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Numerical Simulation Analysis of Three-layer Initial Support for Large-span Tunnel of Changjiang Road South Extension Project and Anti-overthrow Technology

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Abstract
To solve the various construction and technical problems encountered in the process of 'the largest cross-section urban highway tunnel undercover excavation in China', relying on the Suzhou International Rapid Logistic Corridor Project, three key innovative technologies were pioneered, including the three-layer initial support system, the steel bar anti-tilting limitation technology, and the stepping type multi-section lining trolley technology. Based on the relevant software, numerical model was established to simulate the whole process of the construction of 'three-layer initial support' in the large-span tunnel, and the numerical simulation data were compared and analysed with the on-site monitoring data, which verified the feasibility and superiority of the work method, the anti-tipping limitation technology of reinforcement bars ensures the stability of the inner reinforcement bars during the installation process through the limitation of the steel arch and the 'L' type reinforcement bars hanging on the inner reinforcement bars. The steel anti-tipping limitation technology ensures the stability of the steel bars in the installation process through the limiting steel arch and the 'L' type steel bars hanging the inner steel bars, which solves the risk of overturning the large span steel bars in the installation of the large-span tunnels. The stepping multi-section lining trolley technology realises the rapid conversion of different tunnel sections through the innovative stepping combined trolley and rapid section change technology. The creative application of these technologies has demonstrated significant advantages in improving construction efficiency, ensuring safety and reducing costs.
Keywords: *large-span tunnels; simulation analysis; three-layer initial support; anti-slip limiting technology; walk-in lining trolley*

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I. INTRODUCTION

After a long time of technical exploration and engineering experience, the tunnel support system has been developed more perfectly, however, different tunnel projects have different geological characteristics and construction requirements, the complexity and uniqueness of underground engineering make the combination of support structure form and support parameter selection in the complete support system also has a certain degree of flexibility.

At present, scholars at home and abroad mainly adopt the methods of theoretical analysis[1-2], model test[3-6] and numerical simulation[7-13] to study the excavation support problems of large-span double-connected-arch tunnels with a large cross-section in complex and sensitive geology, and quantitatively analyse the effects of various support measures in the construction process during the excavation process of the tunnels.

Yang Xueqi et al.[1] based on the soil-based punching continuous arch tunnel, compared the single-tunnel method without a centre wall with the three-guide-tunnel method, and found that the single-tunnel method without a centre wall in combination with the three-step method could reduce the effective stress concentration, Wang Chao et al.[2] took the two-lane circular shield tunnel diagonal intersection under the airport highway as an example, improved Peck's formula, analyzed the joint influence of the diagonal intersection angle, the slope angle and the uplift deflection angle, and established a prediction model for surface settlement based on the correction coefficient of the strata loss rate.

Lei et al.[3] simulated the shallow-buried biased-arched tunnels through a similar model test to derive the lining and peripheral rock, Li et al.[4] analyzed the surface settlement pattern and the change of surrounding rock stress distribution during the construction of a continuous arch tunnel, Zheng Liuyi et al.[5] combined numerical simulation and on-site monitoring to study the peripheral rock displacement and initial support force under different anchor lengths and shotcrete thicknesses, Li Si et al.[6] proposed three support optimization schemes based on the tunnel project of the Menghua Railway and analyzed the peripheral rock deformation and support force in tunnels with different rock qualities.

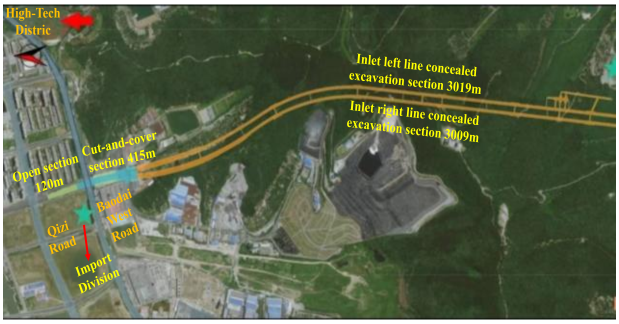
Wang Beihua.[7] investigated the stability of the diaphragm wall, supporting structure force and construction method in the construction of a double continuous arch tunnel on Nanshan Road through numerical simulation, Zhang Hao et al.[8] studied the settlement control of the four-lane tunnel underneath the integrated tube corridor settlement control, Hu Zhiping et al.[9] combined with Xi'an Metro Line 5 and explored the surface settlement, stress changes and deformation rules of the tunnel lining through numerical simulation, Li Haiyun.[10] simulated the excavation of the continuous arch tunnel and analyzed the changes of vertical and horizontal displacement by using the FLAC 3D software, Tang Kunjie et al.[11] analyzed the construction process of the connected-arch tunnel underneath the U-channel of the existing underground, Weng Xiaolin et al.[12] combined model test and numerical simulation to study the mechanical characteristics of the large-span double-connected-arch tunnel underneath the underground structure, Duan Wei et al.[13] simulated the deformation of the drilling and blasting tunnel underneath the existing tunnel and studied the reinforcement effect.

Relying on the double-lane double-arch tunnel of Suzhou Yangtze River Road South Extension Project, this paper investigates the applicability of the support measures such as overrun pipe curtains, glass fibre anchors and MJS horizontal reinforcement piles. Through numerical simulation and on-site measurement, it simulates the construction process of three-layer initial support, compares the displacement changes under different support measures, optimises the construction support method, and puts forward the displacement and deformation control technology of double-arch tunnels with a large cross-section in the weak surrounding rock.

II. PROJECT OVERVIEW

The total length of Suzhou International Rapid Logistics Corridor Phase II - Yangtze River Road South Extension Project is about 6.428km, of which the tunnel section is 6.18km (4.57km for mountain tunnel and 1.61km for cut-and-cover tunnel). The starting point of the project is the intersection of Changjiang Road and Qizi Road, the tunnel goes through Baodai West Road and Qizishan Cemetery, bypasses the landfill and the cemetery area, goes out of the mountain and then goes through Wangshan River and Wuzhong Avenue, and the endpoint is connected to the intersection of Nanguandu Road. Figure 1 is a general view of the project.

The large-span tunnel studied in this paper passes through medium-weathered sandstone and fractured medium-weathered sandstone, with large differences in rock strength, and is prone to problems such as landslides, delaminations and rappelling. For this reason, the tunnel adopts a three-layer initial support structure, with temporary cross braces and a centre wall. The first and second layers of support are used to support the surrounding rock, and the third layer is constructed before the removal of the temporary centre wall and the superelevation arch to replace the temporary structure and ensure the stability of the support. The first layer of support covers 120° of the arch, and large arch footings and prestressed anchors are installed to enhance the support effect. Figure 2 shows a cross-section of the three-layer initial support structure for the large-span tunnel.



(a) Satellite view of continuous arch and large span section

(b) Geographic location and direction map

(c) Surrounding buildings

Figure. 1 General view of the project.

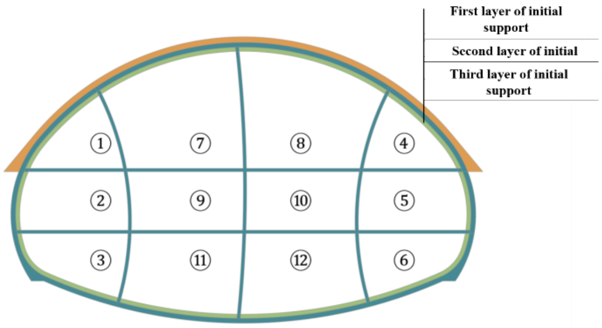


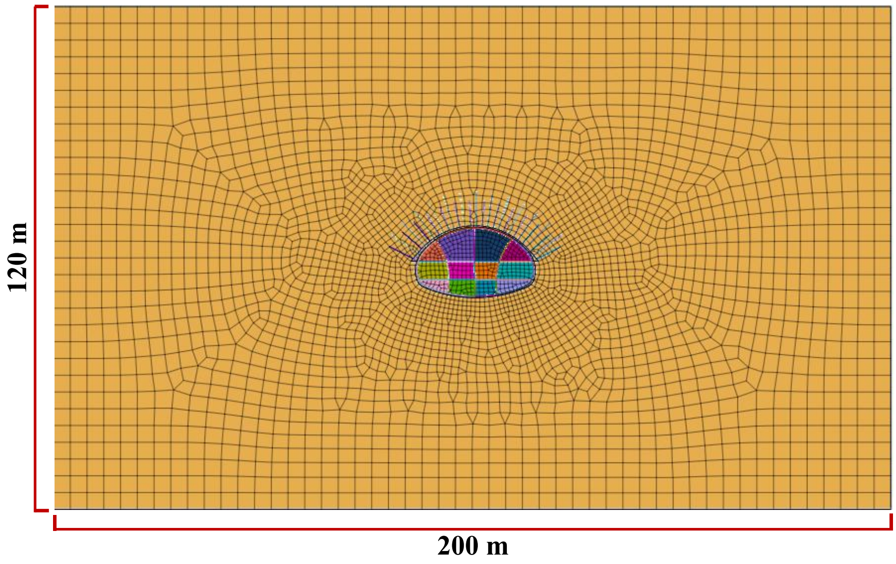
Figure. 2 Cross-section of the three-layer initial support structure of the long-span tunnel.

III. FINITE ELEMENT SIMULATION ANALYSIS OF THREE-LAYER INITIAL SUPPORT

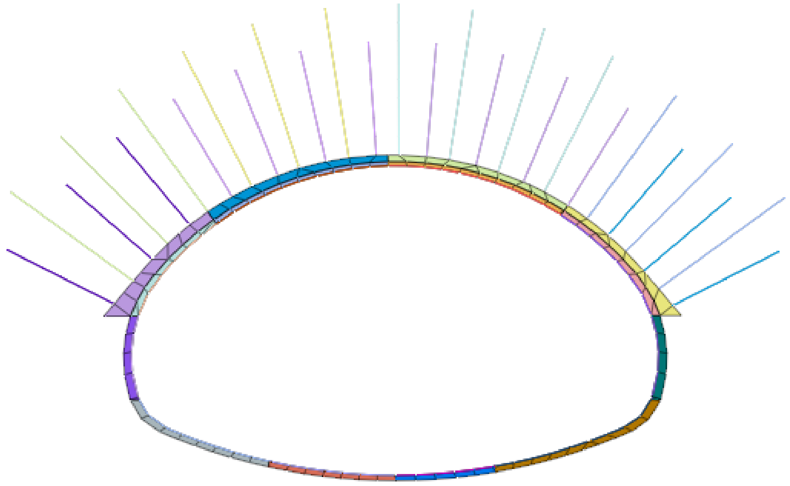
3.1 Numerical modelling

A 2D finite element numerical model was established based on the results of the relevant stratigraphic survey. According to the original stratigraphy, the tunnel is located in the broken medium-weathering sandstone soil layer, and its burial depth is 40 m. The model is 200 m long and 120 m high, and the three-layer initial support model is shown in Fig. 3.

The numerical model is calculated using the Ducker-Prager yield criterion without considering the stratification of the strata and the joints and fissures in the rock mass. The tunnel surrounding rock is regarded as a single, homogeneous and continuous medium, and the effect of tectonic stress is not considered. The initial stress field only considers the self-gravitational stress field, ignoring the influence of groundwater, and the surrounding rock and arch protection model are considered as each homogeneous material. The Mohr-Coulomb elastic-plastic 2D model is used for calculation, and the 1D elastic model is used for the initial support, the second liner, the diaphragm wall, the grouting anchors and the prestressing anchors. The physical parameters involved in the model are shown in Table 1.



(a) Integral model of three-layer support



(b) Three-layer support model

Figure. 3 Numerical modelling of three-layer initial support.

Table. 1 Model physico-mechanical parameters

Earth	Layer thickness (m)	Capacity (KN/m3)	Modulus of elasticity (MPa)	Poisson's ratio	Angle of internal friction (°)	Cohesion (KPa)
Moderately weathered sandstone	10.0	20.0	18.0	0.35	31	100
Arch protection	——	23.0	25.0	0.30	36	150
Priming spray	——	22.0	28000	0.20	——	——
Prestressing anchors	——	22.0	28000	0.20	——	——
Grouting small conduit anchor	——	70.0	32500	0.30	——	——

3.2 Design of excavation conditions

The three-layer initial support construction of the large-span tunnel is carried out by the principle of ‘releasing first and then resisting, combining releasing and resisting’, adopting the programme of releasing the ground stress by overpassing the guide tunnel and then expanding the excavation for the second time, and the simulated construction sequences are as follows:

1) The upper step of the side guide hole is staggered by 15 metres, adopting a three-step method. The first layer of initial support and temporary middle and next door are carried out first, and then the second layer of initial support and temporary elevated arch are carried out with a lag of 3-5 metres.

2) After 8 metres of excavation of the upper step, start excavation of the middle step, complete the first layer of initial support, temporary back arch and middle wall, and then remove the temporary back arch of the upper step.

3) After 8 metres of excavation of the middle step, excavation of the lower step will be carried out to complete the initial support of the second and third layers, and at the same time, the temporary arch of the middle step will be dismantled and backfilled with earth and stone.

4) After the initial support of both side guide holes is completed and monitored and stabilised, the CRD method will be adopted for the construction of the middle guide hole, and the No.7 guide hole will be excavated first to carry out the initial support of the first and second layers.

5) 15 metres after the excavation of the No.7 guide hole, the No.8 guide hole will be excavated and constructed in the same order as No.7.

6) After the completion of the second layer of initial support for the large span arch, the third layer of initial support will pass through the adjacent steel frame and carry out shotcrete construction.

7) After the completion of the third layer of support for the large span arch, the construction of the middle and lower steps of the middle guide hole will be carried out, and the remaining guide holes will continue to adopt the CRD method, with the palm faces staggered by 5 metres.

3.3 Comparative analysis of numerical simulation and field testing

Three measurement lines were arranged in the finite element model, as shown in Figure 4, with 13 measurement points A1-A13 on line 1, 12 measurement points B1-B14 on line 2, and 8 measurement points C1-C8 on line 3.

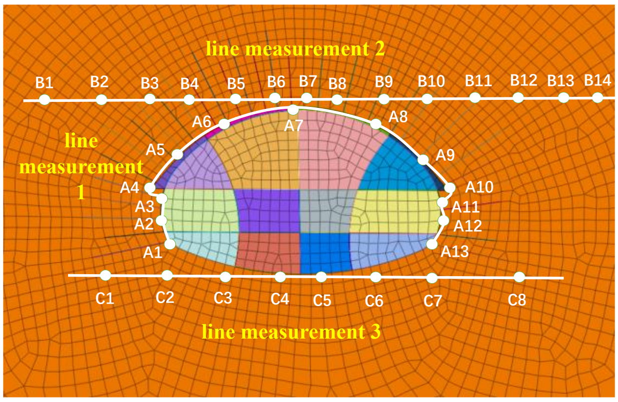


Figure. 4 Model line graph.

A schematic diagram of the location of the field measurement points is shown in Figure 5, the data simulated settlement values and some of the field monitoring settlement data values on site are shown in Table 2, a schematic diagram of the data simulated settlement values and some of the field monitoring settlement data on-site is shown in Figure 6, and the data simulated settlement graphs after one phase of excavation are shown in Figure 7.

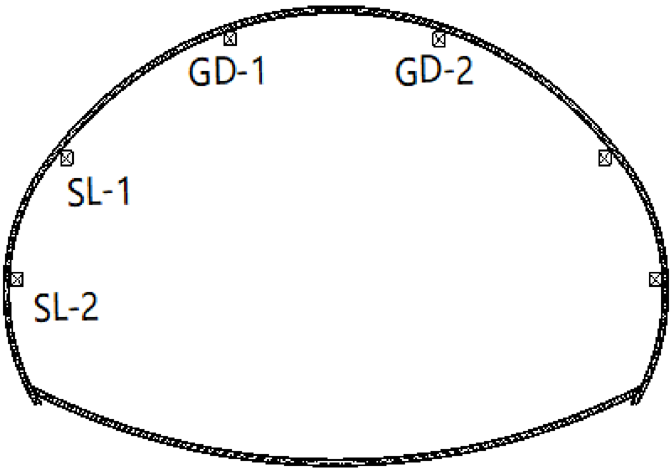


Figure. 5 Schematic diagram of measurement point location

Table. 2 Data modelled settlement values and selected site field monitoring settlement data

Measurement point location	Simulated settlement values /(mm)	0+005 Settlement value at mileage /(mm)	0+015 Settlement value at mileage /(mm)	0+025 Settlement value at mileage /(mm)	0+045 Settlement value at mileage /(mm)
GDMRK-2	3.2	4.3	7.0	6.0	6.2
GDMRK-1	2.8	3.9	6.1	5.9	5.3
SLMLK-1	4.5	6.5	6.9	6.6	7.3
SLMLK-2	3.4	5.0	4.7	6.2	7.2

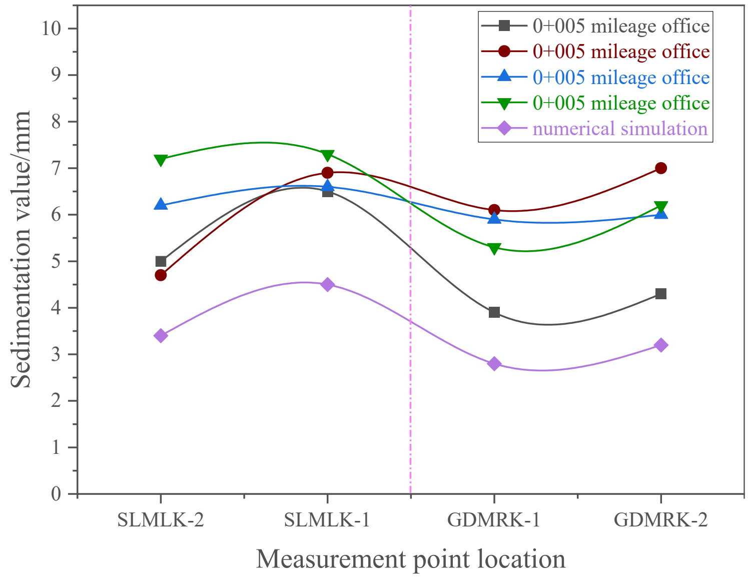


Figure. 6 Schematic diagram of data-modelled settlement values and some site field monitoring settlement data.

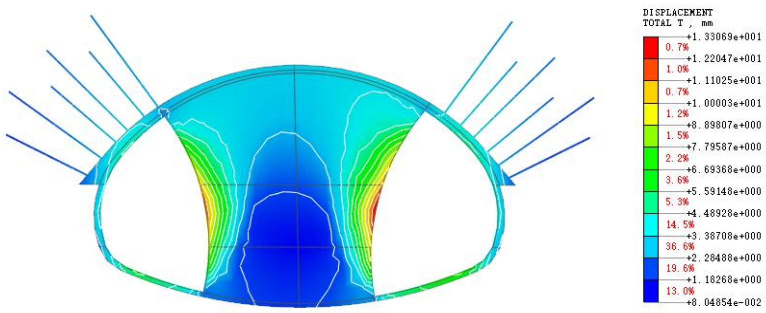


Figure. 7 Simulated settlement of data after one stage of excavation.

The field monitoring data after one stage of excavation was taken and compared with the numerical simulation data after one stage of excavation (Figure. 6). As can be seen from Figure. 6, the first group of 0+005 miles to the fourth group of 0+045 miles of the field data roughly showed a trend of increasing and then stabilising. Specifically, mileage 0+005 is relatively low, while mileage 0+015 increases significantly, followed by mileage 0+025 and 0+045 being relatively stable.

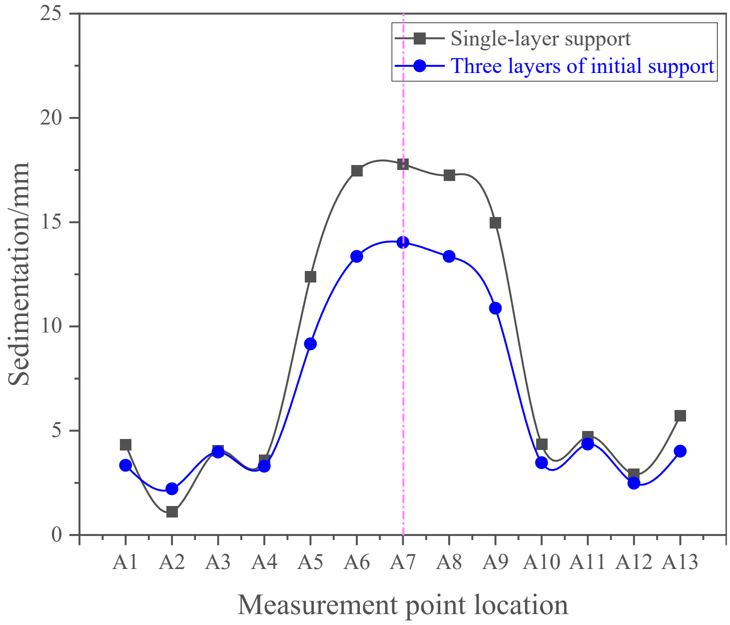
The numerical simulation data trends are closer to mile 0+005, with both having lower values. Although the specific values are different, it can be seen that the simulated data have a similar trend to the field measurements at mile 0+005. The average settlement value at mile 0+005 is approximately 4.93, the average settlement value at mile 0+015 is approximately 6.18, the average settlement value at mile 0+025 is approximately 6.18, and the average settlement value at mile 0+045 is approximately 6.50. The numerical simulation data have an average value of 3.48. The average value of numerical simulation data is 3.48.

The field data had a wide range of fluctuations, ranging from 3.9 to 7.3, while the numerically modelled data had smaller fluctuations, concentrating between 2.8 and 4.5. This suggests that the numerically modelled data is less discrete and more focused. Although there are differences in specific values between the numerical simulation data and the field data, it can be seen that the simulated data are close to the 0+005 mileage of the field data. This may be because the simulated conditions are more similar to the field conditions at mile 0+005, indicating that the numerical simulation can reflect the actual situation to a certain extent.

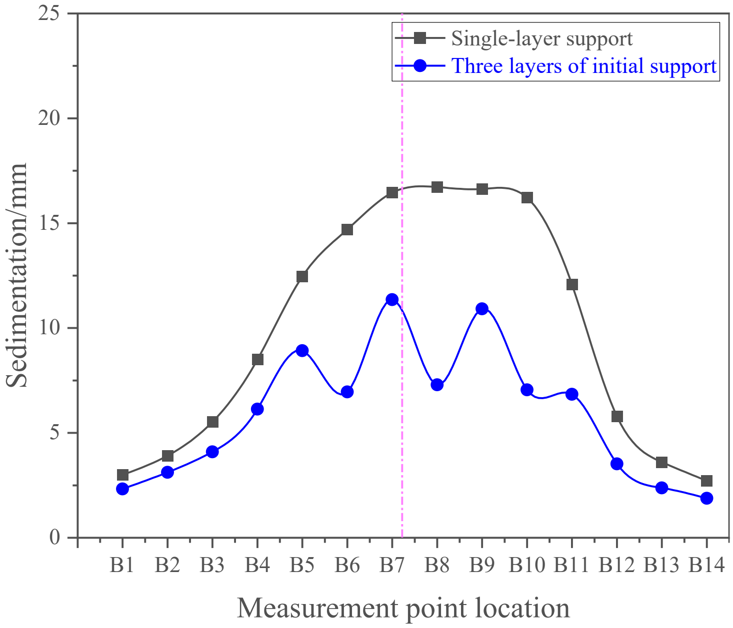
The values of the numerical simulation data are generally lower than those of the field data, which may be due to the deviation of some parameter settings in the simulation process from the actual situation, but the overall trend is similar, which is of important reference value and research significance.

3.4 Displacement and settlement analysis of three-layer support construction versus single-layer support construction

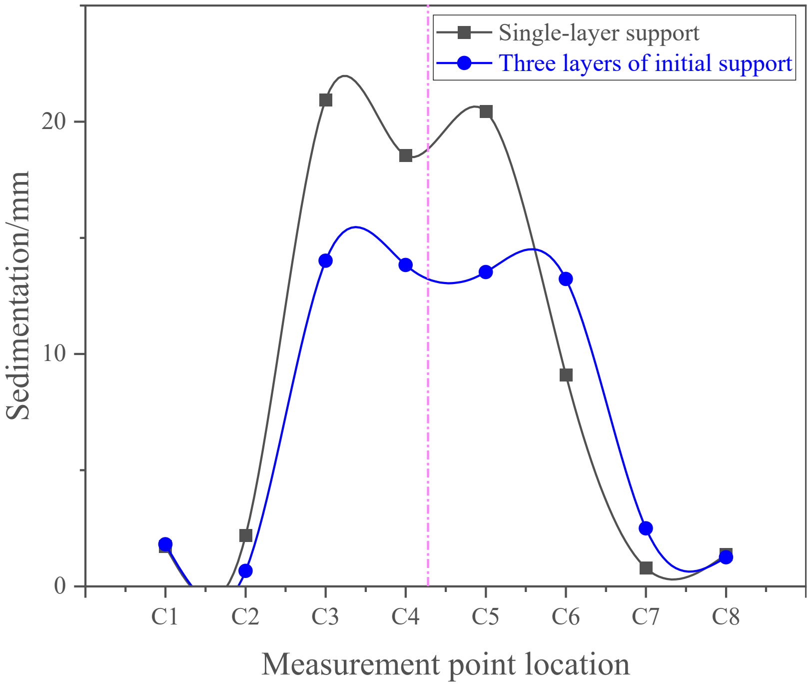
Similarly, the right-span tunnel is taken for the numerical simulation of single-layer support, and the parameters used are the same as those used in the simulation of three-layer support, with the same simplifications and assumptions for comparison. To reflect the comparability, the excavation sequence of the single-layer support is also highly the same as that of the three-layer initial support.



(a) Schematic of settlement displacement of survey line 1



(b) Schematic of settlement displacement of survey line 2



(c) Schematic of settlement displacement of survey line 3

Figure. 8 Schematic of settlement displacement at survey line.

From Fig. 8(a), it can be seen that the single-layer initial support data (A1-A13) are distributed between 1.1115 mm and 17.7802 mm, while the three-layer initial support data are distributed between 2.2118 mm and 14.0277 mm, which shows that the three-layer initial support is more effective in controlling settlement. The maximum settlement value of single-layer initial support is 17.7802 mm and the minimum is 1.1115 mm, while the maximum value of three-layer initial support is 14.0277 mm and the minimum is 2.2118 mm, which shows that the three-layer support is more effective in controlling the large settlement. In addition, the average settlement value of the single-layer initial support is 8.4967 mm, while the average settlement value of the three-layer initial support is 7.0035 mm, which indicates that the three-layer support is more effective in reducing the settlement as a whole. Meanwhile, the single-layer initial support data fluctuates greatly, with higher peaks and lower valleys, while the three-layer initial support data is relatively smooth, indicating that the support effect is more balanced. Comprehensively, compared with single-layer initial support, three-layer initial support can better control tunnel settlement and improve the safety and stability of the project.

From Fig. 8(b), it can be seen that the settlement values of the single-layer initial support data (B1-B14, in mm) are distributed between 2.714 and 16.72627 mm, whereas the three-layer initial support data are distributed between 1.8825 and 11.35745 mm, which shows that the three-layer initial support is more effective in controlling the large settlements. Specifically, the maximum settlement value for the single-layer initial support was 16.72627 mm (B8) and the minimum settlement value was 2.714 mm (B14), while the maximum settlement value for the three-layer initial support was 11.35745 mm (B7) and the minimum settlement value was 1.8825 mm (B14). The maximum settlement value of the three-layer initial support is 5.36882 mm less than that of the single-layer initial support, indicating that the three-layer support is more effective in controlling the large settlement. In addition, the average settlement value of single-layer initial support is 8.11268 mm, and the average settlement value of three-layer initial support is 6.35486 mm, which indicates that the three-layer support can effectively reduce the settlement in general. The data of single-layer initial support fluctuates greatly, and the difference between peak and trough values is large, while the data of three-layer initial support is relatively more stable, and the fluctuation range is small, which indicates that the support effect is more balanced.

From Fig. 8(c), it can be seen that the maximum settlement value of the three-layer initial support is 14.0127 mm, which is significantly lower than that of the single-layer initial support with a maximum settlement value of 20.94439 mm, showing that the three-layer initial support is more effective in controlling the large settlement. The average settlement value of the single-layer initial support is 9.26415 mm, while the average settlement value of the three-layer initial support is 7.10319 mm, which indicates that the three-layer support is more effective in reducing the settlement in general. In addition, the single-layer initial support data fluctuates greatly, and the difference between the peak value and the trough value is large, while the three-layer initial support data is relatively more stable, with a smaller fluctuation range, indicating that the support effect is more balanced. Comprehensively, the three-layer initial support is better than the single-layer initial support in reducing settlement,

controlling the large settlement value and providing a more stable support effect, which improves the safety and stability of the project.
In conclusion, the three-layer initial support is more effective than the single-layer initial support.

IV. REINFORCED ANTI-TILTING LIMIT STEEL ARCH TECHNOLOGY FOR LARGE-SPAN TUNNELS WITH ULTRA-LARGE SECTIONS

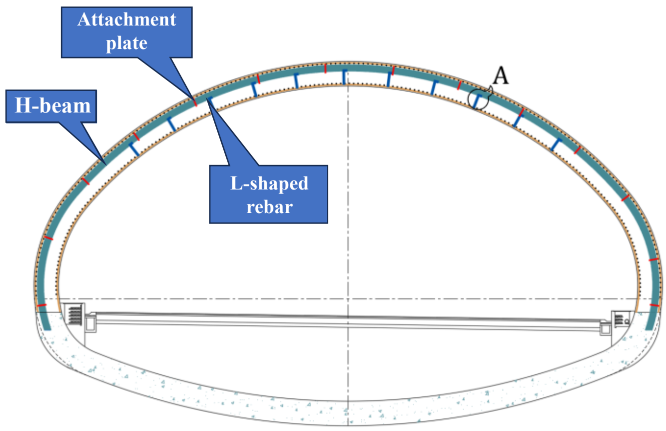
4.1 Overview of workmanship

The maximum excavation span of this project is 30.5 metres, and the excavation height is 18.06 metres. To prevent the large span reinforcement bars from tipping over during the installation process, the project has adopted the limiting steel arch to bear the self-weight of the outer reinforcement bars, and welded the 'L' type reinforcement bars to hang the inner reinforcement bars, to enhance the stability of secondary lining reinforcement bars. The secondary lining of the arch wall was poured at one time, with a large span of reinforcement, and the design was four layers of C28 main reinforcement, which was self-important and had a high risk of overturning. The project department creates a unique anti-tilting technology for the limited steel arch to prevent the large-span reinforcement from tipping over during the installation process.

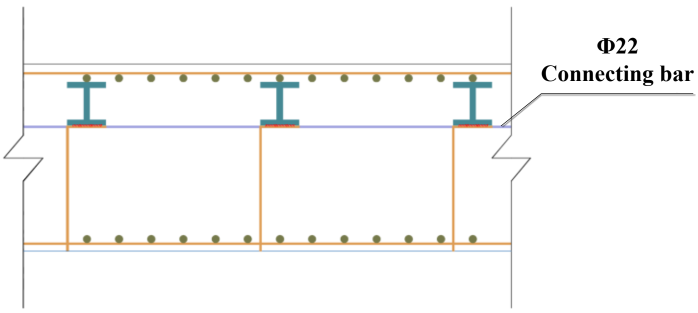
4.2 Technical overview

Combined with the project span tunnel section 'big span' characteristics, to prevent tipping damage during construction, and not destroy the waterproofing system, safety can meet the requirements, the project cost to meet the actual, the use of I-beam steel frame reinforcement. That is, the use of I-beam steel reinforcement of the steel skeleton, longitudinal spacing according to the design of the value of the calculation, the steel frame inside the use of C22 rebar welded connections, ring spacing 2 m, hanging bar using C25 rebar, each ring of I-beam hanging point spacing of 2 m, longitudinal spacing with the spacing of the I-beam.

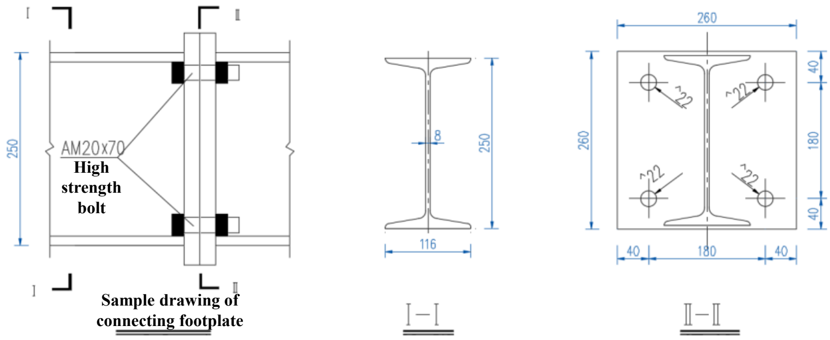
Pre-embedded footing connectors are on both sides of the back-arch concrete, while high-strength bolts are pre-embedded in the back-arch concrete together with the footing connecting plate. The I-beam skeleton is assembled section by section using high-strength bolts and nuts on the steel frame connection plate, and effectively connected with the footing connectors to become a whole. The length of the I-beam inserted into the poured concrete of the back arch is not less than 1 m. The structural diagram of the I-beam reinforcement is shown in Fig. 9, and the site plan of the oversized cross-section reinforced anti-tilting limit steel arch is shown in Fig. 10.



(a) Large span I-beam diagram



(b) Part a sample drawing



(c) Sample drawing of connecting footplate
Figure. 9 Option 2 I-beam reinforcement.

(a) Steel arch site plan

(b) Steel arch installation diagram
Figure. 10 Site plan of oversized cross-section reinforced anti-tilting limit steel arch.

4.3 Advantages of workmanship

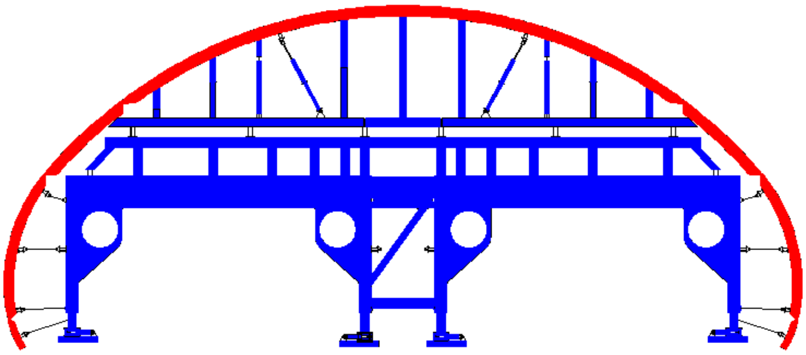
The limited steel arch anti-tilting technology has demonstrated significant advantages of the method by improving structural stability, reducing construction risks, and improving construction accuracy and efficiency in the construction of the large-span tunnel in this project. The innovative application of this technology effectively ensures construction safety and quality and provides effective technical support for the construction of large-span tunnels.

V. WALKING MULTI-SECTION LINING TROLLEY TECHNOLOGY FOR LARGE SPAN TUNNELS WITH CONTINUOUS ARCHES

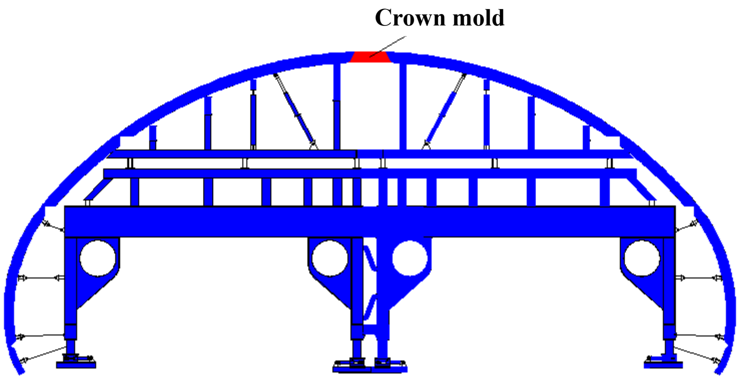
5.1 Overview of trolley construction

According to the project construction planning and on-site construction situation, the left and right lines of the inlet tunnel span one and span two are equipped with a second lining trolley to meet the pouring construction of the tunnel arch wall lining. The length of the left span 1 and span 2 tunnels is 105 m, and the length of the right span 1 and span 2 tunnels is 90 m. The thickness of the left span 1 lining is 110 cm, the thickness of the span 2 lining is 105 cm, the thickness of the right span 1 lining is 100 cm, and the thickness of the span 2 lining is 90 cm.

This project's mega-span walk-in multi-section lining trolley is mainly composed of three parts: steel structure system, hydraulic system and electrical system. The cross-section schematic diagram of the trolley is shown in Figure 11, and the site construction drawings of the large-span second-lining trolley are shown in Figure 12.

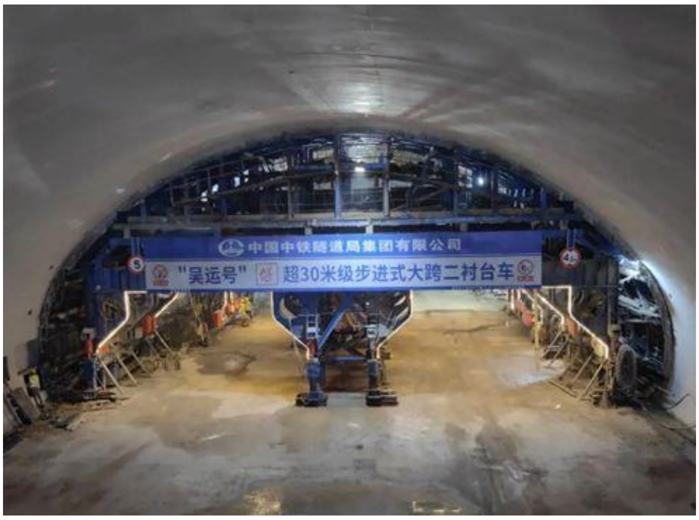


(a) Schematic cross-section of a large-span (I) trolley



(b) Schematic cross-section of a large-span (II) trolley

Figure. 11 Schematic cross-section of overspan step-in multi-section lining trolley.



(a) Overall view of large span second lining trolley

(b) Detailed view of the roof mould and some columns of the large span second liner platform car

Figure. 12 Large span second lining trolley site construction plan.

5.2 Advantages of workmanship

The application of the stepping combination trolley, through the combination of the stepping travelling system and the fast variable section technology, not only improves the construction efficiency and precision but also demonstrates significant advantages in terms of safety, cost control and environmental protection. The innovative application of these methods provides an effective solution for the lining construction of large and multi-section tunnels and ensures the smooth progress of the project.

VI. CONCLUSION

i. For the project 'three-layer initial support' technology, the use of finite element software, ordinary support and three-layer support for the construction of comparative analysis, the results show that the three-layer support on the whole is more effective in reducing settlement. The single-layer initial support data fluctuates greatly, and the difference between the peak value and the trough value is large, while the three-layer initial support data is relatively more stable, with a smaller fluctuation range, indicating that the support effect is more balanced. The three-layer initial support is better than the single-layer initial support in reducing settlement, controlling large settlement values, and providing more stable support effects, which improves the safety and stability of the project.

ii. This project's 'Reinforcement Anti-Tipping Restricted Steel Arch Technology' effectively prevents the risk of large-span reinforcing bars tipping over during installation by increasing the overall stability of the reinforcing steel skeleton. This technology optimises the support structure of the reinforcement skeleton and ensures the stability of the reinforcement during the construction process, thus improving the safety of the overall structure. Rapid section change technology can quickly achieve the conversion of different sections without dismantling the overall frame of the trolley, only by replacing a small piece of top mould and part of the columns and contracting the two frames horizontally, which improves the construction efficiency of the trolley and ensures the quality of the construction, and at the same time, significantly reduces the operational risks brought by multiple dismantling and installation.

iii. The project's 'Large-span Stepping Multi-section Lining Trolley Technology', through the combination of a stepping travelling system and rapid section change technology, not only improves the construction efficiency and precision but also demonstrates significant advantages in terms of safety, cost control and environmental protection. The innovative application of these methods provides an effective solution for the lining construction of large and multi-section tunnels and ensures the smooth progress of the project.

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