Field Experimental Study on Mechanical Characteristics of Primary Supporting in Weak Surrounding Rock Tunnel

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Abstract. Since the poor self-stability of weak surrounding rock when applied the full-face excavation in a tunnel construction, a large surrounding rock deformation are tended to occur, which causes a big security risk. Under the engineering background of gaojiaping tunnel of zheng-wan high-speed railway, the stress of surrounding rock, steel frame, initial shotcrete stress, bolt axial force and extrusion deformation of working face of the tunnel are monitored and analyzed respectively. The results show that the surrounding rock stress, steel frame stress and initial shotcrete stress of the tunnel are significantly affected by surrounding rock lithology and construction disturbance. The plastic zone of surrounding rock can be preliminarily determined as 3m according to the peak value of bolt axial force. The extrusion deformation of the tunnel working face shows that the surrounding rock integrity of the test section is good. The experimental study is helpful to collect the deformation of weak rock mass and provide reference for establishing scientific and reasonable support system.

1. Introduction
Tunnel engineering attracts attention as a control node for high-speed railway projects. Full-face excavation has the advantages of large space, high degree of mechanization, and wide application range, which can effectively improve production efficiency and ensure that construction progress is sustained and stable. In addition, the construction personnel, materials, machines, and time required for divisional excavation and multiple supporting of conventional construction methods can also be reduced; and the closure time of the primary supporting structure is short, and the impact on the surrounding formation is small, reducing the risk of the tunnel structure large deformation caused by widely stress redistribution in the surrounding formation due to divisional excavation, supporting and dismantling temporary shoring. Since the poor stability of weak surrounding rock in a tunnel construction, collapse accidents are tended to occur, which cause a big security risk. How to determine whether full-face construction of a weak surrounding rock tunnel is safe requires to collect and analyze the surrounding rock feedback information during the construction process, so as to take timely control measures before the danger occurs. At the same time, the construction and design parameters can also be adjusted based on the obtained surrounding rock feedback information, and can realize the maximum benefit. Therefore, it is of great significance to study the surrounding rock deformation and the primary supporting mechanical characteristics (Zhou et al.2011) [1].
A lot of field experimental study have been done. Luo et al. (2016) [2] monitored the in-situ deformation of temporary support in two soil tunnels. Results showed that the temporary support presents “convergence-expansion-stability” regularity in the horizontal direction and “settlement–uplift–stability” regularity in the vertical direction. According to the monitoring results, the distribution and potential influenced area of the intersection in the adit and major tunnel were analyzed, the principle of detection and reinforcement in the intersection were also discussed (Liu et al., 2017) [3]. Zhou et al. (2009) [4] analyzed the tunnel deformation law of different surrounding rock conditions in the tunnel slope, and proposed engineering measures to control large deformations; Ou et al. (2013) [5] chose to install shotcrete strain gauge, settlement deformation observations, and other equipment at the typical section to monitor the structure internal forces, the structure settlement and deformation, and analyze the mechanics based on the test results; Tan et al. (2010) [6] monitored the vault settlement and the surrounding rock convergence under the complex structure and conducted comprehensively analysis combined with the construction measures and excavation procedures; In order to study the extrusion displacement characteristics of weak surrounding rock tunnel face and advanced core soil, Ye et al. (2017) [7] monitored the extrusion displacement of F215 structural fragmentation zone of Yushan Expressway tunnel by sliding micrometer, and the extrusion displacement characteristics during the tunnel crossing the weak surrounding rock have been studied. However, during the field experimental study, scholars mostly study one or several working conditions from the surrounding rock stress, steel frame stress, shotcrete stress of primary supporting, bolt axial force and extrusion deformation of tunnel face. The conclusions are too unilateral to fully reflect the stress conditions and interaction of the tunnel surrounding rock deformation and supporting system after excavation, and it’s impossible to make an accurate judgment on the safety. Therefore, relying on the mechanized construction of the Gaojiaping Tunnel import, the study on construction monitoring and information feedback of full-face tunnels in weak surrounding rock are carried out, which has great significance for guaranteeing the construction safety and efficiency. It also has extensive practical application prospects for similar projects in the future.

2. Engineering situation
Gaojiaping Tunnel is located in Nanzhang County, Xiangyang City China. Centermileage is DK451+786, start-end mileage is DK449+037~DK454+535, full length is 5498m, the maximum depth is 320m; the tunnel adopts two-way digging for import and export, import section start-end mileage is DK449+037~DK452+300, full length is 3263m. As shown in Figure 1. The mountain tunnel is a thin covering on the slope, a partially exposed base rock, and a dry land on the surface. The import section passes through the Silurian shale-sandstone formation, the rock formation is soft, and the surrounding rock is of poor self-stability. The groundwater mainly consists of loosely packed pore water, bedrock fissure water, and structural fissure water. Gas and other harmful gases may be existed.

Figure 1. Sketch of monitoring section of test section and import of Gaojiaping tunnel
3. Experimental scheme

3.1. Monitoring section design parameters for primary supporting
The surrounding rock conditions where the monitoring section is located are all poor grade V surrounding rock, and full-face excavation method was adopted. The specific primary supporting parameters are shown in Table 1.

| Supporting form       | Specification parameters       |
|-----------------------|--------------------------------|
| steel frame           | I120b Steel, Full ring, Rows distance 0.8~1.0m |
| bolt                  | Length 4m, Rows distance 1.2×1.0m |
| mesh reinforcement    | φ8mm Steer bar, Spacing 0.2×0.2m |
| shotcrete             | Thickness 0.28m, Strength C20 |

3.2. Section selection and measuring point layout
The DK449+087~DK449+187 sections of the Gaojiaping Tunnel import were designated as the key technology test section for the safety and rapid standardization of the high-speed railway tunnel, the length is 100m, test section spacing is 20m, starting with DK449+095 section, ending with DK449+175 section. In addition, the DK449+138.8~DK449+168.8 sections were set up to measure the extrusion deformation of tunnel face.

The surrounding rock stress, steel frame stress and shotcrete stress of primary supporting were adjusted in measuring point, there were 7 points in DK449+095 section, 8 points in DK449+115 section, 6 points in DK449+135~DK449+175 sections. Each measuring point fixed up 1 vibration string pressure cell, 2 vibrating string strain gauges and 2 vibrating string concrete strain gauges. As shown in Figure 2.

![Figure 2](image-url)

Figure 2. Arrangement of measurement point in monitoring section for surrounding rock stress, steel frame stress and shotcrete stress of primary supporting

The arrangement of the measuring point in five sections point for bolt axial force is shown in Fig. 3. Each bolt is 6m long and uniformly distributed with 4 vibrating string steel bar meter with a spacing of 1.2m.
The above four test items were measured twice a day within one week after the installation, and once a day during 2-3 weeks. After three weeks, the monitoring frequency was reduced correspondingly when the time-history curve is stable. Field installation of each test project is shown in Fig.4.

In the extrusion deformation test section at tunnel face, one horizontal drilling hole was drilled, one horizontal 30m inclinometer tube was buried, and a sliding micrometer was used to measure the
extrusion deformation of the tunnel face. The sliding micrometer is mainly composed of measuring tube, sensing probe, operating lever, control cable and portable readout instrument, etc (Sun et al., 2014) [8]. As is shown in Fig. 5. When using a sliding micrometer, first install the inclinometer tube in the drilling hole, and put a plastic magnetic ring (measuring-ring) on the outer wall of the tube at regular intervals (standard spacing 1.0m). The gap between the inclinometer tube and the whole wall is filled with a binder-mixed slurry so that the measuring-ring is bonded to the rock face. The measuring-ring is integrated with the formation. The sliding micrometer probe is equipped with two sets of high-precision coil systems, the gauge length is 1.0 m. The two coil systems in the probe are sensed through two measuring rings to generate an electrical signal between the two measuring rings which is proportional to actual distance. When the measured medium is deformed, it will drive the measurement to be synchronously deformed to obtain the deformation distribution law reflecting the measured medium along the line.

![Figure 5. Structure and principle of sliding micrometer](image)

4. Result analysis
The paper selected DK449+095, DK449+115, DK449+155 three sections as the representative according to the lithology condition and the change of measuring point arrangement, and carried on the monitoring result analysis.

4.1. Surrounding rock stress
The time-history curves of surrounding rock stress (pressure is positive and tension is negative) in Gaojiaping tunnel monitoring sections is shown as Fig. 6. The distribution of the maximum surrounding rock stress along the tunnel rings in each section is shown in Fig. 7. Some pressure cells did not show a complete reading due to installation mistakes.

![Figure 6. Time-history curves of surrounding rock stress](image)
(1) Through the analysis of the time-history curves of three sections, it can be seen that the law of the surrounding rock stress over time is approximately the same, obeying to the change of “rapid increase, slow increase, fluctuation change, stable convergence” The “rapid increase” phase is completed in 7 days after the measurement, and it can reach more than 2/3 stable value of the surrounding rock stress. The phenomenon shows that under the full-face excavation, the surrounding rock stress increases rapidly and large in amount. It is necessary to do well in “strong supporting and quick closure” so as to suppress the surrounding rock stress release as soon as possible.

(2) The fluctuation change of the DK449+095 section measuring point is about 10~41 days, and it tends to be stable after 41 days. The fluctuation change of the DK449+115 section measuring point is about 10~31 days, and it tends to be stable after 31 days. The fluctuation change of the DK449+155 section measuring point is about 10~18 days and tends to be stable after 18 days. The reason is that the surrounding rock conditions of the three sections are gradually improved. The construction unit must ensure the process safety. Under the conditions of weak surrounding rock, shorter cyclical footage led to the disturbance of the surrounding rock that had completed the primary supporting. As the footage increases, the fluctuation change of the measuring point was shortened correspondingly. The change also shows that the better the lithology, the shorter the surrounding rock self-stabilization time and the stronger the self-stabilization ability.

(3) After several measuring points of DK449+095 and DK449+115 sections reaches the peak stress, the stress fallback appears. The reason is the large fracture of the weak surrounding rock. Before the excavation, the advanced pipe shed and advanced grouting were used to strengthen the surrounding rock in front of the tunnel face, so that the surrounding rock had a certain self-stabilization ability; After the excavation, the surrounding rock was closed into a ring, causing an arching effect on the rear tunnel(Tai et al., 2016) [9]. Under the collective effect, the surrounding rock stress was reduced to a certain degree.

(4) The distribution of the maximum surrounding rock stress along the tunnel ring obviously shows a discreteness. The maximum surrounding rock stress of the same section shows obvious asymmetry, and the stress value of the left side is obviously larger than the right side. According to the geological data of Gaojiaping tunnel, it is known that there is a biased gallery before the test section, and the distribution of ground stress is uneven. The measured ground stress on the left side of the tunnel is significantly larger than the right side. This is consistent with the actual results of field tests.

(5) According to the “Code for Design of Railway Tunnel”(TB10003-2016), the calculated surrounding rock vertical stress in Grade V of deep buried single track tunnels is 0.161~0.19MPa, and the maximum surrounding rock stress value at the monitoring section is 0.08MPa, which is less than the calculation value. This is consistent with the field observation where the surrounding rock has not appeared large deformations, indicating that the surrounding rock deformation condition is fine under the current supporting.
4.2. Steel frame stress

The time-history curves of Steel frame stress (pressure is positive and tension is negative) in Gaojiaping tunnel monitoring sections is shown as Fig.8. The distribution of the maximum Steel frame stress along the tunnel rings in each section is shown in Fig.9. Some pressure cells did not show a complete reading due to installation mistakes. The steel frame stress here is the average of the upper and lower flange stress of the steel frame.

Figure 8. Time-history curves of steel frame stress

Figure 9. Distribution of steel frame stress (unit: MPa)

(1) Through the analysis of the time-history curves of three sections, it also can be seen that the law of the surrounding rock stress over time is approximately the same, obeying to the change law of
“rapid increase, slow increase, fluctuation change, stable convergence”. However, the duration of the "fluctuation change" phase is significantly greater than the surrounding rock stress. The reason is that the steel frame has a higher sensitivity. The changes after the "rapid increase" in the surrounding rock stress will be more apparent in the steel frame stress time-history curve. The time when the steel frame stress tends to be stable is roughly consistent with the surrounding rock stress, which shows that under the current supporting scheme, the surrounding rock and the primary steel frame supporting can better form a whole to exert bearing capacity.

(2) In the time-history curves of Steel frame stress, most of the measuring points are negative, indicating that the steel frame is in a state of pressure. The maximum stress of the steel frame was 51.79 MPa, which is located on the right wall of the DK449+115 section. The steel frame used Q345 joist steel, the maximum steel frame stress is far less than the yield strength of 345MPa, indicating that under the current supporting scheme, the main role of the steel frame structure is the safety protection during the tunnel construction period and the emergency capacity during the running period.

(3) Two measuring points on the left wall and the right wall experienced short-term tension in the first 5 measurement days in the DK449+095 section, and then quickly turn compressed. The author analyzes the reason: In the initial stage, only the arch wall steel frame was completed, the inverted arch steel frame was not completed due to the construction delay, which made it difficult for the steel frame to be closed timely in the same section. The possibility of initial deformation and ground stress inside the steel frame was greatly increased at the time, and it would even affect the stability of the supporting system. It can be seen that “quick closure” is one of the urgent problems to be solved under full-face excavation in weak surrounding rock tunnel construction.

(4) Similar to the surrounding rock stress, the distribution of the maximum steel frame stress along the tunnel ring shows a discreteness. The steel frame stress of the vault, the left and right hances is greater than the left and right side walls, the left and right skewback and the invert in the same section except for individual measuring points, indicating the law of “the large upper part and the small lower part”. This is consistent with the conclusion of the mechanical mechanism under the surrounding rock pressure influence (Li., 2010) [10]. It also shows that the steel frame stress is one of the main bearing forces of the surrounding rock pressure.

4.3. Shotcrete stress of primary supporting

The time-history curves of shotcrete stress of primary supporting (pressure is positive and tension is negative) in Gaojiaping tunnel monitoring sections is shown as Fig.10. The distribution of the maximum shotcrete stress of primary supporting along the tunnel rings in each section is shown in Fig.11. The concrete stress here is the average of the inside and outside concrete stress.

![Figure 10. Time-history curves of shotcrete stress of primary supporting](image-url)
(1) It also can be seen that the shotcrete stress of primary supporting over time is approximately the same as the surrounding rock stress and the steel frame stress, obeying to the change law of “rapid increase, slow increase, fluctuation change, stable convergence”. However, from the analysis of time-history curves, the rate in the “rapid increase” phase is smaller than the surrounding rock stress and steel frame stress, the author believes this is related to the physical and mechanical properties of the concrete itself. The stability time for the shotcrete stress of primary supporting is significantly greater than the time for the surrounding rock stress and the steel frame stress, the reason is that the concrete is greatly affected by the time hardening characteristics.

(2) The maximum compressive stress of shotcrete is 4.29 MPa, which is lower than the bending ultimate compressive strength of converted C25 concrete. Different from the surrounding rock stress and steel frame’s stress, the shotcrete stress of primary supporting is generally characterized by “small upper part and large lower part”. The maximum stress in the same section occurs at the side wall or skewback. The reason is that the invert supporting has not yet been completed in the early period of primary supporting. From the mechanical mechanism analysis, the concrete sprayed on the arch wall can be simplified to a cantilever beam on the same section, and the free end of the cantilever beam is the side wall or skewback, so the stress is increased correspondingly. Accelerating the invert excavation, making the primary supporting closed as soon as possible is the key to solving the problem.

(3) In the same section, the maximum value of the shotcrete stress of primary supporting shows obvious asymmetry, and the stress value of the left section is slightly larger than the stress value of the right section. This is consistent with surrounding rock stress along the tunnel ring, which shows that the shotcrete is better integrated with the surrounding rock in the primary supporting to maintain the stability of the surrounding rock. The asymmetry is less pronounced than the surrounding rock stress, reflecting the stress compatibility of concrete as a flexible support. However, there is no one-to-one correspondence between the maximum concrete stress point and the surrounding rock stress point.

4.4. Bolt axial force

The distribution of bolt axial force along the tunnel rings in each section (tension is positive and pressure is negative) in Gaojiaping tunnel is shown as Fig.12.

![Figure 11. Distribution of shotcrete stress of primary supporting (unit: MPa)](image)

![Figure 12. Distribution of bolt axial force](image)
(1) According to the time-history curves of the bolt axial force, the bolt axial force shows a change law of “rapid increase, slow increase, and stable convergence” over time. After 25 days of measurement, the bolt axial force at each measuring point tend to be stable, indicating that the formation and development of the elastic-plastic zone of the surrounding rock has become stable due to stress redistribution. The stress stabilization time is close to the deformation stabilization time of the surrounding rock.

(2) According to the distribution of bolt axial force along the tunnel rings in each section, the bolt axial force is tensile stress. The distribution of axial force is expressed as “small in both ends and large in the middle”, the maximum value of the bolt axial force at each measuring point is generally located at a depth of 2.4~3.6m, which also the main distribution of the full-length anchor model bolt(Okubo et al., 1984) [11]. According to the elastic-plastic theory, a plastic loose zone is formed around the hole after the tunnel excavation. The deformation of the plastic loose zone is very large, and the deformation of the elastic zone outside the plastic loose zone is very small. In the plastic loose zone, the surrounding rock is deformed toward the tunnel relative to the bolt, and the surrounding rock in the elastic zone deforms outward the tunnel relative to the bolt. Therefore, the peak value of the bolt axial force is mostly at the juncture of the elasto-plastic zone (Zhang et al., 2014) [12]. It can be concluded that the plastic zone thickness of the surrounding rock caused by the excavation in Gaojiaping tunnel test section is approximately 3m.

(3) The maximum bolt axial force is 60.5 kN (stress is 15.5 MPa), which is far less than the standard value of yield strength of 300 MPa, indicating that the bolt plays a unimportant role in the primary supporting. The reason is the influence of the construction process, bolts were carried after the steel frame supporting being completed. Under the full-face excavation, the stress release of the surrounding rock was sufficient, and the bolt supporting was not obvious. The bolt supporting parameters in the condition of Grade V were 1.2 × 1.0m at present. Therefore, the author proposes to appropriately reduce the numbers of bolts, increase the row spacing between bolts, which. It can speed up the early closure of the excavation surface and the primary supporting system of the whole section as soon as possible, which will control the supporting settlement and deformation, and save a lot of project investment.

4.5. Extrusion deformation of tunnel face

The extrusion deformation of the Gaojiaping tunnel face (expressed by cumulative extrusion displacement) is shown in Figure 13.

Figure 13. Results of field measurement
(1) The extrusion deformation of the surrounding rock shows a uniformly growth trend, and there is no sudden change at some nodes, which indicates that the surrounding rock integrity in front of the tunnel face is good, and there is no large joint fracture.

(2) The longitudinal displacement of the surrounding rock near the tunnel face is significantly larger than that far the tunnel face. Cumulative extrusion displacement is related to the surrounding rock quality. Because of the good integrity of the surrounding rock, the cumulative maximum displacement from the initial tunnel face 6m after the first blasting excavation was 11.55mm, and the maximum cumulative displacement measured was about 12.939mm, about 15m from the initial tunnel face.

(3) The stress redistribution of the surrounding rock in front of the tunnel face occurs due to the blasting Excavation. The surrounding rock extrusion deformation appears from the initial tunnel face to the face within about 16-20 m from the initial face, and with the continuous blasting excavation. The influence scope of extrusion deformation continues to advance. According to Lunardi’s theory (Lunardi et al., 2005) [13], the stress redistribution region caused by tunnel excavation is a circle with the center point of the longitudinal plane as the center point and the excavation area Rp as the radius on the longitudinal plane. Based on this, it can be determined that Rp ≈1.4D (D = 14.1m, for the tunnel span).

5. Conclusion
After the tunnel excavation, before the secondary lining is applied, the surrounding rock pressure is mainly shared the whole which is made up of the bolt, steel frame, shotcrete of the primary supporting and surrounding rock. In this paper, through the field test of Gaojiaping tunnel test section, the deformation characteristics of the weak surrounding rock under the full-face excavation and the stress characteristics of the supporting system over time are studied.

(1) For weak surrounding rock tunnels, under the full-face excavation, the surrounding rock stress is released rapidly. Compared with the division excavation method, the surrounding rock deformation is obvious. Therefore, the key of the field construction is “strong supporting and quick closure”. So the primary supporting is closed in time and forms an integral part with the surrounding rock to play an early load-bearing role.

(2) By the peak position of the bolt axial force, it can be concluded the plastic zone of the surrounding rock is about 3.0m away from the tunnel wall, which has a guiding role in the research and control of the surrounding rock plastic loose zone.

(3) According to the monitoring results, the study considered that the design of the primary supporting is conservative. The non-hazardous location of the subsequent lining structure can be optimized, mainly including increasing the cyclical footage, increasing the steel frame spacing, reducing the number of bolts, or taking a slightly lower concrete strength, etc. The optimization can accelerate the construction progress, optimize the lining structure, reduce construction investment and increase economic efficiency. The specific optimization parameters needs to be determined according to the actual situation on the site.

(4) The extrusion deformation of the tunnel face and its front surrounding rock reflects the quality of the surrounding rock in a certain extent. The integrity of the surrounding rock in the Gaojiaping tunnel test section is good according to the measuring result. The disturbance area caused by excavation in front of the tunnel face is approximately 1.4 times the tunnel excavation span.

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