

Research on Deformation Monitoring and Optimization of Initial Support in Railway Tunnels under Different Surrounding Rock Grades

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Abstract : Based on the Ganzhou-Shenzhen High-Speed Railway Shimenshan and Songgangshan tunnel projects, this study systematically investigates the spatiotemporal evolution of deformation in the initial support of tunnels in Class III, IV, and V surrounding rock through extensive field monitoring as the tunnel face advances and over time. The analysis reveals that both crown settlement and peripheral convergence exhibit exponential growth with increasing distance from the tunnel face, generally stabilizing after exceeding three times the tunnel diameter. In terms of temporal evolution, deformation stabilizes approximately 15 days after excavation for Class III rock and 12 days for Class IV and V rock. The goodness-of-fit ($R^2 > 0.92$) for the spatiotemporal models is consistently high, indicating reliable model performance. Based on the characteristics of deformation stabilization, this study proposes reasonable control principles for advance lengths in bench cut construction. It also highlights that the monitored displacements are significantly lower than the limits specified in current design codes, suggesting favorable geological conditions along the alignment and indicating that existing control standards may be overly conservative. To enhance construction efficiency while ensuring safety, the optimal closure distance for the invert is further optimized: it is recommended to be approximately 210 m for Class III, 85 m for Class IV, and 60 m for Class V surrounding rock. The findings of this research can provide valuable references for deformation control, construction process optimization, and code revision in similar tunnel engineering projects.

Keyword: Deformation Monitoring; Construction Optimization; Invert Closure Distance; Time-Space Effect

I. Introduction

Tian XX et al. Error! Reference source not found. investigated the excavation advance length for soil tunnels constructed using the shallow-buried

tunneling method through theoretical derivation. Based on a logarithmic spiral failure mechanism, Liang Qiao et al. derived a calculation formula for the cyclic advance length, establishing the relationship between cyclic advance length and soil parameters.

In 1939, Griggs Error! Reference source not found. conducted creep tests on rocks such as limestone, shale, and sandstone. Over the following decades, numerous researchers have studied the rheological characteristics of rocks from various perspectives. Wawersik et al. Error! Reference source not found. performed shear creep tests on cylindrical granite specimens with artificial joint surfaces using a triaxial creep apparatus. Amadei et al. Error! Reference source not found. conducted a series of triaxial and shear creep tests on jointed surfaces, investigating the influence of shear stress ratios on rheological behavior. Okubo et al. Error! Reference source not found. employed a self-developed rigid testing machine to conduct full-process testing of uniaxial compression curves of rocks, obtaining strain-time relationship curves during the rock creep stage and proposing a constitutive equation describing the three-stage creep of rocks. Maranini et al. Error! Reference source not found. revealed the primary deformation mechanisms of rock creep through uniaxial and triaxial compression creep tests on limestone. Lee et al. Error! Reference source not found. conducted scaled model tests and analyses on the stability of the tunnel face under different cyclic advance lengths, confirming that face stability is significantly influenced by the cyclic advance length. Zheng F et al. Error! Reference source not found. established a three-dimensional numerical model using the finite element software MIDAS GTS NX 290 to determine reasonable excavation parameters for the three-bench seven-step excavation method applied in shallow-buried loess tunnels. Du et al. Error! Reference source not found. proposed a mechanical model to investigate rock-lining interaction under hydrostatic pressure. This model considers the variable mechanical properties (such as elastic modulus) of linings in rheological rock masses, providing valuable references for the safety

assessment of tunnels in service. Fu et al. ^{Error! Reference source not found.}, to determine the optimal exposed length and excavation length for arch crowns at different rock layer elevations, adopted the classical Burgers creep intrinsic structural model. Using a three-step excavation pattern and considering the closure distance and exposed distance of the inverted arch, they clarified the influence laws of tunnel invert excavation on the rheological deformation of surrounding rock at different levels.

The rheological deformation of surrounding rock after tunnel excavation exhibits typical time-space effects. As time and the exposed area increase, the load acting on the lining structure also continuously increases. Yaozhong C et al. ^{Error! Reference source not found.} calculated cumulative damage based on the data transfer method between solvers in ABAQUS software, providing a theoretical basis for selecting the excavation advance length in tunnels constructed using bench blasting. Li S et al. ^{Error! Reference source not found.} employed a three-dimensional continuum rapid Lagrangian analysis to simulate the spatiotemporal evolution of tunnel response during the excavation process. AN XX and Zhong ZL ^{Error! Reference source not found.} used numerical simulation methods to analyze the influence of invert closure distance on tunnel deformation and stress during the construction of tunnels excavated by the bench method, and validated the numerical simulation results with field monitoring data. Shreedharan et al. ^{Error! Reference source not found.} found that inverted arch tunnels may be more effective in reducing roof settlement and floor heave under existing geo-mining conditions.

Currently, most research focuses on the influence of excavation advance length and secondary lining support timing on tunnel stability in soft rock tunnels. There is limited research considering the impact of the time-space effects of invert construction on tunnel deformation and stress characteristics in soft rock tunnels under different surrounding rock grades. Therefore, further research should be conducted on the rheological properties of soft rock under different surrounding rock grades and the influence laws of the time-space effects of invert construction on tunnel stability.

II. Project Background and Monitoring Program.

The GSSG-2 bid section of the preceding works for the Ganzhou-Shenzhen High-Speed Railway, spanning from the Jiangxi-Guangdong provincial boundary to Tangxia, has a main line length of 38.777 km. The primary engineering content includes 20 tunnels totaling 25.911 km. The controlling and critical difficult works within this bid section are the Songgangshan Tunnel and the

Shimenshan Tunnel. Among them, the Songgangshan Tunnel, with a total length of 9,881 m, is the longest tunnel on the entire Ganzhou-Shenzhen Railway (Guangdong section) and passes beneath the subgrade of the Beijing-Kowloon Railway. The Shimenshan Tunnel has a total length of 5,759 m.

1) Songgangshan Tunnel: The portal chainages are DK145+747 (entrance) and DK155+628 (exit). The maximum burial depth of the tunnel is approximately 353 m. Along the tunnel alignment, Class V surrounding rock accounts for 1,469 m (14.9%), Class IV for 1,809 m (18.3%), Class III for 3,008 m (30.4%), and Class II for 3,595 m (36.4%).

2) Shimenshan Tunnel: The portal chainages are DK139+920 (entrance) and DK145+679 (exit). The maximum burial depth is approximately 340 m. Along the tunnel alignment, Class V surrounding rock accounts for 979 m (17.0%), Class IV for 960 m (16.67%), Class III for 3,010 m (52.27%), and Class II for 810 m (14.06%).

The geological conditions along the two tunnels vary considerably, necessitating frequent changes in construction methods. To ensure construction safety and enhance efficiency in sections with different surrounding rock grades, it is imperative to utilize monitoring data to propose optimization recommendations for parameters such as tunnel excavation advance length and invert closure distance tailored to these different rock grades.

Monitoring and measurement must be conducted during tunnel construction to promptly understand the behavior of the surrounding rock and the working state of the support system, thereby ensuring the stability of the surrounding rock and construction safety. Tunnel monitoring and measurement shall be implemented in accordance with the Technical Specification for Monitoring and Measurement of Railway Tunnels ^{Error! Reference source not found.} (Q/CR 9128-2024). The monitoring plan should be formulated based on factors such as tunnel size, topographic and geological conditions, support type and parameters, and excavation method. The monitoring results should be reported regularly to the relevant units.

Using existing known points outside the tunnel or traverse points inside the tunnel as the initial reference, monitoring reference points (designed to be stable, secure, and protected from damage) should be established in the secondary lining sections. The number of monitoring reference points should be 4 to 8. The layout pattern is as follows: a pair of control points is symmetrically installed on the left and right sidewalls approximately every 50-60 m. The control points should employ precision-manufactured product sets (including embedded parts and measurement rod

components). The embedment must be firm and stable. Their positions can be adjusted flexibly if line-of-sight conditions are affected. A total station can be used for crown settlement measurement. The measurement points should be connected to the tunnel's internal traverse points. Measurement points can be installed near the tunnel crown axis by welding or pre-

embedding via drilling. When using a total station, the setup of measurement points and the measurement method are the same as for tunnel clearance convergence measurement. The field monitoring data is collated and analyzed to obtain the deformation profiles for tunnel excavation under each surrounding rock grade, as summarized in Table 1.

Table 1 Summary of Tunnel Monitoring Cross-Section Conditions.

Surrounding Rock Grade	Burial Depth	Construction Method	Number of Cross-Sections
III	Deep Burial	Bench Cut Method	3
IV	Deep Burial	Three-Bench Method	3
V	Shallow Burial	Three-Bench Method with Temporary Invert	3

When the displacement-time curve tends to level off and converge, regression analysis should be performed. If an inflection point appears on the displacement-time curve or a sharp increase in displacement is observed, close monitoring should be conducted, early warnings should be issued, and the monitoring frequency should be increased. Furthermore, based on the monitoring data, a deformation prediction model should be established through regression analysis to guide on-site construction. Specifically, using the field measurement data, fitting analysis is conducted using exponential, logarithmic, and hyperbolic functions, respectively. The trial-and-error method is applied to select the best-fitting function for analysis, thereby deriving the displacement distribution pattern of the initial support. The proportion of initial support displacement relative to the ultimate displacement for each section is then provided.

III. Analysis of Initial Support Deformation Characteristics under Different Surrounding Rock Grades

3.1 Analysis of Initial Support Deformation Monitoring Data for Class III Surrounding Rock

For the deep-buried bench cut method

scenario in Class III surrounding rock, monitoring measurements were conducted at three stable cross-sections. Based on the measured data, regression analysis was performed separately for crown settlement and peripheral convergence to fit envelope regression curves. This analysis yielded the initial support displacement values for each tunnel section, their corresponding proportions relative to the ultimate displacement, and the spatial relationship between initial support displacement and excavation time. According to regression analysis theory, the coefficient of determination R^2 was used as the evaluation index to describe the fitting accuracy of the regression curves, as shown in Equation (1). The deformation monitoring results for the initial support in Class III surrounding rock are presented in Figure 1, where D represents the tunnel excavation diameter in meters. In this paper, D is uniformly taken as 14 m.

$$R^2 = 1 - \frac{\sum_{i=1}^N (y_i - f(x_i))^2}{\sum_{i=1}^N (y_i - \mu)^2}$$

(1)

3.1.1 Analysis of Spatial Characteristics of Tunnel Peripheral Deformation in Class III Surrounding Rock Sections

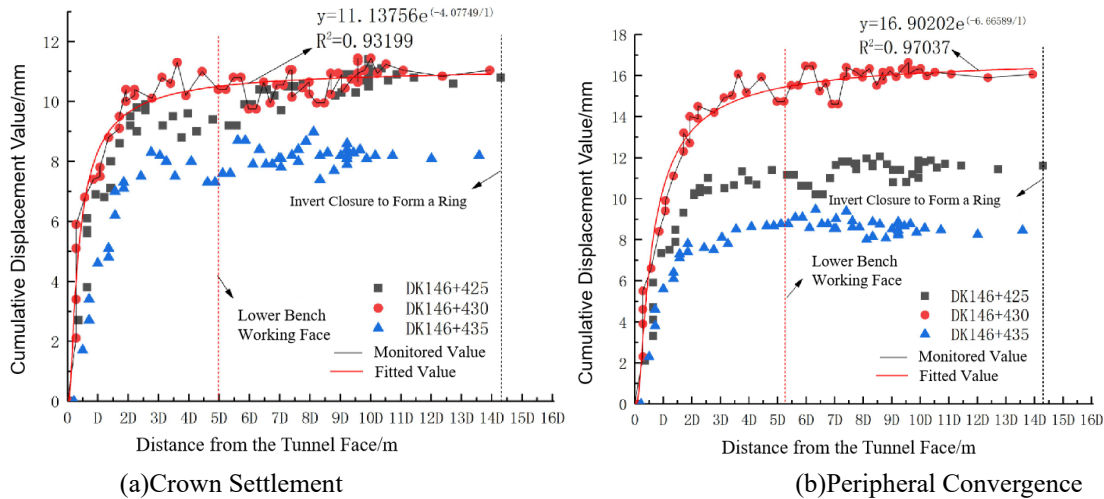


Figure 1 Analysis Diagram of Spatial Characteristics for Initial Support Deformation Monitoring in Deep-Buried Bench-Cut Tunnels within Class III Surrounding Rock

To quantify the deformation patterns, exponential functions were used to fit the variations of crown settlement and peripheral convergence with distance from the tunnel face. The goodness-of-fit (R^2) reached 0.932 and 0.970, respectively, indicating that the exponential model effectively describes the spatial evolution of deformation in this section.

Monitoring data show that for deep-buried bench-cut tunnels in Class III surrounding rock, the crown settlement and peripheral convergence of the initial support both follow an exponential function as the distance from the tunnel face increases. Specifically, at a distance of one tunnel diameter (D) from the face, crown settlement reached 68% of the ultimate displacement, and peripheral convergence reached 63%. At 3D, these values increased to 98% and 90%, respectively. Beyond 3D, displacement stabilized and approached the ultimate values. Overall, displacement essentially converged beyond a distance of 3D behind the tunnel face.

After the upper bench excavation stabilized, the subsequent excavation of the lower bench had minimal impact on the largely stabilized crown and peripheral displacements, with support displacements fluctuating only within a narrow range. The monitoring cross-section completed invert closure at approximately 14.5D (about 210 m) from the tunnel face. Prior to closure, at about 9D from the face, both crown settlement and peripheral convergence had entered a stage of minor fluctuations. This indicates that under these surrounding rock conditions, with an invert closure distance maintained at approximately 210 m, deformation around the tunnel can effectively

converge, and the initial support structure remains in a safe state.

3.1.2 Analysis of Temporal Characteristics of Tunnel Peripheral Deformation in Class III Surrounding Rock Sections

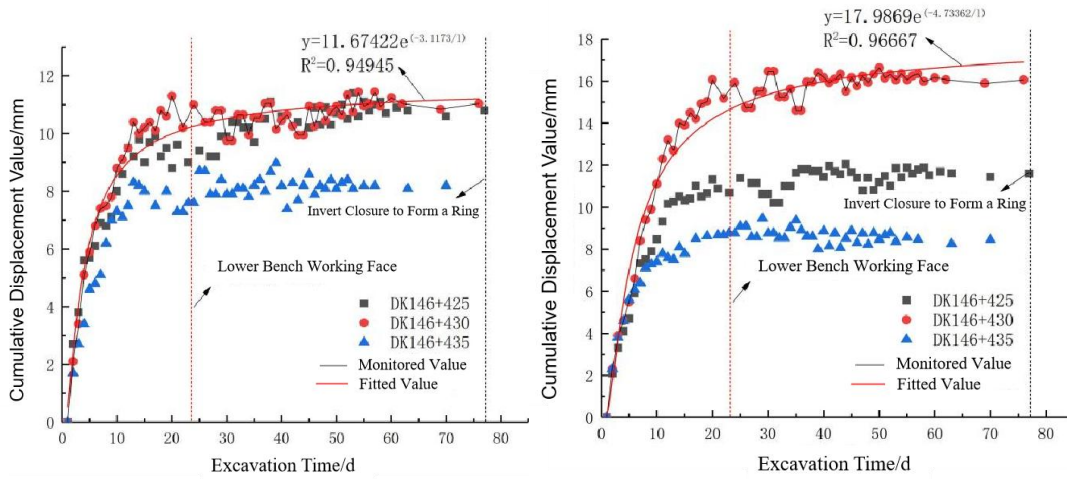
The monitored values of peripheral deformation at the cross-section of the lower bench were extracted and subjected to regression analysis, as illustrated in Figure 2. From a temporal perspective, an exponential function was fitted to the time-series deformation data. The goodness-of-fit (R^2) for crown settlement and peripheral convergence reached 0.949 and 0.967, respectively, indicating an excellent fit and confirming that deformation development over time also follows a distinct exponential pattern. Specifically, 5 days after the excavation of the monitoring cross-section, crown settlement had reached 52% of the ultimate displacement, while peripheral convergence had reached 40%. By day 15, these values increased to 81% and 88%, respectively. Beyond 15 days, the deformation trended towards stabilization.

Comparing the spatiotemporal evolution patterns reveals that the rate of deformation convergence over time is slightly slower than its convergence with distance. Once the excavation of the upper bench exceeds 4D, deformation tends to stabilize both temporally and spatially, making it safer to proceed with lower bench operations at this stage. The invert was closed 76 days after excavation. However, 45 days prior to closure (corresponding to a face distance of approximately 8.5D), the deformation had already entered a phase of minor

fluctuations. This indicates that, over time, deformation convergence precedes spatial stabilization. Once disturbances from subsequent construction activities diminish, deformation converges rapidly.

Based on the aforementioned results, it is recommended to moderately accelerate the

construction pace following lower bench excavation. Furthermore, closing the invert at a distance of 14 – 15D (approximately 210 m) from the tunnel face can effectively balance construction safety and efficiency.



(a)Crown Settlement

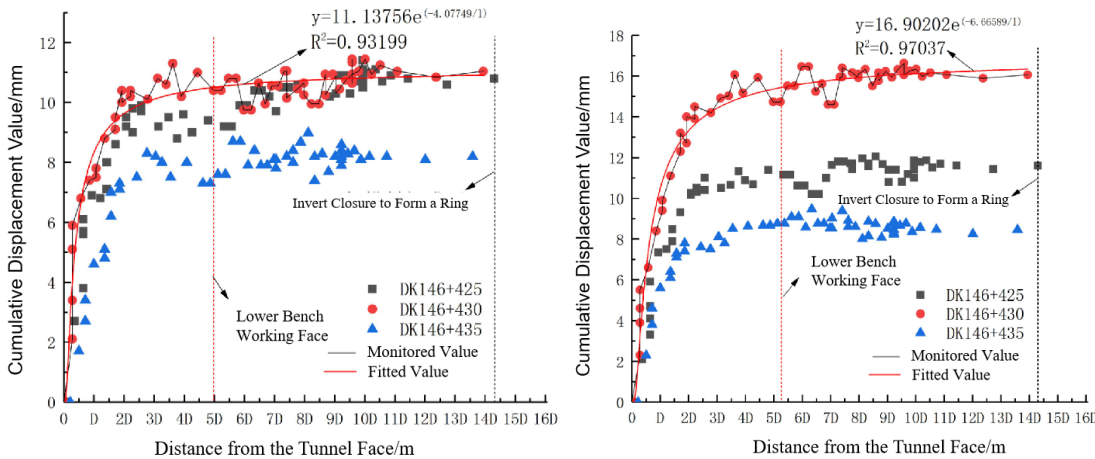
(b)Peripheral Convergence

Figure 2 Analysis Diagram of Temporal Characteristics for Initial Support Deformation Monitoring in Deep-Buried Bench-Cut Tunnels within Class III Surrounding Rock

3.2 Analysis of Initial Support Deformation Monitoring Data for Class IV Surrounding Rock

3.2.1 Analysis of Spatial Characteristics of Tunnel Peripheral Deformation in Class IV Surrounding Rock Sections

For the deep-buried bench cut method scenario in Class IV surrounding rock, monitoring measurements were conducted at three stable cross-sections, as shown in Figure 3.



(a)Crown Settlement

(b)Peripheral Convergence

Figure 3 Analysis Diagram of Spatial Characteristics for Initial Support Deformation Monitoring in Deep-Buried Bench-Cut Tunnels within Class IV Surrounding Rock

Fitting the deformation-spatial data for the Class IV surrounding rock section, the R^2 values of the exponential models for crown settlement and

peripheral convergence are 0.932 and 0.970, respectively, indicating strong model explanatory power. This again verifies the pattern that deformation follows an exponential change with the distance from

the tunnel face. The monitoring results show that the support deformation still develops according to an exponential law as the distance from the face increases, but the convergence process differs from that of Class III rock. At 1D, crown settlement and peripheral convergence have only reached 37% and 45% of the ultimate values, respectively. These values increase to 88% and 96% at 3D, indicating a relatively delayed deformation development, but stabilization is still achieved after 3D.

Similar to Class III rock, the excavation of the lower bench has a minor impact on deformation after the upper bench stabilizes. The invert closure distance in this section is 6.2D (approximately 87 m),

and deformation had already entered a state of minor fluctuations at about 6D before closure. This indicates that in Class IV surrounding rock, reducing the invert closure distance to around 87 m can still ensure deformation convergence and support safety.

3.2.2 Analysis of Temporal Characteristics of Tunnel Peripheral Deformation in Class IV Surrounding Rock Sections

For the deep-buried bench cut method scenario in Class IV surrounding rock, monitoring measurements were conducted at three stable cross-sections, as illustrated in Figure 3.

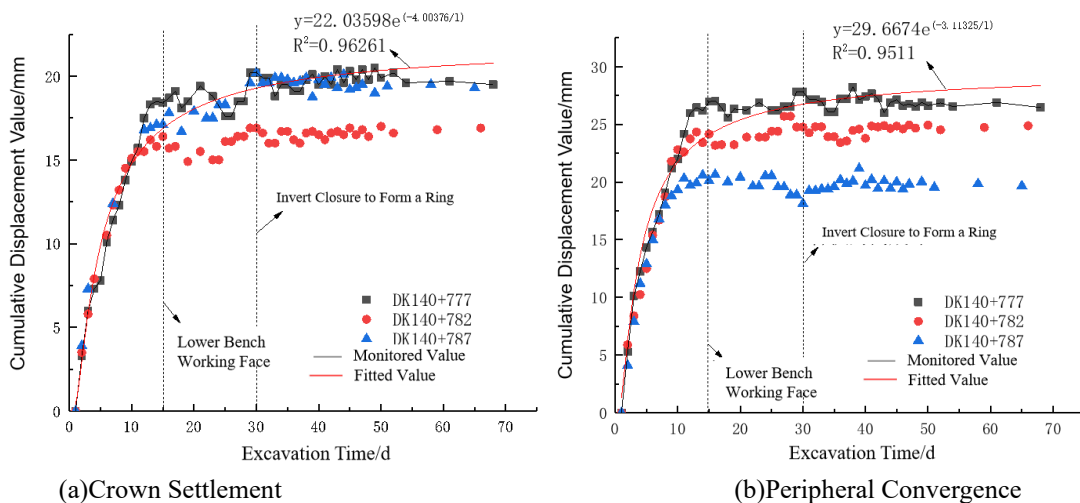


Figure 4 Analysis Diagram of Temporal Characteristics for Initial Support Deformation Monitoring in Deep-Buried Bench-Cut Tunnels within Class IV Surrounding Rock

The monitored values of peripheral deformation at the cross-section of the lower bench were extracted and subjected to regression analysis, as shown in Figure 4. The fitting results for the time series also exhibit high correlation, with R^2 values for crown settlement and peripheral convergence reaching 0.963 and 0.951, respectively. This indicates that the exponential function can accurately reflect the entire process of deformation development over time in Class IV surrounding rock. Specifically, deformation tends to stabilize 12 days after excavation, at which point crown settlement and peripheral convergence have reached 88% and 95% of the ultimate displacement, respectively. A comparison shows that convergence in the temporal dimension still slightly lags behind the spatial process. Deformation enters a stable stage both temporally and spatially after the excavation of the upper bench exceeds 3.5D.

The invert was closed 30 days after excavation, while the deformation had already stabilized 45 days

prior to closure, corresponding to a tunnel face distance of approximately 6D. This again confirms the trend that convergence over time precedes convergence with distance. It is recommended that in Class IV surrounding rock sections, the construction pace can be appropriately increased after the lower bench excavation. Invert excavation should be conducted at approximately 4D (about 56 m) behind the tunnel face, and invert closure should be completed within a range of 3.5D to 6D (approximately 84 m) to achieve a balance between safety and efficiency.

3.3 Analysis of Initial Support Deformation Monitoring Data for Class V Surrounding Rock

For the shallow-buried three-bench method with temporary invert in Class V surrounding rock, monitoring measurements were conducted at three stable cross-sections. The extracted monitoring values are shown in Figures 5 to 6.

3.3.1 Analysis of Spatial Characteristics of Tunnel Peripheral Deformation in Class V Surrounding Rock Sections

For the deep-buried bench cut method scenario in Class V surrounding rock, monitoring measurements were conducted at three stable cross-sections, as shown in Figure 9. Fitting the deformation-spatial relationship for Class V surrounding rock, the R^2 values for the crown settlement and peripheral convergence models were 0.920 and 0.934, respectively. This indicates that the exponential law remains applicable in this type of surrounding rock, although the goodness of fit is slightly lower compared to Classes III and IV, which may be related to its more sensitive deformation response and slightly greater data fluctuation. Monitoring reveals distinct deformation

characteristics: at 1D, crown settlement and peripheral convergence have already reached 54% and 50% of the ultimate values, respectively, increasing to 95% and 99% at 3D, indicating a more rapid development of deformation. The excavation of the middle bench causes a significant increase in the deformation rate, but after it advances 1D (to a face distance of 3D), the deformation rate gradually decreases to zero, and the system regains stability.

The invert closure distance in this section is further reduced to 4.3D (approximately 60 m), and deformation had already entered a state of minor fluctuations before closure. This demonstrates that under Class V surrounding rock conditions, when the invert closure distance is maintained at around 60 m, the deformation around the tunnel tends to converge, and the initial support structure remains safe.

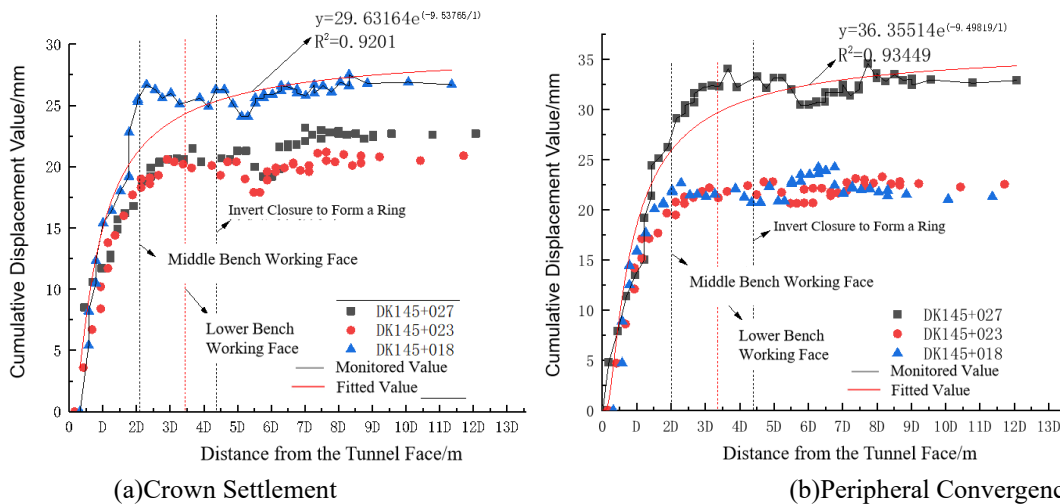
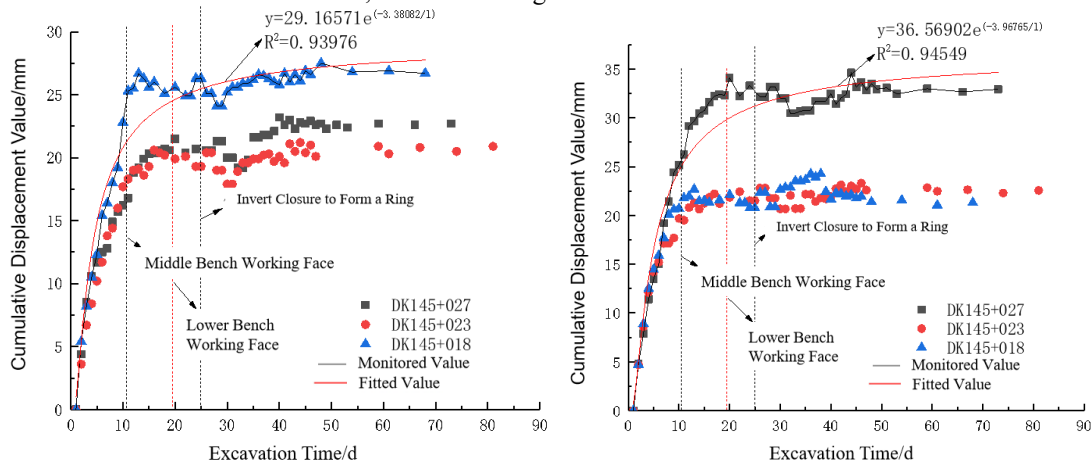


Figure 5 Analysis Diagram of Spatial Characteristics for Initial Support Deformation Monitoring in Shallow-Buried Bench-Cut Tunnels within Class V Surrounding Rock

3.3.2 Analysis of Temporal Characteristics of Tunnel Peripheral Deformation in Class V Surrounding Rock Sections

For the deep-buried bench cut method scenario in Class V surrounding rock, monitoring measurements were conducted at three stable cross-sections, as shown in Figure 6.



(a)Crown Settlement

(b)Peripheral Convergence

Figure 6 Analysis Diagram of Temporal Characteristics for Initial Support Deformation Monitoring in Shallow-Buried Bench-Cut Tunnels within Class V Surrounding Rock

The time-series fitting results for deformation in Class V surrounding rock are satisfactory, with R^2 values for crown settlement and peripheral convergence being 0.940 and 0.945, respectively. This indicates that the exponential model can reliably describe its time-dependent deformation characteristics. From a temporal perspective, deformation tends to stabilize 12 days after excavation, at which point crown settlement and convergence reach 86% and 92% of the ultimate values, respectively. It is noteworthy that its spatiotemporal convergence processes are essentially synchronized: deformation enters a stable stage both at 24 days after excavation and at a tunnel face distance of 4.3D.

aforementioned factors, providing relative ultimate displacement values for crown settlement and wall convergence of initial support in tunnels with different spans and different surrounding rock grades.

Based on the characteristics of the deformation response, a more cautious bench advance sequence is recommended for Class V surrounding rock sections: middle bench excavation should only proceed after the upper bench has advanced at least 2D, and lower bench work should follow only after the middle bench has advanced at least 1D. Invert excavation is recommended to commence at approximately 3.5D (about 59 m) behind the tunnel face and be completed at 4.3D (about 60 m) to prevent deformation from squeezing the lining and inducing uneven stress distribution.

The surrounding rock grades along the Shimenshan Tunnel of the Ganzhou-Shenzhen High-Speed Railway are predominantly Classes III and IV, with Classes V present at tunnel portals, fault zones, and shallow-buried sections. Overall, the stability is relatively good. The surrounding rock grades along the Songgangshan Tunnel are primarily Classes II, III, and IV, with Classes V present at tunnel portals, fault zones, and shallow-buried sections. Overall, the stability ranges from fair to relatively good. Tunnel construction employed the bench cut method, three-bench method, and three-bench method with temporary invert based on the in-situ surrounding rock grades. Considering the tunnel support system and surrounding rock grades, and referencing the ultimate displacement values provided in relevant standards, the monitoring data obtained was collated and studied. This analysis yielded the proportion of deformation displacement inside the tunnel for various sections at different distances from the tunnel face, summarized the overall characteristics of displacement deformation for tunnels on the Ganzhou-Shenzhen High-Speed Railway line, and determined the safe displacement control benchmarks for tunnel construction support under the existing initial support parameters for this railway. The specific results are summarized and simplified in Tables 2 to 4. In Table 2, U_0 represents the baseline recommended values given in Q/CR 9218-2024 Technical Specification for Monitoring and Measurement of Railway Tunnels. In Tables 3 and 4, U represents the ultimate displacement values for corresponding tunnel crown settlement and peripheral convergence, respectively. The adopted safe invert closure distances for Classes III, IV, and V surrounding rock are 210 m (approximately 15D), 85 m (approximately 6D), and 60 m (approximately 4.5D), respectively.

IV. Recommendations for Safe Displacement Control Benchmarks of Initial Support

The control benchmarks for displacement monitoring and measurement inside tunnels should be established based on factors such as geological conditions, tunnel construction safety, long-term stability of the tunnel structure, as well as the characteristics and importance of surrounding structures. China's current technical standard, Q/CR 9218-2024 Technical Specification for Monitoring and Measurement of Railway Tunnels, has formulated corresponding control benchmarks for initial support monitoring and measurement considering the

Table 2 Ultimate Displacement Values for Tunnel Initial Support

Surrounding Rock Grade		III	IV	V
		Deep Burial	Deep Burial	Shallow Burial
Ultimate Displacement Value U_0 /mm	Crown Settlement	20	52	110
	Peripheral Convergence	60	120	240

Table 3 Recommended Displacement Control Benchmarks for Initial Support in Ganzhou-Shenzhen High-Speed Railway Tunnels at Different Excavation Distances

Surrounding Rock Grade	Burial Depth	Construction Method	Distance from the Tunnel Face						Ultimate Displacement Value U/mm	
			0~ D		D ~3 D		>3 D		Crown Settlement	Peripheral Convergence
			Crown Settlement	Peripheral Convergence	Crown Settlement	Peripheral Convergence	Crown Settlement	Peripheral Convergence		
III	Deep Burial	Bench Cut Method	68% U	63% U	98% U	90% U	100% U	100% U	11.05	15.95
IV	Deep Burial	Bench Cut Method	37% U	45% U	88% U	96% U	100% U	100% U	19.9	27.2
V	Shallow Burial	Three-Bench Method with Temporary Invert	54% U	50% U	95% U	99% U	100% U	100% U	25.9	31.7

Table 4 Recommended Displacement Control Benchmarks for Initial Support in Ganzhou-Shenzhen High-Speed Railway Tunnels at Different Excavation Durations

Surrounding Rock Grade	Burial Depth	Construction Method	Excavation Duration						Ultimate Displacement Value U/mm	
			0~5d		5d~12d		>12d		Crown Settlement	Peripheral Convergence
			Crown Settlement	Peripheral Convergence	Crown Settlement	Peripheral Convergence	Crown Settlement	Peripheral Convergence		
III	Deep Burial	Bench Cut Method	52% U	40% U	81% U	88% U	100% U	100% U	11.05	11.71
IV	Deep Burial	Bench Cut Method	39% U	53% U	88% U	95% U	100% U	100% U	19.9	27.2
V	Shallow Burial	Three-Bench Method with Temporary Invert	54% U	43% U	86% U	92% U	100% U	100% U	21.8	31.7

V. Conclusion

Based on the Shimenshan Tunnel and Songgangshan Tunnel of the Ganzhou-Shenzhen High-Speed Railway, this study draws the following conclusions through systematic monitoring of initial support displacement and analysis of its spatiotemporal characteristics:

(1) Tunnel crown settlement and peripheral convergence follow an exponential pattern with increasing distance from the tunnel face in the spatial dimension, generally stabilizing beyond 3D. In the temporal dimension, deformation in Class III

surrounding rock stabilizes approximately 15 days after excavation, while Class IV and V rocks enter a stable stage 12 days after excavation. The high goodness-of-fit ($R^2 > 0.92$) at each stage indicates the high reliability of this pattern.

(2) Based on deformation stabilization characteristics, recommendations for safe advance length control in bench cut construction are proposed: For Class III surrounding rock, lower bench operations can commence after the upper bench excavation exceeds 4D. For Class IV rock, lower bench construction should be initiated after the upper

bench advance exceeds 3.5D. For Class V rock, it is recommended to excavate the middle bench only after the upper bench has advanced at least 2D, and proceed with the lower bench only after the middle bench has advanced at least 1D. At this point, surrounding rock deformation has largely stabilized, and the impact of subsequent construction disturbances is minimal.

(3) Monitoring results show that the initial support displacements for all rock grades are significantly lower than the ultimate limits specified in the Technical Specification for Monitoring and Measurement of Railway Tunnels (Q/CR 9218-2024). This indicates that the overall geological conditions along this railway line are favorable and the current code's control benchmarks are relatively conservative. It is recommended to adopt displacement control standards that more closely align with the actual deformation patterns, based on measured data, to guide construction.

(4) To enhance construction efficiency while ensuring safety, the timing of invert closure can be optimized: For Class III surrounding rock, closure is recommended at approximately 210 m from the tunnel face; for Class IV rock, it can be shortened to about 85 m; and for Class V rock, it should be controlled at around 60 m. This recommendation balances deformation convergence requirements with construction progress, offering good engineering applicability.

CRediT authorship contribution statement

Helin Fu: Writing – review & editing, Resources, Funding acquisition, Conceptualization. Wu Xu: Writing – original draft, Software, Methodology, Investigation. Zhanjun Xu: Supervision, Project administration. Weizheng Zhang: Validation, Data curation. Kui Zou: Validation, Data curation.

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Data availability statement

The data presented in this study are available on request from the corresponding author.

Competing interests

The authors declare that there are no conflicts of interest.

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