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Comparison Between Field Measured Indices of Different Stress Release Plans for High Geo-stress Soft Rock Tunnels

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ABSTRACT

Taking Maoyu Mountain Tunnel on the Lanzhou-Chongqing Railway as the object, this paper measures the surrounding rock pressure, initial support stress and other parameters in the tunnel of the pilot heading and space reservation, two popular methods for the stress release of high geo-stress soft rock tunnels. Then, the measured parameters of the two methods were compared and analyzed, aiming to select the stress release method suitable for the target tunnel. The comparative analysis shows that the maximum stress on the steel frame in initial support of pilot heading is 3.4 times that on the steel frame in initial support of space reservation, reaching the level of 340MPa. To release the stress of the said tunnel, it is recommended to reserve a large space (50cm) and add a flexible support net to deform with the surrounding rock. The flexible support net can withstand large deformation stress, thus reducing the stress on the initial support and that on the secondary lining. The research results show that the space reservation is an easy, efficient and economical way to release geo-stress before excavation.

1. INTRODUCTION

Recent years has witnessed a boom in China's infrastructure construction. Various types of traffic tunnels are under construction in areas with extremely complex geological conditions. Among them, the tunnels in high geo-stress areas are particularly difficult to build.

Under the effect of tectonic movement, high geo-stress rock masses are generally weak and fractured with high tectonic stress. To excavate a tunnel through such rock masses, the initial support often suffers from severe deformation due to the extremely poor self-stability of the surrounding rock, causing distortion and deformation of the steel arch and even severe engineering problems like clearance intrusion and collapse. In this case, the arch may have to be replaced in the later phase, and the construction schedule may be delayed, posing new challenges and pressures to tunnel design and construction. Therefore, the large deformation of tunnel construction in high geo-stress soft rock has become a thorny issue in tunnel design and construction [1].

The stress release before tunnel excavation provides an effective solution to improve the surrounding rock state and mitigate the geo-stress-induced deformation of the surrounding rock. To date, some large deformation control methods, ranging from the active release of geo-stress to the integration of different support plans, have been proposed for the surrounding rock through field tests and numerical simulations, producing positive effects on tunnel construction [2-8]. Nevertheless, there is still no commonly agreed control method for large deformation in high geo-stress soft rock tunnels. Various control methods have been explored, such as pilot heading [9-10], space reservation [11], and release-constraint balance [12], and are still being discussed [13-15]. Most of the relevant studies only target one method. There is no report on selecting the optimal method through the comparison of multiple alternatives.

In view of the above technical problems, this paper carries out field measurements of Maoyu Mountain Tunnel in the newly built Lanzhou-Chongqing Railway according to different pre-excavation stress release plans, and compares the different plans in terms of deformation and support stress, aiming to identify the pre-excavation stress release plans that best suits high geo-stress soft rock tunnels.

2. PROJECT OVERVIEW

2.1 Tunnel conditions

The Lanzhou-Chongqing Railway is a newly built railway in China. Passing through four provincial administrative regions (Gansu, Shaanxi, Sichuan and Chongqing), the railway links up Lanzhou, the seat of Gansu Province, in the north, and Chongqing Municipality in the south. The Maoyu Mountain Tunnel is a double track railway tunnel on the Lanzhou-Chongqing Railway. Located in Linjiangpu Township, Suichang County, Gansu Province, the 8,504m-long tunnel spans between the entrance milepost DK277+308 and the exit milepost DK285+811. In the exit section, the surrounding rock is subjected to large and fast deformation at the excavation depth at 656m and above. For the DK285+175 section, the arch crown settled by 53cm and each arch foot converged by 96cm in ten days after this section have been excavated and supported, putting the deformation rate at

14.3cm/d. In the DK285+220~200 section, the deformation is still not stable after the completion of the inverted arch, while the joint between middle and lower steps deformed by 40cm, resulting in clearance intrusion. The large deformation of the initial support in the construction of the Maoyu Mountain Tunnel is presented in Figure 1 below.

Figure 1. Distortion and deformation of initial steel support in the Maoyu Mountain Tunnel (double track), Lanzhou-Chongqing Railway

2.2 High geo-stress and large deformation

The Maoyu Mountain Tunnel passes through the middle Triassic slate, carbonaceous slate and slate intercalated limestone, as well as lower Triassic slate. The strike of the stratum is parallel to the midline of the tunnel. Under the effect of tectonic movement, the rock mass is extremely fragmented with seepage in many places. If excavated, it is difficult for the rock mass to remain stable by itself. The maximum buried depth of the tunnel is 700m. The surrounding rock, mainly falling in Grade IV, is enhanced by some Grade V initial supports. In the tunnel zone, the horizontal principal stress ranges between the upper bound of 11.45~21.28MPa and the lower bound of 6.81~12.14MPa. The tunnel zone is under extremely high geo-stress, for the ratio between the measured maximum horizontal principal stress R_b and the uniaxial compressive strength of the slate S_H (30MPa) stands at 1.41.

3. STRESS RELEASE TEST PLANS FOR HIGH GEO-STRESS SOFT ROCK TUNNEL WITH HIGH DEFORMATION

3.1 Pilot heading

Pilot heading is a commonly used stress release method in the construction of high geo-stress tunnels. By this method, a pilot tunnel of a certain length is excavated at a proper position of the main tunnel. The deformation of the pilot tunnel can release part of the initial stress, such that the surrounding rock stress is adjusted. In this way, the main tunnel enters the low stress state, which mitigates the support deformation and improves the stress state in the excavation of the main tunnel. Based on the idea of flexible support design, pilot heading allows the surrounding rock to deform to a certain extent, releasing the geo-stress in advance. Thus, the supports are under much less stress, while the surrounding rock is prevented from excessive relaxation and deformation. The stress release and deformation mechanism of pilot heading is shown in Figure 2 below.

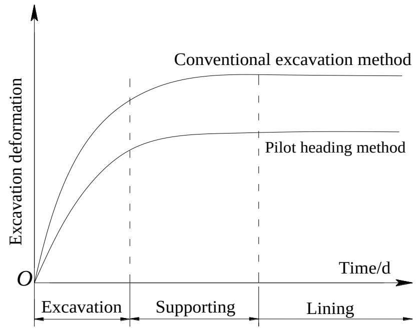

Figure 2. Sketch on the release of deformation mechanism of pilot heading [10]

3.2 Space reservation

The space reservation method refers to reserving a certain range of space outside the initial support of the tunnel. Then, the protection can be determined according to the stability of the surrounding rock. After the tunnel is excavated and the initial support is completed, the deformation of the surrounding rock will fill up exactly the reserved space, thus releasing the geo-stress. Finally, the deformed and loosen areas outside the initial support are backfilled, solidified and grouted at a proper time, so as to improve their self-supporting ability. The principle of the stress release by space reservation is depicted in Figure 3 below.

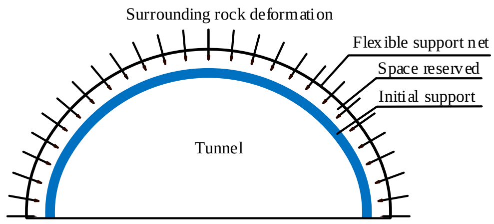

Figure 3. The principle of the stress release by space reservation [11]

The tunnel constructed by space reservation often consists of the following parts: flexible support net, reserved space, initial support, space reserved for the deformation of the initial support, space reserved for the structural enhancement of the initial support (for field tests), and secondary lining.

4. FIELD TESTS ON HIGH GEO-STRESS SOFT ROCK TUNNEL WITH HIGH DEFORMATION

Considering the large deformation of the high geo-stress soft rock tunnel on the Lanzhou-Chongqing Railway and the series of problems arising from arch removal and replacement during tunnel construction, the author carried out pilot heading stress release test and space reservation stress release test at the site of the Maoyu Mountain Tunnel (double track). The test section (length: 30m; maximum burial depth: 450m) is the tunnel exit between mileposts DK285+150 and DK285+120.

4.1 Support parameters and construction methods of the test section

The support parameters and construction methods of the pilot tunnel and reserved space in Maoyu Mountain Tunnel are listed in Table 1 below.

Table 1. Support modes of pilot heading and space reservation

	Pilot heading method DK285+144.5~DK285+120	Space reservation method DK285+094~DK285+079
The support parameters and construction methods of the pilot tunnel	Pilot heading excavation: Full face tunneling is adopted, taking each arch as one excavation step cycle. Pilot heading strengthening: Reinforcement with arch I16 surround for DK285+145~155 section, spacing is 0.5m, sprayed with 20cm C25 concrete. Pilot heading supporting (Figure 4) (1). U29 steel arch, spacing is 1m, 25cm thick C25 mesh concrete is sprayed, advanced small pipe is 3m; (2). I20b steel arch, spacing is 0.5m, sprayed with 27cm C25 concrete. 2m× Φ22 system rock bolt is adopted, and advanced small pipe is 4m.	/
The support parameters of the main tunnel	Reserved deformation: 40cm Initial support: Steel arch H175, spacing 50cm is adopted as reinforcement. The system anchor is arranged at arch crown with 6m length, and with 8m at the side wall. Bar-mat reinforcement with Φ8×20cm×20cm are arranged at the arch wall. sprayed with 33cm C25 concrete. Construction methods: Three steps are used for excavation. Secondary lining: Thickness 55cm C35 reinforced concrete is adopted.	Reserved deformation: 50cm Flexible support net: The main reinforcement with 4xΦ22mm, the mesh spacing with 20cm×20cm, and fixed with radial bolt, circumferential directions spacing is 2m, and axial spacing is 0.75~1.25m, sprayed with 25cm C25 concrete. In order to ensure that the surrounding rock does not drop during excavation, advanced small pipe with 4m length, Φ42 is adopted as support, a row advanced small pipe of ring direction is applied every two construction steps. Initial support: Steel arch H175 is adopted. Rock bolt with length 2.5m, Φ25mm, axial and circumferential spacing 50cm×2m is adopted as reinforcement. Taking fabric and waterproof board as external model, sprayed with 33cm C25 concrete. Four grouting steel pipes with 4.5mΦ42mm are applied as feet-lock bolt, then the grouting is carried out. The reserved deformation space of the initial support is 25cm. In addition, 25cm is reserved as the reinforcing space for the initial support. When the deformation exceeds the allowable value, the arch should be reinforced in time. Construction methods: Three steps are used for excavation. Secondary lining: Thickness 55cm C35 reinforced concrete is adopted.

As shown in Figure 4, the pilot tunnel is supported by grid arch, U29 steel and I20b steel arch.

Figure 4. Field construction of the pilot tunnel in Maoyu Mountain Tunnel (supported by U29 retractable steel frame)

4.2 Analysis of measured deformation of different stress release plans

4.2.1 Deformation measurement of pilot heading

(1) Measurement of pilot tunnel deformation

The arch crown settlement and horizontal convergence of the pilot tunnel were monitored and measured. Figures 5 and 6 respectively show the time-history curves of arch crown settlement and horizontal convergence, which were plotted according to the measured data.

It can be seen from the above figures that both arch crown settlement and horizontal convergence were large and fast in the initial phase. At the beginning of excavation, the arch crown settlement peaked at 80mm and the horizontal convergence reached 372mm within 2 days, and the first 7 days witnessed over 90% of total deformation. During the tests, the U29 retractable steel frame used up the allowable deformation (20cm) in 2 days, failing to ensure the construction safety of the pilot tunnel. The deformation rate gradually decreased only after adding the cover arch. Eventually, the support was replaced with I20b steel frame, sprayed with 27cm C25 concrete. Thus, U29 steel may not be applicable to areas with extremely high stress.

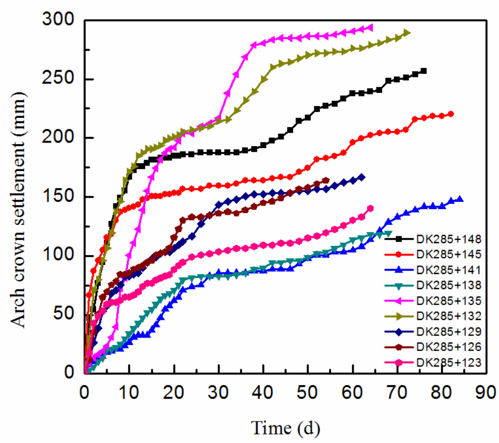

Figure 5. Time-history curve of cumulative arch crown settlement in each section of the pilot tunnel

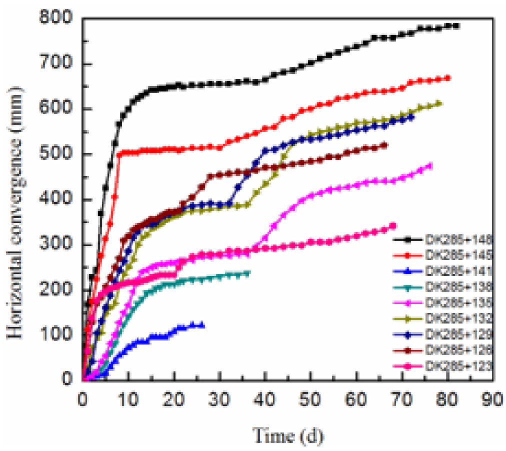

Figure 6. Time-history curve of cumulative horizontal convergence in each section of the pilot tunnel

In addition, the horizontal displacement was greater than arch crown settlement. The horizontal convergence remained high throughout the pilot tunnel, peaking at 789mm, more than twice the arch crown settlement, which peaked at 303mm. This is attributable to the dominance of horizontal tectonic stress, as the direction of the maximum horizontal principal stress differs greatly from the tunnel axis.

(2) Measurement of main tunnel deformation

The arch crown settlement and horizontal convergence of the main tunnel were monitored and measured. The relevant time-history curves are shown in Figures 7~9.

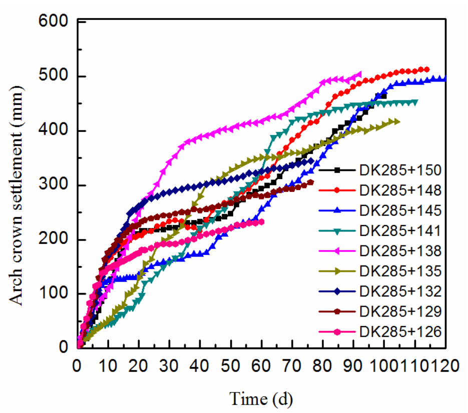

Figure 7. Time-history curve of arch crown settlement in each section of the main tunnel

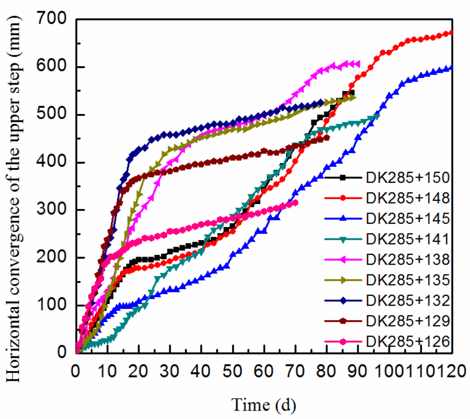

Figure 8. Time-history curve of horizontal convergence of the upper step in each section of the main tunnel

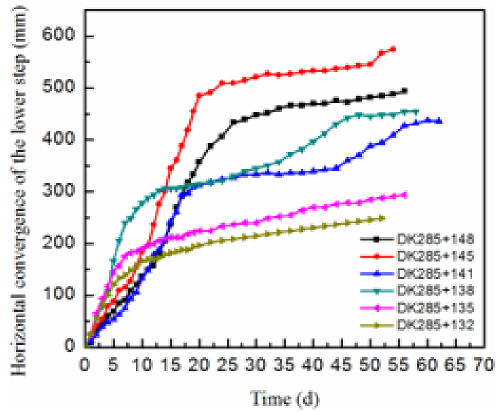

Figure 9. Time-history curve of horizontal convergence of the lower step in each section of the main tunnel

It can be seen from the above three figures that, the pilot heading obviously suppressed the deformation rate in the excavation of the main tunnel. In the three-step construction, it is necessary to preserve the deformation amount, increase the rigidity and strength of the initial support, speed up the closing of the inverted arch, and add secondary lining in a timely manner. Otherwise, the total deformation will remain large, failing to protect the initial support from clearance intrusion.

The main tunnel was excavated after the completion of the pilot tunnel in the test section. An inflection point was observed on the cumulative deformation curve at each measuring point, revealing the impact of main tunnel excavation on the safety and stability of the pilot tunnel. During the excavation of the main tunnel, it is unsafe within the distance equivalent to the diameter of the pilot tunnel. Therefore, the pilot tunnel and the main tunnel should be excavated in alternative manner rather than in parallel.

Despite being favorable to deformation control, long-term stress release hinders the progress of the main tunnel excavation. To improve construction progress, it is necessary to select a proper length for the pilot tunnel. Considering the effects on construction progress, effective release period and frequent switch between processes on construction, the length (30m) of the pilot tunnel at the site is reasonable, in light of the previous construction experience.

4.2.2 Deformation measurement of space reservation

(1) Deformation law of the surrounding rock (flexible support net)

The deformation curves of the surrounding rock (flexible support net) were plotted according to the data measured at 2m, 6m and 10m from the start of the test section.

As shown in Figures 10~12, the surrounding rock deformed rapidly at 10~30mm/d within 15 days after excavation and then deformed slowly at 5~10mm/d. The geo-stress has been fully released according to the trend of deformation rate and amount and the features of deformation curves.

(2) Deformation law of initial support

The deformation curves of the initial support were plotted according to the monitoring data.

As shown in Figures 13~15, the support deformed rapidly at 5~10mm/d within 15d after excavation and then deformed slowly at 2~5mm/d. Under the full release of geo-stress, the initial support deformation has been controlled within the reserved 25cm space according to the trend of deformation rate and amount and the features of deformation curves.

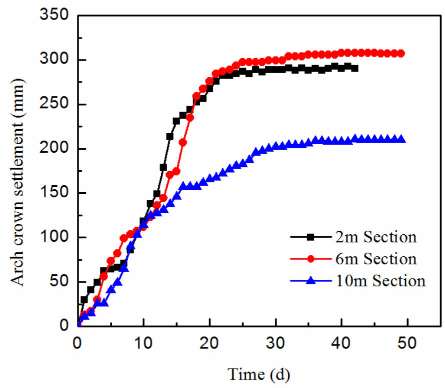

Figure 10. Arch crown settlement curve of the surrounding rock in the monitoring section

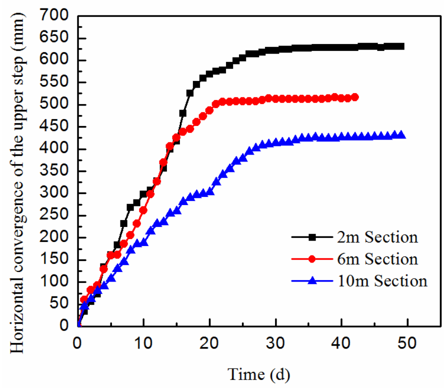

Figure 11. Horizontal convergence curve of the upper step of the surrounding rock in the monitoring section

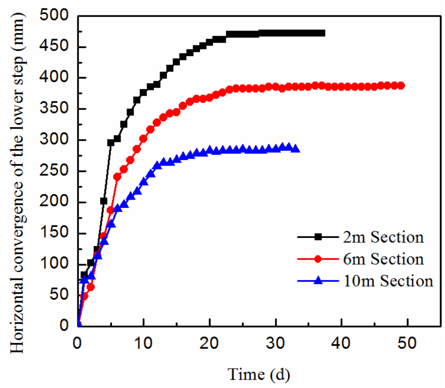

Figure 12. Horizontal convergence curve of the lower step of the surrounding rock in the monitoring section

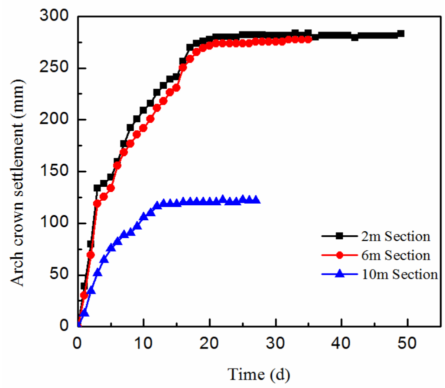

Figure 13. Arch crown settlement curve of the initial support

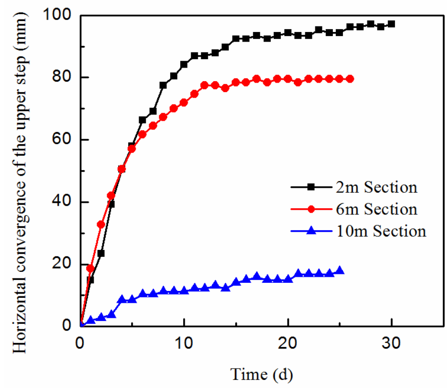

Figure 14. Horizontal convergence curve of the upper step of the initial support

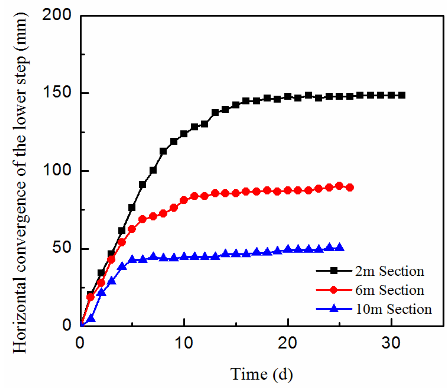

Figure 15. Horizontal convergence curve of the lower step of the initial support

5. ANALYSIS OF MEASURED FIELD STRESS

The field stress monitoring mainly targets the pressure of the surrounding rock, the stress on the concrete and the steel arch in the initial support, as well as the stress on the concrete and rebar in the secondary lining. The monitoring points on each measuring section are shown in Figure 16 below.

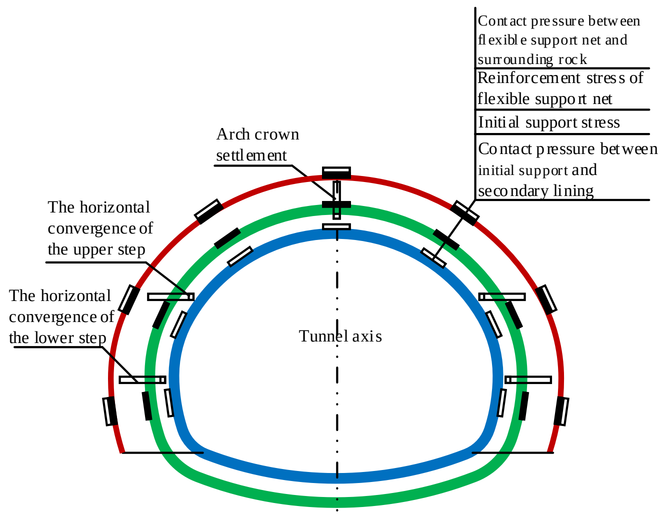

Figure 16. Sketch of monitoring points on each measuring section

5.1 Stress measurement of pilot heading

Figures 17~19 illustrate the stress on the initial support of pilot heading in the test section of Maoyu Mountain Tunnel. To reduce the workload and facilitate measurement, a section was selected to measure the pressure of the surrounding rock, the stress on the concrete in the initial support and the stress on the steel arch in the initial support at the arch crown, left spandrel, left arch foot and left side wall, respectively.

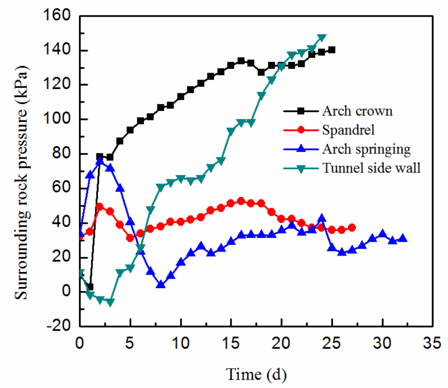

Figure 17. Time-history curve of the pressure of the surrounding rock

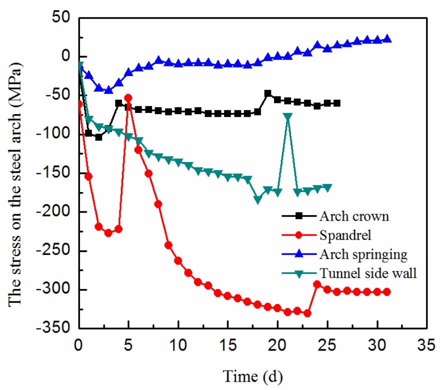

Figure 18. Time-history curve of the stress on the steel arch in the initial support

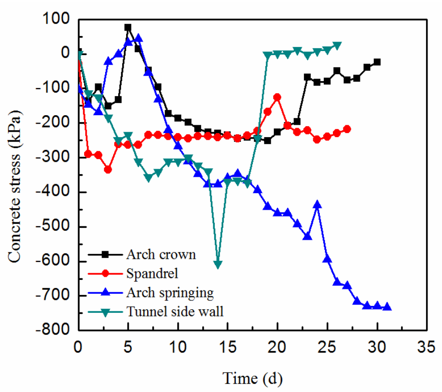

Figure 19. Time-history curve of concrete stress in the initial support

It can be seen from Figures 17~19 that the surrounding rock pressure was relatively small and grew increasingly slowly, despite a certain development in the later phase. The stress on the steel arch increased rapidly in the early phase, indicating that the steel arch carried most of the pressure initially released by the surrounding rock. The stress on the steel arch developed rapidly after arch erection, but slowly in the later phase. The stress on the steel arch at the spandrel (340MPa) was greater than any other measuring position, and surpassed the yield limit.

The concrete layer was subjected to compressive stress, which grew rapidly in the initial phase before becoming stable. The highest stress on the concrete appeared at the side wall.

5.2 Stress measurement of space reservation

Through comprehensive consideration, the peripheral space reserved for stress release was set to 50cm to ensure the desired release effect.

(1) Contact pressure between flexible support net and surrounding rock

Figure 20 provides the curve of the contact pressure between flexible support net and surrounding rock.

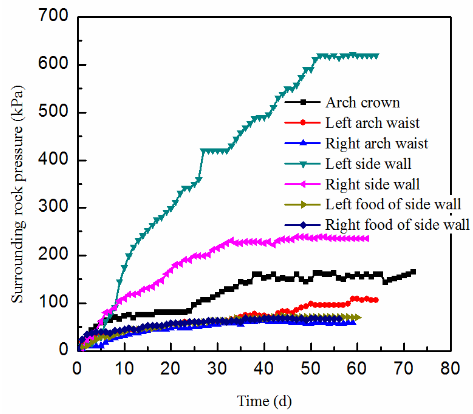

Figure 20. Time-history curve of surrounding rock pressure

As shown in Figure 20, the maximum pressure of the surrounding rock was observed at both side walls: 622kPa at the left side wall and 236kPa at the right side wall. The left surrounding rock pressure was obviously higher than the right one.

(2) Rebar stress on the flexible support net (the tensile stress is positive and the compressive stress is negative)

Figures 21 and 22 respectively present the time-history curves of the rebar stress outside and inside the flexible support net.

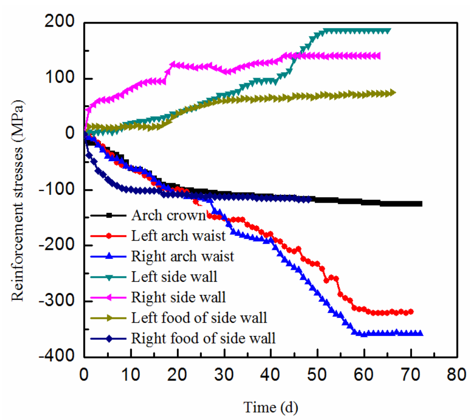

Figure 21. Time-history curve of the rebar stress outside the flexible support net

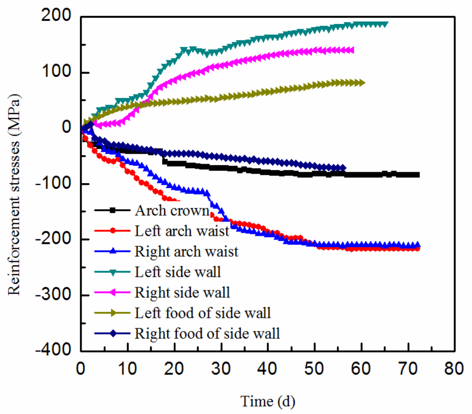

Figure 22. Time-history curve of the rebar stress inside the flexible support net

It can be seen from Figure 21 that the stress on the right arch waist of the rebar outside the flexible support net peaked at 359MPa, greater than the allowable stress. The stress on the left arch waist stood at 320MPa, which is close to the allowable stress. Hence, the two side walls are both under tensile stress.

It can be seen from Figure 22 that the rebar inside the flexible support net obeyed basically the same distribution with that outside the cover, and the upper half of the section was subjected to greater stress than the lower half. This means the two sides of each side wall has entered the tensile state.

(3) Stress monitoring of the steel frame in the initial support

Figures 23 and 24 respectively provide the time-history curves of the stress outside and inside the initial support.

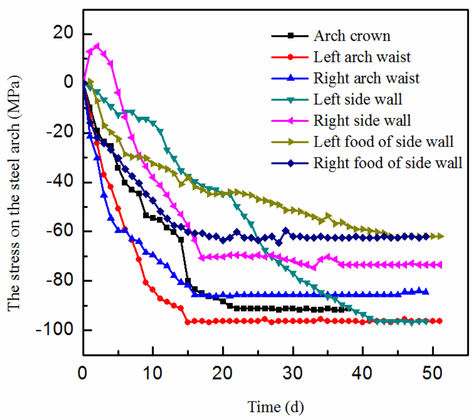

Figure 23. Time-history curve of the stress outside the steel frame in the initial support

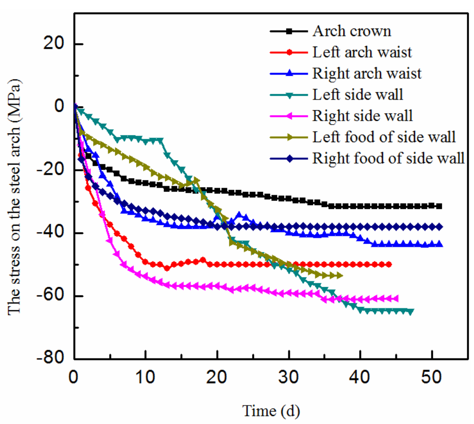

Figure 24. Time-history curve of the stress inside the steel frame in the initial support

Compared with the flexible support net, the steel frame in the initial support took much shorter time to converge under stress and was generally under compression. The maximum stress (100MPa) appeared at the left and right arch waists. In addition, the stress inside the steel frame was smaller than that outside the steel frame, and the stress peaked at the left and right-side walls (65MPa on the left and 60MPa on the right).

(4) Contact stress between initial support and secondary lining

Figure 25 gives the time-history curve of the contact stress between initial support and secondary lining.

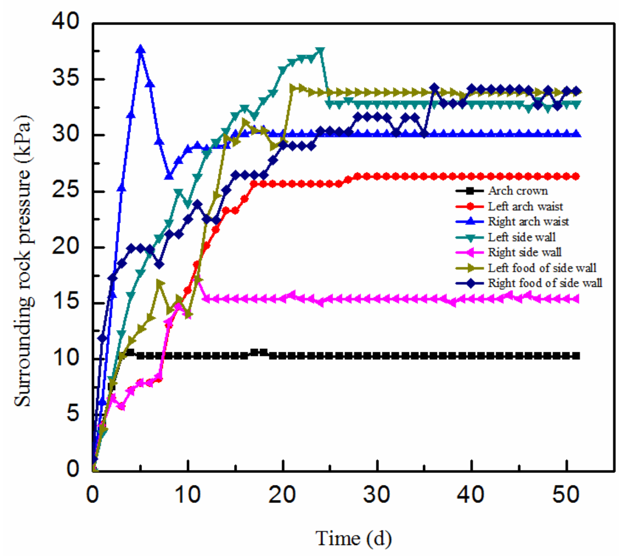

Figure 25. Time-history curve of the contact stress between initial support and secondary lining.

It can be seen from Figure 25 that the contact stress between initial support and secondary lining was small, failing to exceed 40kPa. The stress at each measuring point converged in a short time, and the time to convergence was usually between 10d and 20d.

6. CONCLUSIONS

(1) The high deformation of tunnels is primarily caused by high geo-stress, especially tunnels with large horizontal tectonic stress and weak surrounding rock. A tunnel may deform severely under the combined effect of insufficient stiffness of the initial support, the absence of pre-excavation stress release and the presence of groundwater. Maoyu Mountain Tunnel on the Lanzhou-Chongqing Railway suffers from typical large compressional deformation, which is mainly attributable to the deviation of tunnel axis from the direction of maximum horizontal principal stress and the orientation of rock formation.

(2) Through the comparative analysis on the field measured deformation and stress of different stress release plans, the following support mode was recommended for the pre-excavation release of geo-stress by space reservation in the main tunnel of Maoyu Mountain Tunnel: a large space (50cm) reserved for deformation (including enhancement space), flexible support net + advanced small pipe, H175 steel initial support (0.50m per piece), and 33cm-thick concrete. The measured results show that the support mode fully guarantees the stability of the tunnel structure, while fully releasing the

surrounding rock stress.

The field measured indices (e.g. deformation and stress) were subjected to comprehensive comparison. The results show that the reservation of a large space has a better stress performance than the pilot heading method. From our analysis, it can be seen that the space reservation method is more suitable for pre-excavation release of the geo-stress in high geo-stress soft rock tunnel.

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