Monitoring and numerical simulation analysis of corrugated steel support in weak surrounding rock mountain tunnels

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Abstract. Monitoring is one of the three elements of the NATM, and it plays a guiding role in tunnel construction. At present, there are few engineering projects of using the new corrugated steel assembled structure as the initial support of the tunnel. It is of great practical significance to research its monitoring and measurement, and it can accumulate experience and provide references for the design of the initial support of the corrugated steel. In this paper, based on a weak surrounding rock mountain tunnel in Yunnan Province, which uses the corrugated steel structure as the initial support, through the analysis of the on-site monitoring data and the establishment of the corresponding finite element numerical model, it is found that the stress of the tunnel arch foot is relatively large. At the same time, the monitoring and numerical calculation of the tunnel convergence values are compared and verified, which proves the reliability of the monitoring and the calculation.

1. Introduction

With the continuous development of technology, tunnel construction is developing in the direction of prefabrication and mechanization. The advantages of the new corrugated steel assembled support structure are outstanding, and it has great mechanical characteristics and strong applicability. In the case of weak surrounding rock with loose rock mass and jointed cracks, the use of the new corrugated steel support structure can also achieve the purpose of preventing disasters, speeding up construction and saving cost.

The use of new corrugated steel structure as the initial support of the tunnel is a fresh thing. The monitoring technology is still not perfect. It is very important to do the research of its monitoring and measurement. Through monitoring, we can verify the design level, check the construction quality and scientifically guide the design and construction. In recent years, a large number of scholars have conducted in-depth research on tunnel monitoring technology. Wang\textsuperscript{[1]} analysed the deformation and stress characteristics of the supporting system for the non-symmetrical multi-arch highway tunnel using the NATM, which provided a reference for the design and construction of similar projects. Wang\textsuperscript{[2]} researched the on-site monitoring data of an expressway tunnel with unsymmetrical loadings and compared it with the finite element method. The combination of the two illustrates the importance of information construction. Xia\textsuperscript{[3]} pointed out the time and space range of the excavation impact and the
optimal timing of the tunnel lining support by analysing the monitoring data of the small clear spacing tunnel. Gao[4] researched the monitoring data of a large-section railway tunnel in the seismic area, and pointed out that in the case of large deformation, the traditional shotcrete and anchor support would be difficult to meet the stability requirements of the tunnel. Corrugated steel structures have been used in field tests because of their extensive use in the highway and bridge culverts. Xu[5] conducted a field test on a corrugated steel culvert project and found that the stresses of the peaks and troughs increased rapidly during the filling construction process. Sargand[6] found that the radius of corrugated steel culvert gradually decreased after the end of construction by a field test and finite element analysis of a corrugated steel culvert with a span of 6.4 meters, which is beneficial to reduce the load on the overburden layer of the structure. Flener[7] tested the mechanical properties of four steel corrugated box culverts with spans of 8 meters and 14 meters respectively during backfilling, and compared them with the finite element model. He pointed out that with the increase of span, the influence of soil load on box culvert gradually increased. García[8] demonstrated that the use of sprayed-on cementitious liners to repair corrugated steel pipe culverts is effective through field tests of two 1.2 meters diameter culverts. In summary, it can be seen that the current research on corrugated steel structure mainly focuses on the field test of culvert engineering. There is very little research on the monitoring of the new corrugated steel support structure, which needs to be analysed in depth.

2. Monitoring analysis

2.1. Project overview

The project is located in Yunnan Province, China (As shown in the red line in Figure 1.), and it is designed as a separate two-lane long tunnel. The starting and ending of the position of the left hole is ZK47+212~ZK48+460, with a total length of 1,248 meters and a maximum depth of 131 meters. The starting and ending of the position of the right hole is YK47+205~YK48+460, with a total length of 1,255 meters and a maximum depth of 119 meters. The surrounding rock grade of the tunnel is Grade IV, and the rock mass is mainly dolomite and dolomitic limestone. The occurrence of the rock mass is 130°∠25°. Two types of structural fractures are mainly developed in the rock mass, and their occurrences are 295°∠78° and 64°∠55°. They are slightly open, with the rough surface and no filling. The slope is large and the groundwater in the rock mass is relatively poor.

2.2. Monitoring content and data analysis

When selecting the monitoring content, the content should be comprehensively considered according to the design requirements, the cross-sectional shape of the tunnel, the section size, the buried depth, the surrounding rock conditions, the surrounding environmental conditions, the support type and the construction method. For the new corrugated steel assembled support structure, in order to find out the stress state of the initial support of corrugated steel, the strain gauges are embedded on the surface of the corrugated steel. By measuring the strain, the stress state of the corrugated steel is converted. The final tunnel monitoring contents include the strain of the corrugated steel, surrounding rock pressure, initial lining and secondary lining contact pressure, the strain of the secondary lining and the convergence after the construction of the secondary lining. The monitoring section positions are

![Figure 1. The location of the project.](image)
YK47+315 and YK47+355. The convergences are measured using the convergence meter, and the remaining items are measured using vibrating wire transducers.

For the convenience of description, this paper makes a unified regulation on the sign of the monitoring value: positive value indicates that the initial support of corrugated steel is subjected to the tensile force, the secondary lining is subjected to the tensile force and the convergence is towards the inside of the tunnel; the negative value is opposite.

Due to limited space, some typical monitoring data is selected for analysing.

2.2.1. Strain of the corrugated steel. The strain values of the corrugated steel were measured by vibrating wire strain transducers, and the stress of the corrugated steel was calculated from the elastic modulus of the steel used. Thereby we can find out the stress state of the initial support of the corrugated steel. Each monitoring section has 7 corrugated steel plates, each plate is mounted with two strain gauges on each side of the plate. A strain gauge is also installed at the flange joint between the plates. The measuring point arrangement is shown in Figure 2.

![Figure 2. Layout of the strain gauge of the corrugated steel.](image)

Through the analysis of the measured monitoring data, the time history curves of the strains of the corrugated steel as shown in Figure 3 and Figure 4 are obtained. The time corresponding to the vertical line in the figures is the construction of the secondary lining.

![Figure 3. Time history curve of the strain of the corrugated steel of section YK47+315.](image)

Through the time history curve of the corrugated steel strain of Figure 3, it can be seen that:

Firstly, after the excavation of the face, the strain values of the corrugated steel changed rapidly, and then the changes tended to be gentle. After about one month, they were relatively stable. After the completion of the secondary lining, they changed again. And after about 3 weeks, they became stable again.
Secondly, the historical maximum tensile/compressive strains of most of the measuring points occurred after the secondary lining was completed or after the face was excavated, and the rates of change of the strains were also faster near these two time points. These two construction conditions are critical, so we should pay more attention to the monitoring at these two time points.

Thirdly, the historical maximum compressive strain of the corrugated steel is \(-275.3\mu e\), which occurred at 3-1 measuring point, and the occurrence time was July 22, 2018; the historical maximum tensile strain is \(117.6\mu e\), which occurred at 2-2 measuring point. The time was July 20, 2018. If the elastic modulus of the corrugated steel is taken as 200GPa, the maximum compressive stress of the corrugated steel is 55.1MPa, and the maximum tensile stress is 23.5MPa. Except for the 3-1 measuring point and the 2-2 measuring point, the strains at the 6-1 measuring point and the 6-3 measuring point are also relatively large, indicating that the corrugated steel at the arch foot of the monitoring section is subjected to a relatively large force.

### Figure 4. Time history curve of the strain of the corrugated steel of section YK47+355.

The situation of section YK47+355 is kind of similar to that of YK47+315. By the monitoring data of both two sections, it can be seen that:

1. In terms of time, after the excavation of the face and the construction of secondary lining, the stress of the corrugated steel and its change rate is relatively large, so we need to properly increase the monitoring frequency during these two time points.
2. In terms of space, the stress of the initial support of the corrugated steel near the arch foot is relatively strong, so the attention should be paid to the strengthening of this position during design.
3. In terms of security, the measured maximum stress of corrugated steel is much smaller than the design value. It proves the safety of the corrugated steel support structure.

#### 2.2.2. Strain of the secondary lining.

The measuring points of the strain of the secondary lining are respectively set at the crown of the tunnel, the left and right arch waists, and the left and right arch feet. The monitoring results are shown in Figure 5. According to the figure, we can see that:

At the beginning of the monitoring, the strains on the right arch waist and the right arch foot changed rapidly, and the other three points did not change much. After about 3 weeks, the strain became stable. However, after September 8, 2018, the strains fluctuated. Then the strain values on the left side gradually increased; the strain on the right arch foot decreased after October 11, 2018.

As of the last measurement, the historical maximum tensile strain of the secondary lining is 56.0\(\mu e\), located at the right arch foot, occurred on July 29, 2018. And the historical maximum compressive strain of the secondary lining is \(-71.4\mu e\), located in the left arch foot, occurred on October 19, 2018. The strength of the arch foot is relatively large, which corresponds to the strain of the corrugated steel initial support.
2.2.3. *Convergence.* Five monitoring lines were set to measure the convergence of the tunnel after the secondary lining construction.

As shown in Figure 6, the maximum convergence value of the section YK47+355 is 3.40mm, and the convergence value is basically stable about one month later after the completion of the secondary lining construction. After the secondary lining is completed, the tunnel convergence is relatively small, indicating that the tunnel structure is relatively stable.

3. *Numerical simulation*

For the analysis of the mechanical behaviour of tunnel construction, it is not only possible to monitor and measure the data through on-site monitoring, but also to use numerical simulation analysis methods. According to the geological conditions of the project, combined with the tunnel construction method, the corresponding finite element numerical model is established to provide early warning of the dangerous situation that may occur in the tunnel construction. And the correctness of the numerical simulation method and the on-site monitoring method can be verified by comparison with the on-site monitoring data and the calculation results. In this paper, the large-scale finite element numerical simulation software ABAQUS is used to model and analyse the section YK47+355 of the tunnel.
3.1. Parameter selection

According to the geological condition report of the project, combined with the Code for Design of Highway Tunnel[9], the main mechanical parameters of each layer of surrounding rock are selected as shown in Table 1.

| Stratum | Rock grade | Depth(m) | Volumetric weight (kN·m⁻³) | Modulus of deformation (GPa) | Poisson's ratio | Internal friction angle(°) | Cohesion (MPa) |
|---------|------------|----------|----------------------------|-----------------------------|----------------|-----------------------------|----------------|
| 1       | IV         | 33       | 20                         | 1.8                         | 0.32           | 27                          | 0.20           |
| 2       | IV         | 33       | 21                         | 2.3                         | 0.32           | 28                          | 0.30           |
| 3       | IV         | 39       | 22                         | 2.8                         | 0.32           | 30                          | 0.40           |
| 4       | IV         | 22       | 23                         | 3.3                         | 0.32           | 32                          | 0.50           |

The initial support of the tunnel adopts Q235 corrugated steel with a wave pitch-wave depth-plate thickness of 380mm-140mm-5mm; the secondary lining adopts C30 concrete with a thickness of 35cm.

3.2. Analysis of calculation results

According to the odb file calculated by ABAQUS finite element software, the axial force, the shear force and the bending moment of the initial support of the corrugated steel are extracted, and the results are shown in the Figure 7.

![Figure 7](image_url)

(a) Axial force  
(b) Shear force  
(c) Bending moment

Figure 7. Numerical simulation results of the corrugated steel internal force.

According to the calculation results, the axial force, the shear force and the bending moment near the position of the arch foot of the initial support are relatively large. The maximum axial force is 541kN, the maximum shear force is 41.5kN, and the maximum bending moment is 10.2kN·m. The force at the crown is relatively small. It is consistent with the analysis of the rules obtained from the monitoring.

![Figure 8](image_url)

Figure 8. Vertical displacement of the tunnel.

The vertical deformation of the tunnel is shown in Figure 8. Since the convergence value obtained by the monitoring is the value after the secondary lining construction, the relative displacement between the measuring points corresponding to the measuring line need to be calculated twice. Then do subtract to get the convergence. The numerical calculation results are compared with the convergence values obtained from the on-site monitoring results. The comparing results are shown in Table 2. It can be seen that the relative deviation of the convergence values is less than 20%. The numerical simulation results
and the on-site monitoring data can be mutually verified, which proves the rationality and credibility of both.

Table 2. Comparison of measured and calculated convergences.

| Line | Convergence (mm) | Node | Relative displacement before secondary lining construction (mm) | Relative displacement when stable (mm) | Convergence (mm) | Deviation (%) |
|------|-----------------|------|-------------------------------------------------------------|---------------------------------------|------------------|--------------|
| AE   | 2.44            | 1.82 | 2.07                                                        | 4.35                                  | 2.28             | About 8      |
| BF   | 2.41            | 74,105 | 0.98                                                        | 2.89                                  | 1.91             | About 20     |

4. Conclusion
1) According to the data obtained from the on-site monitoring, the time history curves of the strain and deformation are drawn, and the time and space laws of the strain and deformation of the new corrugated steel support structure are obtained: tunnel excavation and secondary lining construction are key time nodes, monitoring should be strengthened on these two time points; the stress of the position of the arch foot is relatively strong, so the corresponding measures should be taken.

2) The numerical simulation analysis of the project was carried out by finite element software and compared with the convergence value of on-site monitoring. It is found that the two can be in good agreement, which indicates the correctness of both. And it provides reference for the monitoring and design calculation of the initial support structure of corrugated steel in the future.

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