# Research on the Adaptability of Mechanized Construction Methods for Highway Tunnel Sections with Shallow Burial and Asymmetric Loading

Yichun Huang[1], Xiaoyue Kang[2,a], Kai Xu[2,3,b*], Xingyu Chen[1], Dongxing Liu[2,c]

[1]Tunnel and Underground Engineering Research Institute., Zhejiang Communications & Investment Transportation Construction Management Co. Ltd., Ningbo, China
[2]Tunnel and Underground Engineering Research Institute., China Merchants Chongqing Communications Technology, Research and Design Institute Co.,Ltd., Chongqing, China
[3]State Key Laboratory of Hydraulics and Mountain River, Engineering, College of Water Resource and Hydropower, Sichuan University, Chongqing, China

[a]island8492@163.com, [b]xukai7@cmhk.com, [c]liudongxing@cmhk.com
*Corresponding author

**Abstract.** To address the mismatch between construction techniques and efficiency in the context of mechanized construction, as well as the construction risks associated with significant uneven deformation faced by tunnels in shallow-buried and biased portal sections, an innovative approach using the "double-sided heading method for the upper hemisection and bench method for the lower hemisection" is proposed to replace traditional construction methods. Numerical simulations were conducted to calculate the deformation characteristics of the tunnel structure and surrounding rock. The results indicate: (1) The deformation of the surrounding rock gradually increases as tunnel excavation progresses, but within the construction cycle, the settlement deformation of the surrounding rock remains within a controllable range; (2) The maximum lateral deformation of temporary support increases initially with the advancement of construction steps, then decreases, and ultimately stabilizes by the sixth construction step; (3) The settlement deformation of the pipe shed exhibits a similar trend to the deformation of the surrounding rock, both gradually increasing as construction progresses. These findings suggest that the application of the new construction method in the context of mechanized construction not only improves construction efficiency but also ensures construction safety.

**Keywords:** highway tunnel; mechanized construction; method adaptability; numerical simulation

## 1 Introduction

Tunnel engineering, as the cornerstone of modern transportation networks, has always attracted close attention from the engineering community regarding innovations in its


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construction techniques and methods. However, against the backdrop of the strong promotion of mechanization in tunnel construction by the state and the industry, coupled with the special requirements posed by the complex and variable geological conditions at construction sites on the spatial layout of mechanized operations, traditional construction methods are gradually showing signs of fatigue in terms of improving efficiency and adapting to mechanized operations. Especially in the construction of shallow-buried and unevenly loaded entrance sections, how to effectively enhance construction efficiency while ensuring the safety and stability of the project has become a core challenge that urgently needs to be overcome[1]-[2].

Regarding tunnel construction techniques under conditions of shallow burial and unevenly loaded surrounding rock, numerous industry experts[3]-[5], based on specific engineering practices, have comprehensively analyzed the challenges faced in the construction of tunnel portal sections, such as shallow burial, uneven loading, and poor rock quality, and have implemented targeted technical measures within the mountain location and tunnel body. Meanwhile, to promote the widespread adoption and in-depth development of mechanized construction in highway tunnels in China, many scholars and experts have conducted systematic and in-depth research from various dimensions and levels. In terms of mechanized construction techniques, Hong Kairong[6] pointed out from a macro perspective that tunnel and underground engineering construction in the 21st century should follow the scientific development concept of "people-oriented, pursuing comprehensive, coordinated, and sustainable development." Ning Wenguang and his team[7] conducted special research on the mechanized supporting scheme for excavation and support operations in large-section shallow tunnels. Bai Langfeng[8], based on the drilling and blasting method for typical highway tunnels, conducted optimization research on bench height, support structure parameters, bench length, and face stability, and proposed a design scheme suitable for mechanized construction in highway tunnels. Based on the Yangjiawopu super-long and large-section highway tunnel project of the Chengde-Pingquan section of the Capital Ring Expressway G95, Mei Min[9] and others proposed the supporting principles for large-scale mechanized equipment that are "adapted to geological conditions, low in environmental pollution, matched in performance, reliable in function, advanced in technology, controllable in cost, and highly versatile". Xue Jun[10] and others, combining the East Tianshan super-long highway tunnel project, summarized a set of mechanized supporting schemes suitable for full-face excavation of Class IV surrounding rock tunnels through field tests.

Previous literature has fully demonstrated that the improved traditional construction methods have been widely verified and applied in numerous projects in terms of safety and stability. However, these traditional methods still struggle to meet the demands of mechanized construction operation space under policy guidance. In view of this, the "upper semi-section double-side heading method and lower semi-section bench method" was innovatively proposed to replace the traditional construction methods in the Xianjianling Tunnel project. Although this method successfully reduced the construction sequences and improved construction efficiency, the mechanical effect of space unloading during excavation would also differ significantly, subsequently affecting the stress characteristics of the support structure and having a significant impact on the overall construction safety of the tunnel. Therefore, it is necessary to explore the safety and applicability of this new method in the shallow-buried and laterally loaded section of the entrance of the Xianjianling Tunnel, in order to provide useful references for similar projects.

## 2 Project Overview

As the longest tunnel along the entire Shenhai Expressway, the Xiangjianling Tunnel stretches for a total length of 2,244 meters, making it also the longest separated eight-lane tunnel in the Ningbo area. The maximum excavation section width reaches 22.8 meters, with an excavation height of 14.9 meters. The entrance of its left line (As shown in Fig 1) is located at the foot of a hill, characterized by a steep slope and shallow burial of the tunnel. The surface overburden consists of unevenly thick silty clay containing breccia, underlying which is the severely weathered and fractured V-grade Lower Cretaceous Xishantou Formation crystalline tuff of the lower Cretaceous period. Coupled with the influence of faults and crushed rock masses, the stability of the surrounding rock is extremely poor. Additionally, the abundant groundwater conditions and the permeable geological situation increase the risk of water seepage during excavation, adding to the construction difficulty and safety risks.

On the other hand, in response to policy directives and to ensure rapid construction progress, the project department carefully formulated a specialized construction plan for mechanized operations based on the actual conditions and design requirements of the Xianjianling Tunnel. They introduced a suite of machinery and equipment, including "intelligent multi-arm drilling jumbos," "automatic wet-shotcrete spraying robots," "full-section monolithic lining trolleys," and "3D laser scanners.".

**Fig. 1.** The entrance section of the left line of the Xiangjianling Tunnel

## 3 Establishment of a Computational Model

The calculation in this instance intends to adopt the three-dimensional stratigraphic structural method, which encompasses rationalized stratigraphic simulation, structural simulation, construction process simulation, and simulation of their interactions. The core concept of this method is to treat the lining and stratigraphy as a whole, calculating their internal forces separately, and using these calculations to assess stratigraphic stability and design structural cross-sections. Compared to the load-structure method, the stratigraphic structural method considers the interaction between underground structures and surrounding stratigraphy more comprehensively, enabling a more realistic simulation of structural internal forces and stratigraphic deformations under each construction condition. Prior to establishing the finite difference numerical model, we assume that the rock mass is an ideally elastic-plastic, isotropic, and homogeneous medium, and we neglect the time effect of its deformation, treating the vertical geostress field as a gravitational stress field.

## 3.1 Calculation Parameters

During numerical calculations, the Mohr-Coulomb model is adopted for geotechnical materials, while the elastic model is used for support structures. The material parameters are selected based on geological exploration documents, design drawings, and relevant specifications. The specific material parameters are shown in Table 1.

**Table 1.** Material Parameter Table

| **Material** | **Cohesion /MPa** | **Angle of internal friction /°** | **Elastic modulus /MPa** | **Poisson's ratio** | **Tensile strength /MPa** | **Compressive strength /MPa** |
|---|---|---|---|---|---|---|
| Upper half section | 0.2 | 25 | 1800 | 0.39 | 0.64 | 12.70 |
| Lower half section | 0.5 | 30 | 3650 | 0.31 | 0.90 | 20.00 |
| Φ25×5 Hollow grouting anchor bolt | / | / | 200000 | / | 360.00 | 360.00 |
| C25 steel fiber shotcrete | / | / | 30000 | / | 3.07 | 23.80 |
| C25 shotcrete | / | / | 26000 | / | 1.27 | 13.50 |
| Φ6 steel mesh | / | / | 200000 | / | 270.00 | 270.00 |
| Pipe shed | / | / | 800000 | / | 450.00 | 450.00 |

## 3.2 Construction Sequence

The specific construction steps for the change in tunneling method for the current tunnel entrance section are shown in Fig 2. Combined with the special construction plan table for the Xiangjianling Tunnel, the specific construction process for entering the tunnel is as follows:

Step 1: Calculate and balance the initial ground stress in the model.

Step 2: Excavate the upper half of the left guide tunnel, perform initial support, and construct temporary middle walls, with an advance of 1m per cycle.

Step 3: Excavate the upper half of the right guide tunnel, perform initial support, and construct temporary middle walls, with an advance of 1m per cycle.

Step 4: Excavate the three-part core soil, and perform initial support for the arch section, with an advance of 1m per cycle.

Step 5: Excavate the four-part core soil, with an advance of 2m per cycle.

Step 6: Excavate the five-part middle bench, perform initial support for the middle bench, with an advance of 2m per cycle.

Step 7: Demolish the temporary middle walls, excavate the six-part middle bench, perform initial support, perform the second layer of initial support for the arch and wall, with an advance of 2m per cycle.

Step 8: Excavate the seven-part section, perform the first and second layers of initial support, construct the inverted arch and its backfill, and perform molded secondary lining.

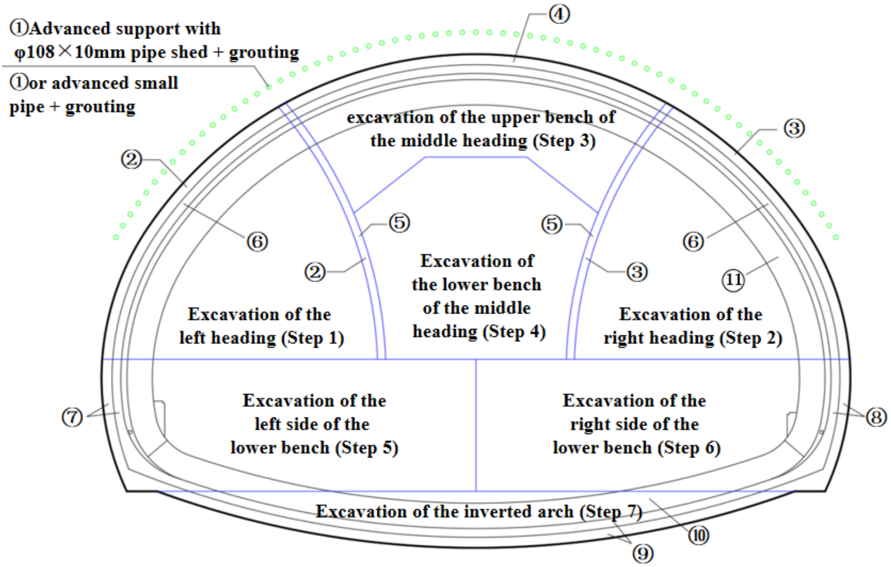
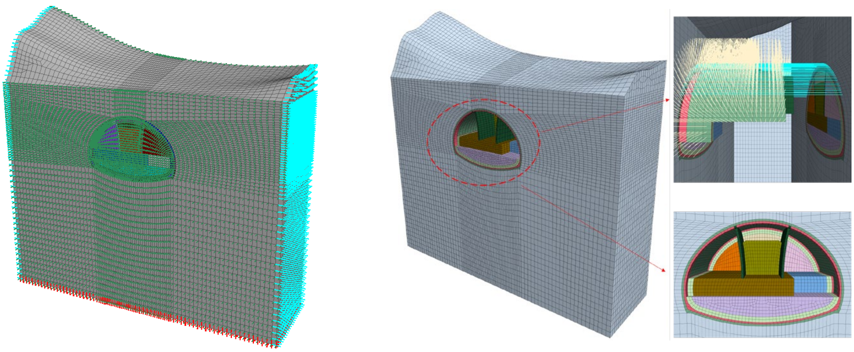



**Fig. 2.** Diagram of Adjusted Construction Sequence for the Method

## 3.3 Calculation Model

The length of the model is set at 70m (more than 3 times the tunnel diameter), with a width of 20m. The tunnel invert is positioned 60m away from the bottom boundary of the model, while the top surface is modeled based on actual topographic information. The tunnel utilizes support measures such as advanced large pipe roofs, grouting anchor rods, and grouting small pipes. The initial support is designed as a double-layer steel frame shotcrete concrete structure, incorporating steel fiber shotcrete, steel mesh, and I-beam steel frames to provide significant support. The secondary lining adopts 75cm-thick cast-in-situ reinforced concrete to ensure long-term stability and safety of the tunnel.



(a) Model Boundary Conditions (b) Three-Dimensional Schematic Diagram

**Fig. 3.** Model Boundary Conditions and Three-Dimensional Schematic Diagram

The boundary conditions are set as shown in Fig 3(a), the ground surface is allowed to deform freely, while the other boundaries are fixed. The load only considers the self-weight of the tunnel structure and surrounding rock, without accounting for the effect of groundwater. Different structural types are simulated using solid elements and Cable elements to ensure the accuracy and efficiency of numerical calculation results.

Mesh generation is a crucial step in numerical calculation. The mesh in key areas of interest is finer, while it is coarser in non-key areas. The model mesh element size is set according to requirements, ranging from 0.5m to 1.5m, all of which are hexahedral mesh elements. After completing the mesh size control, the model mesh elements shown in Fig 3(b) are generated using the built - in hybrid mesh generator of GTS NX.

## 4 Analysis of Construction Method Adaptability

The innovative construction method "upper semi-section double-side heading method and lower semi-section bench method," proposed to accommodate the implementation of mechanized construction techniques, has effectively avoided safety hazards and quality issues arising from technological mismatches. Additionally, it has significantly improved construction efficiency by optimizing the construction sequence. However, compared to traditional methods, the spatial unloading mechanical effect resulting from this change in construction method is more pronounced, posing a direct challenge to the stress characteristics of the supporting structure.

In light of this, a detailed adaptability analysis is conducted to verify the reliability of the new construction method by analyzing the deformation patterns of surrounding rock, temporary support, and pipe roof support structures during the excavation of the shallow-buried and laterally loaded portal section of the Xiangjianling Tunnel, using mechanized construction and the "upper semi-section double-side heading method combined with the lower semi-section bench method," across different construction sequences.

### 4.1 Settlement and Deformation of Surrounding Rock in the Portal Section

It can be seen from Fig 4 that the settlement deformation of the surrounding rock in the portal section of Xiangjianling Tunnel gradually increases with the progress of the tunnel excavation construction. This may be attributed to the fact that during the tunnel excavation process, the surrounding rock is disturbed by the excavation, causing its original mechanical equilibrium state to be disrupted, which leads to stress and deformation in the surrounding rock. As the excavation face continues to advance, this stress and deformation gradually accumulates, making the settlement deformation of the surrounding rock increasingly pronounced. Especially in the entrance section, due to the thin surface overburden and the presence of complex geological structures and weak rock formations, the settlement deformation of the surrounding rock may be more significant. This is the reason why it is important to discuss the deformation laws of the surrounding rock in the shallow-buried and biased-pressure sections of the tunnel entrance under new construction methods.

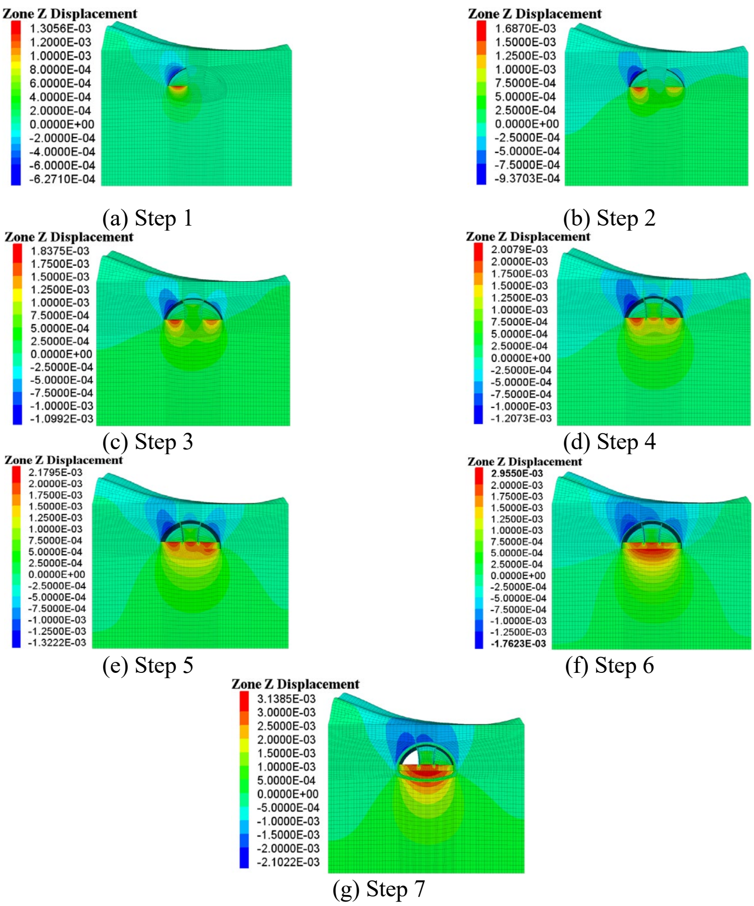



**Fig. 4.** Settlement and deformation of surrounding rock in the portal section

The deformation amounts of surrounding rock and surface at each construction stage were extracted and plotted in a cumulative deformation variation graph as shown in Fig 5, which illustrates the progression with construction stages. The graph reveals that, although the deformation of surrounding rock gradually increases with the advancement of tunnel excavation, the settlement deformation of surrounding rock remains within a controllable range during the construction period. This indicates that the construction method, employing the "upper semi-section double-side heading method combined with lower semi-section bench method" under mechanized construction conditions, and the supporting measures are effective in maintaining the stability of surrounding rock, preventing excessive deformation or instability failure. Additionally, it reflects that the deformation monitoring and control measures during the construction process were effectively implemented, ensuring the safety and quality of tunnel construction.

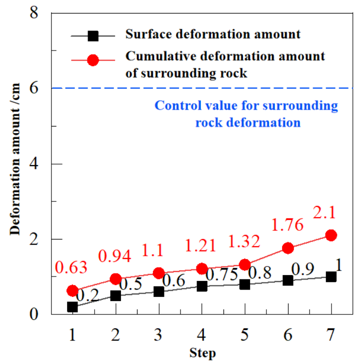



**Fig. 5.** Settlement and deformation of surrounding rock in the portal section

## 4.2 Lateral Deformation of Temporary Support

Extract the maximum horizontal deformation of temporary support at each construction stage and plot a graph, as shown in Fig 6, illustrating the variation pattern of the maximum deformation values as the construction stages progress.

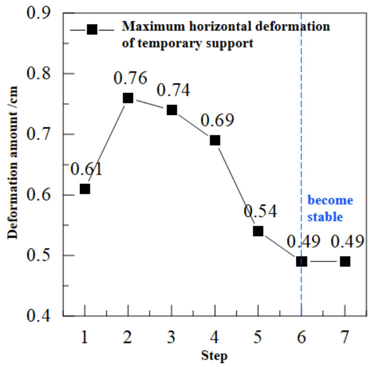
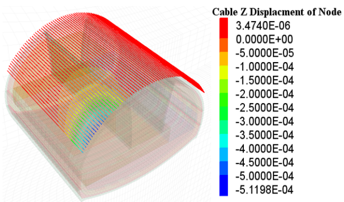



**Fig. 6.** The maximum horizontal deformation of temporary support at each construction stage

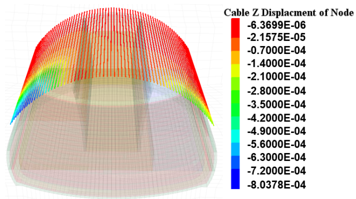
As shown in the diagram, the maximum horizontal deformation of the temporary support initially increases with the progress of construction steps, gradually decreases after the second construction step, and then tends to stabilize from the sixth construction step onwards. This indicates that as tunnel construction progresses, especially after effective support measures are taken, the support structure becomes better at resisting the pressure and deformation of the surrounding rock. Within the construction cycle, which refers to the period between the completion of one construction step and the beginning of the next, the horizontal deformation of the temporary support is strictly controlled within a range of 1cm. This data suggests that the deformation is generally controllable, ensuring both the safe progression of construction and the stability and durability of the tunnel structure.

### 4.3 Settlement and Deformation of Pipe Shed

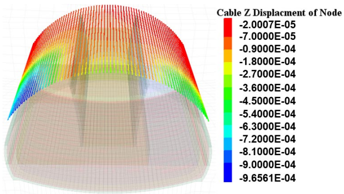
As can be seen from Fig 7, during the construction process of the tunnel entrance section, there is a noticeable shallow burial and bias pressure phenomenon. The settlement and deformation of the pipe roof within the scope of the left guide tunnel are significantly greater than those of other parts of the pipe roof. Therefore, during construction, it is imperative to strictly control the quality of the initial shotcrete application, strictly regulate the lap length of the steel mesh, rigorously manage the grouting effect of the anchor rods, and ensure the overall strength of the support structure.



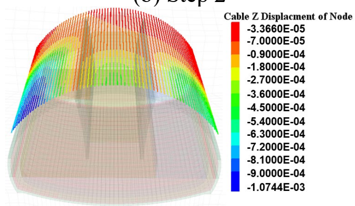

(a) Step 1



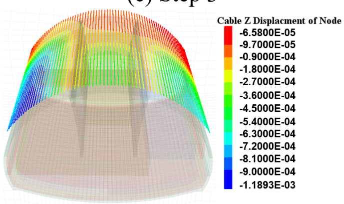

(b) Step 2



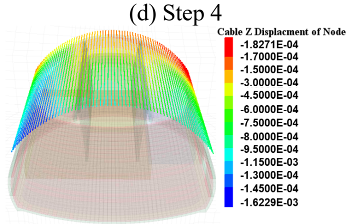

(c) Step 3



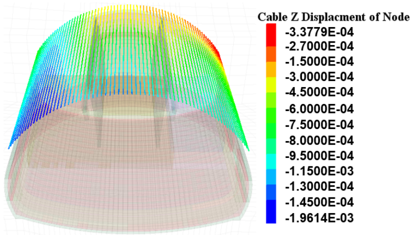

(d) Step 4




(e) Step 5




(f) Step 6




(g) Step 7

**Fig. 7.** Settlement and deformation of pipe roof support

Extract the settlement and deformation values of the pipe roof in each construction stage and plot the trend chart of pipe roof settlement and deformation under various construction stages as shown in Fig 8. From the chart, it can be seen that the settlement and deformation trend of the pipe roof is similar to that of the surrounding rock, both showing a gradual increase in settlement and deformation as the construction stages progress. This indicates that during the construction process, as part of the tunnel or underground engineering support structure, the settlement and deformation of the pipe roof are closely related to the deformation behavior of the surrounding rock, reflecting the impact of stratum disturbance and stress redistribution caused by underground excavation. As the construction stages continue to advance and the excavation face moves forward, the support conditions of the surrounding rock mass gradually deteriorate, thereby prompting corresponding settlement and deformation of both the pipe roof and the surrounding rock. Additionally, the gradual increase in settlement and deformation of the pipe roof also reminds us that during the construction process, close attention needs to be paid to the stability of the support structure, and necessary reinforcement measures should be taken promptly to prevent excessive deformation that may lead to engineering safety issues. By comparing the settlement and deformation data of each construction stage, important basis can be provided for subsequent construction decisions, ensuring the smooth progress of the underground engineering and the safety and stability of the final structure.

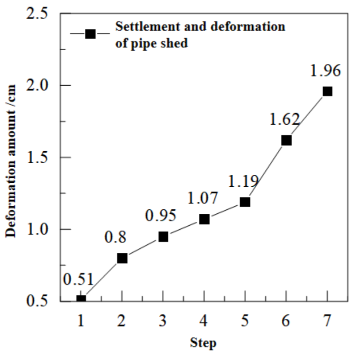



**Fig. 8.** Trend of settlement and deformation of the pipe roof in each construction stage

## 5 Conclusions

Based on the topographical characteristics of shallow burial and asymmetric pressure at the entrance section of the Xiangjianling Tunnel, a study on the tunnel structural mechanical response was conducted in the context of mechanized tunnel construction, involving the modification of the traditional "double-side heading method" to a "double-side heading method for the upper half-section and bench method for the lower half-section". The entire construction process was comprehensively simulated using numerical simulation technology. Based on the simulation results, the following main conclusions were drawn:

(1) As tunnel excavation progresses, the deformation of the surrounding rock gradually increases. However, within the construction cycle, the maximum settlement deformation of the surrounding rock is 2.1cm, which remains within a controllable range. The maximum lateral deformation of the temporary support initially increases and then decreases as the construction steps advance, ultimately stabilizing at the sixth construction step. The trend of settlement deformation in the pipe shed, on the other hand, is similar to that of the surrounding rock, both showing a gradual increase in settlement deformation as the construction steps progress. This demonstrates that the application of new construction methods in the context of mechanized construction not only improves construction efficiency but also ensures construction safety..

(2) Based on the comprehensive numerical calculation results, adjustments can be made to the construction process. Adopting the construction principles of "advanced geophysical exploration, pre-support, short excavation, rapid shotcrete-bolting, frequent measurements, and early lining," a feasible excavation plan and measures for the tunnel body should be formulated to ensure engineering quality. Additionally, the content of monitoring and measurement should be expanded, and the frequency of monitoring and measurement should be increased. If the deformation of the surrounding rock exceeds the design allowable value, in addition to taking measures to strengthen the support, timely feedback should be provided to the design unit.

## Acknowledgment

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