WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2024.148929

ARCHIVES OF CIVIL ENGINEERING

Vol. LXX ISSUE 1 2024

pp. 573 – 587

Research paper

Construction monitoring and analysis of low mountain ridge tunnel

Jian Ouyang[1], Haijun Wang[2], Luxiang Wu[3], Kexin Zhang[4], Xingwei Xue[5]

Abstract: In order to obtain the change rule of surrounding rock structure displacement and supporting structure internal force with time during the construction of the low mountain ridge tunnel, this paper relies on the Xishan Tunnel Project as the background. During tunneling, the displacement around the tunnel, the subsidence of the surface, the internal force of the steel arch and the pressure between the two layers of support are monitored dynamically. According to the above monitoring and measurement data, and the monitoring data analysis and nonlinear regression fitting, the predicted trend curve is obtained, the displacement change rules and characteristics of various surrounding rocks of the tunnel are obtained, to ensure the construction safety and stability requirements of supporting structure, and to provide a reasonable opportunity for the construction of secondary lining.

Keywords: low mountain ridge tunnel, monitoring and measurement, regression analysis

[1]M.Sc., Engineering Department, Guangzhou Expressway Co., LTD, China, e-mail: 1067323@qq.com, ORCID: 0009-0007-1214-0333
[2]M.Sc., Engineering Department, Guangzhou Expressway Co., LTD, China, e-mail: 403287518@qq.com, ORCID: 0009-0009-3982-0034
[3]M.Sc., Engineering Department, Guangzhou Expressway Co., LTD, China, e-mail: 736137652@qq.com, ORCID: 0009-0006-5346-3238
[4]PhD., School of Transportation and Surveying Engineering, Shenyang Jianzhu University, China, e-mail: jt_zkx@sjzu.edu.cn, ORCID: 0000-0001-6610-0045
[5]Prof., PhD., School of Transportation and Surveying Engineering, Shenyang Jianzhu University, China, e-mail: gdansys@163.com, ORCID: 0000-0002-8605-1196

1. Background

Tunnel engineering is a building built in the underground space, that is, the tunnel chamber structure is located in the surrounding rock and soil, the surrounding rock structure generates loads on the tunnel structure, and at the same time bears the loads together with the support structure [1, 4]. Such mechanical characteristics are quite different from ground engineering. In particular, the displacement change and stress status of surrounding rock structures are very complicated due to the influence of many factors, such as the structural characteristics, mechanical properties, physical parameters, the time of initial support structure, the way of the initial support structure and the construction method [5–8]. At the same time, the displacement and stress of the tunnel structure have obvious time and space effects during the whole construction process [9–11].

Therefore, construction monitoring and measurement technology are particularly important in the design and construction of tunneling projects [12, 13]. Using the data obtained from field monitoring, analysis and nonlinear regression fitting can predict and control the possible disasters and diseases in tunnel construction, and can be used to guide the field construction, carry out tunnel safety evaluation, and rationally arrange the construction process, which has very practical significance for ensuring the safety of tunnel construction [14–16].

At present, many domestic and foreign scholars have done research and discussion on tunnel envelope deformation and monitoring and measurement. Lv et al. [17] set up monitoring points to monitor the weak points at the intersection of open and dark tunnels in mountainous areas and simulated the structural deformation and stress of different types of tunnel structures under different conditions by finite element analysis, and the results showed that the actual deformation, stress, and structural damage location were consistent with the numerical simulation results. Kamikoshi et al. [18] studied a new Nagasaki tunnel located near a residential area using the inclined shaft method and introduced the construction method, deformation monitoring, and consideration of excavation conditions for a mountainous tunnel directly below a residential area. Tian et al. [19] studied experimentally the change in the water content of the surrounding rock during excavation, monitored and analyzed the first lining surrounding rock pressure, lining contact pressure, and reinforcement axial force during the construction process Finally, the deformation characteristics of the surrounding rock under different excavation methods were studied by numerical simulation to provide a reference for projects with poor surrounding rock stability. Zhang et al. [20] used the numerical limit analysis method to study the problem of taking values for the stability and ultimate displacement of the surrounding rock in high-pressure highway tunnels, and derived the final safety factor for complete instability of the surrounding rock in tunnels with and without high water pressure strata. Wang et al. [21] studied structural failures and a series of comprehensive management measures during the construction of tunnels through fracture zones based on monitoring data and field investigations in a tunnel in Shaanxi, and verified the reasonableness of the treatment measures, and the results of the study can provide theoretical and technical experience for similar projects in the future. Kavvadas [22] studied ground deformation monitoring in tunnel excavation and introduced the frequently types of ground deformation measurements used in tunnel construction, the difficulties in obtaining these measurements, the most commonly used evaluation methods and the application of deformation measurements in the selection of tunnel excavation and support systems.

This paper takes Xishan Tunnel as the engineering support for tunnel construction monitoring measurement and lining support analysis. There are many shallow buried and faulted sections in the Xishan Tunnel, more grade IV and V surrounding rocks in the cavern section, complicated geology of the stratum, and the tunnel is prone to engineering accidents such as collapse and roofing. The construction mechanics of the Xishan Tunnel was studied through on-site dynamic measurement analysis.

2. Project situation

2.1. Project overview

The whole tunnel adopts a three-centered circular curved wall section, and the cavern adopts a curved wall composite lining. The initial support near the cavern entrance adopts the reinforcement measures of overrunning pipe shed plus a steel arch. The tunnel elevation is shown in Fig. 1, and the tunnel building boundary and tunnel profile design are shown in Fig. 2.

Fig. 1. Tunnel elevation

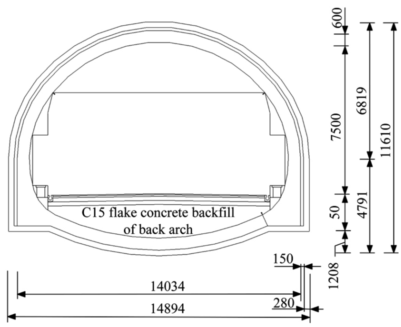


Fig. 2. Xishan Tunnel building boundary and tunnel profile (mm)

2.2. Geological structure

According to the results of physical prospecting, there are 3 main fracture zones in the tunnel site area. Af1 was located at measurement pile No. 0+900, heading NE-SW, inclined to SE, apparent dip angle about 33°, longitudinal wave speed 2500 m/s, width about 20 m. Af2 was located at measurement pile No. 1+180, heading NE-SW, inclined to SE, apparent dip angle about 25°, longitudinal wave speed 2000 m/s, width about 35 m. Df1 was located at measurement pile No. 0+40, heading NW-SE, inclined to SW, apparent dip angle about 58°, longitudinal wave speed 1700 m/s, width about 10 m.

The above fracture zone intersects with the tunnel at a certain angle, which has a certain influence on the tunnel. Its influence is mainly due to the fracture of the surrounding rock and possible water-rich, the regional seismic structure environment needs to be considered in the engineering design and construction, and the ground vibration parameters provided by the seismic risk analysis and zoning results should be designed and constructed.

2.3. Adverse geological condition

At the entrance of the tunnel, a part of the mountain was manually cut off, showing a second-grade steep cut, about a 10–15 m high cliff, with an overall slope of about 45°. The rock is exposed. The upper part is a fully weathered andesite with a thickness of about 2 m, and the lower part is a moderately weathered andesite. The joints and fissures are very developed, and the rock is cut into fragments. Rich vegetation cover for hazel and artificial larch. As shown in Fig. 3, at present, there are occasional pieces of debris falling here, but the amount of debris crumbling is not large, the tunnel construction may cause a large area of collapse, which has a certain impact on the tunnel construction.

Fig. 3. Collapse diagram at the entrance

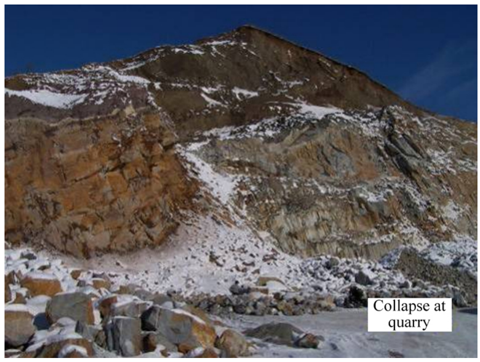


Fig. 4. Collapse diagram at the quarry

There is a quarry on the right side of the tunnel inlet, quarrying work is now in progress, the mountain is cut into a section nearly vertically, in the shape of a secondary steep cut, the height is about 70–80 m section, fresh rocks are exposed in a large area, the rocks are medium – slightly weathered andesite and tuff, joints and fissures are developed, the top of the mountain is rich in vegetation, hazel woods and weeds. As shown in Fig. 4, at present, the quarry is in the process of quarrying, and there has been rock caving, which has a certain impact on the construction and use of the tunnel. In addition, the tunnel site is without collapse, landslide, debris flow and other adverse geological phenomena.

3. Construction monitoring scheme

Xishan Tunnel is a shallow tunnel in the low mountains. The surrounding rock joints and fissures are very developed and the rock is cut into fragments. According to the monitoring and measurement implementation plan, various representative sections of surrounding rock of Xishan Tunnel are selected to monitor the displacement and stress changes, and the monitoring data are processed and analyzed and the nonlinear regression fitting curve is carried out to guide the construction reasonably and correctly.

3.1. Tunnel monitoring section layout

In the tunnel monitoring process, representative sections with characteristics should be selected, the selection of monitoring sections and monitoring measurement points buried principles are as follows.

Monitoring items are divided into required and selected items. Required items (convergence of peripheral displacement and surface subsidence) should be placed on the same section, so that monitoring data can verify each other and reflect displacement changes of surrounding rock in multiple directions. The selected measurement items (the pressure between the two layers of support and the stress of the secondary lining concrete) should also be placed on the same section, so that the monitoring data results can be mutually verified, and the stress condition of the initial supporting structure and the secondary lining can be better analyzed, as well as the safety reserve of the secondary lining.

In addition, the monitoring section layout principle should also follow the following principles. The monitoring section is mainly arranged in the area with poor surrounding rock and unstable surrounding rock, and more monitoring sections can be arranged appropriately. For the sections with relatively good surrounding rock structure, the monitoring section can be appropriately reduced, and a representative section can be selected for monitoring.

According to the above principles, this paper relies on the project monitoring section layout as shown in Fig. 5. Among them, the II type of surrounding rock is hard rock, rock mass is relatively complete, block or thick layered structure. The III type of surrounding rock is hard

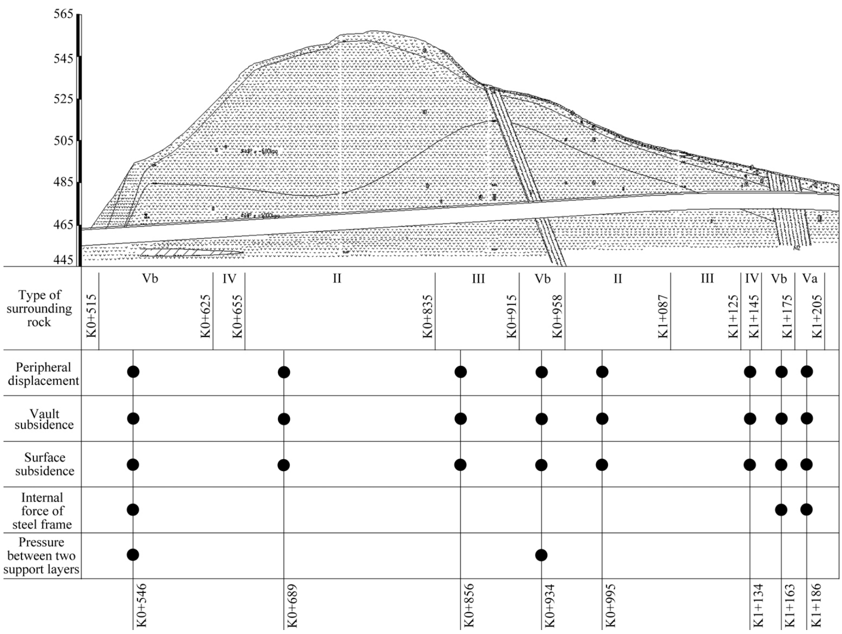


Fig. 5. Xishan Tunnel construction monitoring and measuring section and project map

rock or soft hard rock, the rock mass is relatively complete, blocky or medium thick layer structure. The IV type of surrounding rock is soft rock or soft rock interlayer, and mainly soft rock, the rock mass is relatively complete to more broken, and the structure of thin layer. The V type of surrounding rock is soft rock, which is broken, fractured and loose structure.

3.2. Peripheral displacement monitoring scheme

In this paper, only the monitoring results of three cross-sections in representative sections are selected for analysis, namely, the K0+546 cross-section (V type of surrounding rock), K1+134 cross-section (IV type of surrounding rock), and K0+856 cross-section (III type of surrounding rock), see Fig. 5.

K0+546 section is V type of surrounding rock, excavation method is up and down step construction, according to the tunnel construction monitoring and measurement program, the peripheral displacement measurement is three measurement lines, and the measurement points are arranged as shown in Fig. 6a. K0+856 is III type of surrounding rock, according to the monitoring program, the peripheral displacement measurement is one measurement line, the measurement points are arranged as shown in Fig. 6b. K1+134 section is IV type of surrounding rock, according to the monitoring program, the perimeter displacement measurement is two lines, and the arrangement of measurement points is as shown in Fig. 6c.

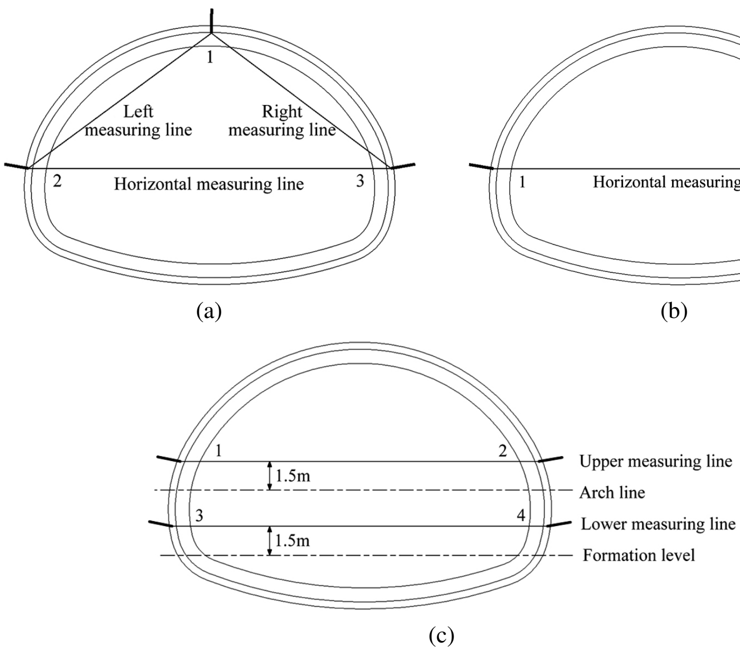


Fig. 6. Displacement measurement line layout around the section: a) K0+546 Section, b) K0+856 Section, c) K1+134 Section

The convergence meter is used to collect the data of the peripheral convergence measurement. First, a rock drill is used at the measuring point to make a hole in the part to be measured, and then the convergent embedded part with an expansion tube is punched in, and the perforated steel tape is fixed, so that the axis of the two embedded parts is in the baseline direction as far as possible, and the other end is fixed to the measuring system.

The measurement frequency of the perimeter displacement is shown in Table 1. The measurement frequency of surface subsidence, internal force of steel arches, and pressure between two layers of support is the same as the measurement frequency of perimeter displacement, and will not be repeated in the following text.

Table 1. Measurement frequency

Time	1~15 d	16 d~1 month	1~3 months	>3 months
Measurement frequency	1~2 times/day	1 time/2 days	1~2 times/week	1~3 times/month

Note: The measurement frequency can be modified according to the actual condition of surrounding rock.

3.3. Surface subsidence monitoring

The surface subsidence monitoring of the shallow buried section of the tunnel is a mandatory item, K1+186 section belongs to the shallow buried section, this section is V-type surrounding rock, and the tunnel section is larger. According to the monitoring program, to more accurately measure the surface subsidence of the section, 11 monitoring points are placed in the section, the layout of the measurement points as shown in Fig. 7.

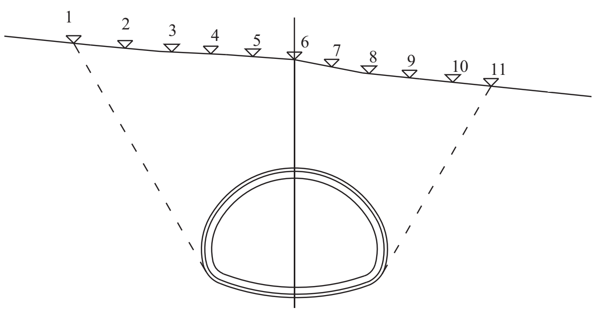


Fig. 7. K1+186 section surface subsidenc

The base point is buried in the area of 3 to 5 times the diameter of the tunnel. Refer to the burying method of standard level points, bury 2 reference points, point 1 and point 11 in the diagram, in order to check each other. In the shallow buried section of the tunnel entrance, a measuring section is set up along the axis of the tunnel, the section spacing is 5 m ~15 m, and 9 measuring points are arranged in each section. At the measuring point, a pit with a length, width and depth of 200 mm was excavated. Then, the embedded parts (self-made) are put into the surface measuring point, and the measuring point is filled with concrete around. The level can be measured after the concrete is consolidated. After the observation, the time-displacement and distance-displacement graphs can be drawn to analyze the data briefly.

3.4. Steel arch internal force monitoring

In the category V surrounding rock, the initial support usually takes the steel arch. The internal force monitoring points of steel arch frame are arranged at sections K0+546 and K1+186, and the measuring points are arranged as shown in Fig. 8. The internal force monitoring of steel arch frame is shown in Fig. 9.

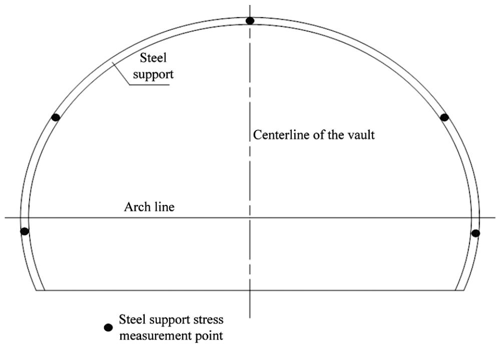
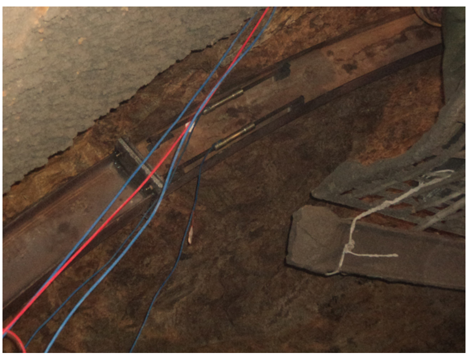


Fig. 8. Arrangement of stress measurement points for steel arches



(a)

(b)

Fig. 9. Steel arch internal force monitoring: a) Steel bar meters burial, b) Steel arch internal force measurement

Steel bar meters are arranged in pairs along the inner and outer edges of the steel arches. Before installation, the steel string steel bar meter is welded in parallel at the measured part of the steel arch. During the welding process, pay attention to cooling the steel bar meter with water. Then, the steel arch is moved to the hole by the worker to install or set up, record the steel bar gauge model, and the steel bar gauge number with transparent tape will be written on the paper number tightly pasted on the wire. Pay attention to assembling the wires into bundles and protect them well to avoid being damaged by construction in the hole. According to the frequency-axial force calibration curve of the reinforcement meter, the measured data can be directly converted to the corresponding axial force value. Then the bending moment can be calculated, and the values of axial force and bending moment can be drawn on the distribution position of each steel bar meter according to a certain proportion on the tunnel cross-section. The distribution diagram of axial force and bending moment of the tunnel steel arch can be formed by connecting each point.

3.5. Pressure monitoring between two layers of support

After the initial support structure is stabilized, the secondary lining can be applied. By placing a pressure box between the two layers of support and collecting data with a comprehensive tester, the pressure between the two layers of support can be obtained. In the K0+546 cross-section, pressure monitoring points between the two layers of support are set up. The arrangement of pressure measurement points between two layers of support is shown in Fig. 10.

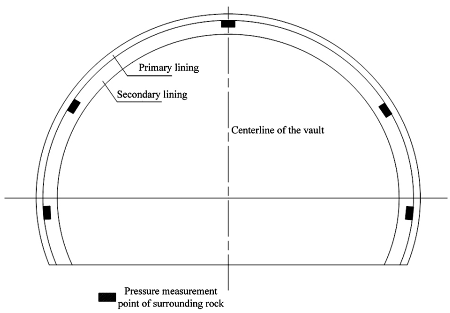


Fig. 10. Arrangement of pressure measurement points for two layers of support

4. Tunnel monitoring results and analysis

4.1. Analysis of displacement monitoring results around the section

Section K0+546 is a V-level surrounding rock, according to the construction monitoring program, the time is reasonably arranged, and the displacement around the monitoring section is monitored in time with the tunnel excavation, and the cumulative change of the temporal curve of the peripheral displacement monitoring data is shown in Fig. 11a.

As can be seen from Fig. 11a, the regularity of peripheral displacement monitoring data is not obvious, and the displacement change fluctuation is small. At the initial stage of tunnel section excavation, that is, within 10^{th} d after the section excavation, the surrounding rock structure is unstable, the displacement changes are particularly obvious, and the convergence rate is fast. The convergence rate of the horizontal and left survey lines is 0.6 mm/d, and that of the right survey lines is 0.35 mm/d. During the 10th to 15th d, the convergence rate of each measurement line slowed down and the surrounding rock tended to be stable.

The final convergence accumulation value of the horizontal measurement line is 10.5 mm, the final convergence accumulation value of the left measurement line is 9.1 mm, and the final convergence accumulation value of the right measurement line is 7.0 mm. They are all within the limit value of 15 mm. From the whole monitoring curve, the horizontal measurement line convergence monitoring data is the largest, in which the left measurement line surrounding rock convergence is close to the horizontal measurement line monitoring data, while the right measurement line surrounding rock convergence is smaller than the horizontal measurement line and left measurement line convergence value, the surrounding rock stability is better.

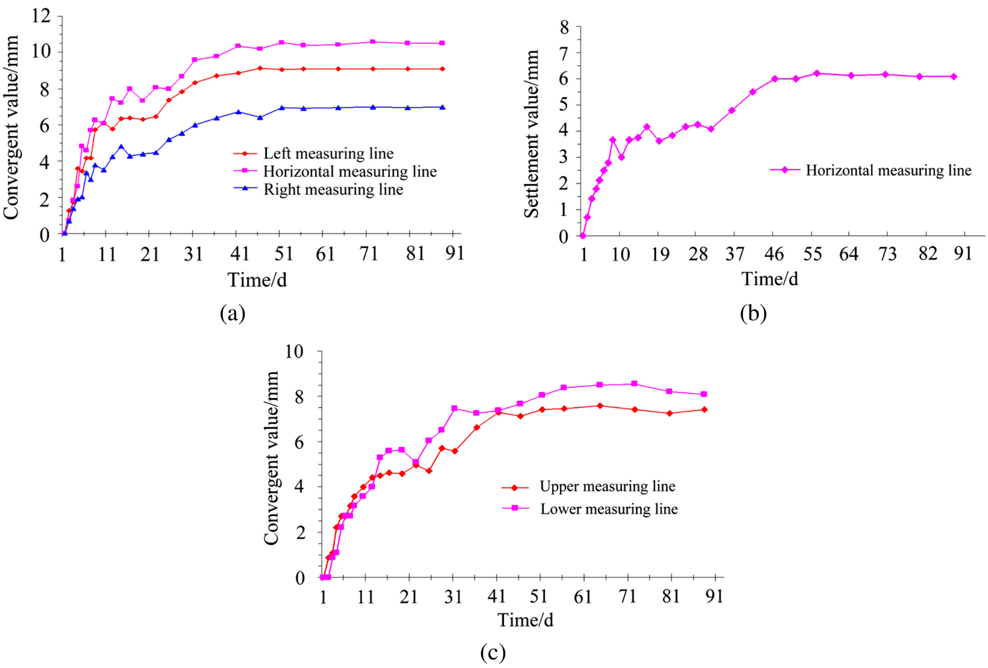


Fig. 11. Temporal graph of peripheral displacement monitoring data: a) K0+546 Peripheral displacement, b) K0+856 Peripheral displacement, c) K1+134 Peripheral displacement

Section K0+856 is a grade III surrounding rock, by the construction monitoring program, the time is reasonably arranged, the displacement around the monitoring section is monitored in time with the tunnel excavation, and the accumulated change trend of the peripheral displacement monitoring data is shown in Fig. 11b.

As can be seen from Fig. 11b, the regularity of peripheral displacement monitoring data is not obvious, and the displacement change fluctuation is small. At the initial stage of tunnel section excavation, the surrounding rock structure is unstable and the displacement changes are particularly obvious within 8^{th} d after section excavation. The convergence rate is very fast, and the convergence rate is 0.6 mm/d. During the 8^{th}–12^{th} d, the monitoring data fluctuated up and down, but the convergence rate slowed down, and the surrounding rock tended to be stable.

K0+856 section horizontal convergence final convergence cumulative value is 6.09 mm, less than the minimum value of the maximum displacement allowed by the specification 0.6%-1.60%. From the whole monitoring curve K0+856 horizontal convergence change curve in line with the tunnel surrounding rock change law, the surrounding rock stability is good.

K1+134 section is type IV surrounding rock, according to the monitoring program, the peripheral displacement is two horizontal measurement lines. According to the construction monitoring program, the time is reasonably arranged, and the peripheral displacement of the monitoring section is monitored in time with the tunnel excavation, and the accumulated trend of the peripheral displacement monitoring data is shown in Fig. 11c. The change of the surrounding rock displacement tends to be stable and in a safe state, and the stability of the surrounding rock is good.

4.2. Analysis of surface subsidence monitoring results

The temporal curve of cumulative changes of surface subsidence monitoring data of K1+186 section is shown in Fig. 12.

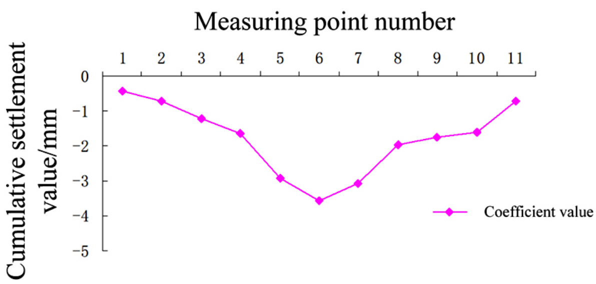


Fig. 12. Cumulative ground subsidence at section K1+186

As can be seen from Fig. 12 of the cumulative settlement curve for section K1+186, the settlement at measurement point 6 (at the top of the vault) is the largest, at 3.6 mm. It is less than the limit value of 10 mm. The subsidence away from the vault decreases gradually, which indicates that the tunnel excavation has a certain influence on the surrounding rock, and the closer the distance to the excavation chamber, the greater the influence. On the contrary, the further away the excavation chamber is, the less the influence will be.

4.3. Analysis of internal force monitoring results of steel arches

A graph of the cumulative value of the internal forces in the steel arch as a function of time was obtained, as shown in Fig. 13 and Fig. 14.

From Fig. 13 and Fig. 14, it can be seen that the steel arches of K0+546 and K1+186 monitoring sections are under pressure at all measurement points, and the pressure at the top

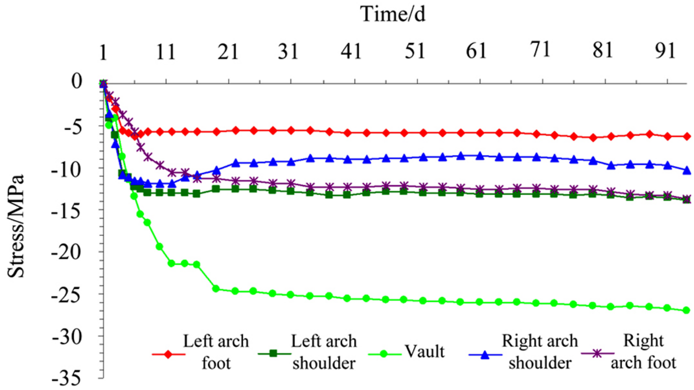


Fig. 13. Cumulative temporal graph of internal force monitoring data for steel arch K0+546

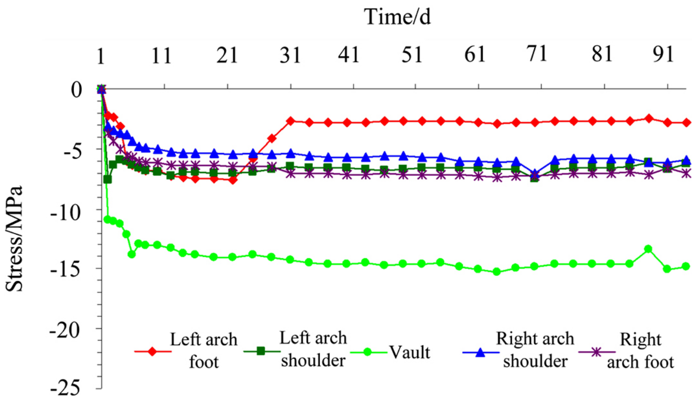


Fig. 14. Cumulative temporal graph of internal force monitoring data for steel arch K1+186

of the arch is the greatest in both sections. From the monitoring data, the top of the arch is the most unfavorable position for the whole section. K0+546 monitoring section, the arch under the greatest pressure, the left and right spinner spinner and right arch foot monitoring data little difference, stress value between 6.0–7.0 MPa, the force balance. The pressure of the left arch foot gradually decreased on the 10th d and became stable on the 30th d. After that, it remained in a stable state with a stress value of –2.78 MPa. From the monitoring data curve of this section, it can be seen that at the beginning of tunnel excavation, the pressure at each measuring point increases rapidly, then changes gently, and finally the data trend is stable, and the initial supporting structure is stable.

At section K1+186, the pressure on the top of the vault is the highest, while the left shoulder and the right foot of the arch are under similar stress, with stress values ranging from –13.60 to –13.80 MPa. The right shoulder of the arch is slightly less stressed, with a stress value of –10.3 MPa. The left foot of the arch is under the least stress, with a stress value of –6.22 MPa. After 15th d, the trend of data at each measurement point is stable, and the initial support structure is stable. The initial support structure is stable. The time to stabilization varies with the surrounding rock at each measurement point. The internal forces of steel arches are less than 146 MPa, which meets the requirements.

4.4. Analysis of pressure monitoring results between the two layers of support

After the initial support structure is stable, the secondary lining can be applied. A pressure box is arranged between the two layers of support to measure the pressure between the two layers of support. A pressure monitoring point between two layers of support is set in section K0+546. Through regular monitoring of the pressure in this section, the cumulative value of pressure between two layers of support changes over time is obtained, as shown in Fig. 15.

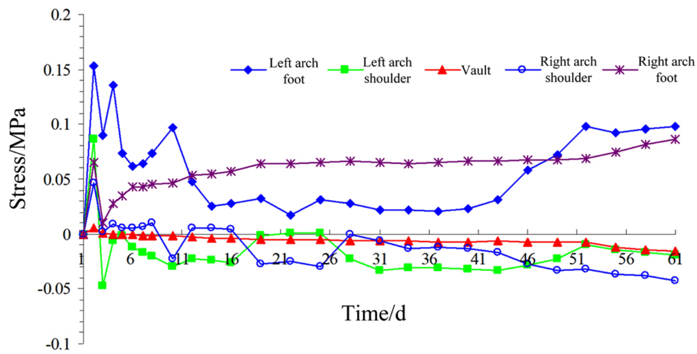


Fig. 15. Cumulative temporal plot of pressure monitoring data between the two layers of support at K0+546

As can be seen from the monitoring data curve in Fig. 15, the load between supports is very small, indicating that the initial supporting structure of this section has well borne the load of surrounding rock. From this point of view, secondary lining has a better safety reserve. The monitoring data at the left arch foot of the pressure measuring point in this section have poor regularity and fluctuate up and down greatly, while the monitoring data at other measuring points have good regularity and fluctuate little. After the monitoring data of each measuring point is stabilized, the value of pressure between the supports of the left arch foot is the largest, which is 0.098 MPa. The second is the right arch foot, which is 0.086 MPa. The rest of the measuring points are kept very small. The data trend is stable and the structure is stable.

5. Conclusions

Combined with the Xishan Tunnel Project in Suifenhe City, this paper monitors and measures the tunnel construction process. Through the tunnel surrounding rock displacement change data analysis, the tunnel surrounding rock displacement change data curve non-linear regression analysis, and tunnel support structure internal force monitoring results analysis, the following conclusions are drawn.

1. The change in displacement around different sections is relatively small, the changing trend is the same. The convergence change curve conforms to the tunnel surrounding rock change law, the surrounding rock stability is good, in a safe state. The surrounding displacement measurement data regression equation coefficient β between 1.0 and 3.0, the better the surrounding rock type, the smaller the regression equation coefficient β.
2. Surface subsidence is greatest at the top of the vault, with a value of 3.6 mm, and gradually decreases to 0.5 mm along the direction of deviation from the vault. This indicates that the excavation of the tunnel has a certain influence on the surrounding rock. The closer the distance to the excavation chamber, the greater the influence, and vice versa.
3. All the measured points of the steel arch at different sections are under pressure, and all of them are under the greatest pressure at the top of the arch. The maximum compressive stress at the top of the steel arch at section K0+546 is –15.26 MPa, the maximum compressive stress at the top of the steel arch at section K1+186 is –27.01 MPa. The top of the arch is the most unfavorable position.
4. The load between the supports is very small, after the data of each measurement point is stabilized, the maximum tensile stress appears at the foot of the left arch, 0.098 MPa, followed by the foot of the right arch, 0.086 MPa. When the initial support structure is stabilized, it plays a good role in bearing the load of the surrounding rock, leaving enough load reserve for the secondary lining, and the structure is safe and reliable.

References

[1] Zhang, Jiesheng, and Yongzheng Qi, "Research on the intelligent positioning method of tunnel excavation face", *Archives of Civil Engineering*, vol. LXIX , no. 3, pp. 431–441, 2022, doi: 10.24425/ace.2023.146069.

[2] H. Yoshimura, T. Yuki, Y. Yamada, "Analysis and monitoring of the Miyana railway tunnel constructed using the New Austrian tunnelling method", *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol.23, no.1, pp. 67–75, Pergamon, 1986, doi: 10.1016/0148-9062(86)91667-0.

[3] Zou, Bao, "A comparative analysis of artificial neural network predictive and multiple linear regression models for ground settlement during tunnel construction", *Archives of Civil Engineering*, vol. 69, no. 2, pp. 503–515, 2023, doi: 10.24425/ace.2023.145281.

[4] R. Bernard, J. Pacovsky and I. Zemánek, "Geo-monitoring performed during the construction of the Valík highway tunnels", *Tunnelling and Underground Space Technology*, vol. 21, no. 3–4, 2006, doi: 10.1016/j.tust.2005.12.007.

[5] S. Robert and M. Josef P., "New Approach of ASFINAG for Tunnel Construction Monitoring of the Tauern Tunnel Project in Austria", *2009 Rapid Excavation and Tunneling Conference – Proceedings*, 2009.

[6] R. Hafeezur, "Numerical evaluation of new Austrian tunneling method excavation sequences: A case study", *International Journal of Mining Science and Technology*, vol. 30, no. 3, pp. 381–386, 2020, doi: 10.1016/j.ijmst.2020.03.009.

[7] B.G. He, X.W. Zhang and H.P. Li, "Ground load on tunnels built using new Austrian tunneling method: study of a tunnel passing through highly weathered sandstone", *Bulletin of Engineering Geology and the Environment*, vol. 78, no.8, pp. 6221–6234, 2019, doi: 10.1007/s10064-019-01499-x.

[8] X.L. Wang, "Geohazards, reflection and challenges in mountain tunnel construction of China: a data collection from 2002 to 2018", *Geomatics, Natural Hazards and Risk*, vol. 11, no.1, pp. 766–785, 2020, doi: 10.1080/19475705.2020.1747554.

[9] H.H. Zhu, J.X. Yan and W.H. Liang, "Challenges and development prospects of ultra-long and ultra-deep mountain tunnels", *Engineering*, vol. 5, no. 3, pp. 384–392, 2019, doi: 10.1016/j.eng.2019.04.009.

[10] B. Du, Y. Du, F. Xu and P. He, "Conception and Exploration of Using Data as a Service in Tunnel Construction with the NATM", *Engineering*, vol. 4, no. 1, pp. 123–130, 2018, doi: 10.1016/j.eng.2017.07.002.

[11] Z. Guan, Y. Jiang and Y. Tanabashi, "A new rheological model and its application in mountain tunnelling", *Tunnelling and Underground Space Technology*, vol. 23, no. 3, pp. 292–299, 2008, doi: 10.1016/j.tust.2007.06.003.

[12] J. Zhou, X. Yang and J. Guo, "Stability predictions for excavations of mountain tunnels based on BQ method and its field verification", *Engineering Failure Analysis*, vol. 141: 106727, 2022, doi: 10.1016/j.engfailanal.2022.106727.

[13] K. Miura, "Design and construction of mountain tunnels in Japan", *Tunnelling and Underground Space Technology*, vol. 18, no. 2-3, pp. 115–126, 2003, doi: 10.1016/S0886-7798(03)00038-5.

[14] C. Liu, D. Zhang and S. Zhang, "Characteristics and treatment measures of lining damage: A case study on a mountain tunnel", *Engineering Failure Analysis*, vol. 128: 105595, 2021, doi: 10.1016/j.engfailanal.2021.105595.

[15] J. Lai, X. Wang and J. Qiu, "Extreme deformation characteristics and countermeasures for a tunnel in difficult grounds in southern Shaanxi, China", *Environmental Earth Sciences*, vol. 77, no. 19, pp. 1–14, 2018, doi: 10.1007/s12665-018-7888-2.

[16] W. Lienhart, F. Buchmayer and F. Klug, "Distributed Fiber Optic Sensing on a Large Tunnel Construction Site: Increased Safety, More Efficient Construction and Basis for Condition-Based Maintenance", *International Conference on Smart Infrastructure and Construction 2019 (ICSIC) Driving data-informed decision-making*, ICE Publishing, pp. 595–604, 2019, doi: 10.1680/icsic.64669.595.

[17] J. Lv, Y. Wu and X. Li, "Mechanical deformation mechanism and verification of sections at junctions of light and dark tunnel in a mountain area", *Journal of Vibroengineering*, vol. 21, no. 4, pp. 962–973, 2019, doi: 10.21595/jve.2018.20285.

[18] T. Kamikoshi, O. Takei and Y. Yoshikawa, "Construction of a mountain tunnel in the neighboring of residential areas", *Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art*, CRC Press, pp. 5730–5739, 2019.

[19] X.X. Tian, Z.P. Song and H.Z. Wang, "Evolution characteristics of the surrounding rock pressure and construction techniques: A case study from Taoshuping tunnel", *Tunnelling and Underground Space Technology*, vol. 125: 104522, 2022, doi: 10.1016/j.tust.2022.104522.

[20] X.L. Zhang, H.Y. Guo, L.C. Ye and X.L. Zhang, "Study on The Evaluation of Surrounding Rock Stability and Limit Displacement of High-Pressure Stratum Tunnel", *IOP Conference Series: Earth and Environmental Science*, vol. 643, no. 1, IOP Publishing, 2021, doi: 10.1088/1755-1315/643/1/012055.

[21] Y. Wang, J. Li and Z.F. Wang, "Structural failures and geohazards caused by mountain tunnel construction in fault zone and its treatment measures: A case study in Shaanxi", *Engineering Failure Analysis*, vol. 138: 106386, 2022, doi: 10.1016/j.engfailanal.2022.106386.

[22] J.K. Michael, "Monitoring ground deformation in tunnelling: Current practice in transportation tunnels", *Engineering Geology*, vol. 79, pp. 93–113, 2005, doi: 10.1016/j.enggeo.2004.10.011.

Received: 2023-06-07, Revised: 2023-10-31