rocks are the dominant factor causing asymmetrical pressure in the tunnel, which in turn significantly influences deformation in the tunnel. Shear and crushing failure are the mechanisms of failure in the surrounding rocks in the

surveyed section, where significant deformation and mud bursting occurred. It indicates that stress and the classifications of surrounding rock masses should be carefully investigated and analyzed during the design and construction of underground engineering works in such a setting.

**Keywords** Yanmenguan Tunnel · Strike-slip faults · Asymmetrical pressure · Large deformation · Mud bursting

## Introduction

A tunnel is subjected to considerable deformation due to stress-related failure in the surrounding rock mass when thrust zones or strike-slip faults transect the tunnel (Dalgic 2002). These deformations, resulting in serious geotechnical problems, can be fixed by flexible or extremely strong support systems. Support systems were often used to prevent large deformations during excavation, whereas flexible methods allow the deformations to develop without restraint. Heavy support systems used in strike–slip fault zones have been found to be more successful than flexible support systems (Aydan et al. 2014).

Investigations for design and construction of tunnels through fault zones were reported by many researchers (e.g., Gianearlo and Giorgio 2004; Kusumi et al. 2006). In China, the most representative study in this area is investigation of the Wushaoling Tunnel built in the Qilian Mountains (Liu et al. 2006). Compared with dip slip faults, strike–slip faults are more complicated and tend to affect larger areas (Wallace et al. 2012). However, little research related to the problems of tunnels passing through an area with strike–slip faults has been undertaken.

✉ Renmao Yuan  
yuanrm@gmail.com

<sup>1</sup> Research Institute of Highway, Ministry of Transport, Beijing 100088, China

<sup>2</sup> Key Laboratory of Active Tectonics and Volcanoes, Institute of Geology, China Earthquake Administration, Beijing 100029, China

<sup>3</sup> Key Laboratory of Engineering Geomechanics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

<sup>4</sup> Department of Civil Engineering, China University of Geosciences, Beijing 100083, China

Many strike–slip faults at the surface consist of en echelon and/or braided segments in many cases probably inherited from previously formed Riedel shears. In a cross-section through a restraining bend of strike–slip faults at the surface, displacements can be dominantly reverse or normal depending on whether the overall fault geometry is transpressional or transtensional. As the faults tend to join downwards onto a single strand in basement, the geometry has led to these being termed flower structure. Fault zones with dominantly reverse faulting are known as positive flowers (pop-up ridges), those with dominantly normal offsets are known as negative flowers (subsidence). The identification of such structures, particularly where positive and negative flowers are developed on different segments of the same fault, are regarded as reliable indicators of strike–slip. (Harding 1990; Woodcock and Fischer 1986).

In this paper, the Yanmenguan Tunnel is presented as a case study to discuss the problems of a tunnel being affected by strike–slip faults. The Yanmenguan Tunnel is excavated through Hengshan Mountain in Shanxi Province, China. Hengshan Mountain, which is composed of metamorphic and magmatic rocks, has undergone extensional and compressive movements through the Precambrian period, and subsequently local NW–SE trending shallow compressive movements (The 3rd Railway Survey and Design Institute 2007) (Fig. 1). Several strike–slip faults and phenomena associated with asymmetrical pressure in the Yanmenguan Tunnel were observed during investigation and excavation, which resulted in significant deformation and mud bursting especially in the section from Sta. 118 K + 30.0 to Sta. 118 K + 200.0 within the tunnel. This section (called the survey section) is taken as a case study to analyze the features of rock failure caused by

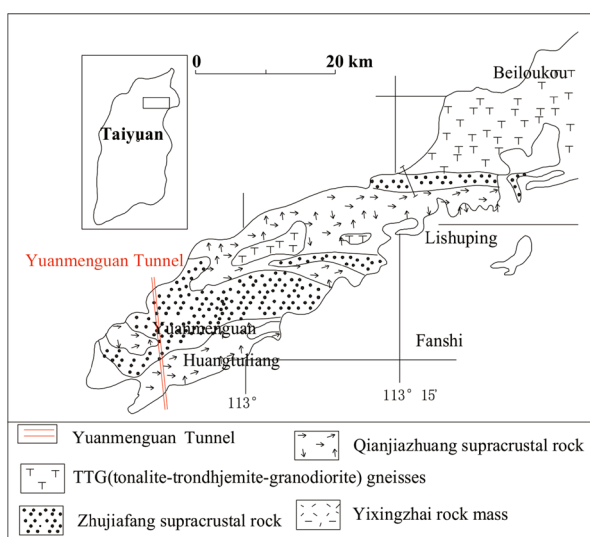
asymmetrical pressure in the restraining bend of the strike–slip fault and to monitor the stress and displacement of surrounding rocks. The purpose of this paper is to propose a suitable construction technique for Yanmenguan Tunnel and also to provide a reference for other tunnels lying within similar fault settings.

## Geological setting

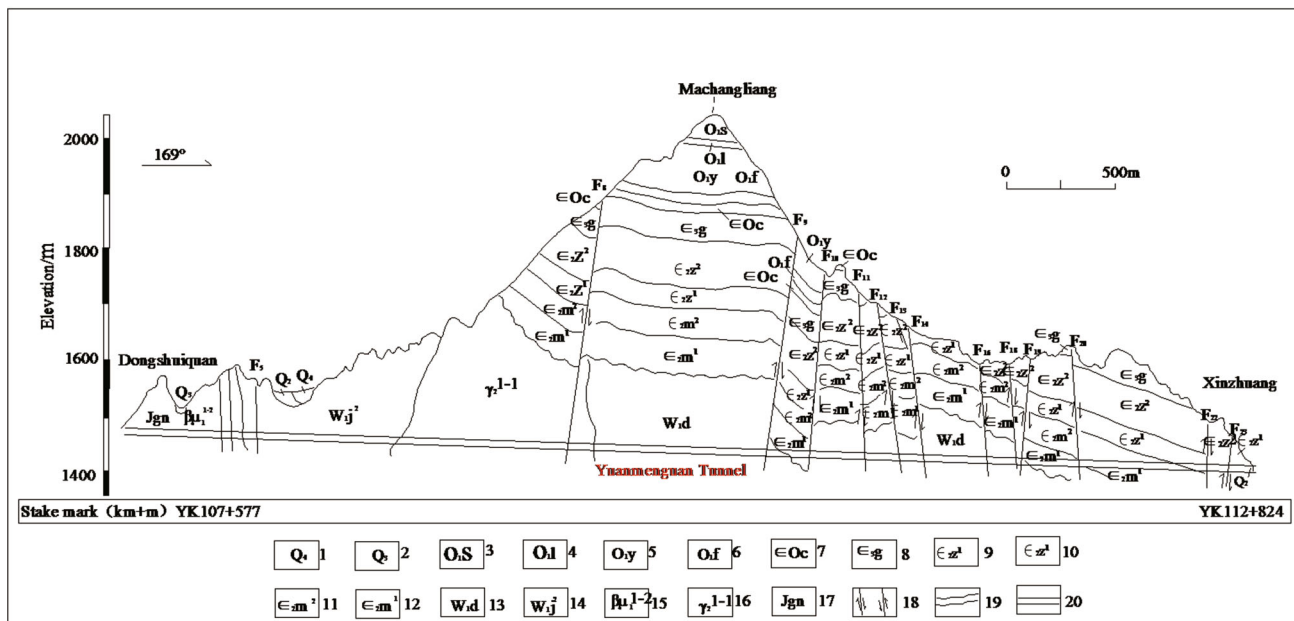
### General geological setting

The Yanmenguan Tunnel in the western part of Hengshan Mountain carries a key section of the Datong–Yuncheng Expressway, which starts west of the village of Miaojiaoyao in Shanyin County and ends to the north of the village of Taiheling in Dai County (Dechao and Dejun 2015). Joints and gneissic schistosity are distributed widely in this area. Most of the structures were formed in the Lvliang period. The lithology of this area is mainly composed of granite, gneiss, and supracrustal rock (Fig. 2).

The starting and ending points of the tunnel are located at Sta. 110 K + 885.0 and Sta. 124 K + 940.0, respectively. The burial depth of approximately 60 % of the tunnel is over 400 m, and about 30 % is over 500 m. The tunnel also crosses one confined aquifer with a maximum discharge of 13 000 m<sup>3</sup>/day. Over 600 discontinuities including 319 joints, 157 gneissic schistositities, 76 dikes, 26 faults, and 11 fold axial planes were mapped by field investigation and geological analysis in the tunnel area (Figs. 2, 3). Four sets of joints (185∠53, 144∠57, 303∠89, 31∠65) were developed well in the study area (Fig. 3). The first two groups indicate the geological condition of low-angle gneissosity, and the

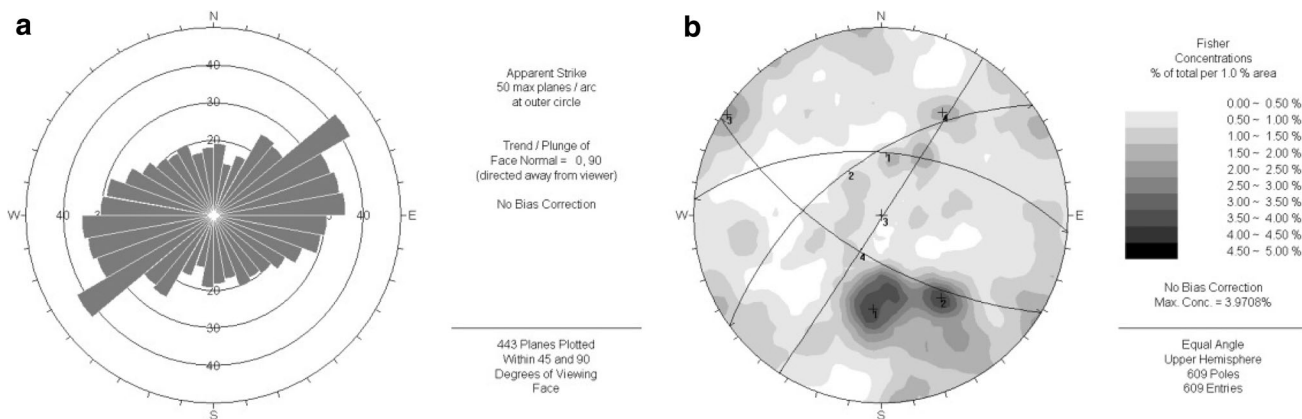


**Fig. 1** Geological map and location of the Yanmenguan Tunnel (*left*) and the landforms around the tunnel (*right*)



**Fig. 2** Schematic engineering geological profile along the axis of the Yanmenguan Tunnel. 1 Quaternary Holocene, 2 Quaternary Pleistocene, 3 Ordovician Sanshanzi group, 4 Ordovician Liangjiashan Group, 5 Ordovician Yeli Group, 6 Ordovician Fengshan Group, 7 Cambrian Ordovician Changshan Group, 8 Cambrian Gushan Group, 9 Cambrian Second: Zhangxia Group, 10 Cambrian First: Zhangxia

Group, 11 Cambrian Second: Mantou Group, 12 Cambrian First: Mantou Group, 13 Five-tai Dianfang Group, 14 Five-tai Jingangku Group, 15 Luliang late diabase dikes, 16 Luliang metamorphic granite, 17 Five-tai mid-plagioclase gneiss, 18 normal faults, reverse fault, 19 stratigraphic boundaries and unconformity boundary, 20 tunnel line



**Fig. 3** Sketch map of geological structure planes. **a** Geological structure equidensite diagram and four groups of major structural planes; **b** Rose diagram of the geological structure planes

latter two groups represent steeper angled joints in the tunnel area. The predominant direction of the maximum horizontal principal stress in the tunnel area is N30°E, and the discontinuities exhibit strike-slip movement features, suggesting the stress features in the tunnel area.

**Analysis of the strike-slip faults**

An idealized strike-slip fault runs in a straight line with a vertical dip and has only horizontal motion, thus there is no

change in topography due to motion of the fault. In reality, as strike-slip faults become large and developed, their behavior changes and becomes more complex. Generally, a long strike-slip fault system follows a staircase-like trajectory consisting of interspaced fault planes along the main fault direction.

Restraining bends are transpressional structures that form where the orientation of a strike-slip fault becomes oblique to the regional slip vector causing local compression or uplift. They also form where two segments of a strike-slip fault overlap, and the relay zone between the

segments experiences transpression (Sanderson and Marchini 1984). Movement on a strike–slip fault can manifest geomorphologically as subsidence in a releasing bend area or as a pop-up ridges (positive flower structures) in a restraining bend, with many local normal faults or local reverse faults (Fig. 4a). In the restraining bend area, thrust faults will accommodate vertical displacement rather than being folded, and this can result in a geological disaster brought about by the large deformation or mud bursting that often occurs when a tunnel is opened, especially when coinciding with heavy groundwater seepage.

Stress measurements suggest that large compressional stresses exist in the tunnel area (Fig. 4b). Tectonic geomorphology also shows that zone no. 2 is a pop-up area, that is to say, zones nos. 1 and 3 moved towards zone no. 2, with opposite directions of motion, thereby squeezing zone no. 2 (Fig. 4c), and resulting in large compressive stress on the body in zone no. 2. The Yanmenguan Tunnel lies exactly within the restraining bend area.

In this study, hydraulic fracturing boreholes are used to measure the in situ stress in the vicinity of the Yanmenguan Tunnel. Results show that the horizontal principal stress value is 20.91 MPa oriented NNE–SSW. This stress is consistent with the regional tectonic pressure direction and is about 30° oblique across the tunnel axis. As such, it will result in significant deformation and mud bursting during tunnel excavation.

In general, the blocks of rock on either side of a strike–slip fault can be described as sliding horizontally and parallel to the strike of the fault. A strike–slip fault can either act as an independent tectonic unit or service as a transferring and accommodating structure in a tectonic system. Compared with similarly scaled dip–slip faults, strike–slip faults have a more severe impact on tunnel construction (Curren and Bird 2014). The structure of such a fault in the vicinity of a tunnel can be further investigated with geophysical techniques.

Several sub-faults have been found on survey profiles along the tunnel axis (Fig. 5). Flower structures are the most typical type of structure observed in the restraining bend of strike–slip faults. EH4 is a magneto telluric sounding system which combines with the controlled source and natural source. Orthogonal components of the electric field ( $E_x$ ,  $E_y$ ) and magnetic field ( $H_x$ ,  $H_y$ ) of the time series is its main observation of the basic parameters. So EH4 resistivity profiling was undertaken between Sta. 117 K + 600 and Sta. 118 K + 250 (Fig. 5, left). Notice that fan-like faults forming the flower structure exist in the shallow area, while a sub-vertical and narrow fault zone (the stem) exists in the deeper area. The fault, Fy14 and Fy15, constitutes the flower structure where the resistivity is very low. This low-resistivity region (Fig. 5, left) consists of amphibole biotite granulite and hornblende-plagioclase gneiss. An apparent flower structure in the section from Sta. 117 K + 600 to Sta.

118 K + 250 and region stress field indicate a restraining bending area of the strike–slip fault.

Figure 5 shows that faults Fy14 and Fy15 have large dip angles. Based on the interpretation of the EH4 resistivity distribution (Fig. 5, right), in the section from Sta. 118 K + 030 to Sta. 118 K + 170, the geological boundaries that intersect the fault zone are obviously staggered by it in the horizontal direction; this apparent offset across the fault is identified as the most direct manifestation of strike–slip faults.

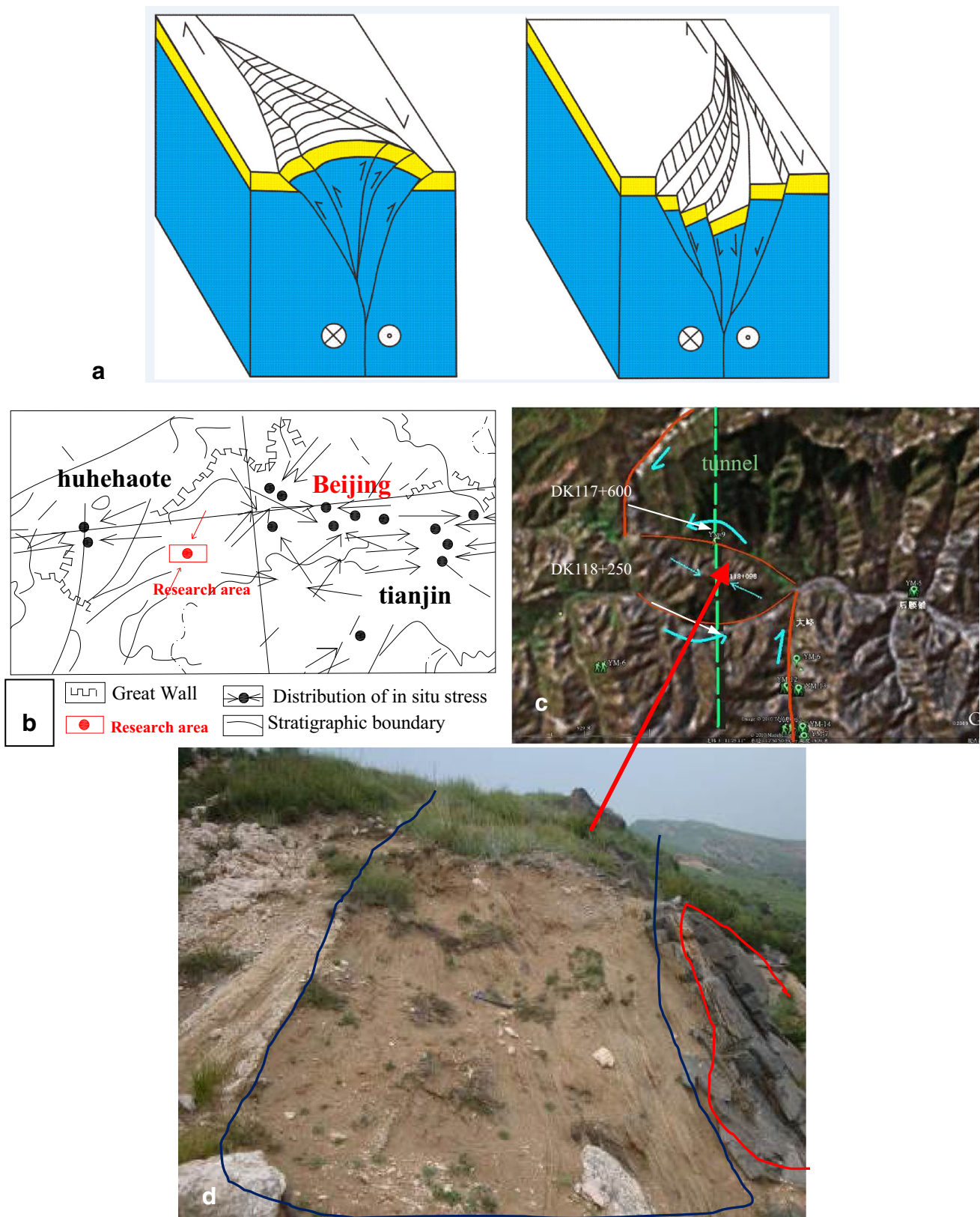
Based on pop-up ridge (the flower structures) and steep fault plane shown in Figs. 4 and 5, it could be concluded that the survey section lies within a restraining bend of a strike–slip fault, and it is subject to large compressional stress. Considering the influence of the strike–slip faults, our research will establish a solid theoretical basis for construction of the Yanmenguan Tunnel.

## Hazards in the Yanmenguan Tunnel

Traversed by a potassic granite dike, the two sides of the survey section consisting of different types of rock have different failure characteristics. Monitoring and observation results show that apparent interfacial shearing, such as shearing along the dike and gneissic schistosity, occurred in the seam-filled and crushed surrounding rocks during the tunnel opening. At the same time, dilatant deformation also occurred in the surrounding rocks as excavation progressed. Several sets of tension fractures and shear fractures are observed to intersect with the tunnel axis at an angle of 45°. Shear fracture surfaces are often smooth and long, extending straight and continuously, whereas tension fracture surfaces are always rough and wide open with poor continuity and irregular shapes. In conclusion, the mechanism of brittle failure in such metamorphic terrains manifests as shear dilatancy and crushing failure of interfaces.

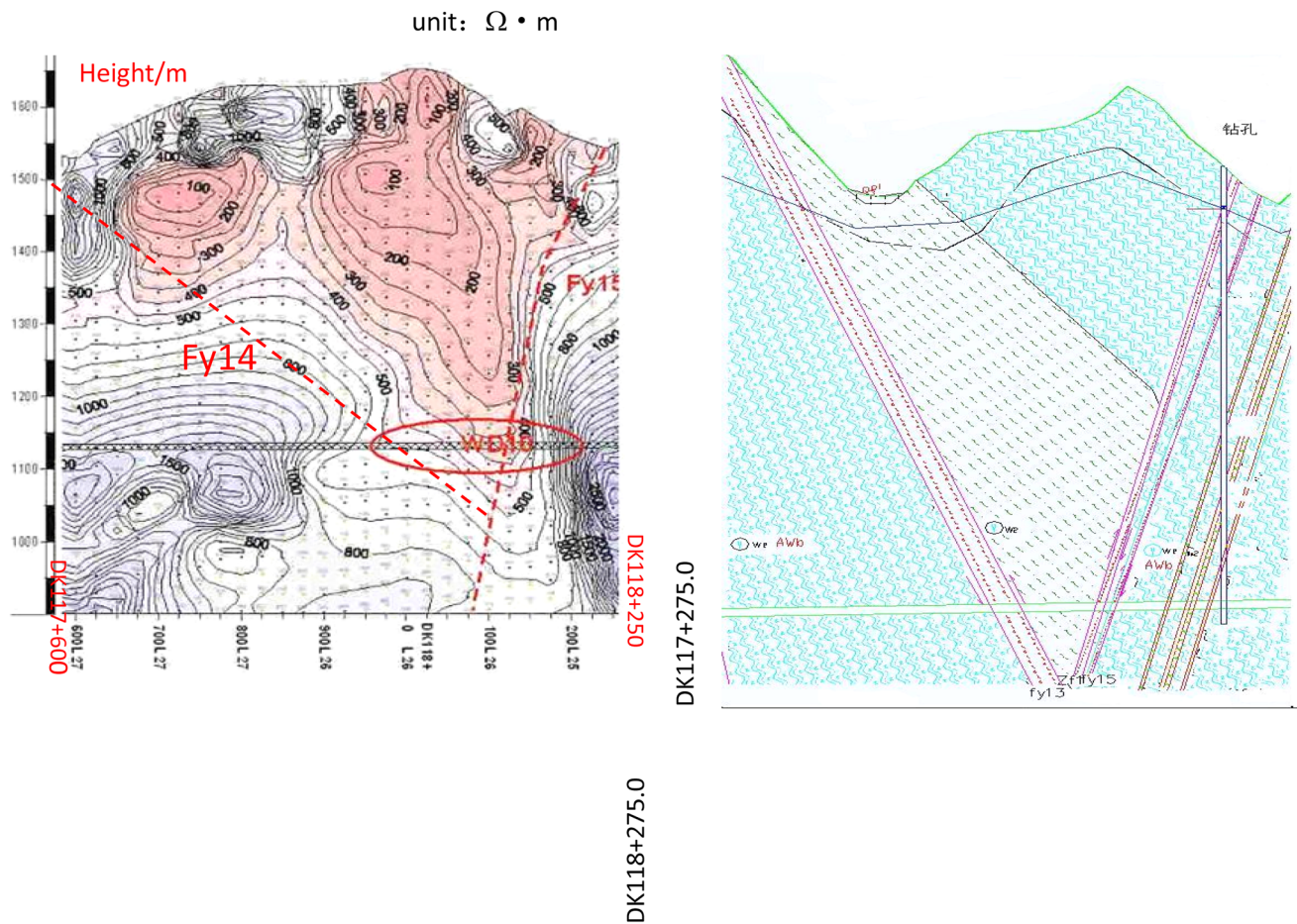
## Asymmetrical pressure

Investigation has shown that the Yanmenguan Tunnel is located in the vicinity of a restraining bend in a strike–slip fault system, and that this tectonic setting has induced large compressional stresses on the tunnel. In general, topographical conditions, geological structures, and tunnel excavation itself can result in asymmetrical pressures in a tunnel (Liu and Zhang 2010). Asymmetrical pressure in a shallow tunnel is primarily related to maximum burial depth and topographical conditions, such as the thickness of overburden and the overlying slope landforms. However, for a deeply buried tunnel, the influence of overlying topographical conditions on asymmetrical pressures is



**Fig. 4** **a** Flower structures developed along minor restraining and releasing bends on a dextral strike-slip fault; **b** stress distribution in the study area (from MA, 1989); **c** tectonic geomorphology in the

tunnel area featuring inter-laminar shear; **d** interfacial shearing dilatancy phenomenon in field near the fault zone



**Fig. 5** EH4 resistivity distribution (*left*) and geological interpretation (*right*) in the tunnel area

negligible; therefore, geologic structures are considered to be the major factors in asymmetrical pressure development.

Rock mass classifications based on rock quality are a key set of parameters for tunnel construction. In the metamorphic rock setting of the Yanmenguan Tunnel, where the restraining bend of a strike-slip fault is developed, the geological conditions are very complicated. Granitic dikes and tonalite-trondhjemite-granodiorite gneiss are observed along the tunnel line, which greatly influence the quality of surrounding rock mass.

In the country rock on the right side of the tunnel, biotite-bearing plagioclase amphibolites are distributed widely (Fig. 6a). Dikes in the rock mass intersect with the tunnel axis at an angle of about  $45^\circ$ . Joints are well developed and several 3- to 5-cm-thick muddy intercalations are observed. Discontinuities are generally spaced from 30 to 60 cm apart. The uniaxial compressive strength of a samples of the rock has been measured at 51.95 MPa. According to the Chinese standard for the engineering classification of rock masses and code for rock and soil classification for railway engineering, the surrounding rock mass of the tunnel can be rated as III (from the Chinese

national standard; the BQ of class III ranges between 450 and 351, whereas the RMR ranges between 50 and 60). Note that the groundwater conditions on the two sides of the survey section are different: rivulets can be observed in the left side, while few are observed in the right side.

The left side of the survey section mainly consists of potassic granite with severely kaolinitized plagioclase. These rocks have extremely low strength and are cemented poorly, which means that they are easily softened by water (Fig. 6b). Some apparent interfacial shears, such as shearing along dikes and gneissic schistositys, occurred in the seam-filled and crushed rocks surrounding the tunnel. Two sets of discontinuities were developed and parts of them were kaolinitized. Again, based on the Chinese standard for engineering classification of rock masses and code for rock and soil classification for railway engineering, the surrounding rock masses on the left side of the survey section can be rated as V (from the Chinese national standard; the BQ of class V is less than 250, whereas the RMR is less than 40).

Owing to significant burial depth ( $>500$  m in places) of the survey section and the different classifications of the



**Fig. 6** The surrounding rocks. **a** Biotite-bearing plagioclase amphibolites; **b** potassic granite

rock mass and groundwater conditions on the left and right sides of the tunnel, stress action on the two sides of tunnel can manifest very differently. Observations also indicated that twisting of the support system's steel ribs and lining cracking frequently occurred on the left side, whereas such effects are seldom found on the right side. These differences indicate that the tunnel suffered asymmetrical pressure here.

### Geo-hazards during tunneling

Some researchers (Liu et al. 2006) suggest that asymmetrical pressure is particularly notable in deep tunnels with high in situ stress. The asymmetrical load that exists in a tunnel would weaken the stability of the surrounding rocks and destroy the support system of the tunnel. The in situ stress test showed that the maximum horizontal principle stress in the Yanmenguan Tunnel is 20.91 MPa with direction of NNE–SSW.

The survey is situated in the middle section of the Yanmenguan Tunnel. This section is the most representative part of the tunnel, located within the compression stress field caused by the restraining bend of the fault. In this area, the quality of rock mass thus is poor because of complicated geological conditions. According to the National Standard of China, classification of rock mass in the survey section was originally rated as III: interlocked and disturbed rock mass with multifaceted angular blocks formed by four or more discontinuity sets; Joint spacing is 10–30 cm and RQD is 80–100; Some of the mica is weathered and the plagioclase is slightly kaolinized; The structure planes occasionally show a rusty tinge.

Therefore, anchor net supports coupled with 12-cm-thick sprayed C25 concrete were employed in preliminary tunnel lining. However, owing to the extreme asymmetrical pressures on the tunnel support system, the preliminary

support on the left side of the tunnel is badly cracked (Fig. 7a). An altered design involving steel frames was then adopted. However, the frames became twisted (Fig. 7a), and the sprayed concrete became cracked and peeled. The tunnel wall thus moved into the tunnel, and a large-scale mud burst comprised mainly of granular potassic granite dike material and a fault gauge occurred in the arch wall of the left side (Fig. 7b).

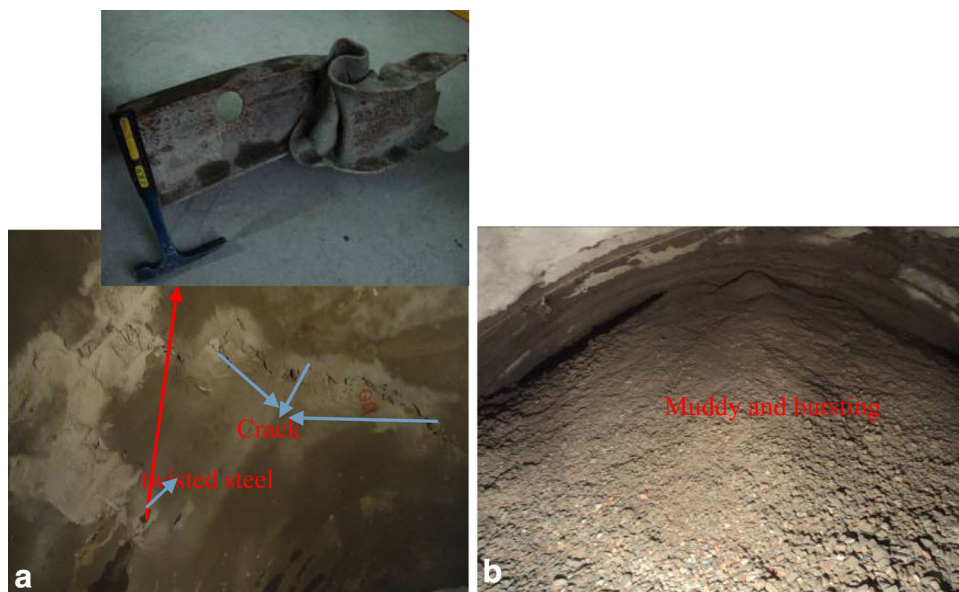
### Geomechanical analysis of the Yanmenguan Tunnel

From July to November in 2010, the geological investigation and mapping around the tunnel area were carried out by authors. A large number of geological materials and data are obtained, including 319 joints, 157 gneissic schistositities, 76 dikes, 26 faults, and 11 fold axial planes. Based on observations and analyses of geological features (Fig. 3), a geomechanical analysis of the tunnel area are then conducted.

### Influence of the restraining bend

The Yanmenguan Tunnel lies exactly within the compressional stress field caused by a restraining bend of a region strike-slip fault system, with a predominant orientation of principal horizontal stress of N30°E. The strike of the tunnel axis is close to S–N. Therefore, the angle of intersection between the tunnel axis and the principal horizontal stress is about 30° (Fig. 4). With regard to the geomorphological conditions, the survey section lies in a mountain range (zone no. 2 in Fig. 4b) in which the restraining bend area of the strike-slip fault is composed mainly of low-strength crushed lamellar amphibolites cut by many dikes. Gullies form the northern and southern

**Fig. 7** Geo-hazards during tunnel opening. **a** Cracking and twisting of support wall; **b** large-scale muddy sand bursting at Sta. DK118 + 90.0



boundaries of zone no. 2. In this area, quartz-mica amphibolites are also occasionally observed. Geomorphic structures are often observed in zone nos. 1 and 3, where stratigraphic boundaries, unconformity surfaces, dikes, and other geological boundaries are staggered.

Large compressional stress and complicated fault structures in the restraining bend area indicate that the geological conditions present in the Yanmenguan Tunnel crossing are very complicated, which can cause serious geo-hazards during tunneling.

#### Stress and displacement monitor in the survey section of the tunnel

According to the national standard of China, geological stress with over 20 MPa is the high stress area. In general, high compressional stress can occur in the restraining bend area of a strike-slip fault system, greatly affecting rock deformation and thereby determining the stability of associated structures.

Tunnel openings can cause stress converge because of the huge compressional stresses in surrounding rock mass. For contact pressure between surrounding rock and initial lining, which can reach three times of its original value. Depending on the specific geological conditions, this effect may cause either a reduction of the excavated area or a collapse. Thus, a basic requirement for successful tunneling is to control convergence and instabilities in the section being excavated. Additional measures are needed for tunnel stability once convergence exceeds the safety levels. Therefore, a system capable of detailed monitoring of tunnel deformation should be established as soon as possible during a tunneling operation.

To investigate and analyze the components of deformation in the Yanmenguan Tunnel, such as the distribution features and the time history of deformation, a series of monitoring points was established by the authors based on anticipated specific geo-hazards and geological conditions (Fig. 8). The monitoring equipment come from Dandong tree of instrument Co. LTD. Tolerances of geological stress and displacement are less than 0.2 % and 0.1 % of full scale (FS), respectively.

The monitoring profile is located at Sta. 118 K + 111.6. The data collected include: vault settlement, tunnel convergence, and contact pressure between the initial lining and surrounding rock. Figure 9 shows that the peak value of contact pressure in the crown of the section is 1.71 MPa, and the maximum value of contact pressure in the left haunch is 1.01 MPa, indicating that the steel ribs and surrounding rocks on the left side of the tunnel are subjected to very high pressures. Over 19 days of monitoring, the contact pressures at the crown and left haunch gradually converged in value and then stabilized at about 0.8 MPa. The contact pressures measured by the sensor in the right side of the survey section are relatively small (0.1 MPa) and stable with a little variation.

The results of the investigation showed that the surrounding rocks on the left side of the tunnel consist of crushed loose sand, and are subjected to severe kaolinitization; these rocks are easily softened by water and have no ability to support the tunnel. However, the surrounding rocks on the right side of the tunnel consist of relatively intact, blocky biotite-bearing plagioclase amphibolites. Therefore, the surrounding rocks can serve as the primary supporting structure, with relatively low stress pressure on the steel ribs. Based on different contact pressures at



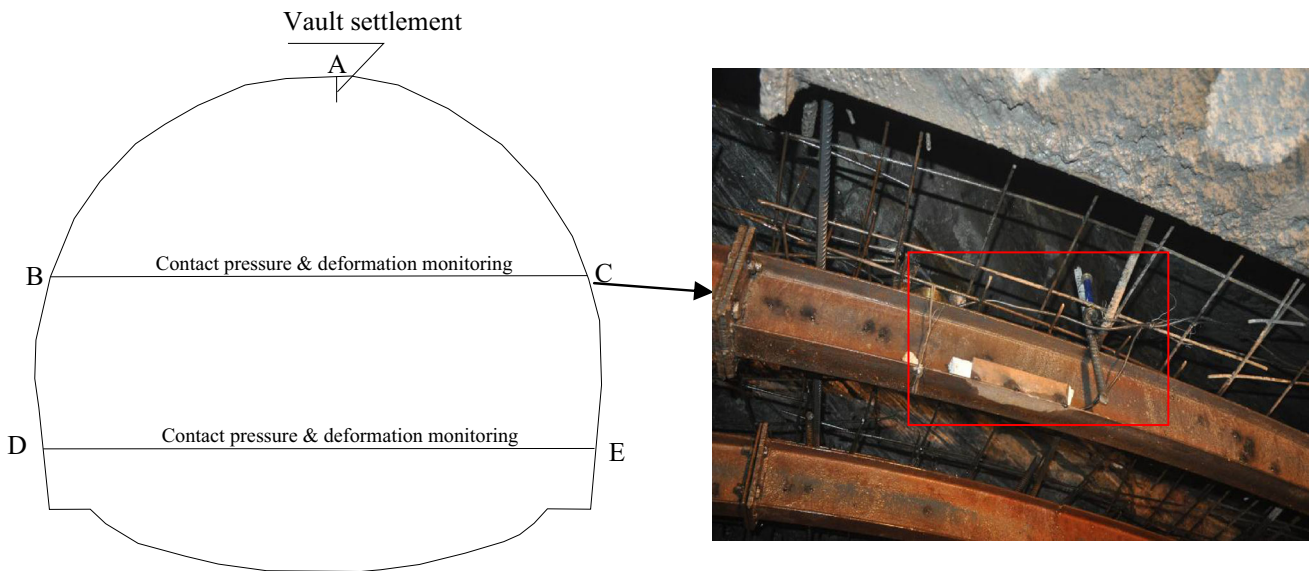


Fig. 8 Sketch of monitoring points for contact pressure and deformation monitoring

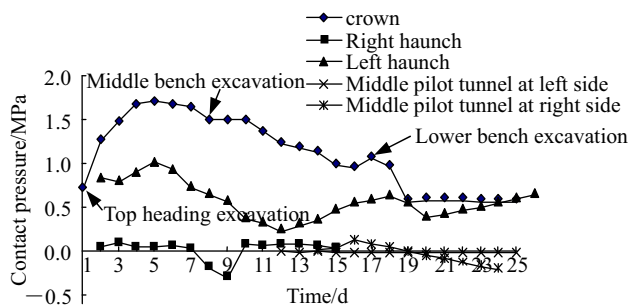


Fig. 9 Contact pressure between surrounding rock and initial lining

various monitoring locations, asymmetrical pressure is obviously inferred within the tunnel (Fig. 9). The contact pressure may even occasionally assume a negative value, which may result from the loose contact between the surrounding rocks and pressure gauges.

The results of monitoring tunnel convergence in the section from Sta. 118 K + 94.6 to Sta. 118 K + 150 are illustrated in Fig. 10. The value of crown settlement is greater than that of horizontal convergence, and the horizontal convergence on the left side is generally greater than that on the right side in most of the monitoring profiles, thereby indicating the significant influence of asymmetrical pressure on tunnel convergence. The monitoring profile from Sta. 118 K + 96.0 shows that horizontal convergence on the left and right sides is 412.52 and 124.18 mm, respectively, while the crown settlement is 306.66 mm. Measurements from all other monitoring profiles also show that the value of the crown settlement is smaller than those of the horizontal convergence on the left side of the tunnel. The monitoring results in the middle section of the

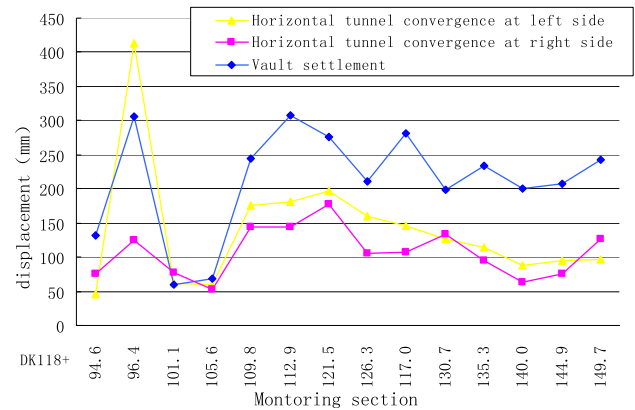


Fig. 10 Monitoring results of deformation in study section

Yanmenguan Tunnel (Fig. 2), where is the central region of the strike-slip fault zone, show that asymmetrical pressure is the dominant factor influencing rock deformation here.

### Mechanisms of stress and displacement change of the tunnel

Time-dependent developments of pressure and deformation are often very important during tunnel deformation analysis, even though rock deformations normally develop slowly. However, in the Yanmenguan Tunnel, the deformation at the working face is large and rapid. The change of rock pressure and rock deformation were noticeable in hours or days. In addition, groundwater seepage, the complicated geological conditions induced by the strike slip fault system, and high in situ stresses make rock

deformation rates increase quickly, resulting in support systems damage and muddy sand bursts.

Mechanisms of rock deformation increasing or mud bursting in the Yanmenguan Tunnel can be explained by following:

- (a) First: in the Yanmenguan Tunnel, the maximum principal horizontal stress (20.91 MPa) is very high, the orientation of which is NNE–SSW, and is consistent with the regional tectonic stress.
- (b) Second: deformation and bursting are connected to squeezing properties of the fault resulting from the high compressional stress field (Fig. 4). Failure occurred when the stress exceeded the strength of rock mass. In cross-section, the displacement of strike–slip faults at the surface are dominantly reverse or normal. In fact, geological conditions in the bending area are more complicated when the strike slip faults become more active.
- (c) Third: the Yanmenguan Tunnel is located in the saturated granite, gneiss, or supracrustal rock area, excavation of which triggered transient seepage. The change of pore water pressure and effective stress are very quickly, which leads to rock deformation. A coupled process of seepage flow, rock squeezing, broken rock, and rock deformation thus need be carried out. However, mud bursting often occurs in the relatively impermeable area.

### Control of large-scale deformation

The techniques used for controlling large-scale deformation in a tunnel can be classified into two categories based on different construction stages: excavating techniques and supporting techniques. During excavation, some techniques, such as bench excavation, short footage driving, light blasting, altering the cross-section shape of the tunnel, and increasing deformation allowance, can be adopted to minimize tunneling in, and consequently, reducing deformation in, the surrounding rocks.

With the variation of surrounding wall and geological condition, the control techniques is sensitive to different rock classification, in order to adopt suitable countermeasure in restraining bend and avoid the geological disaster during tunnel excavation after refer the relevant standards, the authors together with the engineers, who come from the construction enterprise and Railway Survey and Design Institute, propose the support system, as described following:

In the supporting stage, supporting structures including grouting, cover arches, sprayed concrete, steel ribs, anchor bolt systems, and steel fabric can be used to maintain the

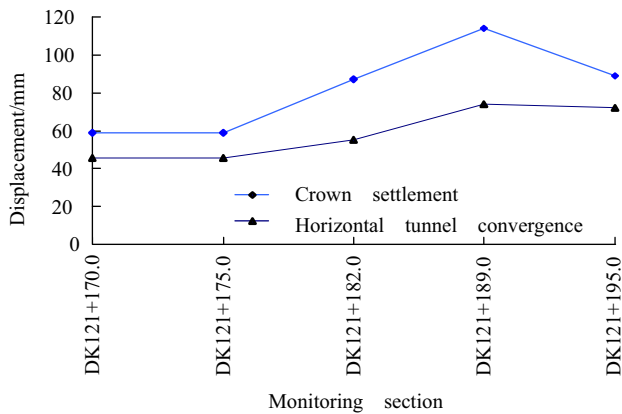


**Fig. 11** Advanced long pipe-shed grouting

stability of surrounding rocks. In the Yanmenguan Tunnel, both flexible and rigid linings were used to strengthen hard and soft rock masses, respectively. Based on the results of monitoring stress and displacement, such measures were employed in the section from Sta. 118 K + 90.0 to Sta. 118 K + 97.8 to replace the center arch. Simultaneously, the surrounding rock masses were reinforced by advanced grouting (Fig. 11).

According to the Q system (Barton 2007), the wall rocks are classified as poor-quality rock masses based on Chinese engineering codes (TB10077-2007 2007; GB 50218—2014 2014). The classification of the surrounding rock mass on the left side of the tunnel was then changed to V from its original II. For the section from Sta. 118 K + 91.4 to Sta. 118 K + 97.5, pretreatment by grouting on the upper pilot tunnel face followed by radial grouting was carried out for the initial supporting stage. The central cover arch constructed of a steel H-beam was then used on the left side after the shortcrete was finished. As for the rock mass surrounding the tunnel section on the right side from Sta. DK118 + 90.0 to Sta. DK118 + 97.8, the classification of which was changed to III from its original II, a fan-shaped steel rib made of H-beam steel was used to maintain the stability of the tunnel after grouting the upper pilot face and radial grouting of the tunnel in the initial supporting stage.

In the section from Sta. 118 K + 0.0 to Sta. 118 K + 100.0, various types of geologic instabilities at different locations need to be considered carefully to avoid disaster. Considering the poor geological condition of the surrounding rock masses in the section from Sta. 118 K + 30 to Sta. 118 K + 97.5, the classification of the rocks were modified to V from its original III. A composite-lining designed for rock masses with a classification of V was therefore installed, the resurrection sliding could be effectively suppressed by H-beam arch frame supporting



**Fig. 12** Deformation of wall rocks after altering construction techniques

structure. In addition, the top-heading-and-bench method that keeps a reserve of core soil was adopted; additionally, the driving distance is cautiously controlled. The initial lining composed of a steel I20b H-beam with a spacing of 60 cm was used to support the tunnel. At the same time, C25 concrete was sprayed with the thickness of 27 cm. The tunnel convergence under the modified construction techniques is illustrated in Fig. 12. Note that the tunnel deformation becomes much smaller than that observed under the original construction method. The crown settlement is 6–11 cm, which is significantly smaller than that before (30 cm), and the tunnel convergence in the horizontal direction decreases to the range of 5–8 cm from the previous value of 56 cm. By increasing the lining strength, tunnel cracking and steel rib twisting are greatly reduced in the tunnel, which indicates the rationality and applicability of the modified control techniques.

Overall in the initial stage, the three-step construction technique is introduced in tunnel opening. The bolt-mesh and sprayed concrete of C25 about 12 cm thickness are used to support the tunnel. However, these technique cannot stop the large-scale deformation. After discussion with different engineers, three-bench with seven-step excavation method and composite-lining system are adopted for tunnel supporting system, which result in well effect and keep a safe working environment.

## Conclusions

The results of the geological investigation of the section the Yanmenguan Tunnel from Sta. 118 K + 30.0 to Sta. 118 K + 200.0 show that the section is located precisely within a restraining bend of a strike-slip fault system. This geological setting has led to complicated geological conditions and a highly compressive stress field. The tunnel is,

therefore, greatly influenced by the strike-slip fault and encountered significant deformation and mud bursting during excavation.

The high stress condition caused by the strike-slip fault combined with the variable rock mass quality of the surrounding rocks are the primary factors that produced asymmetrical pressure in the deep tunnels. Results from monitoring stress and displacement in the tunnel assessed the contact pressure between the surrounding rocks and the initial lining (1.01 MPa), and the tangential stress of the steel ribs (42.72 MPa). Results also showed that the horizontal tunnel convergence on the left side of the survey section (412.52 mm) was greater than that on the right side, thereby showing that the tunnel deformation and the pressure on the lining are mainly induced by asymmetrical pressures.

Differences in the surrounding rock masses and the stress between the two sides of the survey section need to be considered carefully during tunneling. Stability during tunneling can be guaranteed by using differential support types, changing design as needed, and adopting the top-heading-and-bench method, which reserves the core soil.

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