



Supporting mechanism and mechanical behavior of a double primary support method for tunnels in broken phyllite under high geo-stress: a case study

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Received: 7 October 2018 / Accepted: 4 February 2019 / Published online: 19 February 2019
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Abstract

Large squeezing deformation has always been a critical concern in the construction of deep-buried tunnels in soft-weak rock masses. This paper describes a case study on the large deformation mechanism and supporting method of the Maoxian tunnel in Sichuan Province, China, which is located in the core area influenced by the 2008 Wenchuan earthquake and suffered severe large deformation in broken phyllite under high geo-stress. Through a survey on the geological features, the deformation mechanism of surrounding rock and the failure characteristics of supporting structures of the Maoxian tunnel in F1 fault zone were studied. It was found that the occurrence of large deformation was due to the combined action of the high geo-stress and poor self-stability of carbonaceous phyllite. In order to control the squeezing deformation, single and double primary support methods were adopted in succession. A comparative field test was conducted to study their supporting mechanism and mechanical behavior in terms of surrounding rock pressure, internal stress of the steel arch, and axial force and bending moment of the secondary lining. The results revealed that the single primary support method cannot ensure the long-term safety of the tunnel, since many cracks in concrete occurred after about 180 days. The double primary support method, however, was able to control the large deformation and rheological effects of broken phyllite under high geo-stress effectively.

Keywords Broken phyllite · High geo-stress · Large deformation · Maoxian tunnel · Supporting method

Introduction

In recent years, with the rapid development of traffic infrastructure in Western China, many large-scale highways and railways, such as the Chengdu-Lanzhou railway, Sichuan-Tibet highway, Yunnan-Tibet railway and Chongqing-Xian railway, are being or will be constructed in the coming decade. In these traffic projects, due to the complex geological environment of Western China, the total length of tunnels often accounts for 50–80% of the railway's total mileage. Moreover, these tunnels present such characteristics as great length, large sections and deep buried depth. Therefore, when tunneling in this complicated geological environment, the construction and

design of tunnels often must overcome high geo-stress (Zhang et al. 2012a), soft surrounding rock (Li et al. 2014), fault zones (Zhang et al. 2017), abundant groundwater (Shi et al. 2018) and strong earthquakes (Chen et al. 2012; Fan et al. 2018; Shen et al. 2014). Disasters represented by rock bursts, large deformation, in-rushing water and cracking of supporting structures were frequently encountered in the process of tunnel construction (Fang et al. 2016; Meng et al. 2013; Li et al. 2017b; Yang et al. 2017; Zhang et al. 2017).

How to control large squeezing deformation and prevent instability, collapse and concrete cracking has always been a critical subject when constructing tunnels in soft surrounding rock under high geo-stress (Zhang et al. 2014). Because of the uplift of the Tibetan Plateau and its extrusion effect on the eastern region, many tunnels in Western China are under high geo-stress, which makes them suffer continuous extrusion during tunneling excavation (Huang et al. 2009). Moreover, the soft and weak rock mass represented by carbonaceous phyllite is widely distributed throughout Western China. Phyllite is a low-grade metamorphic rock with well-developed foliations. Because of its weak planes, its physical

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and mechanical properties show significant anisotropic characteristics (Xu et al. 2018a, 2018b), which results in obvious asymmetric features of the deformation of the surrounding rock and mechanical behavior of supporting structures (Fortsakis et al. 2012; Zhang et al. 2012b). Furthermore, the phyllite also presents a strong rheological effect, which has a crucial impact on the long-term safety of tunnel structures (Xu et al. 2016). For tunnel engineering, the creep behavior of surrounding rock is one of the main factors that leads to the cracking of secondary linings (Asghar et al. 2017; Manh et al. 2015).

Many studies have investigated the large squeezing deformation mechanism of tunnels in poor surrounding rock under high geo-stress. Hoek and Guevara (2009) sought a supporting method to overcome the large squeezing deformation problem in overstressed rock tunnels. Dwivedi et al. (2013) developed dimensionally correct empirical correlations to predict tunnel deformation for squeezing grounds. Cao et al. (2018) presented the squeezing failure characteristics and countermeasures of deep tunnels in soft and weak rock masses under high horizontal in situ stress. In order to limit the large deformation of soft surrounding rock under high geo-stress, many new types of support systems have been designed, such as the grid steel frame-core tube (Xu et al. 2017), U-type confined concrete steel arch (Li et al. 2018), constant resistance large deformation bolt (Tao et al. 2017), energy-absorbing bolt (He et al. 2014), and yield-support system with highly deformable concrete elements (Barla et al. 2011). However, due to the complexity and high cost of these methods, in addition to the special large deformation mode of tunnels in broken phyllite under high geo-stress, such supporting structures have not been widely used in the tunnel engineering in Western China. In practice, many tunnels in Western China had to increase the thickness of the secondary lining to 1.5–2.1 m in order to limit the large squeezing deformation of broken phyllite under high geo-stress. Therefore, a more reasonable support method is needed to control the deformation of surrounding rock and the failure of supporting structures.

In this paper, the Maoxian tunnel, which is located in the core area impacted by the 2008 Wenchuan earthquake and suffered serious large deformation in the F1 Maoxian-Wenchuan fault zone, serves as a case study to examine the squeezing failure mechanism of deep tunnels in broken carbonaceous phyllite under high geo-stress. Through an analysis of the geological conditions, the deformation behavior of surrounding rock, the failure characteristics of supporting structures, and the large deformation mechanism of the Maoxian tunnel were investigated. In order to limit the squeezing deformation, a double primary support method was proposed. To further study its support mechanism and mechanical behavior, a field test was conducted, the single and double primary support methods were compared in terms of the

surrounding rock pressure, internal stress of the steel arch, and axial force and bending moment of the secondary lining. The findings suggest that the large deformation and rheological effect of broken phyllite under high geo-stress could be effectively controlled by a supporting method that combines two primary supports and a 60-cm secondary lining.

Geological environment and engineering properties

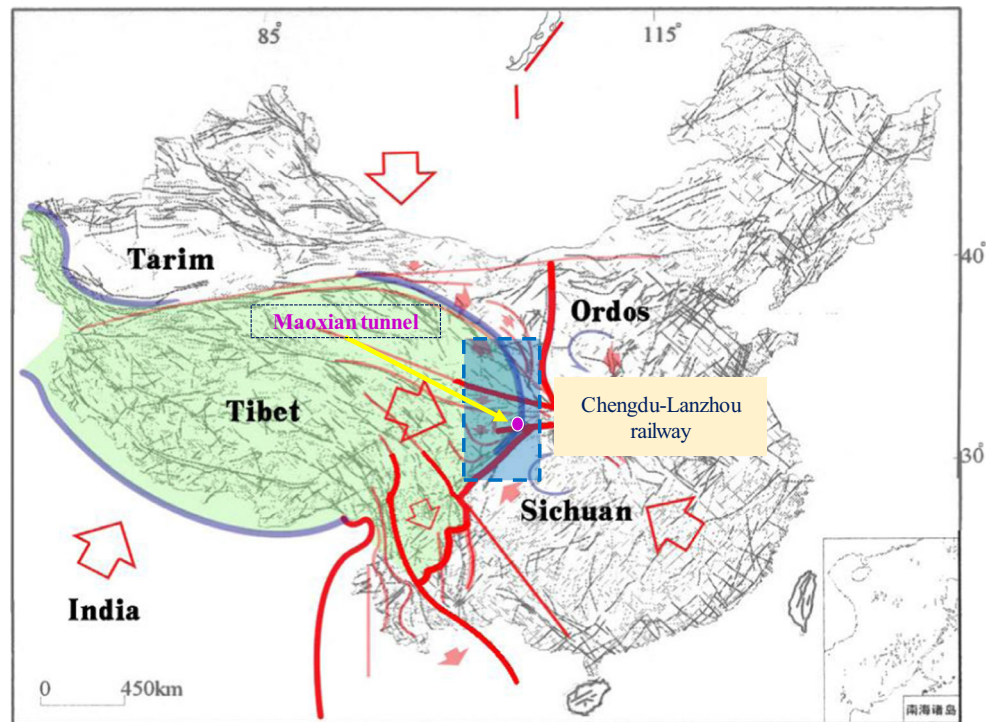
Engineering background of Maoxian tunnel

The Maoxian tunnel on the Chengdu-Lanzhou high-speed railway (Fig. 1) is located near the Longmen mountain fault, which is the seismogenic fault that caused the 2008 Wenchuan earthquake in Sichuan Province, China. The longitudinal profile of the Maoxian tunnel is shown in Fig. 2. Its total length is about 9955 m, and its maximum depth is about 1650 m, with width and height of 9.5 m and 11.5 m, respectively. The geological environment and hydrogeological condition of Maoxian tunnel are quite complicated. Its lithological character consists of carbonaceous phyllite, argillaceous limestone, sericite phyllite and sandstone of Maoxian group in Silurian. The compressive strength of the soft surrounding rock is quite low, and its self-stability is extremely poor. In addition, the rock strata suffered great destruction from the Wenchuan earthquake in 2008, as the shattered rock was broken up even more by repeated rubbing, which caused great security risks for tunnel construction. Affected by strong geologic process, the bedding and joint of the rock mass are developed, with rich fissure groundwater in phyllite and sandstone.

Because of the uplift of the Tibetan Plateau and its extrusion effect on the eastern region, an extensive high geo-stress zone was formed along Hexi Corridor, Qilian Mountains, Qinling Mountains, Wenchuan and Dali (Fig. 1), which places many of Western China's deep-buried tunnels in a high geo-stress environment. More precisely, the Maoxian tunnel is located in the eastern margin of the Qinghai-Tibet Plateau and northwest edge of the Sichuan Basin. The maximum principal stress of the Maoxian tunnel obtained from back analysis is up to 30–40 MPa, and the maximum horizontal stress is 1.4–1.8 times that of the self-weight stress. This implies that the geo-stress of the Maoxian tunnel area is dominated by horizontal tectonic stress.

According to regional geological data, the Maoxian tunnel passes through three main fault zones (Fig. 2), i.e., F1: Maoxian-Wenchuan fault zone, F2: Mupa fault zone, and F3: Jiuding mountain zone. Among them, the Maoxian-Wenchuan fault zone has the greatest impact on tunnel construction. The width of the broken zone is up to 300–450 m, and the buried depth of the tunnel at this fault is about 480 m. The Maoxian-Wenchuan fault is an active fracture, with a

Fig. 1 Regional geological background of Chengdu-Lanzhou Railway in Western China



dipping direction and angle of 322° and 73° , respectively, which intersects with the axial direction of the Maoxian tunnel ($N53^\circ W$) at an angle of about 75° . As shown in Fig. 3, the rock mass revealed in the process of tunnel excavation at the Maoxian-Wenchuan fault zone was steep-dip broken carbonaceous phyllite (dipping angle 87°). The mineral composition of the phyllite was identified and analyzed using X-ray diffraction techniques, which gave the main mineral components as illite (38%), chlorite (48%), quartz (10%) and plagioclase (4%). The uniaxial compressive strength σ_c of phyllite obtained by laboratory experiment was only 2.41 MPa, with very poor cementation and developed bedding (Fig. 4). Especially, when carbonaceous phyllite encounters water, it shows remarkable argillaceous and softening effects. The geo-stress

at the F1 fault zone was tested using the hollow inclusion stress-relief method. The vertical principal stress, maximum horizontal principal stress and minimum horizontal principal stress were 12.7, 21.4 and 15.1 MPa, respectively. Thus, the surrounding rock of Maoxian tunnel suffered strong extrusion pressure from horizontal tectonic stress field.

Failure characteristics

Generally speaking, the difficulty and risk in construction increase greatly when a tunnel enters deep-buried and high geo-stress zones. The greater the buried depth, the higher the risk that the tunnel will encounter a large deformation disaster. Curiously, the large deformation disasters of surrounding rock

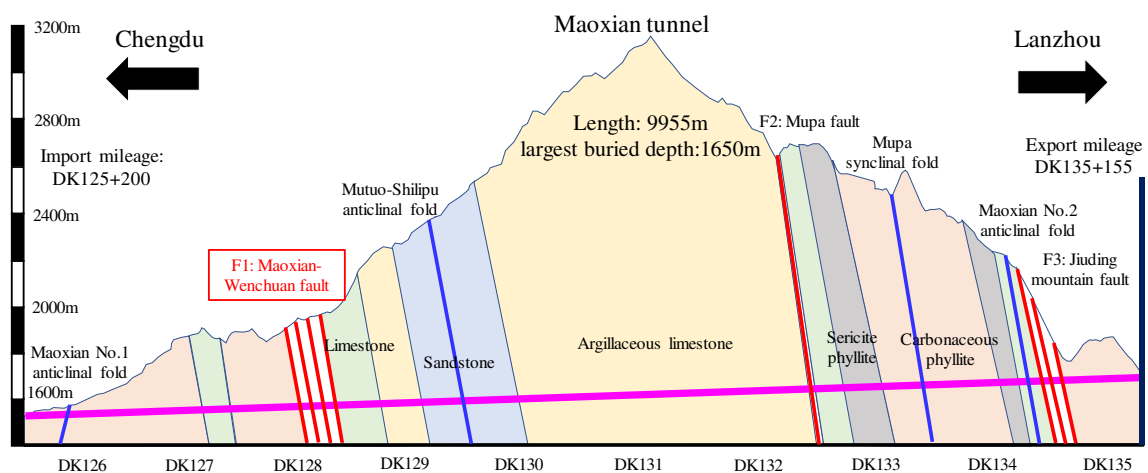


Fig. 2 Longitudinal profile of Maoxian tunnel on Chengdu-Lanzhou Railway

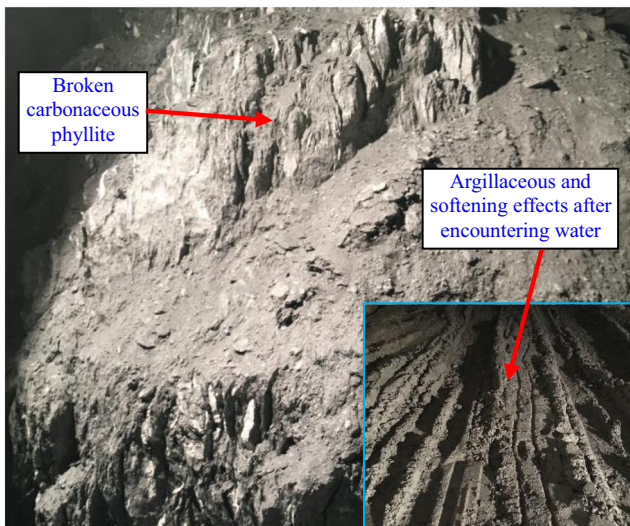


Fig. 3 Broken phyllite revealed at the Maoxian tunnel in the F1 Maoxian-Wenchuan fault zone

and the failure of supporting structures in the Maoxian tunnel mainly occurred in the phyllite section, while the deformation of surrounding rock in the much deeper limestone and sandstone sections was not serious. Figure 5 shows the deformation and failure characteristics at the inclined shaft of the Maoxian tunnel, which is near the main tunnel at the F1 Maoxian-Wenchuan fault zone. Clearly, the inclined shaft encountered significantly large deformation disasters, accompanied by serious distortion of the steel arches and concrete cracking. Because of strong horizontal tectonic stress and well-developed weak bedding of steep-dip phyllite, the large deformation disasters and failure of supporting structures occurred mainly at the left and right haunches of the inclined shaft of the Maoxian tunnel.

Similar to the Maoxian tunnel, many phyllite tunnels in Western China are likely to experience large deformation disasters, even the shallow ones. Because of the widespread distribution of phyllite stratum in Western China, many railway and highway tunnels must pass through phyllite strata,

making large deformation disasters in phyllite tunnels an urgent problem. Therefore, in order to investigate the deformation mechanism of phyllite tunnels, the deformation data, buried depth, maximum geo-stress, rock compressive strength and strength-to-stress ratio of 93 phyllite tunnels in Western China were statistically analyzed, as plotted in Fig. 6. The surrounding rock deformations of phyllite tunnels were discretely distributed as geo-stress, rock compressive strength and buried depth vary. Under a certain geo-stress, rock compressive strength or buried depth, the deformations of phyllite tunnels were distributed across both high and low value zones. However, as geo-stress and buried depth increase and rock compressive strength decreases, the deformations gradually approach the high value zone. This means that the large deformation disaster of phyllite tunnels was not determined by a single factor but several. Therefore, the relationship between deformation and strength-to-stress ratio (σ_c/σ_1) was analyzed, as shown in Fig. 6d. As can be seen, there is a power exponent variation law between the largest deformation and the strength-to-stress ratio; the large deformation disaster of phyllite tunnels was caused by high geo-stress, soft surrounding rock and weak bedding plane.

As mentioned earlier, the rock uniaxial compressive strength and maximum geo-stress of the Maoxian tunnel at the F1 Maoxian-Wenchuan fault zone were 2.41 and 21.4 MPa, respectively. Its strength-to-stress ratio was only 0.11, which indicated a high likelihood that the tunnel will encounter large deformation disasters; however, the maximum geo-stress at the limestone section was as high as 35~40 MPa when the buried depth of the tunnel increased to 1650 m. The uniaxial compressive strength of argillaceous limestone was 27.5~31.4 MPa, resulting in a strength-to-stress ratio in the limestone section of about 0.78, which greatly reduced the risk of large deformation disasters in the tunnel excavation process. Accordingly, the large deformation disasters and failure of supporting structures in the F1 Maoxian-Wenchuan fault zone were the result of the combined action of high geo-stress and poor self-stability of carbonaceous phyllite.

Fig. 4 Micro-layered structure of phyllite: **a** SEM; **b** Polarizing microscope

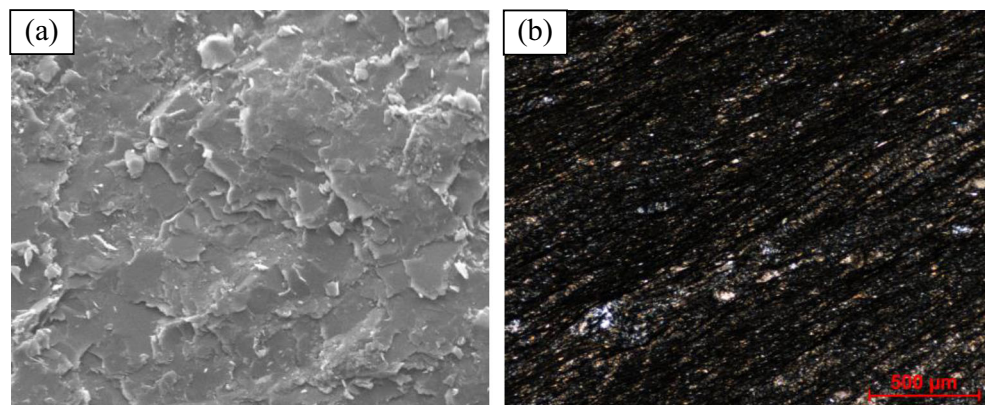
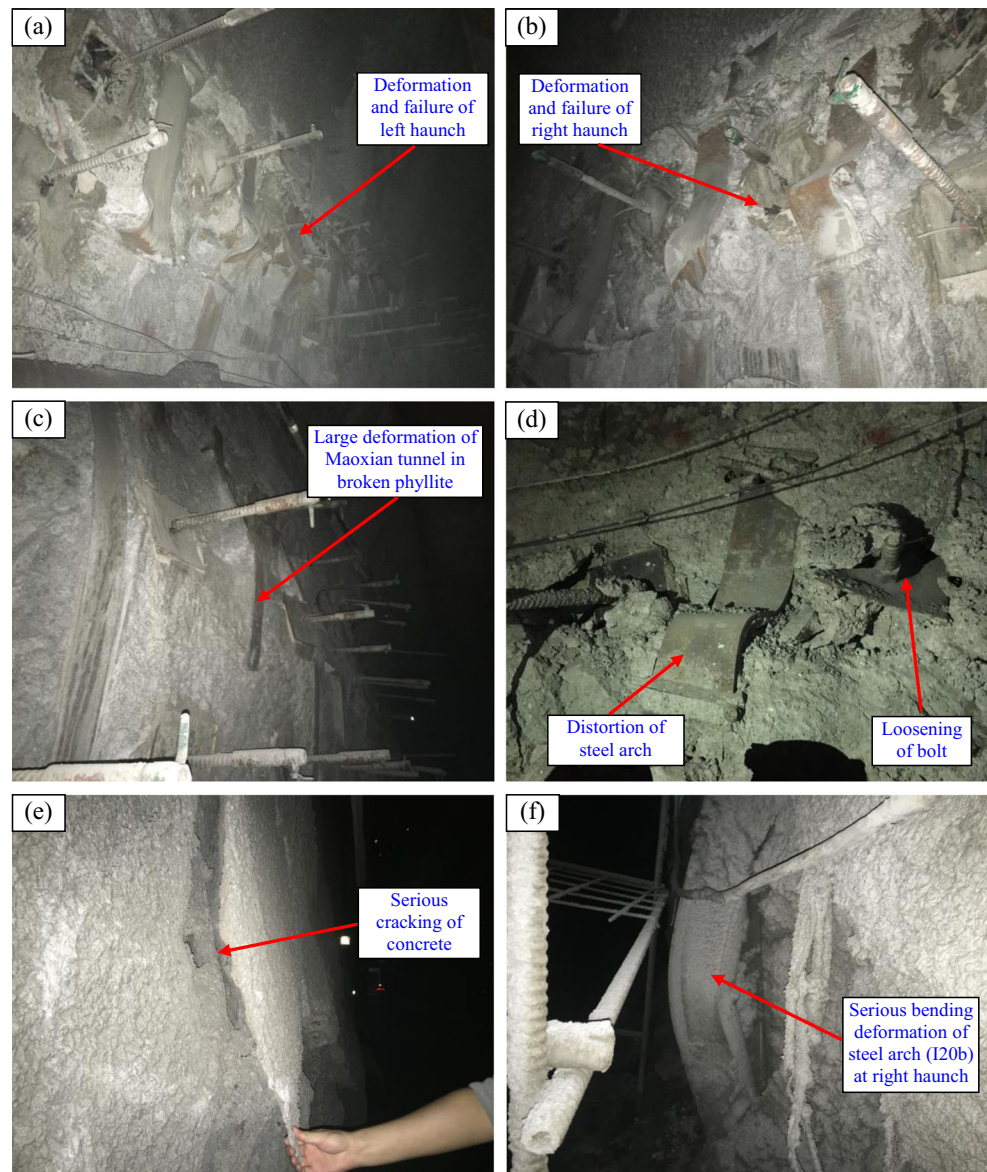


Fig. 5 Deformation and failure characteristics at the inclined shaft



Deformation mechanism

The physical and mechanical properties (e.g., strength, permeability, deformation behavior) of phyllite are significantly affected by weak planes, making the deformation characteristics and mechanical behaviors of carbonaceous phyllite show an obvious anisotropic mechanism (Xu et al. 2018a, b). Moreover, the phyllite also has serious transversely isotropic creep behavior, which has an important impact on the long-term safety of the tunnel structure. For tunnels, time-dependent deformation behavior of the surrounding rock is one of the main factors leading to the cracking of the primary support and secondary lining.

Because of the complicated geological environment and special mechanical properties of the phyllite, the surrounding rock and supporting structures often experience complicated

deformations and failure modes during the construction of phyllite tunnels (Fig. 7). The squeezing pressure, deformation of surrounding rock and structural damage were focused mainly on the two ends of the normal direction of the stratified rock mass.

To further study the deformation mechanism of the Maoxian tunnel at the carbonaceous phyllite section in the F1 Maoxian-Wenchuan fault zone and provide guidance for selecting a reasonable construction method and support plan for the main tunnel, a 1:1 model test of the main tunnel was conducted at the inclined shaft. The two-bench excavation method was adopted, and the length of the mortar bolt was set to 4.5 m. The steel arch type was I20b spaced at intervals of 1 m, and the primary support was C20 concrete set to 24 cm of thickness.

Figure 8 shows the deformation phenomenon of the test section at the inclined shaft of the Maoxian tunnel. After the

Fig. 6 Relationships between deformation and buried depth, maximum geo-stress, rock compressive strength, and strength-to-stress ratio of 93 phyllite tunnels in Western China

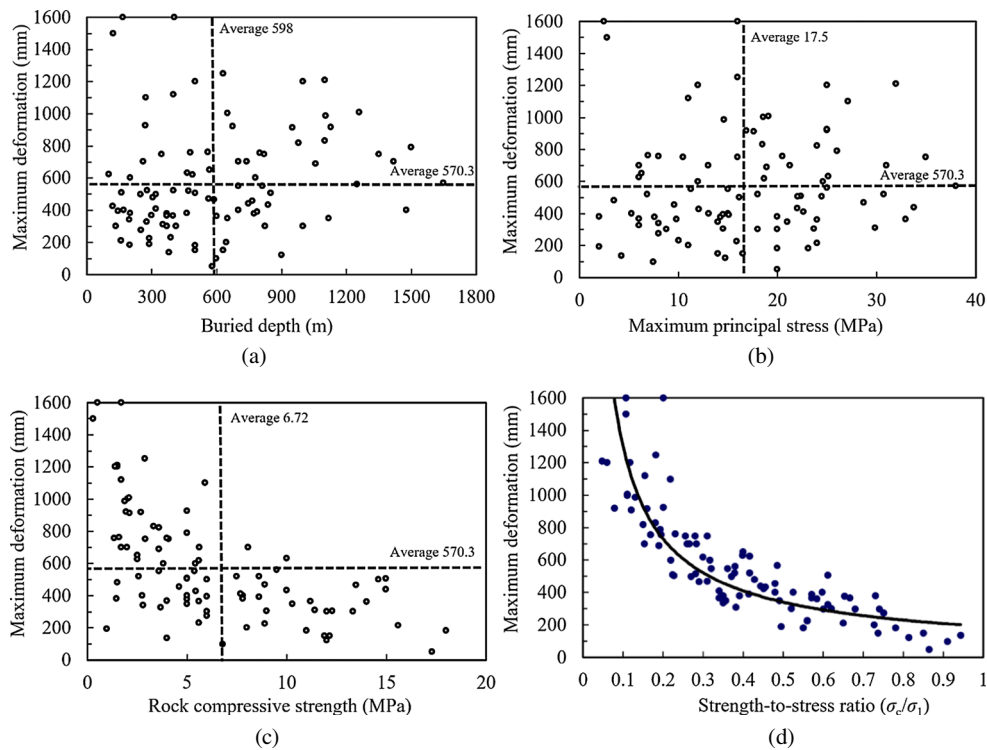


Fig. 7 Failure characteristics of primary support and secondary lining under different strata inclinations

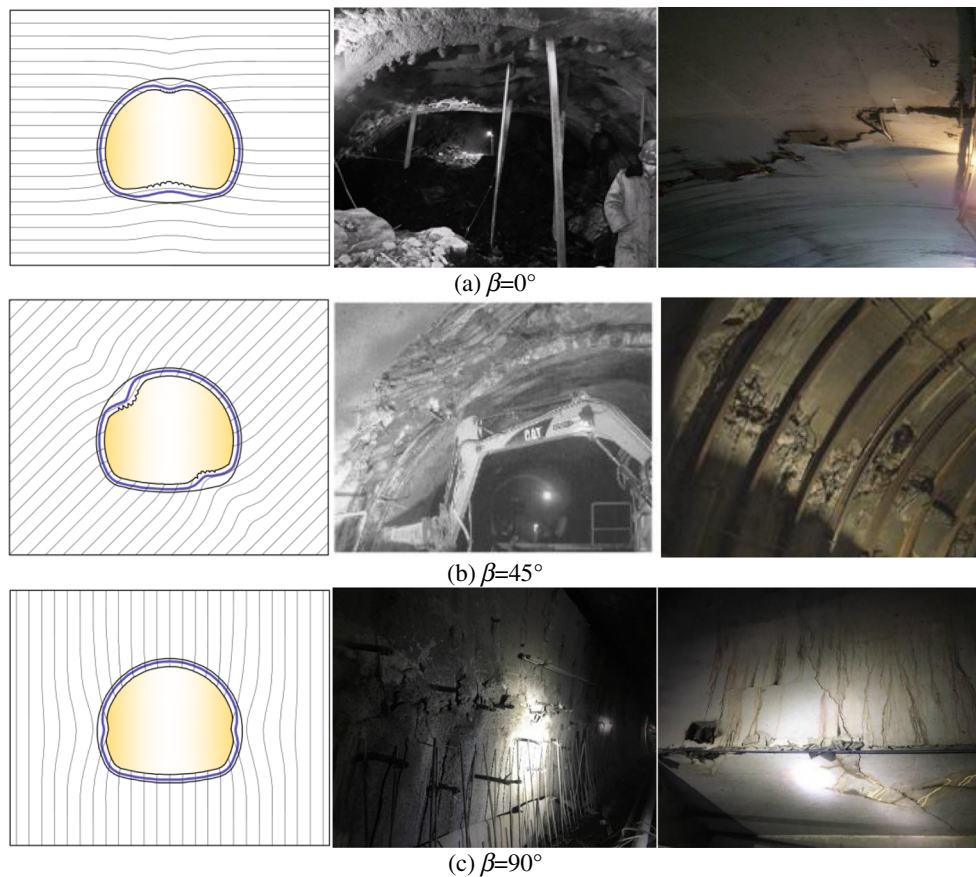
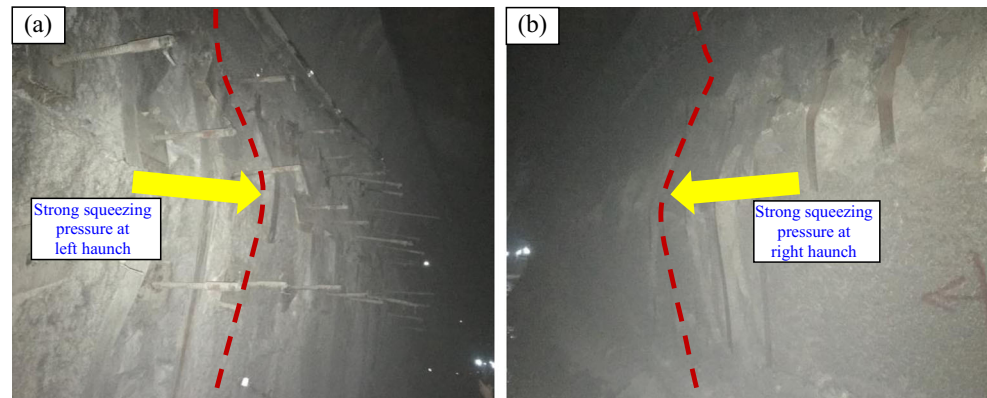


Fig. 8 Large deformation phenomenon of the test section at inclined shaft



excavation of the test section, the tunnel encountered large extrusion deformation. As shown in Fig. 7, for tunnels in steep-dip phyllite stratum under high geo-stress, the extrusion loads tend to be concentrated at the left and right haunches. Influenced by the weak bedding effect of phyllite, the haunch suffered the most serious squeezing pressure.

As time passes, the large squeezing deformation disasters that had occurred at the test section of the inclined shaft of the Maoxian tunnel became increasingly serious. Figure 9 shows the deformation curves (Li et al. 2017a). Consistent with the large deformation phenomenon of surrounding rock, the tunnel deformation characteristics were presented as a strong horizontal extrusion effect. According to real-time monitoring, both the deformation value and deformation rate of the horizontal convergence at the upper, middle and lower benches were much larger than that of the vault settlement.

Because of the soft broken carbonaceous phyllite and its poor self-stability at the F1 fault zone, the horizontal convergence of the sidewall and vault settlement increased quickly after excavation of the tunnel. Only 46 days after excavation of the test section, the deformation of the surrounding rock gradually began to stabilize. The vault settlement and horizontal convergence at S1, S2 and S3 reached 497, 798, 743 and 505 mm, respectively. However, influenced by the remarkable creep behavior of soft surrounding rock under high geo-stress,

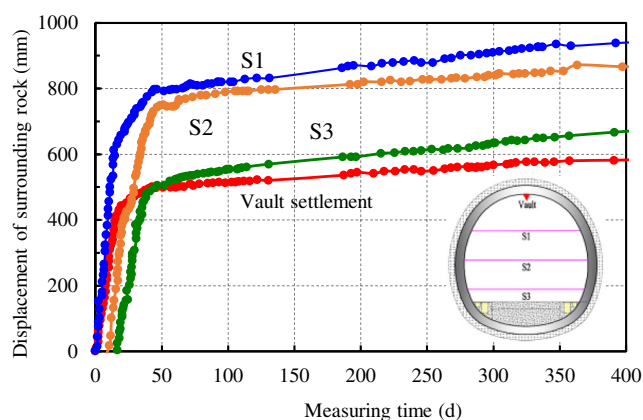


Fig. 9 Deformation curves of test section at the inclined shaft

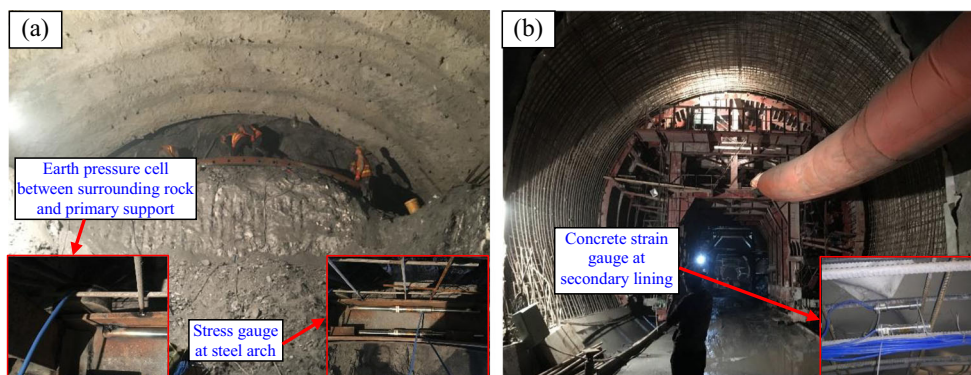
the horizontal convergence and vault settlement still increase continuously during 46–400 days. Controlled by the transversely isotropic mechanical properties of carbonaceous phyllite, even the long-term deformation mechanism of the test section at the inclined shaft of the Maoxian tunnel showed anisotropic characteristics. The creep effect on the two ends of the normal direction of the bedding surface in the phyllite was the most significant, which made the left and right sidewalls of the Maoxian tunnel suffer the most serious large deformation disasters and concrete cracking problems. From 46 to 400 days, horizontal convergence at the upper, middle and lower benches increased by 142, 123 and 162 mm, respectively, while the vault settlement only increased by 78 mm. Therefore, there was a high chance that the main tunnel would encounter large deformation during excavation at the F1 Maoxian-Wenchuan fault zone. Therefore, a more reasonable excavation method and supporting system is needed to limit the deformation of surrounding rock and the failure of supporting structures.

Supporting mechanism and mechanical behavior of single primary support method

Supporting method

It can be seen in Fig. 10a that the surrounding rock revealed at the main tunnel in F1 Maoxian-Wenchuan fault zone (K128 + 190) was mainly broken carbonaceous phyllite in Silurian, with a dipping angle of 87° and a uniaxial compressive strength of 2.41 MPa. Its joints and fissures were well-developed, the measured maximum horizontal principal stress was as high as 21.4 MPa. Comparing with the nearby limestone outside the influence area of the F1 Maoxian-Wenchuan fault, the longitudinal elastic wave velocity of broken phyllite dropped from 3760 m/s to only 1299 m/s. Therefore, under the combined action of strong horizontal tectonic stress and well-developed weak bedding of steep-dip phyllite, the main tunnel in F1 fault was likely to encounter the failure mode shown in Fig. 5c.

Fig. 10 Application of the primary support and secondary lining of Maoxian tunnel



Based on the large deformation of surrounding rock and the failure of supporting structures observed at the inclined shaft of the Maoxian tunnel, a more reasonable support method should be adopted to ensure the safety of the main tunnel in the F1 Maoxian-Wenchuan fault zone. Hence, during the construction of main tunnel in the F1 fault, the excavation method was adjusted from two-bench to three-bench (Table 1). As for the supporting system, the primary support used C25 concrete with a thickness increased to 28 cm, and the secondary lining used C35 concrete with a thickness of 60 cm (Fig. 10).

Some researchers have found that the mortar bolt did not sufficiently reinforce the surrounding rock in the broken phyllite tunnel (Zou et al. 2013). On the one hand, the phyllite was extremely soft and presented a significant water softening effect, which weakened the bond force between the bolt and the surrounding rock. On the other hand, the depth of the loose zone (usually >6 m) in the broken phyllite tunnel often exceeded the length of the bolt (usually 3~6 m), which reduced the reinforcement effect of bolts on the surrounding rock. Thus, in order to handle the potential large squeezing deformation problem of the Maoxian tunnel in the broken carbonaceous phyllite stratum, the steel arch adopted HW175, which has a much higher bending and compression strength than I20b, the length of the mortar bolt was also 4.5 m, but the longitudinal spacing was reduced to 0.6 m.

Using multiple-point borehole extensometer, the internal displacement of surrounding rock at left haunch of Maoxian tunnel were monitored and was illustrated in Fig. 11. It can be seen that the surrounding rock deformation was controlled

within 230 mm after improving the strength of the primary support. Because of the low strength and poor self-stability of broken phyllite in F1 fault zone, the measured depth of loose zone at left haunch of Maoxian tunnel was larger than 8 m. This indicated that the mortar bolt (4.5 m) could not restrict the continuous extrusion deformation of surrounding rock efficiently.

Mechanical behavior of primary support

The measured evolutionary processes of surrounding rock pressure at the main tunnel in the F1 Maoxian-Wenchuan fault zone under the single primary support condition is shown in Fig. 12. Controlled by almost steeply dipping phyllite and horizontal tectonic stress, the mechanical behavior of supporting structures on the left and right sides of the tunnel were basically symmetrical. Hence, only the results measured at the left side are presented. It can be seen in Fig. 12a that the maximum surrounding rock pressure appeared at the tunnel haunch—the squeezing pressure applied on the primary support at the left haunch, left spandrel and vault were 1301, 934 and 638 kPa, respectively (Table 2). After excavation of the tunnel, the pressure between surrounding rock and the primary support increased rapidly. Even after the secondary lining was constructed, the squeezing pressure at the haunch and spandrel still kept growing. Because of this, the deformation of surrounding rock and the damage of supporting structures mainly happened at the haunch.

Table 1 Supporting parameters of the test section and two supporting methods

Supporting parameters	Excavation method	Mortar bolt	Steel arch	First primary support	Second primary support	Secondary lining
Test section at the inclined shaft	Two-bench	4.5 m long and 1 m spacing	I20b with 1 m spacing	24 cm C20	–	–
Single primary support method at main tunnel	Three-bench	4.5 m long and 0.6 m spacing	HW175 with 0.8 m spacing	28 cm C25	–	60 cm C35
Double primary support method at main tunnel	Three-bench	4.5 m long and 0.6 m spacing	HW175 with 0.8 m spacing	28 cm C25	28 cm C25	60 cm C35

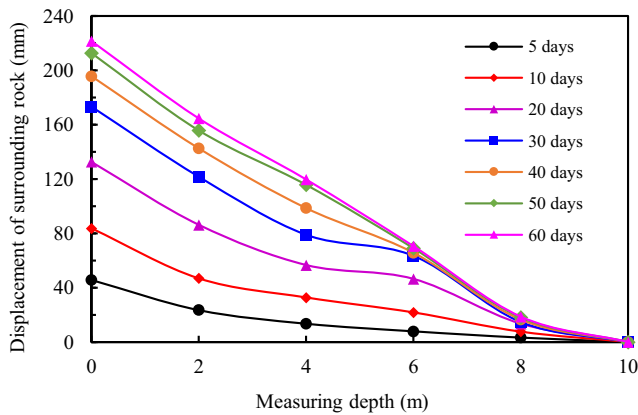


Fig. 11 Internal displacement of surrounding rock at the left sidewall

As for the pressure between the primary support and secondary lining (Fig. 12b), the application of the secondary lining lagged behind the primary support by 65 days. Its maximum value also appeared at the haunch. After suffering the large extrusion deformation, the secondary lining had to bear considerable pressure, which reduced its safety in later operation. Moreover, influenced by the rheological effects of phyllite under high geo-stress, the surrounding rock pressure also has obvious time-dependent evolution characteristics. It took about 200 days for the pressure to gradually stabilize. The surrounding rock pressure between the primary support and secondary lining at the left sidewall (D1), haunch (C1), spandrel (B1) and vault (A) after 238 days were 721, 831, 593 and 512 kPa, respectively. The average ratio of pressure carried by the secondary lining to pressure carried by the primary support was up to 67.4%, which indicated that the secondary lining became the main bearing structure for the broken phyllite tunnel. Due to the poor strength of surrounding rock and high geo-stress, a single primary support is not enough to bear the entire pressure of the surrounding rock.

In Fig. 13, which shows the mechanical behavior of the steel arch, the stress increased rapidly during the first 100 days after the HW175 steel arch was installed. After that, the stress

on the inner side of the steel arch basically remained stable while the stress on the outer side kept growing. This may be due to the continuous extrusion of broken phyllite on the supporting structure, which made the outer side of the steel arch was pressed while the inner side was pulled, resulted the stress on the outer side still growing slowly in 100–300 days. The outer side of steel arch at the left haunch and the inner side of steel arch at the vault reached 263 and 287 MPa, both of which exceeded the yield strength of Q235. Thus, the distortion of steel arch and concrete cracking occurred at the haunch and spandrel of the tunnel when adopting the single primary support method (Fig. 19).

Mechanical behavior of secondary lining

In order to cope with the large deformation disaster of the Maoxian tunnel, compared with the 45 cm of the secondary lining for ordinary sections, the thickness of which increased to 60 cm in the F1 fault zone. Figure 14 shows the mechanical behavior of the secondary lining under the single primary support condition, including the evolutionary processes of the axial force lining, bending moment and safety factor (National Railway Administration of PRC 2017). Based on the monitoring data, it can be concluded that:

- 1) Because of the large squeezing pressure from poor surrounding rock, the axial force of the secondary lining increased rapidly in the first 100 days. After that, although its growth rate gradually decreased, the values kept growing. 238 days after the construction of the secondary lining, the axial force at the left sidewall, haunch, spandrel and vault were 6258, 5192, 7459 and 8610 kN, respectively. Afterwards, the axial force of the secondary lining may continue increasing.
- 2) The evolution characteristics of the bending moment are similar to the axial force. The maximum positive bending moment at the left haunch reached 528.2 kN·m, because

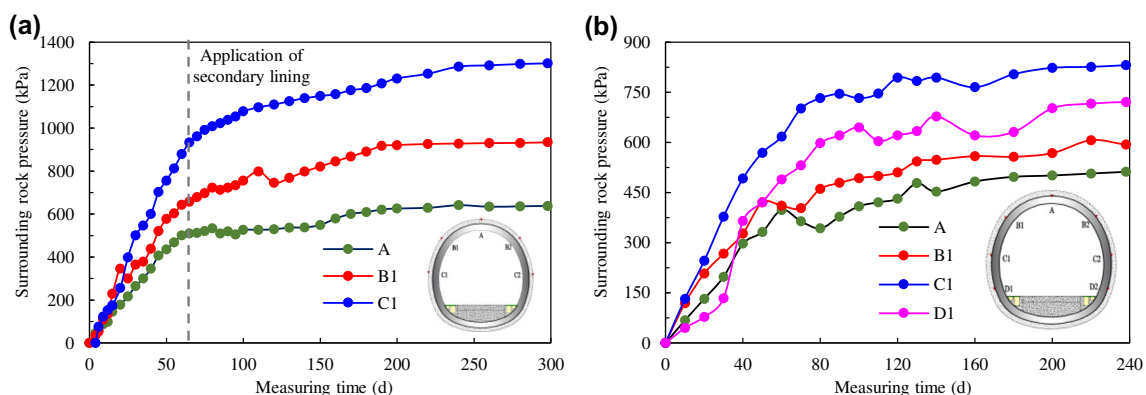


Fig. 12 Surrounding rock pressure under the single primary support method: **a** between surrounding rock and primary support; **b** between primary support and secondary lining

Table 2 Test results of the supporting structures under two supporting methods

Position	Pressure on the first primary support (kPa)		Pressure on the second primary support (kPa)		Pressure on the lining (kPa)		Axial force of lining (kN)		Bending moment of lining (kN·m)		Safety factor of lining	
	Single	Double	Single	Double	Single	Double	Single	Double	Single	Double	Single	Double
Vault (A)	638	564	–	394	512	330	8610	4610	–294	–214	1.56	3.13
Spandrel (B1)	934	799	–	624	593	367	7459	3965	197	143	1.82	3.39
Haunch (C1)	1301	1029	–	789	831	471	5193	2769	528	332	2.14	3.65
Sidewall (D1)	–	–	–	–	721	406	6258	3629	377	241	2.05	3.49

the secondary lining endured the largest surrounding rock pressure at this position. Due to horizontal tectonic stress, a negative bending moment of 294 kN·m appeared at the vault.

- 3) According to the measured axial force and bending moment, the safety factor of the secondary lining was calculated and illustrated in Fig. 14c. Because of the continuously growing surrounding rock pressure, the safety factor decreased gradually once the secondary lining had been constructed. After 238 days, the safety factor at the sidewall, haunch, spandrel and vault were reduced to only 1.5–2.2. Especially for the vault and spandrel, the safety factors were lower than the control criteria of $F = 2.0$ (National Railway Administration of PRC 2017).

Because of the large squeezing pressure applied on the secondary lining, its safety factor was quite low. About 180 days after the tunnel had been constructed, many circumferential and longitudinal cracks occurred at the haunch, spandrel and vault when using the single primary support method in the F1 fault zone (Fig. 15). The cracks were generally wider than 1 mm, and some were wider than 3 mm. Therefore, in order to ensure the stability and safety of the secondary lining during long-term operation, it is necessary to increase the thickness of the secondary lining or reduce its enduring pressure by employing a more reasonable support method.

Supporting mechanism and mechanical behavior of double primary support method

Supporting mechanism

Similar to the Maoxian tunnel, many tunnels along the Chongqing-Lanzhou railway and Chengdu-Lanzhou railway in broken phyllite under high geo-stress have increased the thickness of the secondary lining to 1.5–2.1 m to handle large squeezing deformation disasters. The cost of this support method is quite high. Compared to flexible materials (primary support), rigid materials (secondary lining) are prone to be cracked under large squeezing pressure.

At the same time, due to the poor self-stability and large loose zone depth of broken phyllite, the mortar bolt was unable to enhance the mechanical parameters of the surrounding rock in the anchorage zone sufficiently. Thus, under such conditions, a double primary support method was proposed to control the continuous squeezing deformation of broken phyllite under high geo-stress. The application of double primary support in the Maoxian tunnel in the F1 fault zone is presented in Fig. 16. The second primary support lagged behind the first by about 25 m. Both of the primary supports adopted C25 concrete with a thickness of 28 cm. Meanwhile, HW175 steel arches were still used (Table 1).

Figure 17 shows the support mechanism of the double primary support method. If adopting single primary support

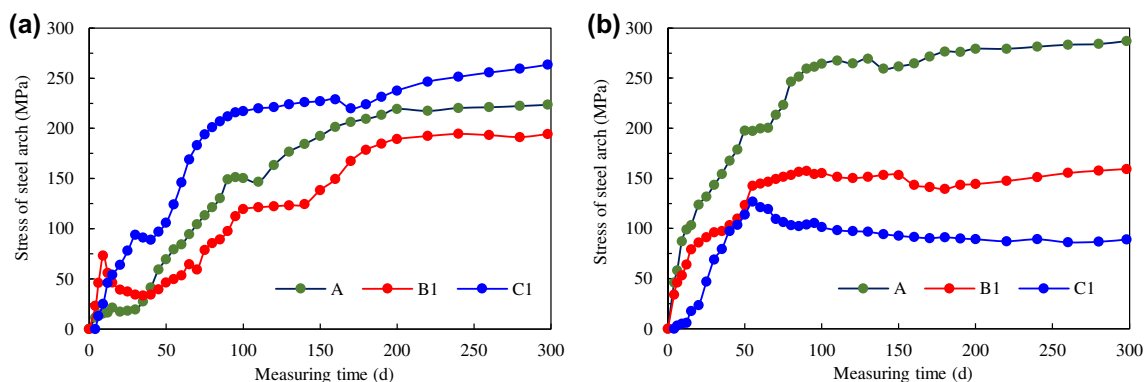


Fig. 13 Measured stress of steel arch under single primary support method: **a** outer side; **b** inner side

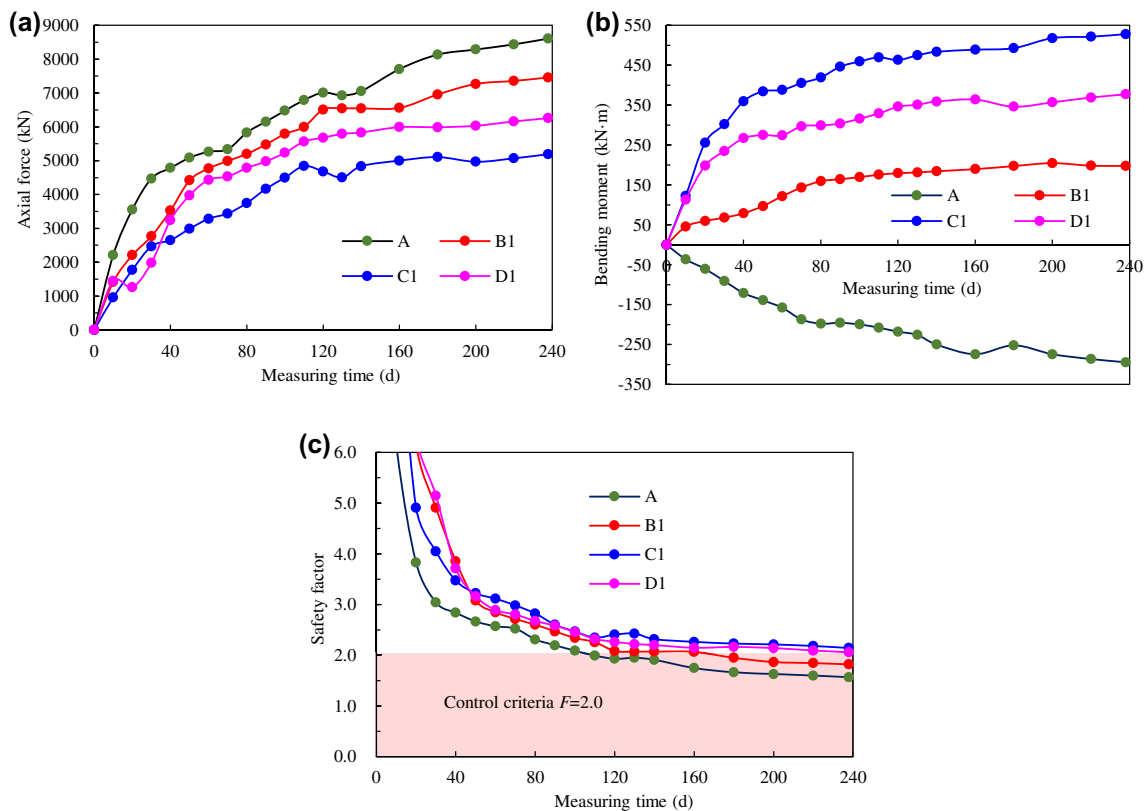


Fig. 14 Mechanical behavior of secondary lining under the single primary support method: **a** axial force; **b** bending moment; **c** safety factor

method with AB, the displacement of the surrounding rock can be controlled within u_1 , but the supporting structures have to bear large squeezing pressure (P_{a1}). This phenomenon indicates that the strength and thickness of the supporting structures must be quite high, which will increase the cost. Hence, merely improving the strength of the support to resist the deformation of surrounding rock is insufficient; however, if the strength and thickness of the primary support are insufficient to resist the large squeezing pressure caused by the poor strength of broken phyllite and high geo-stress, the collapse of surrounding rock and the damage to the supporting structures may occur during construction (ACDF). If a second primary support is added at point D before the first primary support is

damaged, then the displacement of the surrounding rock can be controlled within u_2 , and the squeezing pressure on the supporting structures could be reduced to (P_{a2}). Therefore, the double primary support method (ACDE) was tentatively adopted to handle large deformation disasters in the Maoxian tunnel in the broken phyllite section.

Mechanical behavior of primary support

To check the suitability of the double primary support method in the Maoxian tunnel, we measured the pressure between the surrounding rock and the first primary support; between the first primary support and the second primary support; and

Fig. 15 Secondary lining cracking phenomenon as single primary support method was adopted

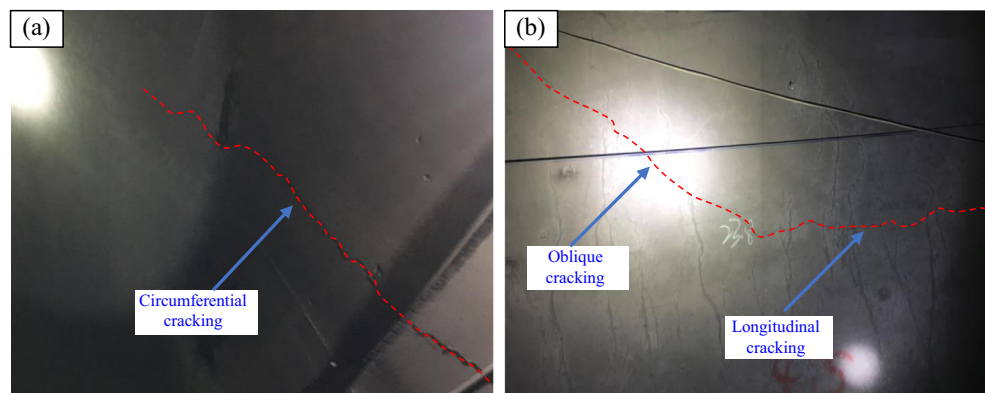
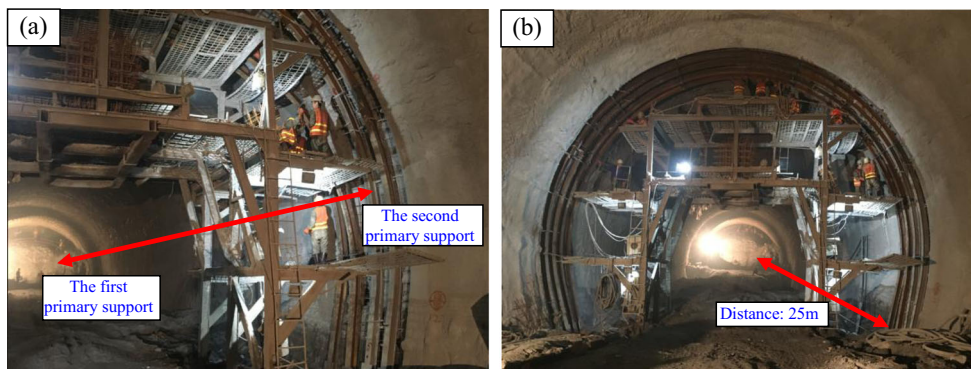


Fig. 16 Application of second primary support at Maoxian tunnel in broken phyllite



between the second primary support and the secondary lining (Fig. 18).

The second primary support was applied 25 days after the first one. The secondary lining was constructed about 55 days after the second primary support. As can be seen, the surrounding rock pressure on the two primary supports increased rapidly before the construction of the secondary lining. Once the secondary lining had been applied, the growth rate gradually decreased. Because of the combined support of the two primary supporting structures, the surrounding rock pressure was stabilized 240 days after the tunnel was excavated; however, the surrounding rock pressure still grew slowly 240 days after, when the single primary support method was used. As for the pressure of the surrounding rock against the secondary lining, it stabilized after about 160 days, proving that the double primary support method effectively controlled the rheological effects of the broken phyllite under high geo-stress.

According to the deformation mechanism observed in Figs. 9 and 12, the squeezing pressure acting on the support structures of the double primary support method also focused on the left and right haunches. Two hundred and thirty-six days

after the tunnel had been excavated, the surrounding rock at the left haunch, spandrel and vault of the first primary support were 1029, 799 and 564 kPa, respectively, as compared with the single primary support method, achieving a pressure reduction of 16.7% (Table 2). The pressure measured at the left sidewall, haunch, spandrel and vault of the secondary lining were 406, 471, 367 and 330 kPa, respectively, an average value reduction of 40.7%. The average ratio of the pressure carried by the secondary lining to that carried by the first primary support was 48.8%, a reduction of 18.6%, as compared with the single primary support method (67.4%).

As for the second primary support, the surrounding rock pressure at the left haunch, spandrel and vault were 789, 624 and 394 kPa, respectively. By calculation, the second primary support endured 26.7% of squeezing pressure from the surrounding rock. This means that the application of the second primary support alleviated the burden of the secondary lining.

The stress characteristics of the steel arch using the double primary support method were similar with those using the single primary support method. The maximum stress measured at the first and second primary supports were 204 and 146 Mpa, respectively. This represents a significant reduction from the 287 MPa of the single primary support method. Because of this, the loosening of bolts, distortion of steel arches and concrete cracking (Fig. 19) gradually disappeared after the double primary support method was adopted.

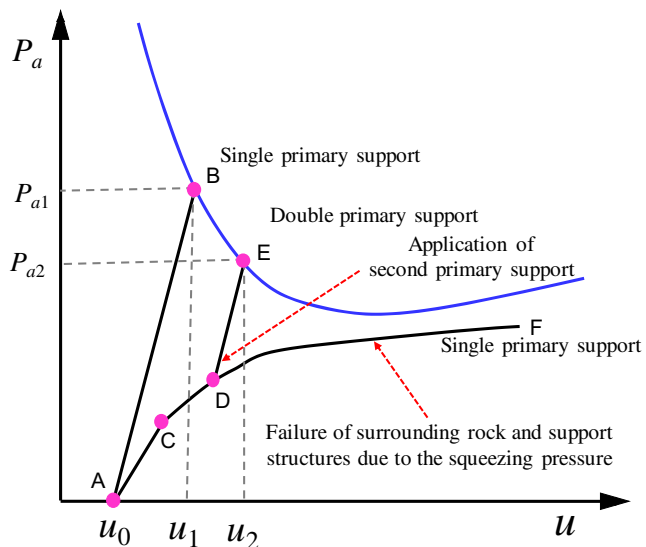


Fig. 17 Supporting mechanism of the double primary support method

Mechanical behavior of secondary lining

The mechanical behaviors of the secondary lining under the double primary support condition are shown in Fig. 20. During 0–50 days, the axial force and bending moment increased rapidly. During 50–160 days, the growth rate gradually decreased. One hundred and sixty days after the secondary lining had been constructed, the force basically stabilized. Whereas the axial force and bending moment kept growing slowly even after 240 days when the single primary support method was used.

The axial force at the left sidewall, haunch, spandrel and vault of the secondary lining were 3629, 2769, 3965 and 4610

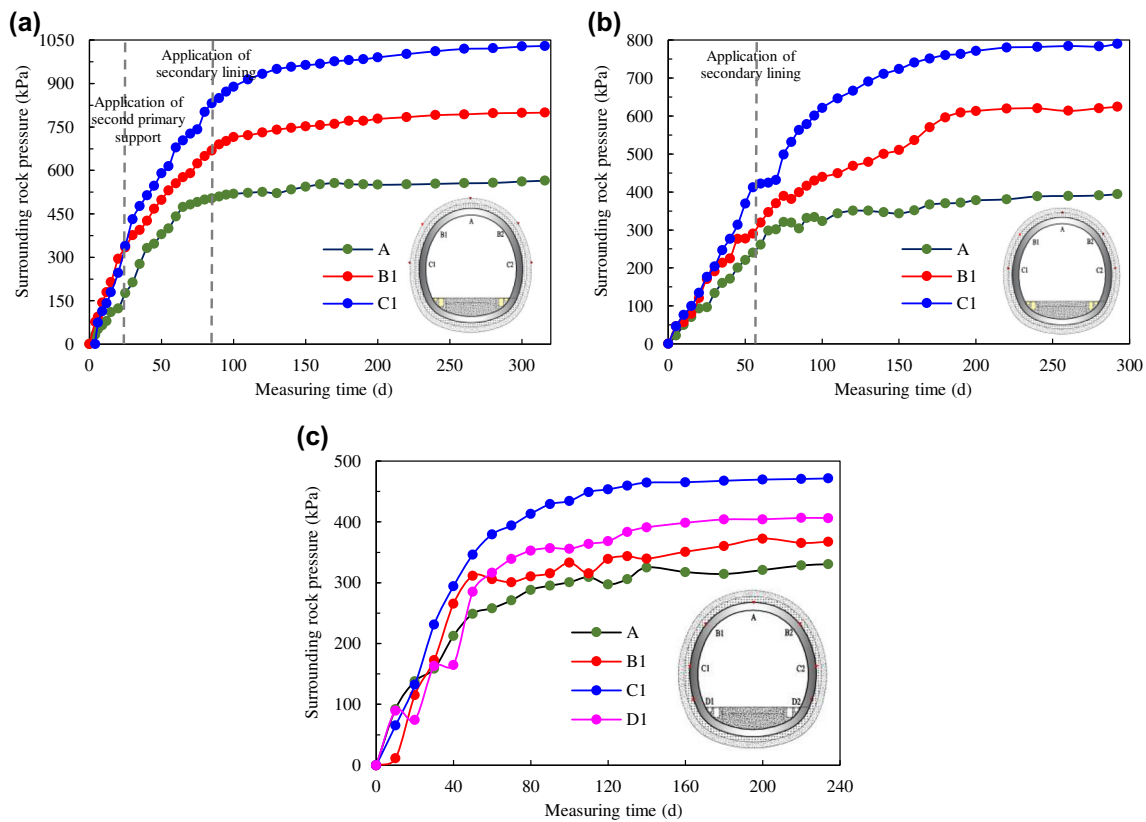
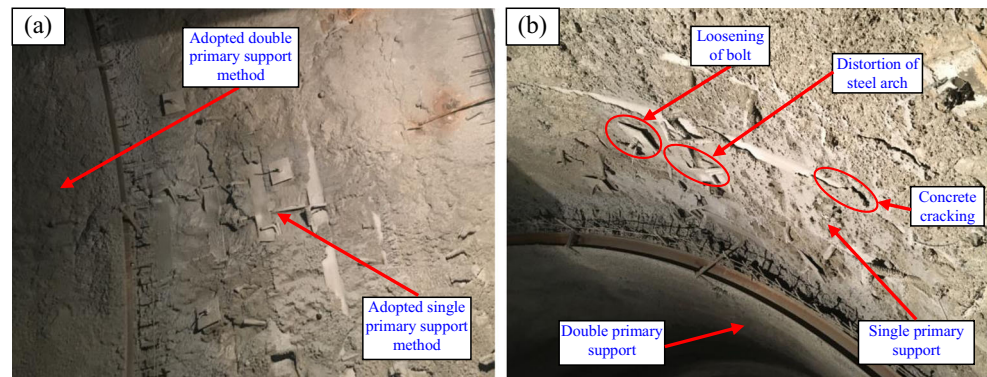


Fig. 18 Surrounding rock pressure under the double primary support method: **a** between surrounding rock and first primary support; **b** between first and second primary supports; **c** between second primary support and secondary lining

kN, respectively, only 57.9%, 53.3%, 53.1% and 53.5% of the axial force experienced when using single primary support method. Meanwhile, the bending moment at the left sidewall, haunch, spandrel and vault of the secondary lining were 241, 332, 143 and -214 kN·m, respectively. Although the secondary lining still has to bear large squeezing pressure, the axial force and bending moment remain greater than that of the ordinary tunnel; however, compared with the single primary support method, the average axial force and bending moment were reduced by 45.5% and 33.4% after the double primary support method was adopted.

As shown in Fig. 20c, due to the application of second primary support, the safety factor of the secondary lining was improved to 3.1–3.6. Each test point was in a safe range. Their safety factors were all above the control criteria of $F=2.0$, which indicates that the double primary support method can effectively limit the large deformation disaster of the tunnel. Moreover, the secondary lining was in a stable condition about 200 days after construction, as shown in the evolutionary characteristics of the safety factor while the force kept growing and the safety factor decreased slowly even after 240 days, when the single primary support method was adopted. This means

Fig. 19 Comparison of failure characteristics of the two support methods



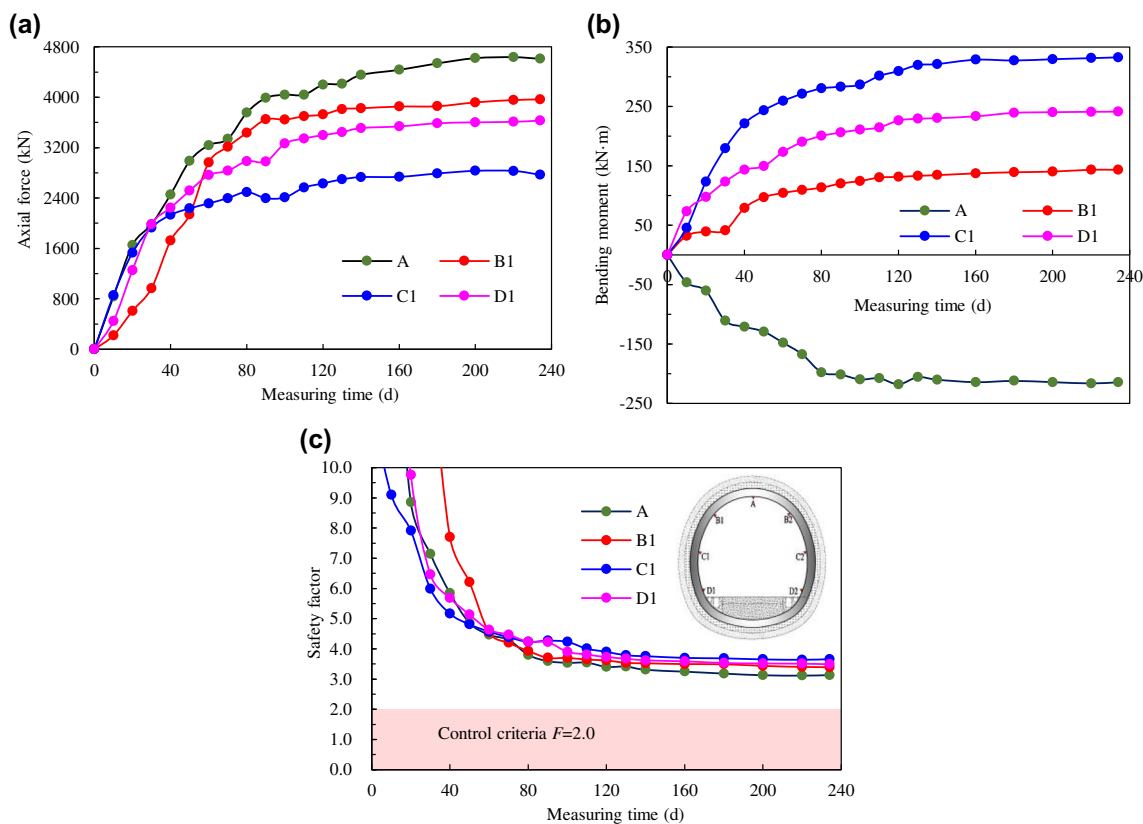


Fig. 20 Mechanical behavior of the secondary lining under double primary support method: **a** axial force; **b** bending moment; **c** safety factor

that the rheological behavior of the broken phyllite under high geo-stress could also be restricted by the combined supporting effects of the two primary supports and the 60-cm secondary lining. This method ensures the tunnel safety under the creep effect of weak rock during long-term operation.

Altogether, the double primary support method could be a practical and effective way for tunnels in broken carbonaceous phyllite under high geo-stress. Firstly, it can ensure the safety of the supporting structure compared with the ordinary single primary support method. Secondly, compared with the previous method of simply increasing the thickness of secondary lining, its cost can be greatly reduced. At last, the construction application of double primary support method is relatively simple, whereas other construction methods, such as grouting reinforcement, yielding bolt and pipe shed, are more complicated.

Conclusions

The large deformation mechanism of the Maoxian tunnel, a typical tunnel in broken phyllite under high geo-stress in Sichuan Province China, was investigated in terms of its deformation behavior and failure characteristics. The supporting mechanisms of single and double primary support methods were analyzed, and their corresponding mechanical behaviors

were compared. Based on the results of this study, our conclusions are as follows:

- (1) The large deformation disasters and supporting structures failures of the Maoxian tunnel at the F1 Maoxian-Wenchuan fault zone were due to the combined high geo-stress and poor self-stability of broken carbonaceous phyllite. Influenced by the horizontal tectonic stress and well-developed weak bedding of phyllite, the maximum squeezing pressure appeared at the left and right haunches of the tunnel.
- (2) Due to the poor strength of broken phyllite and high geo-stress, the surrounding rock pressure was up to 1301 kPa. When the single primary support method was adopted, the secondary lining had to bear 67.4% of the squeezing pressure. Its safety factor was lower than the control criteria of $F = 2.0$. Many instances of concrete cracking occurred after 180 days.
- (3) Compared with the single primary support method, the average surrounding rock pressure reduced by 16.7%, and the secondary lining only had to carry 48.8% of the squeezing pressure after the double primary support method was adopted. The average axial force and bending moment of the secondary lining were reduced by 45.5% and 33.4%, respectively. As a result, its safety factor was improved to 3.1–3.6. This finding indicates

that the large deformation and rheological effect of broken phyllite under high geo-stress could be effectively limited by the combined supporting effects of the two primary supports and a 60-cm secondary lining.

Acknowledgments This research was supported by the National Key R&D Program of China (No. 2016YFC0802210) and 2017 Doctoral Innovation Fund Program of Southwest Jiaotong University.

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