

Degradation Law of Tunnel Surrounding Rock Performance and Engineering Management Measures Based on Dynamic Displacement Back Analysis

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Abstract: Tunnel construction is accompanied by higher risks, and the mechanical properties of the tunnel Surrounding Rock (SR) will change with the excavation of the tunnel. To better understand the performance degradation law of the surrounding rock during tunnel construction, this study selects a domestic mountain tunnel project as the research object and uses a 30m long tunnel to construct a finite element model. It proposes a dynamic displacement back-analysis method for the elastic modulus, a parameter of the surrounding rock, based on the theory of the loose zone. The dynamic displacement back analysis is carried out on the finite element model. The calculation results showed that the root mean square errors of the tunnel finite element model vault settlement data and the real data were 0.17mm, 0.10mm and 0.75mm, respectively, when the deterioration function was selected as a linear function, a sine function, and no deterioration was considered. The dynamic displacement back-analysis results based on the sine deterioration function achieved the highest accuracy. The sine function was the most suitable choice for the degradation function of the surrounding rock's elastic modulus. Based on this condition, an analysis of the timing of secondary lining construction was carried out. The results showed that, under conditions that meet the requirements of relevant construction specifications, selecting the working condition with the minimum maximum stress in the surrounding rock was the most suitable time for constructing the secondary lining. This research result also provides a reference for improving the quality level of tunnel engineering management in China.

Keywords: Dynamic displacement back analysis; tunnel surrounding rock; performance degradation; finite element analysis.

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1. Introduction

Tunnel engineering plays an important role in infrastructure construction, especially in areas with complex terrain and harsh natural conditions (Pan et al., 2021 and Gu et al., 2021). However, the complexity of the Surrounding Rock (SR) stress state during tunnel construction and its impact on engineering safety and quality have long been difficult and pressing issues in engineering technology research and practice (Wu et al., 2021). The stress on the surrounding rock during tunnel construction is complex and influenced by geological conditions, groundwater, crustal stress distribution and other factors. During stress redistribution in the tunnel surrounding rock, its mechanical properties, stability, and permeability will change (Luo et al., 2021). This change will further affect the support structure, stress state and tunnel overall stability. Therefore, in tunnel construction, analyzing the SR stress state and elucidating the mechanisms underlying the impact of mechanical response and seepage field changes on tunnel safety are helpful for reasonable site selection, design, construction, and operational management, thereby reducing the risk of tunnel engineering. At present, the technical routes for analyzing the stress state of the surrounding rock mainly include measurement methods, theoretical analysis methods, numerical simulation methods, and dynamic model methods (Ma et al., 2021; Gao et al., 2020). These methods have been widely applied in practical engineering and have achieved some results, but they still have shortcomings. For example, the measurement method makes it difficult to obtain continuous, detailed data and is greatly limited by real-world conditions. The theoretical analysis method is greatly limited in practicality due to the influence of geological conditions and calculation models. Although numerical simulation and dynamic model methods can accurately predict stress changes in the surrounding rock, their calculations are complex and sensitive to parameter values. Therefore, the study focuses on the dynamic identification and engineering control of the degradation of the surrounding rock performance during tunnel

construction, aiming to address the following core questions. What functional law does the degradation of the surrounding rock elastic modulus follow during tunnel excavation? How to optimize the construction timing of secondary lining using the results of dynamic displacement back analysis? To address these issues, this article introduces a dynamic time-varying degradation function based on the loose circle theory and displacement back analysis theory. It also constructs a dynamic displacement back-analysis framework that accounts for the time-varying nature of surrounding rock parameters. This framework not only maintains the traditional inversion method's ability to identify surrounding rock parameters but also introduces a degradation function to characterize the dynamic evolution of the surrounding rock's mechanical properties during excavation. Through this, the study thereby theoretically extends static parameter inversion to dynamic process inversion. The innovation of this article lies in combining engineering degradation mechanisms with back-analysis theory, thereby deepening the theoretical understanding from "parameter identification" to "process deduction" and providing a theoretical basis for the dynamic control of tunnel construction.

This study is divided into three sections. The first section mainly elaborates on the hazards and background research of the deterioration of the surrounding rock performance. The second section mainly focuses on designing a finite element model of the surrounding rock for a specific tunnel project, determining the extent of its loosening zone, and developing a dynamic Displacement Back (DB) analysis method. The third section mainly uses the dynamic DB to analyze the SR deterioration law of parameters and conclude this law.

2. Related Works

The SR state during tunnel construction directly affects the safety of construction personnel and equipment. Professors and engineers in tunnel engineering have conducted extensive research to explore fundamental changes in the performance of tunnel surrounding rock during construction, including its physical and chemical properties. Ding et al. (2021) conducted several investigations into the failure characteristics and energy dissipation mechanisms of tunnel SR subjected to cyclic loading. The findings of the research highlighted that the failure progression of the surrounding rock subjected to cyclic loading was impacted by multiple factors, such as the number of cycles, load amplitude, and properties of the surrounding rock; The failure modes of surrounding rock were characterized by extension, shear, and loosening, and as cycles increased, the failure modes showed a complex trend; In terms of energy dissipation, the surrounding rock of the tunnel exhibits obvious energy absorption characteristics under cyclic loading, which was closely related to the degree of rock failure. Wang et al. (2020) explored the application of the pulse reflection method to hidden-structure detection in tunnel surrounding-rock research. The entry point of this study was to discuss how to use pulse reflection methods to detect hidden structures in the surrounding rocks of tunnels, including tunnel support structures and groundwater levels. The study also explored the advantages and disadvantages of pulse reflection methods, as well as future directions for development. Luo et al. (2021) focused on the mechanical response laws of tunnel SR and tunnel lining in large-span three-hole tunnels. The core issue of this study was to explore the stress situation and interaction mechanism of the tunnel surrounding rock and lining in large-span three-hole tunnels. The research results showed that the stress in the SR of the large-span three-hole tunnel tended to stabilize after 10-20 days of continuous excavation of the corresponding section. Zhao et al. (2021) found that some untreated cavities with a lower risk of safety issues were often overlooked to reduce costs. Therefore, the author used finite-difference software to establish a 2D rock-tunnel hydraulic model with karst caves, simulated the tunnel excavation process, accounting for seepage and conducted numerical simulations to compare outcomes when the karst caves were situated at various positions relative to the tunnel. These findings can serve as a guide for karst rock tunnel engineering. Tian et al. (2020) carried out laboratory experiments on the zonal fracture mode of tunnel SR. The outcomes revealed that the initial SR fracture occurred at the intersection of the bottom and side walls of the tunnel, resulting in varying degrees of impairment of the tunnel's side walls and dome. The study proposed that the radial stress-strain exerted on SR was the primary cause of the emergence of the zonal fracture phenomenon, but the extent of the fracture was restricted. Bai et al. (2022) developed a 3D coupling algorithm to investigate the failure patterns of tunnel SR under high-altitude stress conditions. Results showed that the coupled algorithm achieved precise and efficient multi-scale simulations of rock disturbances.

In summary, previous scholars and tunnel engineers have developed various analytical models or conducted numerous tests based on real tunnel engineering to explore changes in the mechanical and physical performance of the tunnel surrounding rock during excavation. However, these studies lack sufficient research on the degradation of SR parameters during tunnel excavation, necessitating this study.

3. Tunnel Surrounding Rock Performance Model

At present, in practical engineering applications, the surrounding rock parameters are mainly determined through indoor tests and some on-site in-situ tests. However, due to the discontinuity, heterogeneity, and nonlinear characteristics of rock and soil, these two methods still have obvious drawbacks, such as test results that do not fully reflect their physical and mechanical properties (Zou et al., 2021; Usman et al., 2023). Meanwhile, the disturbance and destruction of surrounding rocks during the sampling process, as well as environmental differences and sample "size effects" in indoor experiments, also affect the accuracy of parameter analysis (Cui et al., 2021). The traditional displacement back analysis can only obtain the final "equivalent parameters" after SR deterioration and stability, but cannot reveal the entire deterioration process. In-depth research into the deterioration process of tunnel SR parameters is needed through dynamic displacement back analysis.

3.1. Engineering Data Acquisition, Range Detection and Parameter Inversion Methods

Before constructing a dynamic back analysis method, two key prerequisites need to be clarified. The first concerns the selection of inversion parameters. In this study, the elastic modulus (E) of the surrounding rock is used as the sole dynamic

inversion parameter for the following reasons. Among the parameters in the Mohr-Coulomb strength criterion, the elastic modulus is most sensitive to the displacement field of the surrounding rock and is a key mechanical indicator for controlling instantaneous deformation and stress redistribution during excavation. The strength parameters, such as the cohesive force c and the internal friction angle ϕ , primarily govern the final extent and failure mode of the plastic zone. For the stability analysis of Class IV surrounding rock, which mainly focuses on deformation control, this study examines the dynamic attenuation of the elastic modulus to effectively capture the main contradiction in rock performance degradation. Other parameters are treated as fixed values based on geological exploration reports to ensure the suitability of the inversion problem (its uniqueness and stability). The second, regarding the definition of "dynamic": The "dynamic" displacement back analysis in this article does not refer to rheological or viscoplastic analysis that considers time dependence, but specifically refers to an inversion mechanism in which parameters are updated with the excavation construction sequence (spatial advancement process). The core lies in assigning different elastic modulus values to the corresponding areas in the surrounding rock model. These values are assigned based on the preset degradation function for different excavation steps (corresponding to different distances between the monitoring section and the palm face). This approach achieves a "quasi-static" recursive inversion of mechanical parameters as they evolve with the construction process. This method aims to characterize the dynamic response process of the surrounding rock state to changes in spatial position during tunnel excavation.

This study focuses on a typical mountain tunnel in eastern China, which is a 530-meter-long single-bore tunnel designed for 60 km/h two-lane, second-class highway traffic. Its cross-section has a clear height of 5.0 m and a clear width of 14.0 m. The tunnel passes through a hilly area with Grade IV-V surrounding rock, according to the "Technical Code for Highway Tunnel Construction." Grade IV surrounding rock is characterized by relatively low weather, good integrity, and moderate fracturing, exhibiting favorable stability, small deformation, and high bearing capacity during excavation. Key geotechnical parameters considered in the study include the elastic modulus, compressive strength, internal friction angle, and cohesion of the surrounding rock, which directly influence its mechanical behavior and construction safety.

Monitoring measurements can monitor the deformation of the tunnel SR in real time and provide data support for dynamic displacement back analysis (Huang et al., 2020). The upper step structure is the part of the tunnel where SR is subjected to concentrated stress. Fig. 1 shows the arrangement of monitoring points. The measurement points are all arranged in the cross-section after the tunnel is excavated. Three convergence measurement points need to be arranged in a single cross-section, including one at the arch crown and one at the arch waist on each side.

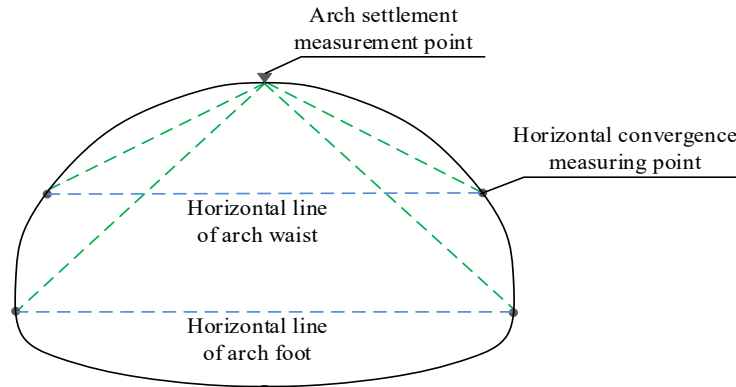


Fig. 1. Schematic diagram of monitoring points layout on the tunnel upper steps

The arranged measuring points need to monitor the vault settlement, horizontal convergence and surface subsidence. The first two items are obtained by a convergence meter. A monitoring section is arranged every 25 meters. The last item is measured with a Dumpy level and placed in the shallow, buried section above the portal. In addition, the allowable values of maximum deformation, deformation rate and other indicators during tunnel construction are obtained in accordance with the "Technical Specification for Highway Tunnel Construction" (JTG/T 3660-2020). During tunnel excavation, the stress distribution around the tunnel will change due to excavation disturbances, forming a loose circle. In this case, if the surrounding rock is modeled as homogeneous, the calculated results will be inaccurate. Therefore, before conducting the displacement back analysis, it is necessary to determine the extent of the tunnel's loose zone. Assuming that the entire surrounding rock model is divided into n parts, the rock mass that has not been affected by excavation is treated as a separate area, and the remaining area is treated as a loose area. SR's displacement problem can be formulated as a displacement analysis problem with multiple unknowns. Eq. (1) can be obtained from the knowledge of Computational mechanics.

$$[K]\{u\} = \{F\} \quad (1)$$

In Eq. (1), $[K]$, $\{F\}$, and $\{u\}$ respectively represent the total Stiffness matrix, load matrix and displacement deformation matrix of the surrounding rock. In this study, the surrounding rock is considered an equivalent linear-elastic body, and Eq. (2) is obtained.

$$[K] = E\{K^+\} \quad (2)$$

In Eq. (2), $\{K^+\}$ and E are the total Stiffness matrix of the equivalent linear elastic body and the overall SR elastic modulus, respectively. If E_j is the initial elastic modulus of Zone j , then there is Eq. (3).

$$\sum_{j=1}^n \frac{1}{a_j} E_j \{K_j^+\} \{u\} = \{F\} \quad (3)$$

In Eq. (3), a_j is the elastic modulus reduction coefficient for zone j , and K_j^+ is the equivalent linear elastic stiffness for zone j . And from Eq. (1) to (3), Eq. (4) can be obtained.

$$\{u\} = \{u(a_1, a_2, \dots, a_n)\} \quad (4)$$

It can be seen from the analysis of Eq. (4) that the precondition for obtaining the minimum value of the expansion term J obtained from the Taylor series expansion of Eq. (3) is that Eq. (5) must be satisfied.

$$\frac{\partial J}{\partial a_j} = 0, (j = 1, 2, \dots, n) \quad (5)$$

If the number of monitoring displacement values for a known project exceeds the number of SR parameters to be inverted, and each monitoring displacement value is independent of the others, SR parameter values can be inverted and calculated according to Eqs. (1) to (5). Then, the SR range-loosening zone and corresponding SR parameters can be obtained. Given the presence of a Ground-Penetrating Radar (GPR) instrument at the project site for this study, a GPR method with high testing speed and minimal disturbance to the surrounding rock is chosen to measure the extent of the loose zone. The measurement results show that the approximate depths of the loose circles at the arch crown, left and right arch waists, side walls, and arch bottom in SR are 2.7m, 2.2m, 1.8m, 2.0m, and 1.2m.

To simplify the research conditions, a 30m long local tunnel with unchanged mechanical SR properties along the tunnel direction is selected from the project as the research object. Subsequent studies are calculated based on conditions from tunnel excavation to the key pile number, and the SR level for this section is Grade IV.

Research indicated that elastoplastic constitutive equations yielded more accurate results than elastic models (Fu et al., 2024). While an elastic model was initially adopted for preliminary static analysis of stress and deformation in surrounding rock, the Mohr-Coulomb model was subsequently employed to better simulate the elastoplastic behavior and instability of the rock mass during excavation. This model accounts not only for elastic deformation but also effectively describes plastic flow and failure induced by stress concentration. The Mohr-Coulomb criterion is particularly suitable for displacement back-analysis. Therefore, an elastoplastic model using this criterion is selected as the medium for this study. Certain parameters are obtained through geological investigation to reduce the number of unknowns and improve inversion accuracy. Given that the chosen displacement back-analysis is more dynamic and computationally demanding than static analysis, a single surrounding-rock parameter is selected for inversion. Dynamic displacement inverse analysis deduces the mechanical properties and state of the surrounding rock from real-time monitoring data, offering several advantages: it captures the rock's real-time response during excavation, overcomes the limitations and uncertainties associated with laboratory or in-situ tests, and provides a scientific basis for construction decision-making, thereby optimizing safety. Among the four parameters of the Mohr-Coulomb criterion, the elastic modulus exhibits the highest sensitivity in terms of displacement and deformation. Changes in this parameter produce more significant variations in displacement. To enhance analysis accuracy, the surrounding rock elastic modulus is therefore selected as the sole inversion parameter.

3.2. Dynamic Displacement Inverse Analysis of Tunnel Surrounding Rock Performance Degradation

The dynamic displacement back analysis developed in this study improves upon the static DB. The essence of the calculation of the latter is to find the minimum point on the Describing function of the closest real surrounding rock parameters. There are many methods to find this point, but the golden section method is a relatively straightforward and efficient approach. The calculation process of this method is to select a very wide range of intervals (a, b) . Considering that the minimum point of the function $f(\cdot)$ If the test is within this interval, a method similar to the halfway method continuously narrows the interval containing the minimum value until the approximate solution meets the requirements (Wang et al., 2024; Sato et al., 2025). Specifically, two segmentation points c and d within (a, b) are first set, and the method for selecting point c is shown in Eq. (6).

$$c = (1 - \alpha)a + \alpha b \quad (6)$$

Among them, α is 0.618, and the selection method for point d is shown in Eq. (7).

$$d = \alpha a + (1 - \alpha)b \quad (7)$$

The segmentation positions of point c and point d are shown in Fig. 2.

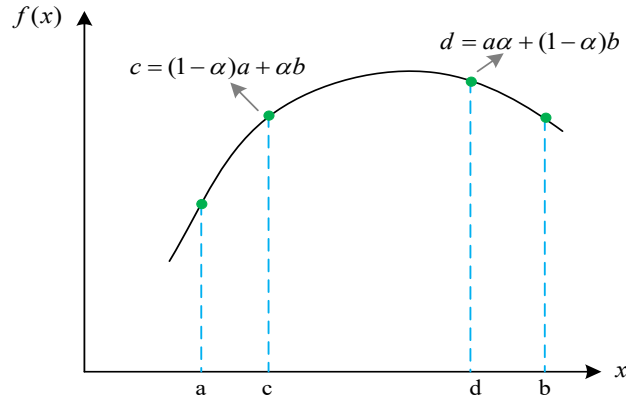


Fig. 2. The segmentation positions of points c and d in the golden section method

Then $f(c)$ and $f(d)$ are calculated for points c and d . When $f(c) < f(d)$, the minimum point is considered to be in the interval (a, d) , and (a, d) is taken as the interval (a_1, b_1) for the second round of calculation. On the contrary, when $f(c) > f(d)$ it is considered that the minimum point is in the interval (c, b) , and (c, b) is taken as the interval (a_1, b_1) calculated in the second round. Subsequently, it is calculated in the same way until the accuracy requirements are met, yielding the approximate minimum point. Before conducting dynamic displacement back analysis, understanding the general deterioration pattern of SR parameters E During excavation, it is needed. As tunnel excavation progresses, the influence of the tunnel face on SR gradually diminishes, leading to a corresponding increase in internal stress within the SR. Meanwhile, the structure of the surrounding rock also becomes fragmented, which means that SR-corresponding parameters will deteriorate (Lee et al., 2025; Prasetyo et al., 2024). The rock mass in front of the tunnel is affected by excavation, and SR parameters begin to deteriorate. As excavation continues, the degree of deterioration will also intensify. When the tunnel excavation distance exceeds a certain range, the surrounding rock will no longer be affected by the end effect. Moreover, when the driving time is sufficiently long, the surrounding rock structure becomes more stable, and the rate of parameter degradation no longer intensifies. Therefore, the correlation between SR deformation, parameter degradation, and the tunnel excavation process is shown in Fig. 3.

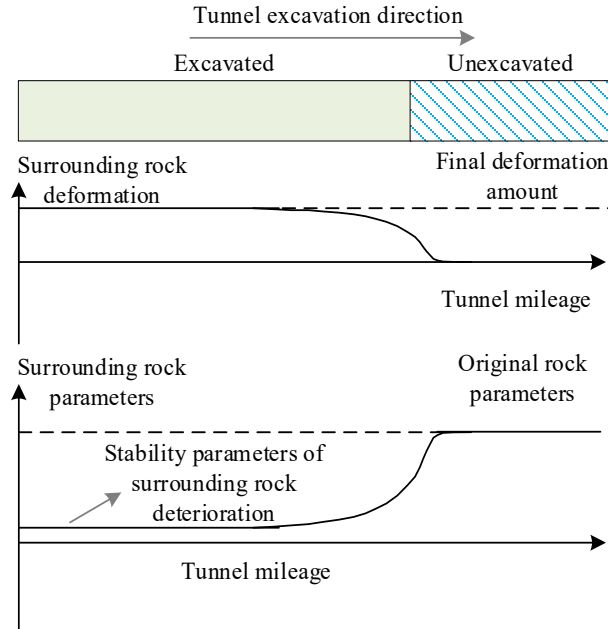


Fig. 3. Correlation between deformation and parameter degradation of surrounding rock and tunnel excavation process

In numerical back-analysis simulations, SR parameters deteriorate, and the degree of deterioration varies with distance from the face. Therefore, it is necessary to input the calculation parameters of each region in the three-dimensional numerical model. During the static displacement back analysis process, the parameters of the model are unique, but the parameters at different positions during the dynamic displacement back analysis calculation are also different. This means that multiple surrounding rock parameters need to be input for each dynamic displacement back analysis calculation. Therefore, this study provides the following settings: SR parameters deterioration form is a fixed function, and after

verifying the accuracy of this function, the function with higher accuracy can be selected as the final description method for the deterioration law.

After completing the basic work above, a dynamic analysis method is designed. The dynamic back analysis of tunnel SR displacement needs to utilize on-site settlement data for the arch inside the tunnel and account for the deterioration of the SR elastic modulus. Now, a deterioration function of surrounding rock parameters in advance is set, and then whether the function is reliable is verified to obtain the deterioration function equation between the elastic modulus E and the excavation steps n . It is assumed that the project will be constructed at a conventional speed of two meters per day. The data variation relationship between monitoring sections E and n can be described in Fig. 4. The starting point of the excavation steps in Fig. 4 is the monitoring section.

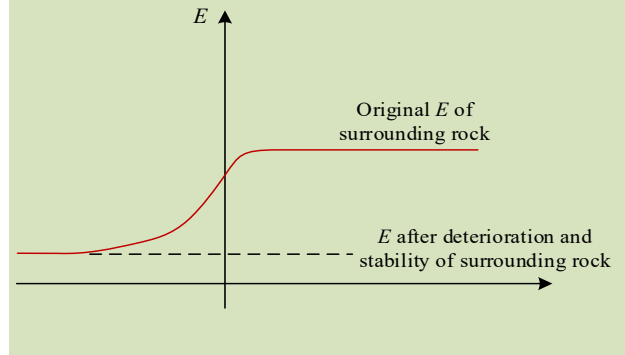


Fig. 4. Data relationship between excavation steps and elastic modulus of monitoring section

Now, two types of functional relationships between arbitrary cross-sections E and n are first proposed. The first type is a linear function type, and the relationship function is shown in Eq. (8).

$$E(n) = k_1 n + k_2 \quad (8)$$

In Eq. (8), $E(n)$ is the degradation function, k_1 and k_2 are the undetermined parameters in the degradation function. The degradation function image of the first-order function type is shown in Fig. 5. The abscissa n_A corresponding to point A in Fig. 5 represents the excavation steps when the SR of the monitored section is stable, and the ordinate E_A corresponding to point A represents the stable mechanical parameters of the SR degradation process, which are calculated by the static displacement back analysis method. The abscissa n_B of point B is determined by searching for the loose zone range in the rock mass in front of the palm, while the ordinate E_B of point B can be obtained by consulting the geological exploration report of the project.

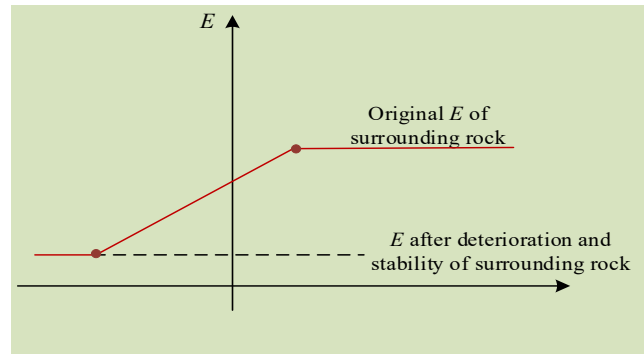


Fig. 5. Degradation function image of linear function type

According to the coordinates of points A and B, Eq. (8) can be rewritten as Eq. (9).

$$E(n) = \frac{E_A - E_B}{n_A - n_B} (n - n_A) + E_A \quad (9)$$

According to Eq. (9), the corresponding elastic modulus can be set at different positions in the model. Another selected function type is the sine function, as shown in Eq. (10).

$$E(n) = A \sin(\omega n + \varphi) + B \quad (10)$$

In Eq. (10), ω and φ are also undetermined parameters. The initial rapid decay and later gradual stabilization trend described by the sine function physically corresponds to the typical evolution of rock damage and stress redistribution during tunnel excavation: in the early stage of excavation, the unloading disturbance is severe, structural damage develops rapidly, and mechanical parameters degrade quickly. As the palm face moves away and the initial support effect is exerted, the rate of rock damage slows down and gradually reaches a new dynamic equilibrium. The inverse analysis process for the degradation function of the sine function type is similar to the first degradation function. The explanation of model assumptions and parameter selection: The numerical model and inversion method constructed in this study are based on the following core assumptions and parameter selection criteria to clarify their applicable boundaries and improve repeatability: (1) Model simplification assumption: The study assumes that the selected 30-meter tunnel section has uniform geological conditions and a constant surrounding rock grade of IV, and without considering the dynamic influence of groundwater; The study simplifies the three-dimensional excavation process into sequential quasi-static steps, excavating 2m at each step and immediately implementing initial support. (2) Material constitutive model selection: Although the initial analysis uses an elastic model, the core calculation is based on the elastic-plastic Mohr-Coulomb criterion. This choice is based on its ability to reasonably describe the shear yield and stress-release behavior of Class IV surrounding rock, and on the fact that its parameters have clear physical meaning and are readily obtainable from geological reports. (3) Selection of key inversion parameters: In the Mohr Coulomb criterion, parameters (elastic modulus E , cohesive force c , internal friction angle φ), elastic modulus E is selected as the only dynamic inversion parameter. This choice is based on parameter sensitivity analysis (previous research and preliminary calculations have shown that displacement fields are most sensitive to changes in E). Meanwhile, strength parameters such as c and φ are taken as fixed values based on geological exploration reports. This focuses on the mechanism of rock stiffness degradation, the dominant deformation process, while ensuring the suitability of the inversion problem. (4) The preset form of the degradation function: Comparing linear and sine functions is a preliminary attempt based on mathematics. The former represents the simplest linear decay relationship, while the latter can simulate the nonlinear degradation process that starts fast and then slows down. The comparison of these two forms aims to explore the basic forms of degradation laws, and their effectiveness is ultimately verified by measured data. This study used Midas simulation software to construct a finite element model of the tunnel for subsequent calculations. The calculation process is shown in Fig. 6.

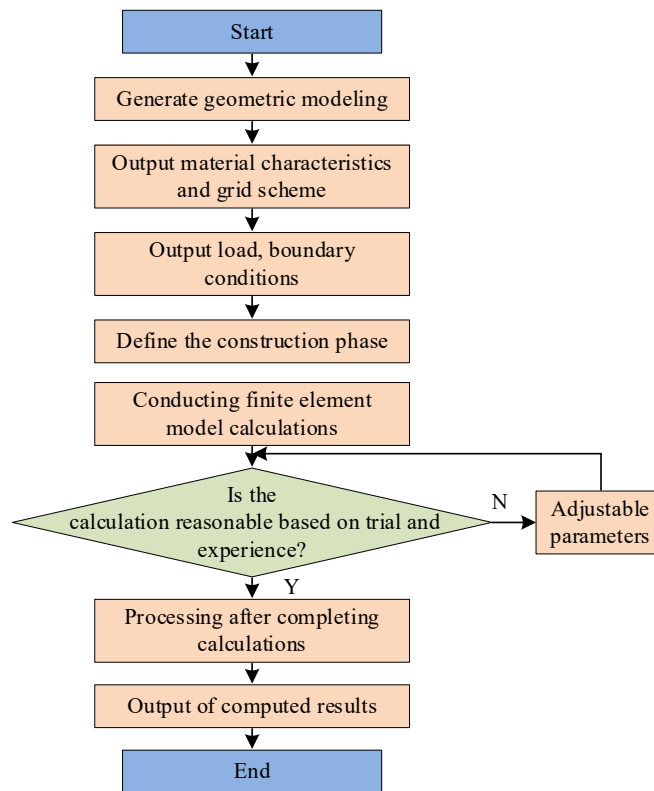


Fig. 6. Simulation calculation process based on Midas software

The finite element model in this study treats the surrounding rock as an elastoplastic material governed by the Mohr-Coulomb strength criterion. A three-dimensional numerical model of a 30-meter tunnel section was constructed using Midas simulation software, with mesh discretization applied to both the surrounding rock and supporting structures to ensure computational accuracy. Boundary conditions were set as follows: horizontal displacement constraints around the model, a vertical displacement constraint at the bottom, and no top constraint to simulate realistic excavation effects. To simplify calculations, the excavation process was simulated in steps, with shotcrete support applied immediately after each 2-meter advance. Stress and strain profiles from the finite element analysis were used to examine changes in the stress state

of the surrounding rock during excavation, revealing stress distribution and deformation characteristics. This provides intuitive data support for understanding the mechanical behavior and the evolution of the surrounding rock's performance.

4. Analysis of Model Results

Now, dynamic displacement back-analysis technology is used to simulate and calculate the finite element model for the tunnel project setup. Due to the fact that the degradation function set is divided into two types: linear function and sine function, the analysis process should also be treated separately. To compare the effectiveness of the dynamic displacement back analysis developed in this study, the static displacement back analysis method is now used to perform the same calculation of surrounding rock degradation.

4.1. Calculation Results Analysis in the Case of Linear and Sinusoidal Functions

The main difference between static and dynamic analysis in finite element modeling lies in how time is accounted for. Static analysis assumes that the external load remains unchanged once applied, so its calculation primarily concerns the stress and deformation of the structure in the equilibrium state. The dynamic analysis accounts for time effects and load changes, capturing the instantaneous response and real-time deformation of the surrounding rock during excavation. In the excavation process, static analysis usually uses the step method to obtain the steady-state stress field and displacement state by removing the surrounding rock layer by layer and updating the boundary conditions in real time. In the dynamic analysis, the time history of excavation is simulated, the load is gradually applied, and its influence over time is analyzed. During the simulation, the displacement, stress and strain states of the surrounding rock are monitored in real time to capture the rapid response and potential local damage caused by excavation. Using these two analytical methods, the study can evaluate the performance and stability of the surrounding rock from multiple perspectives and provide comprehensive information and recommendations for tunnel design and construction management.

Firstly, under the degradation function rule of the first-order function type, the calculation results of the two methods for the finite element model are demonstrated below. Observing it, both dynamic and static displacement back analysis methods can roughly simulate the actual settlement of the tunnel arch crown, but the data calculated by dynamic displacement back analysis is closer to the actual data. Overall, the root-mean-square deviations of the dynamic and static displacement back analysis methods are 0.17mm and 0.41mm, respectively, and the maximum absolute errors are 0.82mm and 0.95mm. From the perspective of the numerical variation trend, when the negative distance between the monitoring section and the palm surface is large, the settlement of the arch top is the largest because the support structure of the palm surface is farther from the monitoring surface and thus plays a weaker supporting role. As the horizontal axis value in Fig. 7 approaches 0m, the settlement of the arch crown rapidly decreases. After the horizontal axis value exceeds 0m, the rate of descent of arch settlement slows and tends to converge.

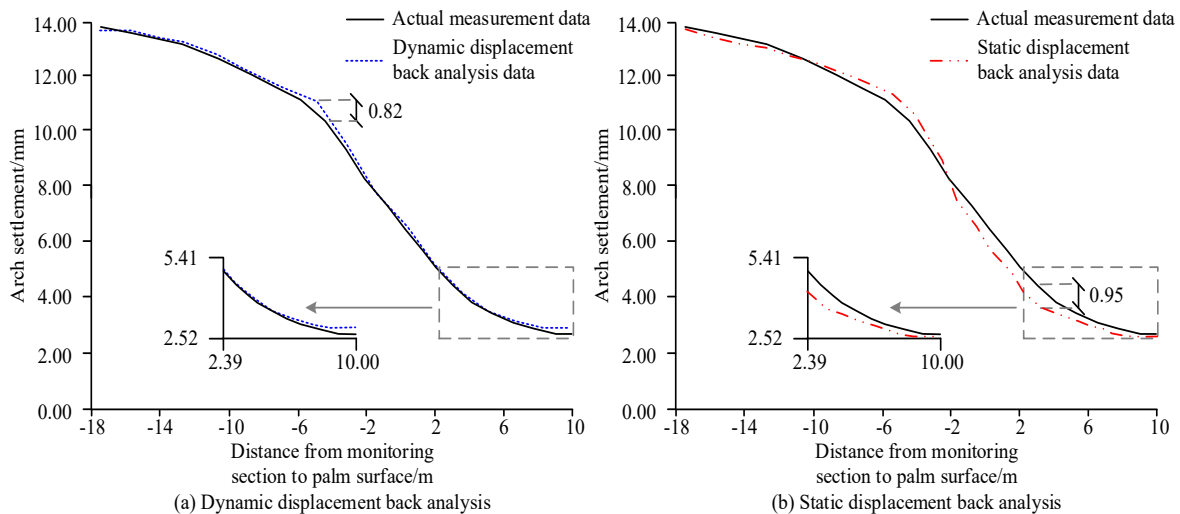


Fig. 7. Statistics of arch settlement under the condition of first-order deterioration function

Similarly, under the degradation function rule of the sine function type, the calculation results of the two methods are shown in Fig. 8. Observing it, both dynamic displacement back analysis and static displacement back analysis methods can roughly simulate the real settlement of the tunnel arch crown, but the data calculated by dynamic DB is still closer to the real data. The Root-mean-square deviation between the data obtained by dynamic and static DB and the real data is 0.10mm and 0.22mm, respectively, and the maximum absolute error of the two is 0.30mm and 0.39mm, respectively. From the perspective of numerical variation trend, there is an overall negative relationship between the distance between the monitoring section and the palm face and the settlement of the arch crown, which is consistent with the results obtained in Fig. 7. Moreover, when the horizontal axis value is greater than 0m, the decrease rate of the settlement of the arch crown slows down and gradually converges.

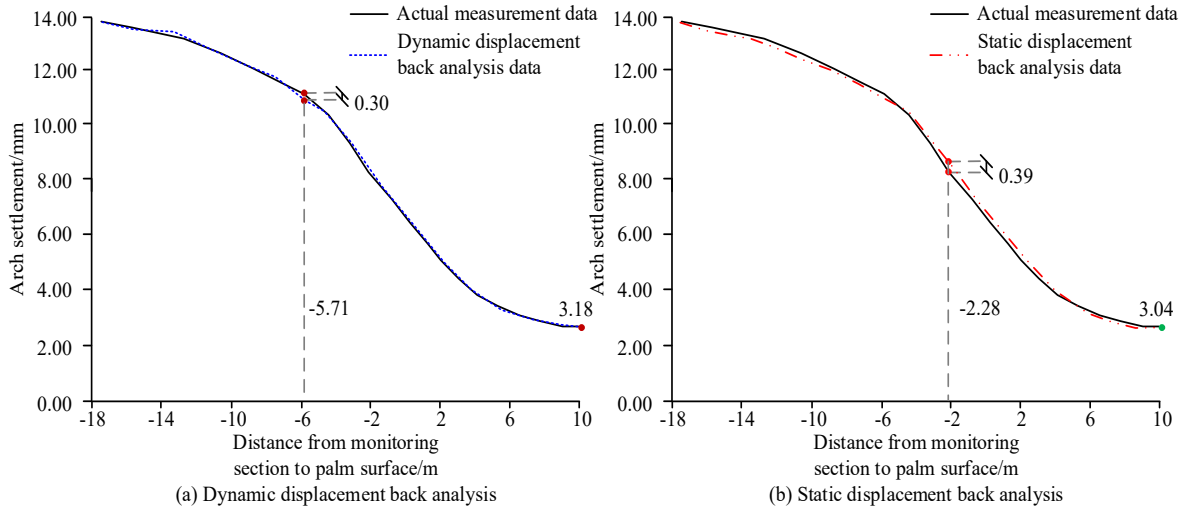


Fig. 8. Statistics of arch settlement under sinusoidal deterioration function conditions

Fig. 9 shows a comparison of the arch settlement obtained using dynamic DB, assuming the deterioration mode for each SR. Observing it, the differences between the arch settlement data obtained using the first-order deterioration function and the sinusoidal deterioration function, and between the arch settlement data calculated without considering the deterioration of SR and the actual data, were small, whereas the difference between the arch settlement data obtained using the first-order deterioration function and the actual data was significant. It indicated that, for the selected tunnel engineering project, SR within the SR loosening zone did indeed exhibit a certain degree of physical performance degradation. Specifically, the Root-mean-square deviation between the primary deterioration function, the sinusoidal deterioration function, and the vault settlement data, without considering deterioration, and the real data were 0.17mm, 0.10mm, and 0.75mm, respectively. The dynamic DB based on the sinusoidal deterioration function had the highest accuracy. In Fig. 9, the prediction effect of the non-degraded model seems to be good, but it should be noted that the non-degraded model does not consider the actual physical changes of the surrounding rock in the construction process, but only regards the surrounding rock as a relatively constant and homogeneous material, which lacks an effective reflection of the complexity of the actual construction situation.

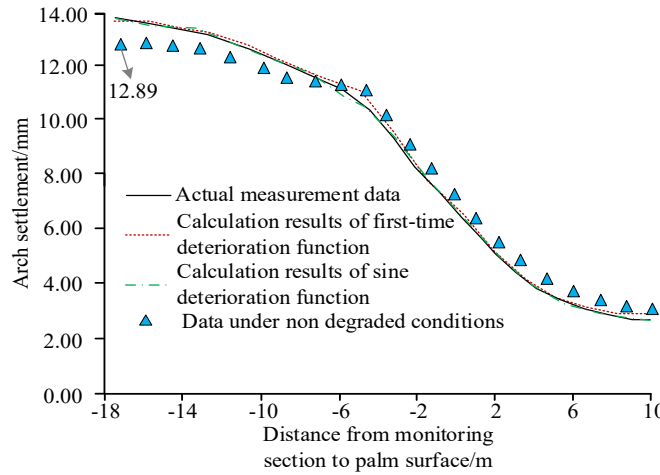


Fig. 9. Comparison of arch settlement under different assumptions of surrounding rock deterioration

4.2. Statistical Patterns Analysis Under Different Timing of Secondary Lining Application

Therefore, the sine function is chosen as the function describing rock degradation. Based on simulation analysis data, the numerical relationship between the elastic modulus E in the loosening zone and the distance n between the cross-section and the tunnel face can be obtained, as shown in Eq. (11).

$$E = \begin{cases} 0.12, (n \leq -5.0) \\ 0.46 \sin(0.55n + 1.16) + 0.58, (-5.0 < n < 0.75) \\ 1.03, (n \geq 0.75) \end{cases} \quad (11)$$

The analytical expression of Eq. (11) is shown in Fig. 10. The horizontal axis in Fig. 10 represents the number of excavation steps, with one step representing two meters of excavation.

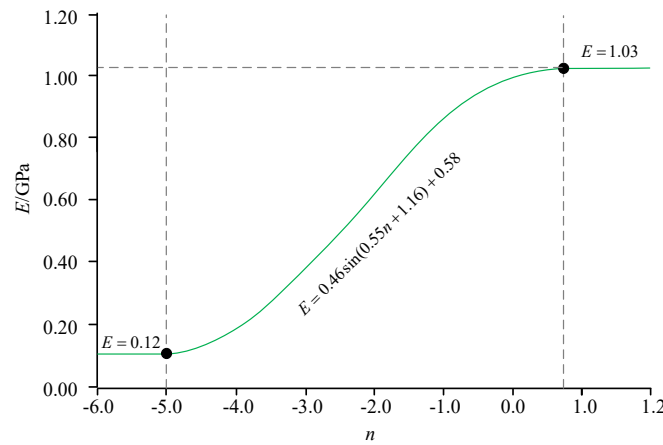


Fig. 10. Relationship between elastic modulus E in the loosening ring and distance from cross-section to palm face n

Using the sine function as the degradation function of the loose zone SR, the parameters of the tunnel finite element model were calculated using the dynamic DB, and an attempt was made to analyze the settlement and deformation laws of the tunnel arch under different timing of secondary lining construction. Fig. 11 shows the Results. Considering the actual construction situation of the tunnel, secondary lining was added at distances of 4m, 8m, 12m, 16m, 20m, 24m, and 28m from the tunnel face. In Fig. 11, the horizontal axis is the distance from the palm face in meters when the second lining is in place, while the left vertical axis represents the arch settlement and the horizontal convergence on one side, both in millimeters. The right side represents the maximum internal force of the second lining (in kPa). In Fig. 11, as the distance from the palm surface increased during the second lining, the arch settlement and the horizontal convergence length on one side gradually decreased. Moreover, when the distance from the palm surface during the second lining was between 4m and 12m, the data changed most markedly. Therefore, as the distance from the palm surface increased during the second lining, the maximum internal force of the second lining first decreased and then slightly increased. Because the later the construction of the second lining, the more pressure was released from SR, and the smaller the internal force of SR that the second lining needed to bear. Therefore, from the perspective of the internal force of the second lining, the construction time of the second lining cannot be too early.

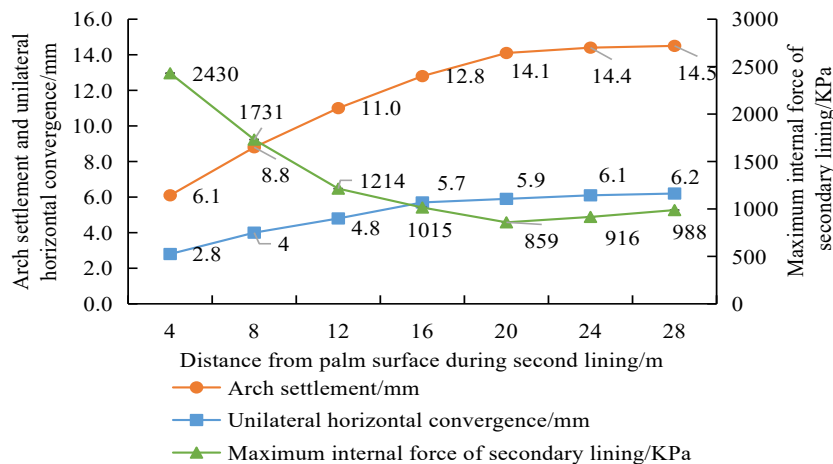


Fig. 11. Surrounding rock deformation and maximum internal force variation of lining under different conditions

Based on the research results in Fig. 11 and the requirements for second-lining construction, a distance of 20m from the tunnel face was selected as the optimal timing for support. In other words, this type of tunnel should be adjusted towards this goal as much as possible during construction management to improve the safety of tunnel excavation. However, in different tunnel construction scenarios, the lining design and construction requirements will be affected by many factors, including geological conditions, surrounding rock types, groundwater levels and excavation methods. For example, in hard, high-strength surrounding rocks, the design of the lining may focus on providing the necessary support and stability, using less thick, high-strength materials to reduce self-weight. In weak or broken surrounding rock, the lining needs greater deformation resistance and is usually designed thicker and made of high-toughness materials to resist higher surrounding rock pressure and deformation. In addition, in high-water-level environments, the lining needs to have good waterproofing performance; waterproof additives may be added to the material, or a waterproof structural design may be used to avoid the impact of water seepage on tunnel safety. During excavation, timely lining construction based on stress changes in the surrounding rock before and after excavation is also key to preventing subsequent deformation and collapse.

Finally, a comparison was made between the calculation efficiency of the arch crown settlement technology content method using a single degradation function and a sine degradation function, without considering the deterioration of surrounding rock conditions, in Fig. 12. The different style icons represent different calculation methods for arch displacement, and the corresponding colored lines represent the data fitting curves of the corresponding methods. Observing Fig. 12, it can be seen that when the number of calculations was small, the per-degradation-function calculation time was the highest. When the number of calculations exceeded 400, the calculation time for a sinusoidal degradation function was the highest.

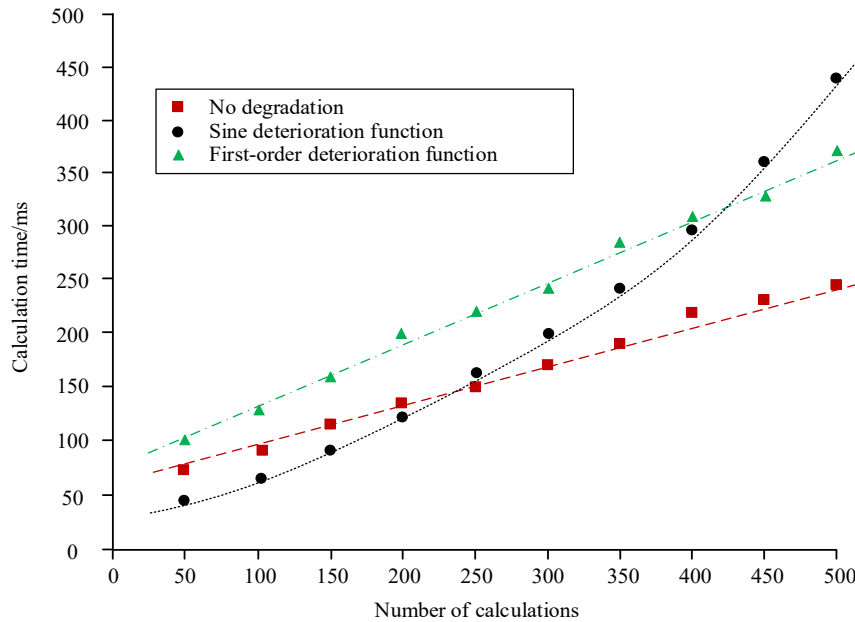


Fig. 12. Comparison of calculation efficiency of various arch settlement calculation methods

5. Conclusion

To investigate the degradation of the performance of tunnel surrounding rock, this study constructs a finite element model based on a specific tunnel project and a dynamic DB. The simulation results using the tunnel finite element model showed that when the first-order deterioration function was used, the Root-mean-square deviation of the vault settlement obtained by the dynamic and the static DB and the real data was 0.17mm and 0.41mm, respectively, and the maximum absolute error of the two was 0.82mm and 0.95mm, respectively. When the sine deterioration function was used, the Root-mean-square deviation between the vault settlement obtained by dynamic and static DB and the real data was 0.10mm and 0.22mm, respectively, and the maximum absolute error of the two was 0.30mm and 0.39mm, respectively. Without considering the deterioration of the surrounding rock, the Root-mean-square deviation between the vault settlement and the real data was 0.75mm. The dynamic displacement back-analysis results based on the sine degradation function achieved the highest accuracy. Choosing the sine function as the surrounding rock degradation function, it was found that as the distance from the second lining to the working face increased, the settlement of the arch crown and the horizontal convergence length on one side gradually decreased. Moreover, when the distance from the working face to the second lining was between 4m and 12m, the data changed most markedly, but the maximum internal force of the second lining showed a pattern of first decreasing and then slightly increasing. Therefore, it was found that in tunnel construction, the timing of secondary lining support should be determined by minimizing the SR internal force in the loose zone while meeting industry standards. Therefore, engineering managers can make the decision-making process easier by doing the following: First, they can use dynamic displacement back analysis to determine the real-time degradation function of the surrounding rock. This is a better approach than just relying on geological exploration and empirical analogy to determine design parameters. Secondly, they should make "minimizing surrounding rock stress" the key quantitative indicator for determining when to carry out secondary lining construction, rather than relying on fixed distances or empirical timeframes. This adjustment transforms support decision-making from static and empirical judgment to a closed-loop optimization process based on real-time monitoring data and dynamic model feedback. The combination of the sinusoidal deterioration function used in the study can effectively capture the nonlinear response of the surrounding rock to deformation, failure, and seepage, and ensure construction safety. In hard rock or complex geological conditions, the nonlinear plastic model can more accurately reflect changes in the stress state and automatically capture the degradation of the surrounding rock modulus.

This study theoretically extended traditional static displacement back analysis to dynamic process inversion and developed a new framework, "spatiotemporal dynamic model and sequential inversion," by introducing parameter degradation functions. Meanwhile, the nonlinear attenuation law of mechanical parameters in loose circles was quantitatively revealed, shifting the understanding from a spatial concept to a dynamic mechanical region with quantitative

evolution laws. Furthermore, a closed-loop theoretical paradigm of "identifying degradation mechanisms to predicting system response to optimizing engineering decisions" was established, providing a systematic theoretical analysis path for the dynamic design and intelligent construction of tunnel engineering. The dynamic displacement back analysis method proposed in this study and the identified sinusoidal degradation law were validated in a specific engineering case (an IV-level surrounding-rock mountain tunnel). The method framework, which combines the theory of loose circles, constructs parameter degradation functions, and performs dynamic inversion, has methodological reference value and can provide ideas for analyzing the time-varying performance of other types of surrounding rocks. However, when applied to geological conditions with significant differences, such as extremely soft rocks, high ground stress, or water-rich formations, the specific form and key parameters of the degradation function need to be recalibrated and validated based on on-site monitoring data, and the support strategy should also be adjusted according to corresponding theories and specifications. The limitations of this study mainly stem from the necessary simplifications and assumptions in its methodological construction. Firstly, the numerical model was based on the assumption that the surrounding rock properties are uniform and did not consider the dynamic effects of groundwater, which differs from the actual heterogeneity and water-force coupling effects of the strata. Secondly, although simplifying the complex degradation mechanism of the surrounding rock into a spatiotemporal degradation function that relies solely on a single elastic modulus can capture the main issue, this approach fails to fully capture how strength parameters such as cohesion and the internal friction angle evolve synergistically. In addition, the inversion analysis treats arch settlement as the primary constraint and does not simultaneously fuse multi-point and multi-directional displacement data, potentially limiting the spatial resolution of parameter identification. Finally, the obtained laws are validated under specific geological conditions (IV-grade surrounding rock), and caution should be exercised when directly transplanting their functional forms and parameters to other rock grades or complex geological environments. Targeted monitoring data must be used for recalibration.

Author Contributions

Yi Zheng contributed to conceptualization, methodology, software, validation, analysis, and investigation. Yanzheng Li contributed to data collection, draft preparation, manuscript editing, visualization, supervision, project administration, and funding acquisition. All authors have read and agreed with the manuscript before its submission and publication.

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Declaration of Artificial Intelligence (AI) Tools

The authors confirm that no AI tools were used in the preparation of this manuscript.

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