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Stability Analysis and Safety Evaluation of Surrounding Rock in Shallow-buried Concealed Tunnel Construction

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Abstract: In the construction of shallow-buried concealed tunnels, the control of surrounding rock stability is a core challenge, which is crucial to construction safety and structural performance. A two-dimensional model was established using Midas GTS NX, combined with bench cut method excavation simulation. The laws of vault and surface settlement were quantitatively analyzed through displacement nephograms, and the spatiotemporal characteristics of surrounding rock displacement were revealed. The results show that under the established excavation and support measures, the displacement and settlement meet the specification requirements. Meanwhile, the Analytic Hierarchy Process (AHP) was introduced to determine weights and analyze the coupling correlation of factors through judgment matrices, clarifying the influence degrees of surrounding rock grade, support strength, and other factors to achieve multi-dimensional evaluation. Furthermore, the Fuzzy Comprehensive Evaluation method was integrated to quantify the mapping relationship between surrounding rock stability and safety, and the safety grade was obtained. Finally, measures such as strengthening support, optimizing excavation parameters, refined exploration, and improving management were proposed to enhance surrounding rock stability and reduce construction risks.

Keywords: Shallow-buried concealed excavation; Surrounding rock stability; Bench cut method; FAHP

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1. Introduction

In the construction of shallow-buried concealed tunnels, controlling surrounding rock stability is a core challenge that is critical to construction safety and structural performance. The shallow burial depth renders the surrounding rock mechanically vulnerable, and excavation is prone to inducing vault settlement and surface deformation. If surface settlement exceeds the allowable limit during construction, it will not only affect the flatness of hub functional areas or the construction accuracy of ongoing facilities but may also lead to construction suspension for remediation, resulting in project delays and substantial economic losses.

In the field of surface settlement prediction for shallow-buried tunnels, Peck proposed a classic empirical formula for estimating the volume of settlement trough based on the concept of ground loss using a large amount of measured data, which has become a commonly used method for surface settlement prediction in engineering [1].

O'Reilly supplemented through research on the settlement characteristics of clay and sand that the width coefficient of the settlement trough increases with the tunnel burial depth. In studies on special scenarios and model optimization, Saeid R proposed a Shallow Tunnel Classification System (STCS) based on the maximum settlement value, evaluating tunnel stability by integrating parameters such as burial depth and diameter [2,3]. She Fangtao et al. modified the traditional curve function for loess strata, improving the accuracy of longitudinal settlement description [4].

Xudong Wang et al. established a two-dimensional settlement propagation model based on the random medium theory, incorporating the randomness and inhomogeneity of soil layers to enhance prediction accuracy [5]. Dechun Lu et al. constructed a unified displacement function for circular tunnel sections, clarifying the law that vault settlement is greater than bottom rebound [6].

In terms of surrounding rock stability analysis, Cao Shiwei established a relational model including flatness ratio and bias pressure angle, revealing the correlation between tunnel failure modes and surrounding rock pressure [7]. Xie Jiajie proposed a surrounding rock stress calculation formula covering multiple factors such as ground load and support structure [8]. Regarding the application of numerical simulation technology, Guan Hongbing, Zhu Yongxiang et al. used FLAC 3D to simulate double-line shield tunnels, obtaining the laws of surface settlement curves [9]. Wang Jinhua conducted stochastic finite element analysis by combining ABAQUS and Matlab, verifying the consistency of settlement curve calculations [10].

Zhu Bin explored the disturbance characteristics of soil caused by overlapping tunnel construction using Midas software [11]. In field monitoring research, Yang Haiqin et al. confirmed the consistent downward trend of surface and vault settlement through comparison [12]. Cheng Zhengmin et al. obtained the excavation displacement laws of large-section variable-cross-section tunnels using the CRD method [13]. Miao Xueyun et al. acquired data on surface settlement, surrounding rock moisture content, and steel arch stress through testing components for tunnels in the loess tableland area [14].

Current research mostly focuses on ordinary shallow-buried tunnels, lacking special analysis for hub core area scenarios. Key construction issues such as the adaptive selection of excavation methods, the matching accuracy between numerical simulation parameters and hub strata, and the quantitative evaluation of "surrounding rock deformation, construction safety" still need in-depth exploration, which is difficult to fully meet the requirements of safe and efficient tunnel construction.

2. Project overview and construction simulation

2.1. Project overview

The research object is a shallow-buried concealed tunnel constructed by the bench cut method, with two main tunnels (left and right). Each tunnel has a net width of 18.5 m and a clear height of 5 m, with uniform structural dimensions to meet the engineering design load and traffic requirements. Before excavation, the outer contour of the tunnel and the middle internal bracing were poured in the soil using C40 concrete.

After pouring, taking the boundary between the silty clay layer and the coarse gravel layer as the dividing line, the upper and lower bench cut method was adopted for excavation, following the sequence: left half of the upper bench, left half of the lower bench, right half of the upper bench, and right half of the lower bench.

The exposed strata from top to bottom are Quaternary surface layer (fill soil, miscellaneous fill), alluvial-proluvial layer, eluvial-slope wash layer, and Carboniferous Shidengzi Formation bedrock, with significant differences in engineering mechanical properties among each layer.

2.2. Construction simulation

For the shallow-buried concealed section of the North Airport Tunnel, this study used GTS NX to establish a 2D model to simulate bench cut excavation.

Based on Saint-Venant's principle and the 18.5 m net width of the tunnel, the model was set to 100 m in length and 33.8 m in width. Since the distance from the tunnel top to the ground surface is only 6.25 m, the silty clay within 50 m on both sides of the central axis was reinforced by grouting with C20 concrete [15].

The Mohr-Coulomb model was applied to the soil layers, with parameters shown in the **Table 1** and **Figure 1** below.

Table 1. Mechanical parameters of each rock-soil layer and material

Rock-soil layer or material	Elastic modulus (kPa)	Poisson's ratio μ	Unit weight (kN/m³)	Cohesion C (MPa)	Internal friction angle φ (°)
Silty clay	50	0.3	15	22	11
Coarse gravel sand	100	0.3	16.5	5	20
Strongly weathered argillaceous siltstone	200	0.34	22	10	25
C20 grouted soil layer	500	0.2	22	10	23
C40	30	0.2	26	—	—

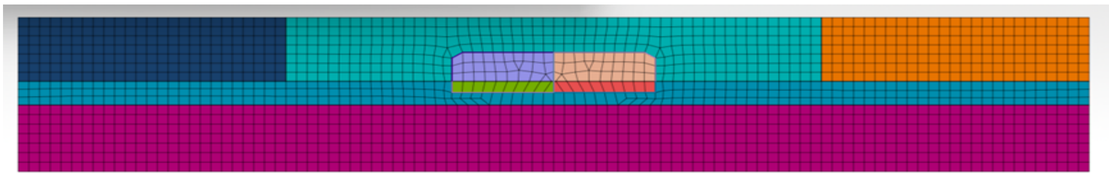

Figure 1. Tunnel construction model.

2.3. Analysis of simulation results

(1) Excavation of the left upper bench

It showed the characteristics of "upper settlement and lower heave". The maximum settlement above was 17.70 mm, the heave below was 7.53 mm, and the surface settlement was 12.6 mm. The settlement increased with the burial depth up to the tunnel top; only the left soil showed slight displacement.

(2) Excavation of the left lower bench

The deformation mode remained unchanged, but the displacement decreased. The maximum upper settlement was 16.38 mm, the lower heave was 5.76 mm, and the surface settlement was 11.3 mm.

(3) Excavation of the right upper bench

The "upper settlement and lower heave" pattern persisted. The upper settlement on the left was 14.59 mm and on the right was 13.6 mm; the lower heave on the right was 7.70 mm. The surface settlements on the left and right were 9.5 mm and 10.1 mm, respectively. The settlement increased with the burial depth up to the tunnel top, with only slight displacement on the right.

(4) Excavation of the right lower bench

The displacement further decreased. The top settlements on the left and right were 13.96 mm and 12.2 mm; the lower heaves were 5.2 mm and 4.9 mm; the displacements on both sides were 3.34 mm and 3.35 mm (basically symmetrical).

In summary, the entire excavation process was dominated by "upper settlement and lower heave", with displacement decreasing as excavation progressed. Surface settlement was significantly affected by shallow burial, while disturbances on both sides were small, verifying that the "support-first, excavation-later" approach is effective in controlling deformation.

3. Risk evaluation of surrounding rock stability in shallow-buried concealed tunnels based on FAHP

3.1. Determination of evaluation index weights

Following the core principle of the Analytic Hierarchy Process (AHP) – "focusing on dominant factors and ignoring secondary ones" – key control factors were extracted from numerous factors affecting tunnel excavation. Finally, a risk evaluation system for shallow-buried concealed tunnel construction was established, including 5 secondary indicators and 17 tertiary indicators.

Combined with actual conditions, comparisons were made between each index in the criterion layer and each factor within the criterion layer to obtain the judgment matrices of evaluation indicators for the criterion layer and the scheme layer. Weight vectors were calculated based on the judgment matrices at all levels, and consistency tests were conducted on the judgment matrices.

Judgment Matrix of Criterion Layer Evaluation Indicators

$$A_0 = \begin{pmatrix} 1 & 1/5 & 1/3 & 1/2 & 1/4 \\ 5 & 1 & 3 & 5 & 2 \\ 3 & 1/3 & 1 & 2 & 1/2 \\ 2 & 1/5 & 1/2 & 1 & 1/3 \\ 4 & 1/2 & 2 & 3 & 1 \end{pmatrix}$$

The maximum eigenvalue and the corresponding eigenvector that can be obtained through calculation

$$\lambda_{0\max} = 5.0682$$

$$a_0 = \left(0.1138, 0.8012, 0.2925, 0.1706, 0.4800\right)$$

The weight vector is obtained after normalization

$$\omega_0 = \left(0.0613, 0.4312, 0.1574, 0.0918, 0.2583\right)^T$$

$CI = 0.0170$, $RI = 1.12$, and $CR = 0.0152$ are calculated, so A meets the requirements, and this result can be used as the final decision weight.

Similarly, the consistency of the judgment matrices for the evaluation indicators in the scheme layer all meet the requirements. Based on the calculated weights of each factor, the excavation section size has the greatest impact, followed by vault settlement, while precipitation has the smallest impact, with the influence degrees of other factors falling in between.

3.2. Fuzzy-based construction safety risk analysis of shallow-buried concealed tunnels

To comprehensively evaluate the construction and excavation risks of shallow-buried concealed tunnels, this study refines several scheme layer indicators from multiple criterion layers (such as hydrogeological conditions and tunnel design conditions). It classifies the risk occurrence levels (e.g., "very likely", "likely") under each indicator and establishes the judgment matrix for the scheme layer.

The fuzzy synthesis operation for hydrogeological conditions is calculated as follows.

$$A_1 = \begin{pmatrix} 0 & 0.1 & 0.7 & 0.2 & 0 \\ 0 & 0.4 & 0.5 & 0.1 & 0 \\ 0 & 0.3 & 0.5 & 0.2 & 0 \\ 0 & 0.2 & 0.6 & 0.2 & 0 \end{pmatrix}$$

$$\omega_1 = \left(0.0721, 0.4761, 0.2471, 0.2047\right)$$

$$S_1 = \omega_1 \times A_1 = \left[0, 0.3127, 0.5349, 0.1524, 0\right]$$

Similarly, the fuzzy comprehensive evaluation for other criterion layers can be obtained. Then, a multi-level fuzzy comprehensive evaluation is conducted on them.

$$A = \begin{pmatrix} 0 & 0.3127 & 0.5349 & 0.1524 & 0 \\ 0 & 0.3763 & 0.5000 & 0.1172 & 0.0065 \\ 0 & 0.3526 & 0.4352 & 0.2000 & 0.0122 \\ 0 & 0.0742 & 0.6000 & 0.2000 & 0.1258 \\ 0 & 0.3649 & 0.5351 & 0.1000 & 0 \end{pmatrix}$$

$$\omega_0 = \left(0.0613, 0.4312, 0.1574, 0.0918, 0.2583\right)^T$$

$$S = \omega_0 \times A = \left[0, 0.3380, 0.5102, 0.1355, 0.0163\right]$$

The comprehensive evaluation result of the excavation risk of the shallow-buried concealed tunnel is obtained. This design adopts the principle of maximum membership degree, with the risk level value being 0.5102, corresponding to the risk evaluation result of "accidental".

4. Conclusion

To address the issue of risk management and control in the excavation of shallow-buried concealed tunnels, this study first identified key risk factors and constructed an evaluation system through literature research combined with engineering practice. Then, it established a risk evaluation system based on the Analytic Hierarchy Process (AHP), coupled with the fuzzy comprehensive evaluation method to quantify the risk level, and formed a control scheme.

The core results are as follows.

(1) Midas GTS NX simulation shows that after the excavation of this large-section tunnel, the top settlement and bottom heave are significant, and both decrease with the progress of excavation

(2) An evaluation index system including 5 criterion layers and 17 scheme layer factors was constructed. Weight calculation indicates that 5 factors such as excavation section size and vault settlement are core risk factors; after dividing the risk levels through fuzzy comprehensive evaluation, protective measures were proposed in combination with risk characteristics, providing support for construction safety.

Disclosure statement

The author declares no conflict of interest.

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