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A Study on the Stability of Tailings Pond Based on Plastic Displacement and Safety Factor

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Abstract: The displacement deformation of tailings ponds serves as important early warning indicators for its instability, and accurately identifying plastic displacement is crucial for establishing a safety early warning system for tailings ponds. This study proposes a method for identifying plastic displacement in tailings ponds, systematically analyzes the variation pattern of plastic displacement with applied loads, and establishes the relationship between plastic displacement and the safety factor. The results indicate that the dam body is in the elastic deformation stage during the initial loading period. As the load increases, it enters the plastic deformation stage, and upon reaching the breaking load, the plastic displacement increases sharply. The maximum plastic displacements are 55.986 mm, 49.009 mm, and 44.197 mm, occurring at the sliding arc of the dam body. Furthermore, the safety factor exhibits a nonlinear inverse relationship with plastic displacement: the lower the safety factor, the greater the plastic displacement. Particularly when the safety factor drops below 1, the plastic displacement increases dramatically, indicating imminent dam failure. Based on these findings, the study provides an early identification basis for the instability risk of tailings ponds and proposes a scheme for establishing an effective early warning system, which holds significant engineering application value.

Keywords: Safety factor; Plastic displacement; Model experiment; Stability

Online publication: May 28, 2026

1. Introduction

A tailings pond is a facility constructed by building a dam at a valley entrance or enclosing an area to store tailings or other industrial wastes. In 2008, an extraordinarily severe dam failure accident occurred in Shanxi Province, China, resulting in 277 deaths and 4 missing persons (2021) [1]. In 2019, the Brumadinho tailings pond in Minas Gerais, Brazil, failed after being decommissioned for three years, causing 270 deaths or missing persons. Therefore, safety monitoring and disaster early warning for tailings ponds are of critical importance (2020) [2].

Displacement is the main content of safety monitoring for tailings ponds and the most direct indicator for identifying their safety status. As a core content of safety assessment for tailings ponds, displacement monitoring directly reflects the operational status and potential risks of the tailing's ponds. Currently, research on displacement monitoring in tailings dams mainly focuses on two aspects: one is the methods for obtaining displacement monitoring data, such as drones (2020) and distributed scatterer interferometric synthetic aperture radar (DS-InSAR) (2023) [3,4]. The other is the prediction of dam displacement using mathematical algorithms, such as the CS-SVM model (2021), BP neural network (2019), and grey theory (2017) [5–7]. It can be seen that the current processing of monitoring data is primarily based on pure algorithmic prediction, with insufficient consideration of the physical mechanisms of tailings pond deformation and its influencing factors. In 2019, the tailings pond in Minas Gerais, Brazil et al. had a deformation rate of -47 mm/a before its failure, whereas the Baiyan tailings pond of the Wengfu Phosphate Mine (2017) recorded a maximum settlement displacement of -57.8 mm/a in 2014 and has remained in safe operation to date [4,7]. Therefore, it is difficult to assess the stability of a tailings pond solely based on monitoring the total displacement. The reason is that many factors affect the displacement of tailings ponds, such as changes in the spatial distribution of the phreatic line, dam construction, and sliding of the tailings pond can all cause variations in the dam's displacement. Yan et al. proposed an intelligent method for extracting tailings pond information from high-resolution satellite images, but its accuracy for displacement monitoring in tailings ponds is insufficient [8]. Du et al. developed a novel InSAR time-series approach to obtain ground displacement maps of tailings ponds and to identify settlement caused by dam construction. Xie et al. studied the consolidation settlement patterns in the tailings pond area near the Great Salt Lake in Utah, and the results showed that high-resolution surface displacement measurements using InSAR can significantly improve our understanding of tailings settlement processes [2,9]. These studies indicate that while displacement monitoring data can be used to identify the operational characteristics of tailings ponds, but assessing the stability of a tailings pond solely based on total displacement is inaccurate. In fact, the key to determining the safety of a tailings pond lies in plastic displacement, and the identification of plastic displacement is particularly important. Therefore, how to identify plastic displacement from monitored displacement data has become a critical scientific and technological issue for early identification of tailings dam disasters and safety assessment. However, existing research has not yet given sufficient attention to this.

In summary, this study aims to fill the gap in research on displacement of tailings ponds. By deeply analyzing the mechanisms underlying displacement in tailings ponds, this paper innovatively proposes a method for identifying plastic displacement of tailings ponds. Specifically, a numerical model of the tailings pond is established using the finite element method to determine the elastic displacement in this study. By separating the elastic displacement from the measured total displacement, the plastic displacement is successfully identified, and the relationship between plastic displacement and the safety factor is established. This process reveals the dynamic characteristics of tailings pond deformation, and plastic displacement can be used to more directly and accurately assess the stability of the tailings pond. Based on this, a monitoring-data-based early identification and warning system for tailings pond instability and disaster prevention is proposed, significantly improving the accuracy and timeliness of tailings pond stability monitoring.

2. Model loading experiment of tailings pond

2.1. Experimental device

The model experiment was conducted in a model tank, which serves as the primary site for constructing the tailings pond model and performing the experiment. The tank measures 3.5 m in length, 1.2 m in width, and

1.5 m in height. The main body of the experiment tank is made of transparent tempered glass, reinforced with angle steel, and the outline of the tailings pond is marked on the outside of the tempered glass.

The material used for constructing the tailings dam is fine tailings sand. Through particle size gradation experiments, the uniformity coefficient of the fine tailings sand was found to be 9.08, and the curvature coefficient was 1.57, indicating that the particle distribution is uniform and suitable for use as dam construction material in tailings dam model experiments. In accordance with the "Standard for Geotechnical Test Methods", experiments were conducted on the fine tailings sand, and the basic physical parameters obtained are shown in **Table 1**.

Table 1. Physical and mechanical parameters of tailings pond construction materials

Area	Dam construction material	Natural density/ (kg/m^3)	Cohesive force/ (kPa)	Internal friction angle/(º)	Coefficient of permeability/(m/s)
Initial dam	Gravel	2400	15.00	40.00	2.00×10^{-4}
Accumulation dam	Tail fine sand	1680	1.20	33.77	1.43×10^{-6}

2.2. Experimental plan

During the experiment, pore pressure gauges were embedded in the tailings dam, and water was added to maintain a constant water level on the deposition beach, while the dam body was allowed to reach a steady-state seepage field. When constructing the tailings dam, lime was placed in layers to facilitate observation of dam deformation and arc formation. Subsequently, stepwise loading was applied at designated locations and when the readings from the pore pressure gauges remained constant, it indicated that the deformation induced by the current loading increment had been completed. After each loading, the dam body was scanned using a three-dimensional laser scanner with millimeter-level accuracy. The data before and after scanning data were imported into post-processing software for analysis. Specifically, using the matching function of the post-processing software, the scanned data of the dam before and after loading were registered, and the coordinates of the same points before and after the load were extracted to obtain the displacement data of the tailings dam. The lime placement and loading process are shown in **Figure 1**. This experiment was divided into three groups. The initial dam slopes both inside and outside the tailings dam were 1:1.5. Tn dams in the three groups were 1:1.5, 1:2, and 1:2.5, respectively. The experimental conditions are detailed in **Table 2**.

Figure 1. Schematic of lime layering and loading process.

Table 2. Experimental conditions of tailings pond model

Case	Slope ratio of the initial dam	Slope ratio of the Accumulation dam
Case1		1:1.5
Case2	1:1.5	1:2
Case3		1:2.5

2.3. Analysis of experimental results

According to the results of the three-dimensional laser scanning in the experiment, we found that the displacement near the toe of the tailings dam slope was small, and no sliding occurred in this area when the tailings dam failed. Therefore, a total of four observation points were set at intervals of 10 cm downward from the crest of the stacked dam. The location of the points is shown in **Figure 2.**

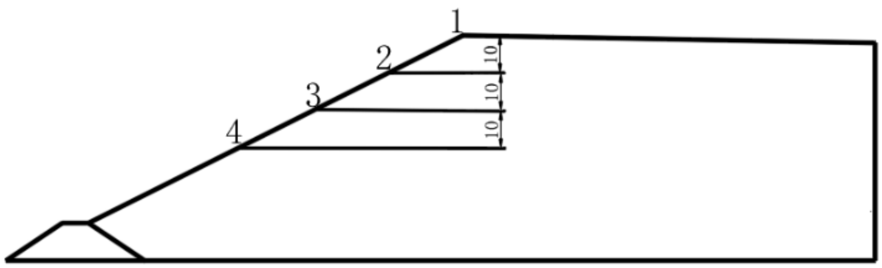
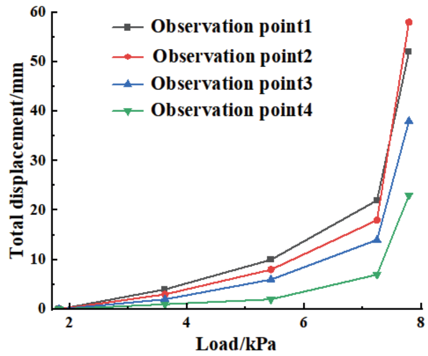
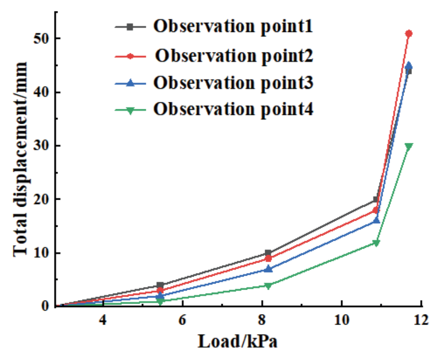


Figure 2. Schematic diagram of point selection.

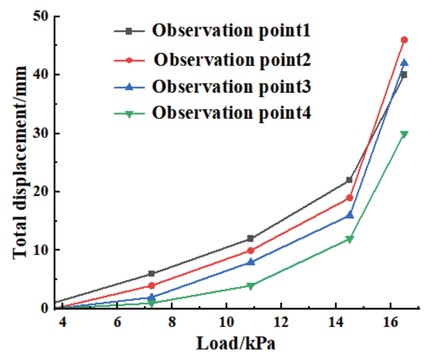
Combining **Figure 3** and the experiment, it can be seen that after the first loading stage, the surface of the embankment dam showed almost no change, with only slight deformation. During the second loading stage, a slight depression appeared on the surface of the embankment dam, and settlement deformation began to occur in local areas. At this time, among the selected monitoring points, Points 1 and 2 exhibited slight displacement changes of approximately 4 mm. During the third loading stage, the displacement continued to increase, with a rising rate of increase. Entering the fourth stage, the dam body showed a tendency to slide downward, with displacements of points 1 and 2 increased to 20–22 mm and 18–19 mm, respectively, while the displacements of points 3 and 4 increased to 14–16 mm and 7–12 mm. By observing the displacement changes at the monitoring points, it is evident that points 1 and 2 experienced significantly greater increases in displacement, indicating significant damage tendencies in these areas, and the sliding failure of the dam gradually forms. In the final stage of loading, the displacements at various points of the dam increased sharply. In particular, the displacements at points 1, 2, and 3 reached 38–58 mm, and the displacement at point 4 reached 23–30 mm, indicating that these areas experienced severe deformation. The dam underwent a transition from local instability to overall failure, ultimately leading to the overall collapse of the tailings dam, as shown in **Figure 4**. A comparison of the three sets of experiments reveals that the larger the slope ratio of the accumulated dam, the smaller the load required for failure, while the displacement at failure becomes larger, and the sliding arc at failure becomes smaller. Specifically, when the accumulated dam slope ratio was 1:1.5, the failure load was 7.79 kPa, and the displacement at the maximum displacement monitoring point 2 at failure was 58 mm. When the slope ratio was reduced to 1:2 and 1:2.5, the failure load increased to 11.69 kPa and 16.49 kPa, respectively, while the displacement at point 2 decreased to 51 mm and 46 mm. This is because a larger slope ratio raises the center of gravity of the dam and increases the slope angle, thereby increasing the sliding force and reducing the anti-sliding stability of the dam, which results in a smaller load required for failure. At the same time, as the slope ratio increases, stress concentration on the slope surface becomes more significant, leading to larger displacements at failure.



(a) Case1



(b) Case2



(c) Case3

Figure 3. Load-Displacement relationship curve.

(a) Front view of tailings dam failure

(b) Side view of tailings dam failure

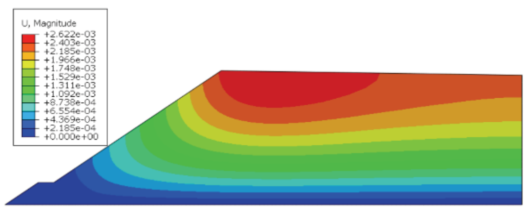
Figure 4. Tailings dam failure diagram.

3. Identification and analysis of plastic displacement

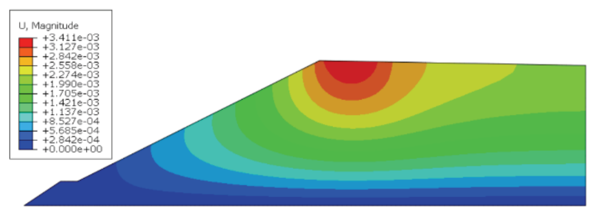
After completing the model experiments, the total displacement data of the tailings dam were obtained. To further analyze the plastic displacement of the tailings dam, a numerical simulation approach was adopted in this study. Using the ABAQUS finite element software, a numerical model of the tailings pond was established to simulate the displacement distribution of the tailings dam under different loading conditions. Based on the elastic-plastic displacement theory, the displacement before the occurrence of plastic strain is first identified as the elastic displacement, and then the elastic displacement is subtracted from the total displacement to obtain the plastic displacement. Meanwhile, the safety factors under corresponding working conditions were calculated through numerical simulation. The numerical simulation not only validated the experimental data but also further revealed the relationship between plastic displacement and the stability of the tailings dam, providing in-depth analysis and early warning basis for the instability of the tailings pond.

Figure 5 shows the elastic displacements under different accumulated dam slope ratios. By locating the corresponding observation points in the figure, the elastic displacements at these points were obtained. Subsequently, the elastic displacements were subtracted from the total displacements measured in the experiments to obtain the plastic displacements at each point. For the different working conditions, the elastic displacements of observation points 1, 2, 3, and 4 were extracted. For the accumulated dam slope ratio of 1:1.5, the elastic displacements at the corresponding points were 2.622 mm, 2.014 mm, 1.423 mm, and 0.924 mm, respectively. For the slope ratio of 1:2, the elastic displacements were 3.239 mm, 1.991 mm, 1.237 mm, and 0.786 mm, respectively. For the slope ratio of 1:2.5, the elastic displacements were 2.936 mm, 1.803 mm, 0.965 mm, and 0.613 mm, respectively.

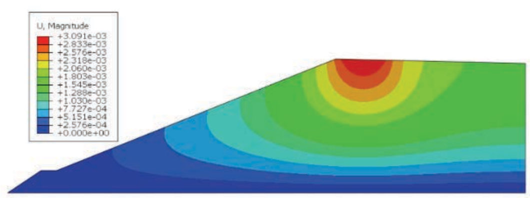
Based on the experimental data, the relationship curves between plastic displacement and uniformly distributed load are shown in **Figure 6**. It can be observed from **Figure 6** that during the first stage of loading, the dam body experienced slight deformation and remained within the elastic range. In the second stage of loading, the total displacement exceeded the elastic displacement, and the tailings dam entered the plastic deformation stage. Among the selected monitoring points, only points 1 and 2 reached a plastic displacement of 1 mm, indicating still relatively small displacements. In the third stage of loading, as loading continued, the plastic displacement further increased, and signs of sliding began to appear in the middle and upper parts of the dam body. In the fourth stage of loading, the maximum plastic displacements under different working conditions increased to 19.38 mm, 16.76 mm, and 19.06 mm, respectively. By observing the displacement variations at these monitoring points, it is evident that Points 1 and 2 exhibited larger displacements, indicating that these have the most severe failure tendencies and could become the main weak points for sliding and instability of the tailings dam, with dam sliding failure gradually forming. In the final stage of loading, when the load reached the failure load, the tailings dam suddenly failed, and the plastic displacement increased sharply, with the maximum plastic displacement occurring at point 2. Using the laid lime, it was observed that the sliding arc and the most severely damaged area of the tailings dam were located around Point 2, where the surrounding region experienced significant plastic deformation. Compared with point 2, the plastic displacement at point 4 is smaller, which verifies the sliding characteristics of the dam failure, that is, sliding from the upper to the lower part, ultimately leading to the complete instability of the tailings dam.



(a) Case1

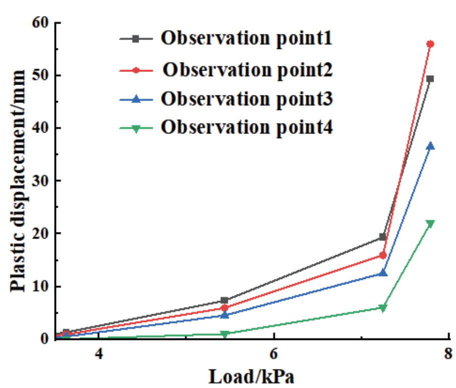


(b) Case2

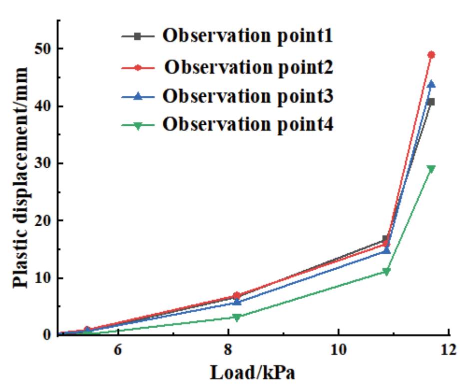


(c) Case3

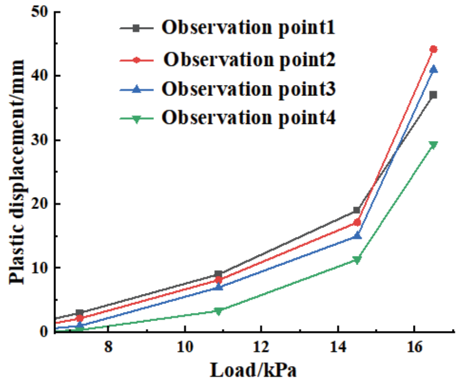
Figure 5. Elastic displacement diagram.



(a) Case1



(b) Case2



(c) Case3

Figure 6. Relationship between plastic displacement and load.

4. Analysis of plastic displacement and safety factor

By selecting the maximum plastic displacement values under different load conditions for each working condition, and calculating the corresponding safety factors with finite element analysis, the relationship between plastic displacement and safety factor was established, as shown in **Figure 7**. It can be observed from **Figure 7** that the safety factor and plastic displacement exhibit an inverse relationship, and the variation is nonlinear. The safety factor decreases as the plastic displacement increases. When the safety factor is 1.458, the maximum plastic displacement is 1.378 mm. When the safety factor decreases to 1.179, 1.024, and 0.97, the plastic displacement increases to 7.378 mm, 19.378 mm, and 55.986 mm, respectively. Moreover, when the plastic displacement is small, the safety factor decreases rapidly. And when the plastic displacement is small, the safety factor decreases rapidly. As the safety factor approaches 1, the rate of decrease slows down, but the plastic displacement increases significantly. In particular, when the safety factor falls below 1, the plastic displacement increases sharply. The maximum plastic displacements under working conditions 1, 2, and 3 are 55.986 mm, 49.009 mm, and 44.197 mm, respectively, ultimately leading to the failure of the tailings dam. The tailings dam is mainly composed of fine tailings sand. Under external loads, the stress-strain relationship of the fine tailings sand exhibits significant nonlinear characteristics. Especially near the failure state, the strength of the material decreases, resulting in a rapid increase in plastic displacement. This nonlinear mechanical behavior is the fundamental reason why the safety factor decreases as plastic displacement increases. As the load continues to increase, the plastic deformation inside the tailings dam accumulates continuously, causing the shear strength of the material to gradually degrade. In the stage of small plastic displacement, the shear strength degrades relatively slowly, and the safety factor decreases rapidly; however, as plastic displacement further increases, the degradation of shear strength accelerates, the decreasing trend of the safety factor slows down, but the increase in plastic displacement becomes significantly larger. Particularly when the safety factor is close to or below 1, the strength of the tailings dam is approaching or has reached its limit state, and the plastic displacement increases dramatically, eventually triggering instability and failure of the dam body. This phenomenon indicates that the failure of the tailings dam often occurs when the safety factor is close to or below 1. At this stage, although the change in safety factor slows down, the deformation of the dam body intensifies significantly, ultimately leading to the instability and failure of the tailings dam. This analysis provides important theoretical support for the stability assessment and design of tailings dams. An empirical formula can be fitted based on **Figure 7**.

$$y = 32.108x^{-8.35} \tag{1}$$

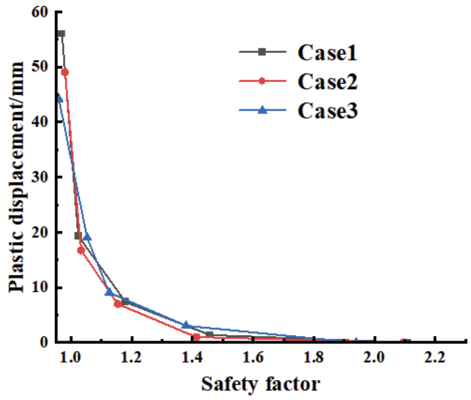


Figure 7. Relationship diagram between safety factor and plastic displacement.

5. Conclusion

Plastic displacement is a key factor affecting the stability of tailings ponds. This paper conducts an in-depth study on the plastic displacement of tailings ponds, using finite element software to establish a numerical calculation model. Through this model, the elastic displacement of the tailings pond is determined, and the plastic displacement is obtained in combination with experimental data. The relationship between plastic displacement and the safety factor is established, and an early identification and warning system for tailings pond instability disasters based on displacement monitoring data is constructed. The following conclusions are drawn:

(1) In this study, model experiments of a tailings pond were conducted to simulate the deformation and failure process of the tailings dam under different loads, and the displacement data of the tailings dam under various loading conditions were obtained. This provides a reliable theoretical basis for understanding the deformation behavior of tailings ponds under different loads.

(2) By establishing a finite element numerical calculation model, the elastic displacement of the tailings pond was determined, and the plastic displacement was calculated by combining it with the experimental data. It was found that at the initial stage of loading, the dam body is in the elastic deformation stage; as the load increases, the dam body enters plastic deformation, especially when the load reaches the failure load, the plastic displacement increases sharply. The maximum plastic displacements under different working conditions were 55.986 mm, 49.009 mm, and 44.197 mm, and these occurred at the sliding arc of the dam body.

(3) The relationship between plastic displacement and the safety factor of tailings ponds was established, and it was found that the safety factor and plastic displacement exhibit an inverse nonlinear relationship. As the safety factor decreases, the plastic displacement increases significantly. In particular, when the safety factor falls below 1, the plastic displacement increases sharply, indicating that the dam body is approaching failure. Specifically, when the safety factor was 1.458, the maximum plastic displacement

was 1.378 mm; when the safety factor decreased to 0.97, the maximum displacement increased to 55.986 mm. Based on this, an early identification basis for the instability risk of the tailings pond can be provided, thereby enabling the establishment of an effective early warning system and the implementation of preventive measures in advance to ensure the safety of the tailings pond.

Disclosure statement

The author declares no conflict of interest.

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Study on the Evaluation Method of Highway Tunnel Service Performance Based on the Analytic Hierarchy Process

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Abstract: Current specifications mainly evaluate the highway tunnel service performance in the operation period from the integrity or defect status of tunnel engineering structures and mechanical and electrical facilities, yet fail to fully take into account the durability of tunnel structures or facilities, traffic flow smoothness, riding comfort and other performance dimensions. Therefore, by adopting research methods including literature research, theoretical analysis and expert investigation, an evaluation indicator system for the highway tunnel service performance was established based on the Analytic Hierarchy Process (AHP), and calculation models for each indicator were constructed, thus ultimately realizing the quantitative evaluation of tunnel service performance. Finally, based on the data of 33 ordinary highway tunnels in Shandong Province in 2025, the service performance scores of these tunnels were calculated, and the tunnels were ranked by maintenance priority according to the calculation results. This research provides an important basis for the maintenance decision-making of ordinary highway tunnels in Shandong Province.

Keywords: Highway tunnel; Service performance; Analytic hierarchy process; Maintenance decision

Online publication: Jun 11, 2026

1. Introduction

At present, China's highway tunnel industry has stepped into a new stage of equal emphasis on construction and maintenance [1]. A large number of highway tunnels opened to traffic in the early years have encountered problems such as the attenuation of service performance, prominent diseases in structures and facilities, and reduced traffic comfort [2]. Maintenance and management agencies of highway tunnels typically formulate maintenance strategies for tunnels within their jurisdiction based on the outcomes of routine inspections and technical condition evaluations. However, in accordance with *Technical Specification for Highway Tunnel Maintenance* (JTG H12-2015), the scope of such routine inspections and technical condition evaluations is mainly limited to assessing the integrity or defect status of tunnel structures and mechanical and electrical facilities, while failing to fully account for critical aspects including the durability of tunnel structures and facilities, traffic flow smoothness, and riding comfort. Therefore, it is essential to establish a service performance evaluation method for highway tunnels that can comprehensively characterize the safety, durability, traffic flow smoothness and riding comfort of the tunnel, thereby enabling a holistic assessment of the actual operation status of highway tunnels.

A large number of scholars have conducted a certain amount of research on the theories, indicators and methods of highway tunnel service performance evaluation. Dongping Li systematically elaborated the factors influencing the variation of highway tunnel service performance, as well as the geological and hazard problems existing in the service process of highway tunnels [3]. Chao Liu et al. summarized a systematic set of evaluation indicators for highway tunnel service performance from the three core dimensions of tunnel investigation, design and construction, and subsequently established a tunnel service performance evaluation method grounded in fuzzy theory [4]. Fang Xu identified the evaluation indicators for highway tunnel service performance using the improved TOPSIS method, and subsequently established an evaluation model for highway tunnel service performance grounded in Bayesian network theory [5]. Hehua Zhu and Xuezeng Liu developed a set of rapid identification equipment for tunnel structural defects and diseases, and further established an analysis platform for the service performance of highway tunnel structures based on a digital model-driven integrated numerical simulation and analysis methodology, which enables efficient performance analysis of highway tunnel structures [6]. Changhou Li et al. established an evaluation method for the long-term service performance of highway tunnels accounting for time-varying effects, on the basis of the time-varying degradation behavior of tunnel lining bending stiffness [7]. This method delivers a solid theoretical foundation for the long-term performance prediction of highway tunnel service performance. Li Yu et al. established a systematic evaluation indicator system from the perspective of operational safety and riding comfort of long-distance continuous tunnel clusters, and further extended and enriched the connotation and defined scope of highway tunnel service performance [8]. Yue Yang et al. additionally accounted for key factors including the operational performance of mechanical and electrical facilities, traffic environment, and safety management conditions, and subsequently established a systematic set of operational safety evaluation indicators for expressway tunnels [1]. Fayou Deng, Caichu Xia and Chongbang Xu proposed a health status evaluation method for highway tunnels grounded in neutrosophic theory, which overcomes the inherent limitation of the evaluation methods specified in the current valid specifications: their inability to implement robust service performance evaluation of highway tunnels under uncertain service conditions [9]. Huajie Zhu accounted for eight key influencing factors, namely traffic volume, precipitation, incline and vertical shafts, adverse geological conditions, lane count, service life post opening, tunnel length, and technical condition rating of tunnel structures, and subsequently established a systematic health status evaluation indicator system for operational expressway tunnels [10].

Most existing studies on the service performance evaluation of highway tunnels have predominantly focused on the defects and diseases of tunnel structures, whereas insufficient consideration has been given to the operational performance of mechanical and electrical facilities, the durability of tunnel structures and facilities, traffic flow smoothness, and riding comfort. To address this research gap, this study adopts a holistic perspective, fully accounts for four core evaluation dimensions including safety, durability, traffic flow smoothness and riding comfort, develops a comprehensive and systematic evaluation indicator system for highway tunnel service performance on the basis of the Analytic Hierarchy Process (AHP), establishes calculation models for each individual indicator, and ultimately proposes a complete evaluation methodology for the service performance of highway tunnels.

2. Evaluation indicators and calculation models of service performance

The evaluation indicators for the highway tunnel service performance should be selected based on society's demands for highway tunnels as an infrastructure. On the premise of striving for comprehensiveness and perfection, principles such as rigor, conciseness and highlighting key points should also be taken into account [11]. Based on a systematic literature review, societal demands for highway tunnels can be classified into the following four hierarchical dimensions: "safety", "durability", "traffic flow smoothness", and "riding comfort". Focusing on the aforementioned four hierarchical demand dimensions, the first-level evaluation indicators for highway tunnel service performance can be classified into four categories: Safety Indicator, Durability Indicator, Traffic Flow Smoothness Indicator, and Riding Comfort Indicator. The schematic diagram of the first-level evaluation indicator system is presented in **Figure 1**.

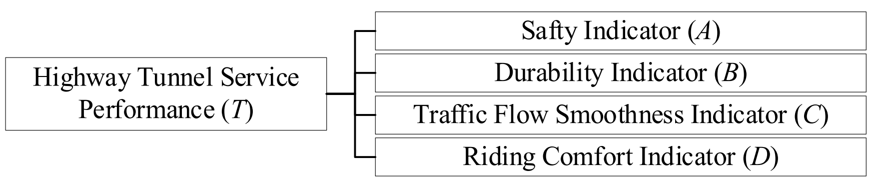

Figure 1. First-level evaluation indicator system for highway tunnel service performance.

Based on the Analytic Hierarchy Process (AHP), the calculation model for the service performance score T of highway tunnels is established, as shown in Equation (1). Herein, a, b, c and d represent the weights of the four first-level indicators, respectively. Considering that the public holds different expectations for tunnels of various highway classifications in terms of safety, durability, traffic smoothness and riding comfort, the value-taking criteria for the four weights are thus defined as presented in **Table 1**.

$$T = a \times A + b \times B + c \times C + d \times D \tag{1}$$

Table 1. Weight value-taking for first-level indicators of highway tunnel service performance

Highway classification / Weight of indicator	Class I	Class II
Weight of safety indicator (a)	0.40	0.50
Weight of durability indicator (b)	0.30	0.30
Weight of traffic flow smoothness indicator (c)	0.20	0.15
Weight of riding comfort indicator (d)	0.10	0.05

2.1. Safety indicator

Numerous factors influence the safety of highway tunnels. From a macro perspective, compliance with highway tunnel technical standards (i.e., the conformity between the actual configuration of structures or facilities and the current technical standards), structural safety and facility safety are all key factors affecting the overall safety of highway tunnels. Thus, the Safety Indicator can be further divided into Technical Standard Compliance Indicator, Structural Safety Indicator and Facility Safety Indicator (as shown in **Figure 2**).

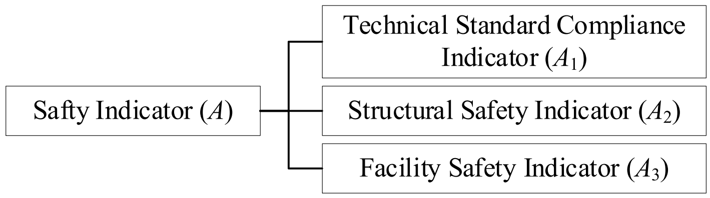

Figure 2. Safety Indicator system for highway tunnels.

The calculation model for Safety Indicator is shown in Equation (2), where a_i denotes the weight corresponding to each of the three second-level indicators. Considering the influence of tunnel length on the safety indicator, the value assignment of the weights is presented in **Table 2** (For long and extra-long tunnels, the structural and facility safety is of vital importance to the overall safety of the tunnel, and thus relatively higher values are assigned to a_2 and a_3).

$$A = \sum_{i=1}^{3} a_i \times A_i \tag{2}$$

Table 2. Weight value-taking for safety indicator of highway tunnels

Weight of indicator \ Type of tunnel	Short tunnel	Medium tunnel	Long tunnel	Extra-long tunnel
Weight of technical standard compliance Indicator (a_1)	0.40	0.30	0.20	0.10
Weight of structural safety indicator (a_2)	0.30	0.35	0.40	0.45
Weight of facility safety indicator (a_3)	0.30	0.35	0.40	0.45

2.1.1. Technical standard compliance indicator

Technical standard compliance indicator assesses the conformity between the actual configuration of tunnel structure or facilities and the prevailing technical standards, and is composed of two sub-indicators: Technical Standard Compliance Indicator for Tunnel Structure and Technical Standard Compliance Indicator for Mechanical and Electrical Facilities. Of these, Technical Standard Compliance Indicator for Tunnel Structure is composed of Compliance Indicator for Cross Channel Spacing, Compliance Indicator for Drainage Ditch Layout, Compliance Indicator for Tunnel Alignment, Compliance Indicator for Construction Clearance, and Compliance Indicator for Maintenance Walkway Height; the Technical Standard Compliance Indicator for Mechanical and Electrical Facilities is composed of Compliance Indicator for Power Supply and Distribution Facilities Configuration, Compliance Indicator for Lighting Facilities Configuration, Compliance Indicator for Ventilation Facilities Configuration, Compliance Indicator for Fire Fighting Facilities Configuration, and Compliance Indicator for Monitoring and Communication Facilities Configuration. The Technical Standard Compliance Indicator system is shown in **Figure 3**. The calculation model for A_1 is presented in Equation (3). Given that the tunnel structure and mechanical and electrical facilities are of equal importance, an identical weight of 0.5 is assigned to both secondary indicators. The calculation models for A_{11} and A_{12} can be uniformly expressed by Equation (4), and the tertiary indicators along with their corresponding weight values are listed in **Table 3**.

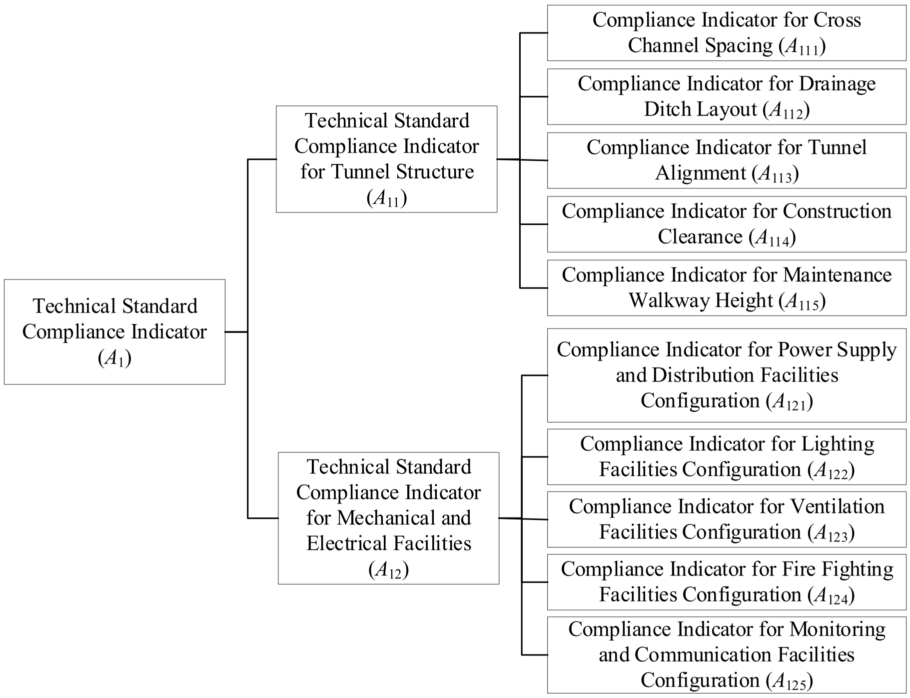

Figure 3. Technical standard compliance indicator system.

$$A_1 = 0.5 \times A_{11} + 0.5 \times A_{12} \tag{3}$$

$$A_{1i} = \sum_{i=1}^{2} \sum_{j=1}^{5} a_{1ij} \times A_{1ij} \tag{4}$$

Table 3. Technical standard compliance indicators and their corresponding weight values

Secondary indicator	Tertiary indicator	Weight	Indicator values		
			Fully compliant	Basically compliant	Non-compliant
A_{11}	A_{111}	0.2	1	0.8	0.5
	A_{112}	0.2	1	0.8	0.5
	A_{113}	0.2	1	0.8	0.5
	A_{114}	0.2	1	0.8	0.5
	A_{115}	0.2	1	0.8	0.5
A_{12}	A_{121}	0.23	1	0.8	0.5
	A_{122}	0.18	1	0.8	0.5
	A_{123}	0.19	1	0.8	0.5
	A_{124}	0.21	1	0.8	0.5
	A_{125}	0.19	1	0.8	0.5

2.1.2. Structural safety indicator

Structural Safety Indicator is designed to assess the safety status of tunnel structure and affiliated engineering facilities. In accordance with the *Technical Specifications for Highway Tunnel Maintenance* (JTG H12-2015), this indicator can be further decomposed into two subordinate indicators: Technical Condition Indicator and

Special Inspection Indicator. Specifically, Technical Condition Indicator is characterized by the results of the technical condition assessment for tunnel structure and affiliated engineering facilities. Correspondingly, Special Inspection Indicator, as a subordinate evaluation dimension, is composed of three tertiary indicators: Crack Condition Indicator, Water Leakage Condition Indicator, and Lining and Surrounding Rock Condition Indicator. Structural Safety Indicator system is presented in **Figure 4**. The calculation model for Indicator A_2 is specified in Equation (5). Tunnel operation and maintenance units routinely conduct qualitative and quantitative evaluation of tunnel structure safety based on periodic inspection and technical condition assessment results, while special inspection results are usually adopted as a supplementary approach to enrich the data pool and evaluation dimensions for tunnel structure safety assessment. On the basis of literature review and expert consultation, the two secondary indicators are assigned a weight of 0.8 and 0.2 respectively.

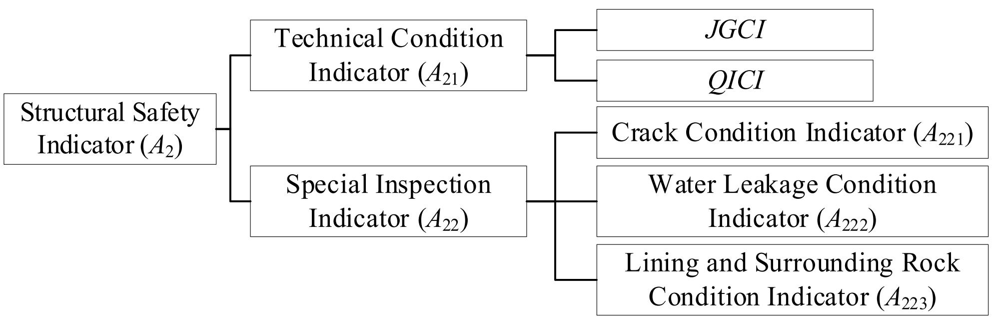

Figure 4. Structural safety indicator system.

$$A_2 = 0.8 \times A_{21} + 0.2 \times A_{22} \tag{5}$$

The calculation model for indicator A_{21} is specified in Equation (6). In this formula, *JGCI* represents the technical condition score of tunnel structure, while *QTCI* represents the technical condition score of affiliated engineering facilities. Considering that the safety performance of tunnel structure exerts a dominant influence on the overall safety of the highway tunnel, the weight of the technical condition score for tunnel structures is determined as 0.8, and the weight for the technical condition score of affiliated engineering facilities is set to 0.2 accordingly.

$$A_{21} = 0.8 \times JGCI + 0.2 \times QTCI \tag{6}$$

The calculation model for indicator A_{22} is specified in Equation (7). On the basis of systematic literature review and expert consultation, the three tertiary indicators are assigned weights of 0.4, 0.4 and 0.2 respectively, in accordance with their contribution to the tunnel structural safety evaluation.

$$A_{22} = 0.4 \times A_{221} + 0.4 \times A_{222} + 0.2 \times A_{223} \tag{7}$$

To quantify the indicator values of Crack Condition Indicator A_{221} and Water Leakage Condition Indicator A_{222} (both tertiary indicators under the Special Inspection Indicator), two core parameters are systematically defined: the crack density of the tunnel lining (pavement) is the ratio of the total number of cracks detected in the lining (pavement) to the total length of the tunnel, and the water leakage density of the tunnel lining (pavement) is defined in the same manner as the ratio of the total number of water leakage points in the lining (pavement) to the tunnel length. The indicator values are determined based on the correlation between the actual defect density of the target tunnel and the mean defect density of the baseline sample (shown in **Table 4**). Finally, the final value of indicator A_{221} is calculated as the product of the lining crack density indicator value and the pavement crack density indicator value, while the final value of indicator A222 is calculated as the product of the lining water leakage density indicator value and the pavement water leakage density indicator value.

Table 4. Indicator values for crack condition and water leakage condition

Indicator	Defect density is zero	Defect density between 0 and the mean defect density	Defect density is greater than the mean defect density
Value of lining crack density	1	0.8	0.5
Value of pavement crack density	1	0.8	0.5
Value of lining water leakage density	1	0.8	0.5
Value of pavement water leakage density	1	0.8	0.5

As a tertiary indicator under the Special Inspection Indicator system, Lining and Surrounding Rock Condition Indicator A_{223} is quantified by comprehensively incorporating five subordinate evaluation factors: lining thickness and compactness (A_{2231}), thickness of the lining's concrete cover (A_{2232}), surrounding rock classification(A_{2233}), compactness of the invert filling layer (A_{2234}), and karst development condition beneath the invert filling layer (A_{2235}). The calculation model for Indicator A_{223} is specified in Equation (8), with the detailed value determination standards for each of its subordinate indicators listed in **Table 5**.

$$A_{223} = \sum 0.2 \times A_{223i} \tag{8}$$

Table 5. Indicator values for lining and surrounding rock condition

Indicator	Indicator value	Scoring criteria
A_{2231}	1	The pass rate for lining thickness reaches 90% or higher, and the lining is free of defects such as voids or lack of compaction
	0.5	The pass rate for lining thickness is less than 90%, or the lining has defects such as voids or lack of compaction
A_{2232}	1	The concrete cover thickness for the reinforcing bars in the tunnel's lining meets the original design specifications.
	0.5	In some sections of the tunnel, the cover thickness of the lining reinforcement does not meet the original design specifications.
A_{2233}	1	The tunnel borehole rock mass consists primarily of Class I, II, and III rock.
	0.8	The tunnel borehole rock mass consists primarily of Class IV rock
	0.5	The tunnel borehole rock mass consists primarily of Class V and VI rock
A_{2234}	1	The infill layer of the tunnel's invert is dense and free of defects.
	0.5	The backfill layer of the tunnel invert is not compacted or contains defects
A_{2235}	1	There is no karst beneath the tunnel invert fill
	0.5	There is karst formation beneath the tunnel invert fill layer

2.1.3. Facility safety indicator

Similar to Structural Safety Indicator, Facility Safety Indicator is used to assess whether there are any safety hazards in the tunnel's mechanical and electrical facilities during operation. According to the

Technical Specifications for Highway Tunnel Maintenance (JTG H12-2015), Facility Safety Indicator can be further categorized into Technical Condition Indicator and Special Inspection Indicator. Technical Condition Indicator is characterized by the assessment results of the technical condition of power supply and distribution facilities, lighting facilities, ventilation facilities, firefighting facilities, and monitoring and communication facilities; whereas Special Inspection Indicator consists of Lightning Protection and Grounding Indicator, Firefighting Facilities Indicator, Suspended Load-Bearing Capacity Indicator, and High-Voltage Facilities Indicator. Facility Safety Indicator system is shown in **Figure 5**. The calculation model for indicator A_3 is shown in Equation 9 (based on expert survey results, the weights assigned to indicator A_{31} and A_{32} are 0.7 and 0.3, respectively).

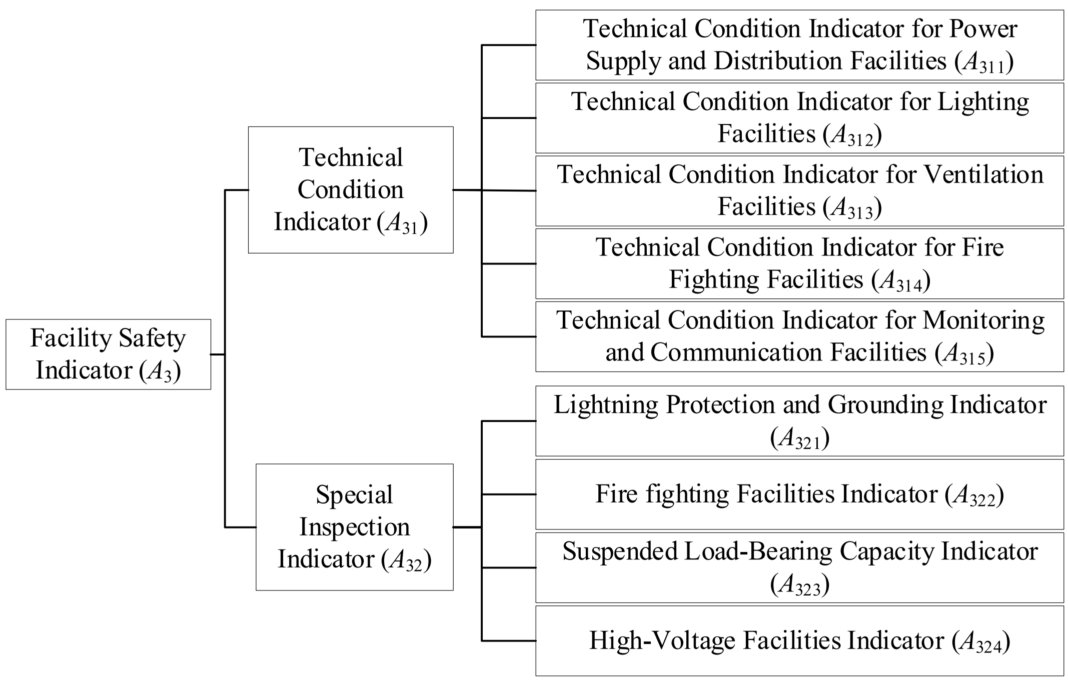

Figure 5. Facility safety indicator system.

$$A_3 = 0.7 \times A_{31} + 0.3 \times A_{32} \tag{9}$$

The calculation model for indicator A_{31} is shown in Equation 10. According to the *Technical Specifications for Highway Tunnel Maintenance* (JTG H12-2015), the weighting values for the five sub-indicators are shown in **Table 6**.

$$A_{31} = \sum_{i=1}^{5} a_{31i} \times A_{31i} \tag{10}$$

Table 6. Weighted values for technical condition indicator of mechanical and electrical facilities

Weight of Technical condition indicator for power supply and distribution facilities	Weight of technical condition indicator for lighting facilities	Weight of technical condition indicator for ventilation facilities	Weight of technical condition indicator for firefighting facilities	Weight of technical condition indicator for monitoring and communication facilities
0.23	0.18	0.19	0.21	0.19

The calculation model for indicator A_{32} is shown in Equation 11 (based on the results of expert surveys, the weights of the four sub-indicators were all set to 0.25); the scoring criteria for the four sub-indicators are shown in **Table 7**.

$$A_{32} = 0.25 \times \sum_{i=1}^{4} A_{32i} \tag{11}$$

Table 7. Scoring criteria for special inspection indicators for mechanical and electrical facilities

Indicator	Indicator value	Scoring criteria
A_{321}	1	A special initiative was launched and has yielded positive results.
	0.8	Special initiatives were launched, but the results were mixed.
	0.5	Special initiatives were launched, but the results were disappointing
	0	No specific initiatives have been undertaken
A_{322}	1	A special initiative was launched and has yielded positive results.
	0.8	Special initiatives were launched, but the results were mixed.
	0.5	Special initiatives were launched, but the results were disappointing
	0	No specific initiatives have been undertaken
A_{323}	1	A special initiative was launched and has yielded positive results.
	0.8	Special initiatives were launched, but the results were mixed.
	0.5	Special initiatives were launched, but the results were disappointing
	0	No specific initiatives have been undertaken
A_{324}	1	A special initiative was launched and has yielded positive results.
	0.8	Special initiatives were launched, but the results were mixed.
	0.5	Special initiatives were launched, but the results were disappointing
	0	No specific initiatives have been undertaken

2.2. Durability indicator

The overall durability of a tunnel is composed of the durability of tunnel structure and mechanical and electrical facilities. Further analysis reveals that the durability of tunnel structure is influenced by the strength of the lining, the depth of carbonation, and the corrosion of reinforcing bars; therefore, Durability Indicator of Tunnel Structure can be composed of Lining Strength Indicator, Carbonation Depth Indicator, and Reinforcing Bar Corrosion Indicator. Durability Indicator for Mechanical and Electrical Facilities consist of Pavement Brightness Indicator and Equipment Corrosion Indicator. Consequently, Durability Indicator system is shown in **Figure 6**.

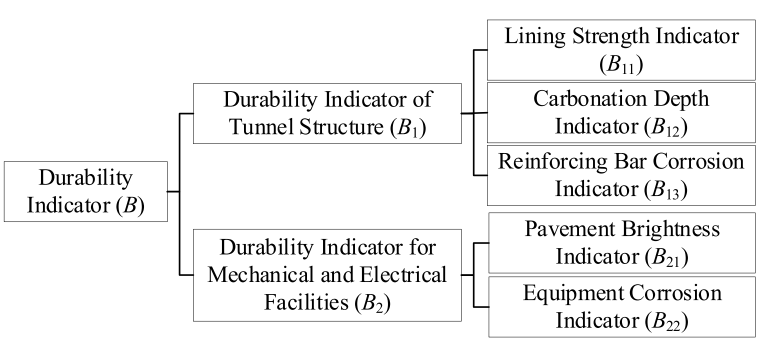

Figure 6. Durability indicator system for highway tunnels.

The calculation model for indicator B is shown in Equation 12 (since the durability of tunnel structure and mechanical and electrical equipment has an equal impact on the overall durability of the tunnel, the weight for both indicators is set to 0.5).

$$B = 0.5 \times B_1 + 0.5 \times B_2 \tag{12}$$

The calculation model for indicator B_1 is shown in Equation 13, and the scoring criteria for its sub-index are shown in **Table 8** (where K_C is the ratio of the average carbonation depth of the component to the average cover thickness of that type of component).

$$B_1 = 0.4 \times B_{11} + 0.2 \times B_{12} + 0.4 \times B_{13} \tag{13}$$

Table 8. Scoring criteria for durability indicator of tunnel structure

Indicator	Indicator value	Scoring criteria
B_{11}	1	The strength of the tunnel lining meets the design values
	0.5	There are sections of the tunnel where the lining strength is less than the design value.
B_{12}	1	$K_C < 0.5$
	0.8	$0.5 \leq K_C < 1.0$
	0.6	$1.0 \leq K_C < 1.5$
	0.4	$1.5 \leq K_C < 2.0$
	0.2	$K_C \geq 2.0$
B_{13}	1	There is no evidence of reinforcing bar corrosion in the tunnel lining.
	0.5	The tunnel lining exhibits signs of reinforcing bar corrosion.

The calculation model for indicator B_2 is shown in Equation 14. Indicator B_{21} is calculated based on the inspection results of each lighting section on-site and the design requirements; its calculation model is shown in Equation 15, and its scoring criteria are listed in **Table 9**.

$$B_2 = 0.7 \times B_{21} + 0.3 \times B_2 \tag{14}$$

$$B_{21} = \frac{\sum_{i=1}^{n} B_{21i}}{n} \tag{15}$$

Table 9. Scoring criteria for pavement brightness indicator

Indicator	Indicator value	Scoring criteria for the value of each randomly selected lighting section
B_{21}	1	Measured brightness value / Design value ≥ 1.3
	0.8	1 ≤ measured brightness value / design value < 1.3
	0.5	Measured brightness value / Design value < 1

The criteria for the value of indicator B_{22} are shown in **Table 10**.

Table 10. Scoring criteria for equipment corrosion indicator

Indicator	Indicator value	Scoring criteria
B_{22}	1	All mechanical and electrical equipment is free of corrosion
	0.8	Some mechanical and electrical equipment shows slight signs of corrosion
	0.5	There is severe corrosion of the mechanical and electrical equipment

2.3. Traffic flow smoothness indicator

Tunnel flow smoothness can be characterized by traffic volume and travel speed. On the one hand, if the actual traffic volume is less than the design traffic volume, the tunnel's flow smoothness is considered good; conversely, it is considered poor. On the other hand, if the actual travel speed within the tunnel is faster than the design speed or the speed limit, the tunnel's flow smoothness is considered good; conversely, it is considered poor. Based on this, the Traffic Flow Smoothness Indicator system is shown in **Figure 7**. The calculation model for indicator C is shown in Equation 16, and the scoring criteria for c_1 and c_2 are shown in **Table 11**. The scoring criteria for C_1 and C_2 are shown in **Table 12**.

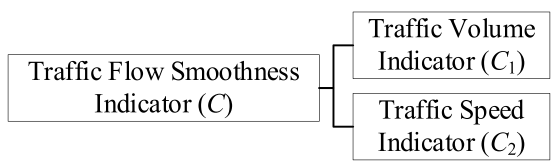

Figure 7. Traffic flow smoothness indicator system.

$$C = \sum_{i=1}^{2} c_i \times C_i \quad (16)$$

Table 11. Weighted values for traffic flow smoothness indicator

Tunnel type / Weight of indicator	Short tunnel	Medium tunnel	Long tunnel	Extra-long tunnel
Weight of traffic volume indicator (c_1)	0.90	0.80	0.70	0.60
Weight of traffic speed indicator (c_2)	0.10	0.20	0.30	0.40

Table 12. Scoring criteria for traffic flow smoothness indicator

Indicator	Indicator value	Scoring criteria
C_1	1	Actual traffic volume / Design traffic volume ≤ 1
	0.8	1 < Actual traffic volume / Design traffic volume ≤ 1.2
	0.5	Actual traffic volume / Design traffic volume > 1.2
C2	1	Actual speed / Design speed (or speed limit) > 1.2
	0.8	1 < Actual speed / design speed (or speed limit) ≤ 1.2
	0.5	Actual speed / Design speed (or speed limit) ≤ 1

2.4. Riding comfort indicator

Riding Comfort Indicator consist of Pavement Riding Comfort Indicator, Lighting Environment Comfort Indicator, and Improvement and Renovation Indicator; Riding Comfort Indicator system is shown in **Figure 8**. The calculation model for indicator D is shown in Equation 17; the scoring criteria for d_1, d_2, and d_3 are listed in **Table 13**, and those for D_1, D_2, and D_3 are listed in **Table 14**.

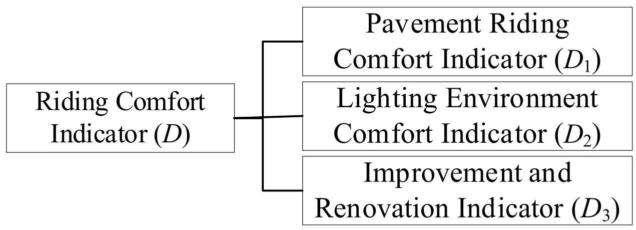

Figure 8. Riding Comfort Indicator system.

$$D = \sum_{i=1}^{3} d_i \times D_i \tag{17}$$

Table 13. Weighted values for riding comfort indicator

Weight of indicator \ Tunnel type	Short tunnel	Medium tunnel	Long tunnel	Extra-long tunnel
Weight of pavement riding Comfort indicator (d_1)	0.30	0.40	0.40	0.50
Weight of lighting Environment comfort Indicator (d_2)	0.30	0.30	0.40	0.40
Weight of improvement and renovation indicator (d_3)	0.40	0.30	0.20	0.10

Table 14. Scoring criteria for riding comfort indicator

Indicator	Indicator value	Scoring criteria
D_1	1	PQI ≥ 95
	0.9	90 ≤ PQI < 95
	0.8	80 ≤ PQI < 90
	0.7	70 ≤ PQI < 80
	0.6	60 ≤ PQI < 70
	0.5	50 ≤ PQI < 60
D_2	1	Overall Uniformity of Pavement Brightness ≥ 0.4
	0.8	0.3 ≤ Overall Uniformity of Pavement Brightness < 0.4
	0.5	Overall Uniformity of Pavement Brightness < 0.3
D_3	1	Improvement projects designed to enhance riding comfort have been carried out.
	0.5	No projects have been carried out to improve riding comfort.

3. Engineering case study

33 highway tunnels in Shandong Province were selected. Data on the tunnels' basic information, operational management, structure and facilities, as well as the results of the 2025 technical condition assessment, were collected. Using calculation models of service performance introduced above, service performance scores were calculated for all 33 tunnels. Based on these results, the tunnels were ranked in order of maintenance priority (the lower the service performance score, the poorer the service performance, the higher the maintenance priority). Because a large amount of data was used in the calculations, **Table 15** shows only the results and a portion of the data.

Table 15. 2025 Shandong province highway tunnel service performance scoring and maintenance priority ranking

Tunnel name	Tunnel length (m)	Jgci	Qtci	Service performance scoring	Maintenance priority ranking
Dongfeng tunnel (Right)	50	79.5	98.33	73.37	1
Dongfeng tunnel (Left)	50	77.75	98.33	73.6	2
Pingyindong tunnel (Left)	360	70	98.55	74.01	3
Pingyindonga tunnel (Right)	360	71.25	98.55	74.29	4
Pingyin tunnel (Left)	440	77.5	100	76.56	5
Pingyin tunnel (Right)	440	77.5	100	76.56	6
Yiheyuan tunnel	126	74.75	100	77.44	7
Taojiakuang tunnel (Right)	1440	73.5	100	80.66	8
Huangshan tunnel (Right)	498	76.75	100	80.73	9
Huangshan tunnel (Left)	495	80.5	100	81.09	10
Taojiakuang tunnel (Left)	1000	78.5	100	81.19	11
Dongkuang tunnel (Right)	965	73.75	100	81.33	12
Wuyan tunnel (Right)	350	81.25	100	81.72	13
Dongkuang tunnel (Left)	960	73.75	100	81.89	14
Pizishan tunnel (Left)	455	79.75	100	82.61	15
Pizishan tunnel (Right)	456.5	78.75	100	82.68	16
Huangjiakuang tunnel (Right)	580	79	100	83.74	17
Huangjiakuang tunnel (Left)	580	74.5	100	83.76	18
Wuyan tunnel (Left)	360	76.25	100	83.84	19
Puqiuling tunnel	390	79	91.67	85	20
Songxianling tunnel	446	77.5	100	85.21	21
Yunmenshan tunnel (Left)	432	76.75	100	85.56	22
Yunmenshan tunnel (Right)	432.3	77.5	100	85.9	23
Shibapan tunnel	590	80.25	100	86	24
Magongci tunnel	735	77.75	100	87.75	25
Tuoshan tunnel (Right)	330	77.5	100	87.81	26
Tuoshan tunnel (Left)	331.7	78.75	100	87.9	27
Shuishiling tunnel	650	81.75	100	88.56	28
Chenyuling tunnel	528	80.25	100	89.24	29
Yangkou tunnel (Right)	3880	77.75	100	89.97	30
Yangkou tunnel (Left)	3880	77.75	100	90.43	31
Shuangdingshan tunnel	485	72.25	91.67	91.44	32
Mashidian tunnel	275	73.5	100	91.82	33

4. Conclusion

Through this study, the following conclusions can be drawn:

(1) Highway tunnel service performance can be evaluated in terms of safety, durability, traffic flow smoothness, and riding comfort. Specifically, the safety evaluation should consider compliance with technical standards as well as the safety of tunnel structures and facilities; the durability evaluation

should take into account both the durability of tunnel structure and mechanical and electrical facilities; and traffic flow smoothness can be assessed in terms of both traffic volume and travel speed. and the evaluation of riding comfort should comprehensively consider the comfort of the pavement and lighting environment, as well as the status of tunnel upgrades and renovations.

(2) A calculation model for highway tunnel service performance established based on the Analytic Hierarchy Process (AHP) enables the quantitative calculation and evaluation of service performance during the operational phase, thereby avoiding the shortcomings of subjective qualitative evaluations; simultaneously, the calculation results can provide data support for tunnel maintenance management units to make scientific decisions regarding tunnel maintenance.

Disclosure statement

The authors declare no conflict of interest.

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Application of Smart Management Technology in Municipal Engineering

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Abstract: With the development of smart cities, the scale and quantity of municipal construction projects continue to increase, while construction techniques and technologies are constantly innovating. This has led to the gradual emergence of issues in traditional extensive municipal engineering management practices. The application of smart management technology enables comprehensive technological means to manage municipal engineering projects throughout their entire lifecycle, implementing precise control measures for each construction phase, thereby enhancing engineering management efficiency and quality. This article will analyze the connotation of smart management technology and explore its specific application methods in conjunction with various stages of municipal engineering. Finally, based on the current application status of smart technologies, corresponding suggestions will be proposed to promote the intelligent transformation of municipal engineering management.

Keywords: Smart management technology; Municipal engineering; BIM technology; Digital twin model

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1. Introduction

The development of urbanization has placed higher demands on the control of construction quality and progress in municipal engineering projects, and traditional experience-based management methods can no longer meet the current needs of municipal engineering management [1]. Therefore, in recent years, China's municipal construction management has gradually transitioned towards intelligent management. The application of intelligent management technologies in municipal engineering management promotes the digital transformation of traditional experience-based control models, enabling linked control across various project processes. This fundamentally addresses the drawbacks of traditional single-point control and lays the foundation for the efficient development of municipal engineering projects.

2. The connotation of intelligent management technologies

Intelligent management technologies refer to collaborative management technology models constructed using artificial intelligence, big data, Internet of Things (IoT), and other technological means, with data collection, analysis, modeling, and application as key supports [2]. The characteristics of intelligent management technologies lie in their integration of multiple technological models, enabling precise identification of deficiencies in municipal engineering control through accurate data analysis, and the formulation of corresponding control plans to achieve precise and full-process control of projects. Intelligent management technologies can be divided into four management modules in municipal engineering management: First, technology-driven data management. In project management, technologies such as sensors and drones can be used to collect relevant data from the project site, providing data support for the establishment of subsequent management models and effectively eliminating the subjective management drawbacks of traditional empiricism. Second, collaborative and linked management. Intelligent management technologies can effectively address information asymmetry issues across various management stages and departments by providing a basis for collaborative operations through information aggregation. Third, intelligent predictive capabilities. The application of intelligent management technologies enables the early identification of control risks through the construction of construction models before project management issues arise, ensuring efficient risk control [3].

3. The application of intelligent management technologies in various stages of municipal engineering projects

3.1. Application of intelligent management technologies in the design stage of municipal engineering projects

The design stage of municipal engineering projects is the overall planning phase, encompassing tasks such as on-site data aggregation, drawing preparation, and construction plan formulation [4]. However, traditional construction design primarily employs two-dimensional design and textual descriptions, making it difficult to form intuitive design content and lacking sufficient participation from various departments, hindering the realization of collaborative effects. The application of intelligent management technologies can leverage engineering data to construct three-dimensional models (GIS geographic information systems and BIM technology), thereby visually presenting information such as construction site topography, engineering structures, and pipeline routes to relevant departments. Furthermore, the three-dimensional design approach not only facilitates the timely identification of design issues by designers but also enhances the accuracy of construction cost estimation, effectively preventing design changes and budget overruns during construction. Additionally, the application of intelligent technologies in design provides a collaborative communication platform (artificial intelligence collaborative design platform) for project participating departments, enabling the sharing of design data and providing designers with design opinions from different disciplines to ensure the completeness of the design. The types and parameters of technologies applied in intelligent management during the design stage can be found in **Table 1**.

Table 1. Application parameters of intelligent management technologies

Smart management technical parameter	Parameter	Technical mode	Application function
GIS spatial positioning accuracy	± 0.5 m	GIS (Geographic Information System)	Construction terrain and on-site survey

Engineering quantity calculation error	≤ 3%	BIM Technology	3D model construction and cost accounting
Collaborative design speed	≤ 3s	AI Collaborative Design Platform	Multi-department collaborative design

3.2. Application of intelligent management technologies in the construction stage of municipal engineering projects

The construction stage of municipal engineering projects is the implementation phase of the main building structure, involving a wide range of engineering management tasks. Management personnel need to strengthen control from multiple dimensions, including construction progress, quality, and safety. Meanwhile, the complex environment and large number of personnel on municipal construction sites lead to an increase in uncontrollable factors. In such cases, relying solely on manual inspections and paper-based information exchange can significantly impact construction management efficiency [5]. Moreover, delayed or inadequate information transmission can easily result in misalignment in engineering management tasks, potentially leading to quality and safety risks in severe situations. The application of intelligent management technologies enables comprehensive control over construction projects, fosters collaboration among departments, and enhances construction management and communication efficiency. Firstly, in terms of construction progress control, BIM technology can be utilized to construct a construction progress model based on the construction plan and conditions. Simultaneously, sensors can be employed to collect real-time construction data on-site for simulating the actual construction progress. By comparing these two models, the reasonableness of the construction progress can be assessed. If significant deviations in the construction progress are detected, the system automatically issues an alert, prompting progress management personnel to promptly identify the cause and adjust the construction plan to resolve project delays. Secondly, for construction quality control, the Internet of Things (IoT) can be employed to monitor the construction process in real-time. Sensors for various construction parameters, such as temperature and compaction, can be deployed on-site to continuously monitor construction quality and upload the monitoring data. This allows management personnel to assess construction quality and mitigate quality risks. Thirdly, in construction safety control, AI video recognition technology can be adopted to identify safety risks during construction, providing references for safety management. For instance, in deep foundation pit construction, identification devices for parameters such as foundation pit displacement and subsidence can be deployed to issue early warnings about safety issues. Once the monitored parameters exceed the threshold, the system automatically triggers an alarm, prompting construction personnel to promptly reinforce the foundation pit and evacuate to prevent personnel casualties caused by foundation pit collapse [6]. Furthermore, AI video recognition technology can accurately identify whether construction personnel are wearing safety protective gear and detect any non-compliant operations. Upon detecting non-compliant behavior, the system automatically issues voice alerts and pushes the non-compliance information to the management personnel's terminals, providing references for safety management rectification work. Finally, in construction resource management, the application of intelligent management technologies enables the identification and analysis of information such as construction progress and material usage patterns to determine the application time of inventory materials. This facilitates reasonable planning for material procurement, arrival, and usage, avoiding excessive material accumulation on-site that leads to management cost waste or delayed material transportation that affects project progress. To ensure a more concise and clear discussion of the application of intelligent management technologies in the construction stage of municipal engineering projects, **Figure 1** is used to analyze the specific application process.

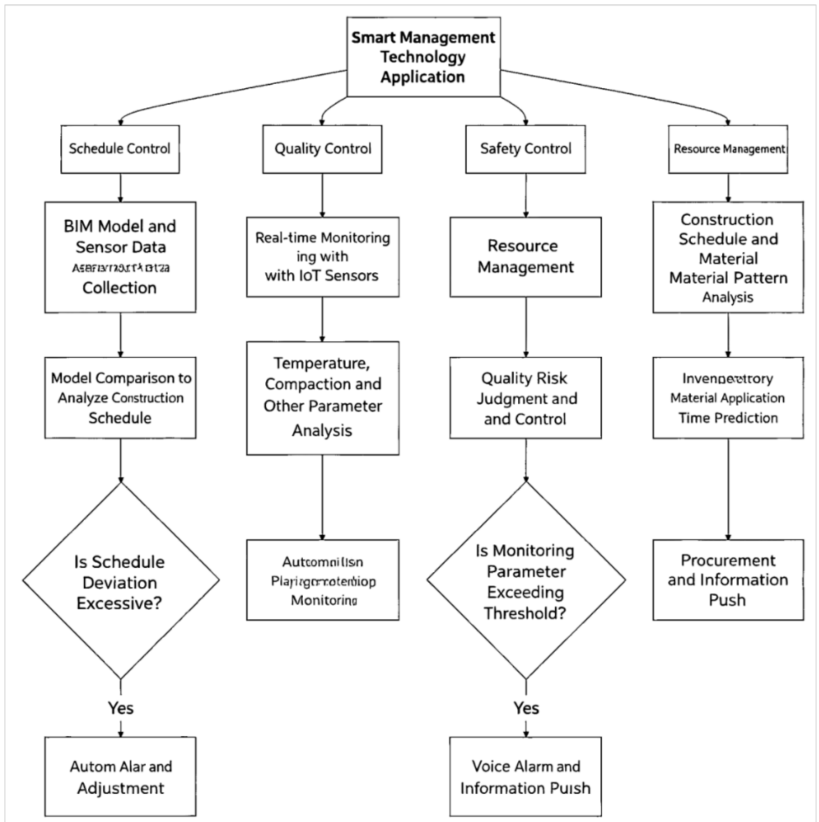

Figure 1. Application of smart management technology in the construction phase of municipal engineering projects.

3.3. Application of smart management technology in the acceptance phase of municipal engineering projects

Project acceptance during municipal engineering construction is pivotal for quality control. The primary tasks in this phase involve comparing the construction results with design standards and industry norms to determine whether the project meets delivery criteria. Traditional municipal engineering projects mainly rely on manual acceptance methods, which are not only inefficient but also prone to human measurement errors, leading to inaccurate acceptance results and affecting the project delivery process. The application of smart management technology in the acceptance phase can transform the traditional on-site measurement acceptance method into a virtual model acceptance mode. Acceptance personnel can construct a BIM engineering model through data collection and compare it with the design model to quickly identify differences and promptly investigate the causes of deviations. Moreover, the model can reflect various parameters of the construction project in real-time, offering more precise and comprehensive data compared to manual measurements, effectively avoiding operational errors and omissions in manual acceptance. Taking the acceptance of pipeline network projects as an example, BIM model comparisons can quickly inspect information such as the buried depth and direction of the pipeline network to determine if it meets design requirements [7]. Simultaneously, simulating construction parameter models enables precise detection of parameters such as the slope and flatness of the pipeline network, with the detected data automatically stored in the project archives for future quality issue tracing. Compared to manual acceptance, the application of smart management technology in the acceptance phase offers significant advantages in terms of the accuracy of parameter measurements and inspection efficiency, effectively avoiding the influence of external factors and human experience on acceptance results. Furthermore, it enables non-destructive testing of the project, such as using radar or laser technology to inspect the internal structure of concrete, ensuring the accuracy of inspection results. Additionally, the application of digital platforms in project acceptance facilitates the construction of a collaborative acceptance platform. This allows construction personnel, supervisors, designers, and others to participate jointly in the acceptance process and provide acceptance opinions from different professional perspectives, facilitating the timely identification and resolution of project issues. Moreover, acceptance reviews by various departments can also be completed through digital platforms, reducing the delivery time of review materials and thereby shortening the acceptance cycle.

3.4. Application of smart management technology in the operation and maintenance phase of municipal engineering projects

The task of operation and maintenance management involves the operation and maintenance of infrastructure after the delivery of municipal engineering projects. This phase has a long duration and needs to run through the entire process of project operation. The management goal in this phase is to identify and address potential quality hazards and defects in the project to ensure its operational quality. Traditional municipal engineering operation and maintenance primarily rely on manual inspections and post-incident remediation, which is a passive approach. If defects are not identified promptly, the scope of the defects may continue to expand, affecting subsequent repair quality and increasing maintenance costs. The application of smart management technology in the operation and maintenance management phase can transform the operation and maintenance management mindset from passive response to proactive prevention and control, enabling regular project inspections [8]. Firstly, a combination of monitoring technology and IoT technology can be used to monitor faults and defects in municipal engineering projects. For example, water level sensors can be installed in pipeline network projects, and settlement sensors can be installed at roadbed locations to collect operational parameters of the project in real-time for operation and maintenance personnel to assess the project's operational status. Simultaneously, operation and maintenance personnel can set risk thresholds in the intelligent detection system. Once parameters reach the threshold range, the system will automatically issue warnings, prompting operation and maintenance personnel to take timely and effective corrective measures and conduct fault investigation and prevention. For instance, in the operation and maintenance management of road and bridge projects, drones can be used for regular inspections of bridges, with inspection data automatically uploaded to ensure the accuracy and timeliness of data collection. Secondly, integrating big data and artificial intelligence technologies can enhance project risk prediction capabilities. Big data technology can collect and analyze various parameters during project operation, such as project defects and maintenance records. Artificial intelligence technology can then be used to predict project risks and develop operation and maintenance management plans based on the prediction results for proactive prevention and control, thereby improving fault prevention and control efficiency and reducing operation and maintenance costs. For example, in the operation and maintenance management of drainage pipeline networks, data analysis of pipeline operation may reveal a slowdown in water flow velocity and a reduction in water volume, indicating a potential blockage in the pipeline. Simultaneously, artificial intelligence can analyze the water flow velocity to determine the scope of the blockage, allowing operation and maintenance personnel to promptly clear the blockage in advance and avoid risks such as pipeline bursts caused by blockages. Additionally, the application of big data technology facilitates the rational optimization of operation and maintenance resource allocation. It can reasonably allocate inspection and operation and maintenance personnel based on the project's operational status and fault occurrence patterns, ensuring optimal resource allocation. Finally, the integrated application of BIM and GIS technologies in the operation and maintenance of municipal facilities can accurately locate project faults, reducing the time required for fault investigation during operation and maintenance [9].

4. Recommendations for the application of smart technologies in municipal engineering projects

The application of smart management technology in municipal engineering project management can enhance the quality and efficiency of full-process project control. However, certain issues still exist in practical applications, necessitating further optimization and improvement of smart management technology:

Firstly, ensure the adaptability of technology to management tasks. Different types of municipal engineering projects and construction phases have varying management needs. Therefore, reasonable technology solutions should be selected based on project requirements when applying smart technologies to avoid template-based applications. Simultaneously, attention should be paid to the integrated application of technologies to achieve complementary advantages and provide more powerful technical support for municipal management by constructing a joint intelligent technology platform.

Secondly, strengthen the optimization of the data system. The application of smart management technology relies on data as its core carrier. If the data system is improperly constructed, leading to inaccurate data, it will inevitably affect the efficiency of smart management technology applications. Based on this, municipal management departments need to optimize the data system and construct an integrated database for data collection, storage, analysis, and application to ensure data integrity. Additionally, standardize the data in the database to avoid affecting compatibility during data transmission and provide favorable conditions for data sharing among departments.

Thirdly, improve smart management systems. Management systems serve as the basis for implementing management tasks. When formulating systems, construction industry standards should be used as references, and targeted management norms should be developed based on the characteristics of municipal engineering projects. Simultaneously, strengthen the security control of smart management technology applications to ensure the security of data during collection, transmission, and application. Finally, improve smart evaluation mechanisms to assess the application effects of smart management technology and promote continuous optimization of its application [10].

5. Conclusion

In summary, the application of smart management technology in municipal engineering project management can effectively overcome the drawbacks of traditional manual management, enable visual management and facilitate the timely identification of construction issues by management personnel to avoid project construction changes or rework. Simultaneously, it can conduct real-time supervision of the quality, safety, and progress of the construction process, improving project control efficiency. Moreover, the application of smart management technology in post-construction operation and maintenance can transform passive approaches into proactive ones, achieving precise prevention and control of project faults. In the future, as smart management technology continues to evolve, its application scope in municipal engineering projects will become broader. However, it is still necessary to ensure the adaptability of technology to management content and implement effective data security control to provide long-term guarantees for the in-depth integration of smart management technology and municipal management work.

Disclosure statement

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The Application of AIGC in BIM Teaching of Prefabricated Buildings under the Blended Teaching Model

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Abstract: Against the backdrop of the construction industry's transition towards industrialization and intelligence, prefabricated buildings have emerged as a core direction for promoting high-quality development in the sector. BIM (Building Information Modeling) technology, as a pivotal tool for lifecycle management in prefabricated buildings, directly influences the effectiveness of professional talent cultivation. The blended teaching model, which integrates the advantages of online and offline instruction, breaks through the temporal and spatial constraints of traditional teaching. Meanwhile, the rapid development of AIGC (Artificial Intelligence Generated Content) technology offers new solutions to address challenges in BIM teaching for prefabricated buildings, such as insufficient practical scenarios, lack of personalized guidance, and outdated teaching resources. This paper analyzes the current status and pain points of BIM teaching for prefabricated buildings under the blended teaching model and proposes targeted application strategies and safeguard measures. The aim is to optimize the BIM teaching process, enhance teaching efficiency and quality, cultivate compound talents in BIM for prefabricated buildings who meet industry demands, and provide theoretical references and practical insights for the reform of teaching in the prefabricated building field.

Keywords: Blended teaching; AIGC; Prefabricated buildings; BIM

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1. Analysis of current status and pain points in BIM teaching for prefabricated buildings under the blended teaching model

1.1. Current status of BIM teaching for prefabricated buildings

The integration of prefabricated buildings and BIM technology represents a significant trend in the current development of the construction industry. Vocational colleges and universities offering architecture-related majors have introduced BIM courses for prefabricated buildings and adopted a blended teaching model combining online and offline instruction. Online teaching utilizes internet platforms to disseminate course resources and conduct virtual simulation exercises, while offline instruction strengthens students' practical skills through hands-on training, case studies, and group discussions. Many vocational colleges have also started collaborating with construction enterprises to introduce project cases, and some have equipped themselves with BIM laboratories and prefabricated building component model teaching aids, achieving an initial integration of theory and practice. However, from a practical teaching perspective, current courses often focus on basic BIM modeling operations, with insufficient coverage of BIM applications throughout the lifecycle of prefabricated buildings. Additionally, the connection between online and offline components in blended teaching is not smooth, and due to limited faculty expertise, teachers with both BIM technical skills and practical experience in prefabricated engineering are relatively scarce. Consequently, it is challenging to deeply integrate industry needs with teaching content during practical instruction, leading to a certain gap between teaching effectiveness and talent cultivation requirements.

1.2. Core pain points in BIM teaching under the blended teaching model

Under the blended teaching model, the core pain points in BIM teaching manifest at multiple levels.

Firstly, online resources are monotonous. The online resources provided by institutions are often static, such as recorded lectures and electronic courseware, resulting in weak interactivity and relevance. This diminishes students' enthusiasm for autonomous online learning and makes it difficult for teachers to accurately assess students' learning outcomes.

Secondly, there is a shortage of hardware and software for practical teaching and training resources. Offline teaching fails to precisely address students' weaknesses identified during online learning. Moreover, BIM teaching places higher demands on practical operations, but the updates to BIM software and hardware in institutions are relatively delayed, leading to insufficient virtual simulation training resources for prefabricated buildings. Students find it difficult to access real-world BIM application scenarios in projects, rendering practical teaching superficial.

Thirdly, an appropriate teaching case system has not been established. Current teaching cases primarily revolve around traditional building projects, with relatively few and insufficiently systematic cases tailored to BIM teaching for prefabricated buildings. Consequently, students cannot gain an in-depth understanding of the key points of BIM technology application in various stages of the lifecycle of prefabricated buildings, including design, component production, and on-site construction, resulting in a disconnect between teaching content and industry trends in prefabricated buildings.

Fourthly, there is a disconnect between teaching content and actual industry needs. The practical BIM technology application requirements and cutting-edge technological methods in prefabricated building projects are not swiftly translated into actual course content during teaching. As a result, institutions still focus on traditional BIM skill transmission, making it difficult for students to deeply match the skills they learn in school with enterprise job requirements. After graduation, students often need to re-familiarize themselves with job tasks, leading to a deviation between talent cultivation and job demands.

1.3. Necessity of applying AIGC in BIM teaching

Firstly, AIGC can help address the pain points of blended teaching resources and practical training, compensating for teaching resource shortcomings. In response to issues such as a scarcity of teaching cases and insufficient training resources for BIM in prefabricated buildings, AIGC can leverage construction industry data and real project information to rapidly generate diverse teaching cases and simulate virtual training scenarios. Simultaneously, it can formulate personalized online learning recommendations and plans based on students' actual situations, enhancing the relevance and interactivity of online teaching. Additionally, by utilizing virtual reality technology, AIGC can facilitate highly realistic practical training, addressing the problems of outdated hardware equipment and relatively monotonous practical scenarios in institutional teaching, thereby improving the effectiveness of blended teaching.

Secondly, AIGC can drive the upgrading of blended teaching models and talent cultivation to meet industry demands. The existing teaching model fails to effectively cultivate students' AIGC-assisted design capabilities. As industry development gradually moves towards the deep integration of AIGC and BIM technology, incorporating AIGC into BIM teaching can establish an "AI + BIM" blended teaching model. This not only promotes teaching innovation but also ensures that BIM teaching content deeply aligns with industry trends, enabling students to grasp and understand cutting-edge AIGC technology applications in the industry through learning. This closely aligns with the demands for new architectural talents in the context of the construction industry's transformation and upgrading, contributing to enhancing the quality and level of talent cultivation.

2. The application of AIGC in BIM teaching for prefabricated construction under the blended teaching model

2.1. Strengthening the construction of teaching resources

Under the blended teaching model, the primary task of applying AIGC in BIM teaching for prefabricated construction is to strengthen the construction of teaching resources, ensuring sufficient resource support for teaching practice. In practice, leveraging AIGC technology can specifically address the shortcomings of BIM teaching resources for prefabricated construction, thereby resolving issues such as the scarcity of case resources and the monotony of resource formats in current teaching practices. In practice, AIGC technology can deeply integrate with real projects to rapidly generate BIM teaching cases that are closely related to the entire lifecycle of prefabricated construction, embedding core aspects such as design specifications, component fabrication, and construction organization planning into the teaching cases. Relying on architectural terminology databases and prompt templates during the teaching process, standardized practical training task sheets, technical document templates, and other targeted teaching resources can be generated, thereby enriching the resource formats of BIM teaching for prefabricated construction and promoting teaching innovation.

2.2. Promoting the optimization of teaching models

Driving teaching innovation through the deep integration of AIGC and BIM technology can effectively promote the reconstruction of the blended teaching model for BIM in prefabricated construction, thereby breaking away from the disconnected state of online and offline teaching under traditional models. In the online teaching segment, AIGC technology can be utilized to establish an intelligent learning assistance system that deeply integrates students' BIM learning progress and practical operation data, enabling personalized delivery of learning tasks, Q&A resources, and other materials. Additionally, it can simulate the actual work scenarios of BIM projects for prefabricated construction through the platform, allowing students to engage in virtual practical training via online channels and enhancing their practical skills. In offline teaching, AIGC can assist in the practical application of BIM technology, organizing students for group discussions and analyses. During teaching practice, operations can be carried out following processes such as information extraction, content generation, and manual review, enabling students to complete BIM technical document compilation for real projects through this process. This forms a comprehensive educational model that deeply integrates online virtual training and offline practical application, helping to strengthen students' professional competence and abilities, and enhancing the quality and effectiveness of BIM teaching for prefabricated construction.

2.3. Strengthening the construction of faculty

Faculty development is key to integrating AIGC into BIM teaching for prefabricated construction under the blended teaching model. Therefore, institutions can utilize AIGC to develop exclusive faculty training resources, explaining practical methods of generative AIGC-assisted BIM teaching to teachers during training, helping them broaden their professional horizons, and enabling them to utilize AIGC in teaching practices. Furthermore, institutions should guide teachers to deeply learn the practical operation essentials of AIGC, transforming AIGC into a teaching assistance tool that can assist teachers in organizing BIM professional knowledge points for prefabricated construction, designing professional teaching plans, and pushing cutting-edge technological information on the integration of AIGC and BIM based on the latest industry research findings and actual enterprise needs. This enables teachers to promptly update their knowledge structures, deeply understand AIGC technology, and deeply integrate AIGC into BIM teaching for prefabricated construction, thereby enhancing teaching effectiveness and cultivating a composite faculty team.

2.4. Strengthening student capacity building

Strengthening student capacity building is a crucial aspect of promoting the integration of AIGC into BIM teaching for prefabricated construction. Therefore, AIGC can be fully utilized in teaching to gradually guide students in in-depth learning, such as having students use AIGC to extract information from BIM models and compile technical documents, thereby enhancing their ability levels and enabling them to master BIM practical skills. Additionally, teachers should assign practical training tasks involving AIGC-assisted BIM design for prefabricated construction, allowing students to practice "human-machine collaboration" during task participation, thereby cultivating their innovative thinking and engineering problem-solving abilities. Finally, teaching should deeply integrate with real project case verification processes, enabling students to participate in complete AIGC-assisted BIM project operations, thereby exercising their full-process practical abilities, giving them a profound understanding of cutting-edge industry technologies, and promoting their transformation from traditional skilled talents to "innovative + composite" talents.

2.5. Improving the evaluation system

Relying on AIGC technology for BIM teaching in prefabricated construction requires the improvement of the evaluation system to precisely align with the requirements of the blended teaching model. In practice, AIGC can be utilized for full-process data collection and real-time data analysis of students' online learning behaviors, BIM model operation processes, and technical document compilation results, thereby evaluating students' learning processes [1]. Furthermore, the evaluation can deeply integrate architectural professional standards, utilizing AIGC for intelligent initial evaluations of students' BIM practical results and technical document compilation quality, providing evaluation opinions from dimensions such as professionalism and accuracy in this process. Subsequently, teachers conduct manual review evaluations, thereby creating a comprehensive evaluation model that combines intelligent initial evaluations with manual reviews. After completing the evaluation, the AIGC system provides each student with a personalized ability analysis report, pointing out their ability weaknesses and directions for improvement, enhancing teaching levels and quality [2].

3. Safeguard measures for the application of AIGC in BIM teaching of prefabricated buildings under the hybrid teaching model

3.1. Improving policy support for teaching reform

Under the hybrid teaching model, the application of AIGC in BIM teaching of prefabricated buildings necessitates the enhancement of policy support for teaching reform. Therefore, institutions should closely align with the transformation and upgrading of the construction industry as well as the development goals of prefabricated buildings, introduce specialized reform policies, and integrate them into the talent cultivation plans and core course content of architectural majors. This will clarify the application positioning of AIGC technology and the implementation standards for BIM teaching of prefabricated buildings [3]. Simultaneously, corresponding incentive measures should be established to encourage teachers to utilize AIGC for BIM teaching and drive pedagogical innovation centered around it. Finally, detailed implementation rules should be formulated by deeply integrating the characteristics of BIM teaching for prefabricated buildings, thereby standardizing the application process of AIGC in various aspects of hybrid teaching. This will provide clear institutional guidance and safeguards for teaching reform, facilitating its orderly progression [4].

3.2. Establishing a stable technical support system

Establishing a stable technical support system aids in facilitating the integration of AIGC into BIM teaching of prefabricated buildings, enhancing the effectiveness and quality of hybrid teaching. In practice, institutions should collaborate with technical teams to develop lightweight AIGC-assisted BIM teaching tools and establish data interfaces between BIM and AIGC platforms, enabling precise extraction of model information and intelligent generation of documents in teaching practice scenarios [5]. Additionally, a technical service platform should be established during teaching practice to provide services such as tool maintenance, version updates, and problem-solving, ensuring the stability of teaching equipment. Continuous updates should also be made to the architectural professional database and teaching prompt template library, providing ample technical support for the integration of AIGC into BIM teaching of prefabricated buildings [6].

3.3. Increasing investment in teaching

The practical application of AIGC in BIM teaching of prefabricated buildings under the hybrid teaching model necessitates increased investment in teaching, encompassing both hardware and software aspects. On the hardware front, BIM teaching computer lab equipment should be promptly updated, equipped with computers and servers compatible with AIGC technology, and an integrated online-offline teaching and training platform should be established to meet the synchronous training needs of BIM modeling and AIGC practical operations [7]. From a software perspective, institutions should purchase genuine AIGC teaching platforms, BIM software, and prefabricated virtual simulation resources to ensure ample resource support for teaching practice and enhance teaching levels and effectiveness [8].

3.4. Promoting alignment between teaching and industry practice

Deep alignment between teaching and industry practice is crucial for enhancing the quality of hybrid teaching and facilitating the in-depth application of AIGC in BIM teaching of prefabricated buildings. Therefore, a collaborative education model between institutions and enterprises should be established to promote the deep integration of AIGC teaching applications with industry practice [9]. In practice, "AIGC + BIM" training bases can be jointly established with social prefabricated building enterprises, incorporating real enterprise project cases, the latest AIGC application technologies, and industry standards to effectively transform actual enterprise project processes into teaching and training content. Additionally, institutions should strengthen cooperation with external experts during teaching practice, jointly develop training projects and course resources with them, and organize students to participate in real projects, effectively aligning teaching content with real job requirements and enhancing students' practical skills and professional competence [10].

4. Conclusion

The study reveals that the application of AIGC in BIM teaching of prefabricated buildings under the hybrid teaching model faces numerous challenges, spanning multiple dimensions such as resources, modes, faculty, and evaluation. The practical application of AIGC technology can overcome current teaching limitations and achieve teaching innovation from dimensions such as resource construction and mode optimization. Furthermore, corresponding safeguard measures can provide support for the practical application of AIGC technology in BIM teaching of prefabricated buildings, facilitating their deep integration. This effectively enhances students' professional competence and skills, nurturing a continuous stream of "AIGC + BIM" composite architectural talents for the development of the prefabricated building industry. In the future, the integration of AIGC and BIM teaching in prefabricated buildings will evolve towards intelligence and depth, with human-machine collaboration becoming the mainstream of teaching practice. Subsequent research can seek breakthroughs in directions such as quantitative evaluation of AIGC teaching effectiveness and the development of personalized teaching systems to further promote and deeply integrate AIGC into BIM teaching of prefabricated buildings, driving high-quality development in architectural education.

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Technical Condition and Disease Analysis of Civil Structure of Highway Tunnels in Hebei Province

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Abstract: Based on the latest regular inspection data of civil engineering structures from 639 highway tunnels in Hebei Province, this article reveals the relationship between different road technical grades, tunnel types, and the technical conditions of civil engineering structures through multi-dimensional statistical analysis of technical conditions. It also analyzes and summarizes the frequently occurring sub-items of tunnel civil engineering structural defects, as well as common defect types and causes. This has important practical value for tunnel maintenance and management units to optimize maintenance strategies and improve management and maintenance levels.

Keywords: Highway tunnel; Civil engineering structure; Technical condition analysis; Disease analysis

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1. Introduction

As an important component of transportation infrastructure, the structural safety of highway tunnels is directly related to the traffic capacity and operational safety of road networks. With the continuous increase in the operational lifespan of highway tunnels in China, various defects have gradually emerged in tunnel civil structures under the combined effects of complex geological conditions, heavy traffic loads, and environmental erosion, posing severe challenges to maintenance and management work [1]. In recent years, domestic scholars have conducted certain research on tunnel technical conditions and disease mechanisms. For example, Liu Wenbin et al. analyzed regular inspections of 98 highway tunnels and found that lining damage, water leakage, pavement, and drainage facilities are the main issues in the civil structures of highway tunnels in southern provinces of China [2]. Luo Ziqing et al. analyzed the defects in the civil structures of 111 highway tunnels in karst areas in central and western Guangxi and found that these defects are mainly concentrated in the lining, portal, maintenance roads, and drainage facilities [3]. Zheng Kexi et al. established a knowledge base of civil structural defects in operational tunnels based on existing tunnel inspection data [4]. Chen Yuanyuan and Wang Jinyu et al. also summarized common defects and their causes in tunnel civil structures during operation based on inspection data [5,6]. In summary, although domestic scholars have made some progress in research on technical conditions and disease mechanisms, systematic research on a large sample size at the provincial level is still relatively lacking. Especially for Hebei Province, as a transportation hub in North China, the analysis of the technical conditions of its tunnel civil structures holds significant reference value for similar regions.

2. Project overview

The operational environment of highway tunnels in Hebei Province is complex, and due to the long-term combined effects of diverse geological conditions, heavy traffic, and environmental factors, the problems of civil engineering structural defects are increasingly evident.

To systematically evaluate the technical conditions of civil engineering structures with different technical levels and tunnel types, and to reveal the distribution patterns and causes of typical defects, a total of 639 tunnels were included in this statistical analysis. According to the technical level of tunnels, there are 499 national expressway tunnels, accounting for 78.09%, and 140 national and provincial trunk line tunnels, accounting for 21.91%, as shown in **Figure 1**. According to the tunnel type, there are 242 short tunnels ($L \leq 500$ m), accounting for 37.87%, 140 medium tunnels ($500 \text{ m} < L \leq 1000$ m), accounting for 21.91%, 197 long tunnels ($1000 \text{ m} < L \leq 3000$ m), accounting for 30.83%, and 60 extra-long tunnels ($L > 3000$ m), accounting for 9.39% [7]. Refer **Figure 2**.

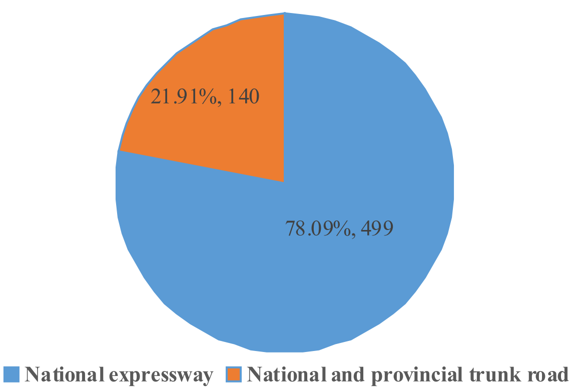

Figure 1. Statistical chart of tunnel technology classification.

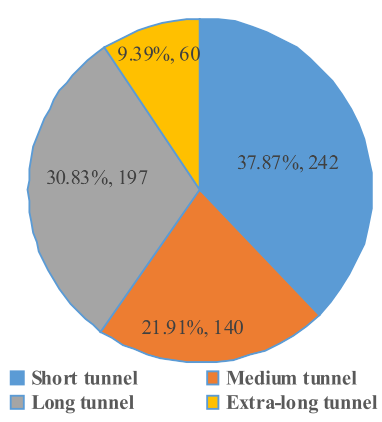

Figure 2. Statistical chart of tunnel type classification.

3. Analysis of technical conditions of civil engineering structures

3.1. Relationship between technical conditions and road technical grades

To explore the differences in the technical condition of tunnel civil structures under different road technical grades, and thereby provide a basis for maintenance units to reasonably formulate targeted maintenance management strategies, this paper takes 639 tunnels in Hebei Province as the research objects and conducts a comparative analysis of the technical conditions of their civil structures according to the road technical grade they belong to. The relevant results are shown in **Figure 3** and **4**. The results show that the overall technical condition of tunnel civil structures in Hebei Province is at a good level, but there are significant differences among tunnels on different grades of roads: the average score of the civil structure technical condition for 499 national expressway tunnels is 81.55, with 99.80% of tunnels rated as type 1 and type 2, indicating that the overall structural condition of national expressway tunnels is good and the maintenance management level is high. In contrast, the average score of the civil structure technical condition for 140 national and provincial trunk line tunnels is 79.62, with 88.57% of tunnels rated as type 1 and type 2. Although generally still good, it is obviously inferior to that of national expressway tunnels. In addition, among the national and provincial trunk line tunnels, there are still 16 tunnels with civil structure technical conditions rated as type 3 or above, accounting for 11.43%, meaning that these tunnels have relatively obvious structural defects and should be repaired and treated in a timely manner. Overall, the civil structure technical condition of national expressway tunnels is significantly better than that of national and provincial trunk line tunnels. Accordingly, Hebei Province should consolidate the existing high-standard maintenance management achievements of national expressway tunnels and proactively and effectively take improvement measures for the relatively weaker technical conditions of national and provincial trunk line tunnels.

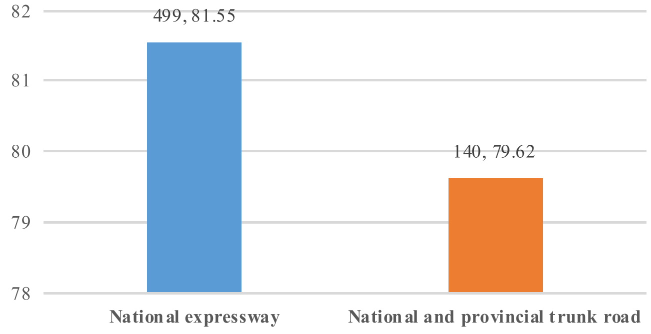

Figure 3. Average scores of tunnel technical conditions across different road technical grades.

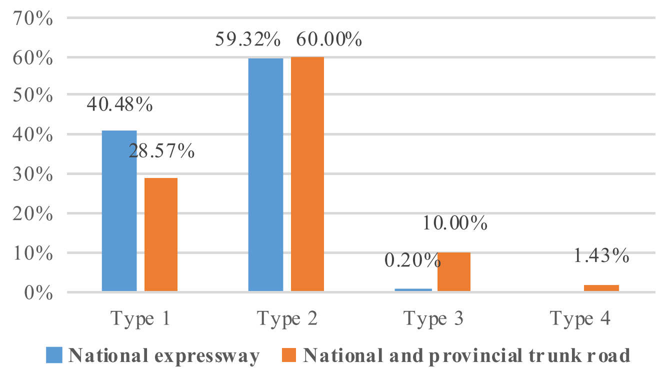

Figure 4. Percentage of tunnel technical conditions at different road technical grades.

3.2. Relationship between technical conditions and tunnel types

To explore the relationship between the technical condition of tunnel civil structures and tunnel types, and to provide a reliable basis for differentiated maintenance decisions, this paper takes 639 tunnels in Hebei Province as the research objects. The technical conditions of civil structures are compared and analyzed according to tunnel length categories, as shown in **Figures 5** to **7**. The results indicate that there is a certain correlation between the technical condition of tunnel civil structures and tunnel length: short tunnels have the best technical condition of civil structures, with an average technical condition score of 82.88, and tunnels rated as type 1 and type 2 account for 98.76% of the total sample. As tunnel length increases, the technical condition of civil structures shows a declining trend. The average scores for medium and long tunnels are 81.03 and 79.44, respectively, and the proportion of tunnels rated type 3 or above correspondingly rises. For medium tunnels, the proportion of Class 3 or above tunnels is 4.29%, and for long tunnels, it is 3.56%. However, the average technical condition score of extra-long tunnels slightly rebounds to 79.85, and the proportion of Class 1 and 2 tunnels rises to 98.34%, which is likely due to the resource preference and stricter management measures allocated to extra-long tunnels during operation and management.

Overall, it shows that the technical condition of tunnel civil structures becomes increasingly severe with the increase in tunnel length, and the difficulty and complexity of maintenance also correspondingly increase. However, examples of ultra-long tunnels also illustrate that appropriate resource investment and optimized management methods can mitigate or even reverse this negative trend. Therefore, in tunnel maintenance management, managing units should, while ensuring the safe operation of ultra-long tunnels, focus on medium- and long tunnels as key objects for improving technical condition and preventive maintenance.

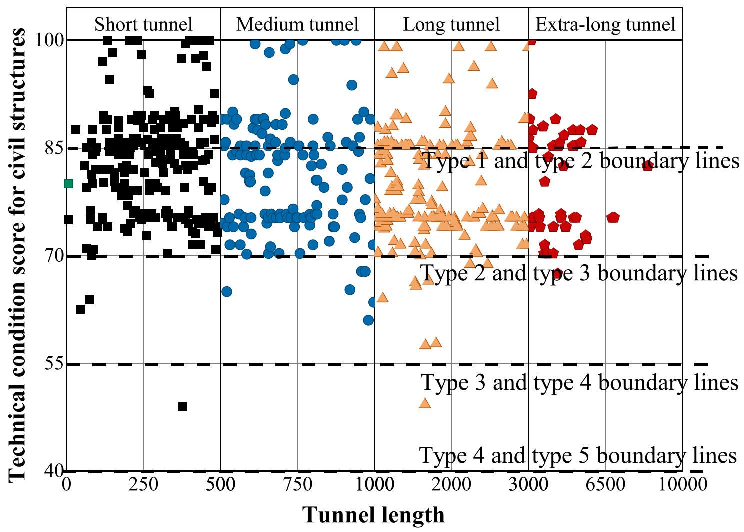

Figure 5. Relationship between technical condition score and tunnel type.

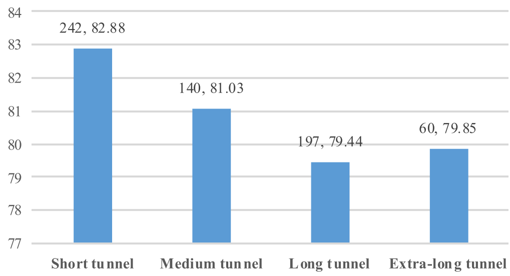

Figure 6. Average scores of different types of tunnel technology conditions.

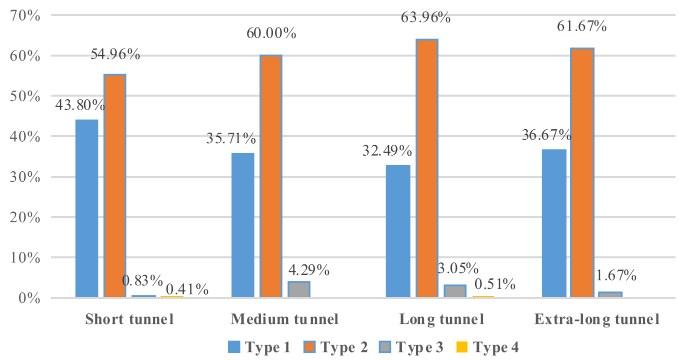

Figure 7. Percentage of different types of tunnel condition values.

4. Analysis of typical defects in civil engineering structures

To explore the main sub-item defects affecting the technical condition of tunnel civil engineering structures and provide a reference for maintenance and management by the maintenance and management unit, this paper statistically analyzes the proportion of each sub-item condition value in the latest regular inspection of 639 tunnel civil engineering structures, as shown in **Figure 8**. The results indicate that the defect rates of lining, pavement, maintenance access, and interior decoration in tunnel civil engineering structures are 91.24%, 73.08%, 72.14%, and 76.06%, respectively, which are the main sub-items with concentrated defects. The proportion of lining condition value 2 is as high as 41.31%, significantly higher than other sub-items, indicating that lining defects are often the most frequent and most influential defects on civil engineering structures, significantly restricting the technical condition rating of civil engineering structures. Although pavement, maintenance access, and interior decoration are mainly condition value 1 (67.14%, 71.36%, and 74.96%), the high proportion reflects widespread defects, requiring attention to long-term accumulated defects. The proportions of condition value 1 for portal, tunnel entrance, and sign markings are 12.99%, 25.35%, and 18.78%, respectively, indicating a certain range of minor defects. In comparison, the possibility of defects in drainage facilities and ceiling embedded parts is relatively low (both < 9%).

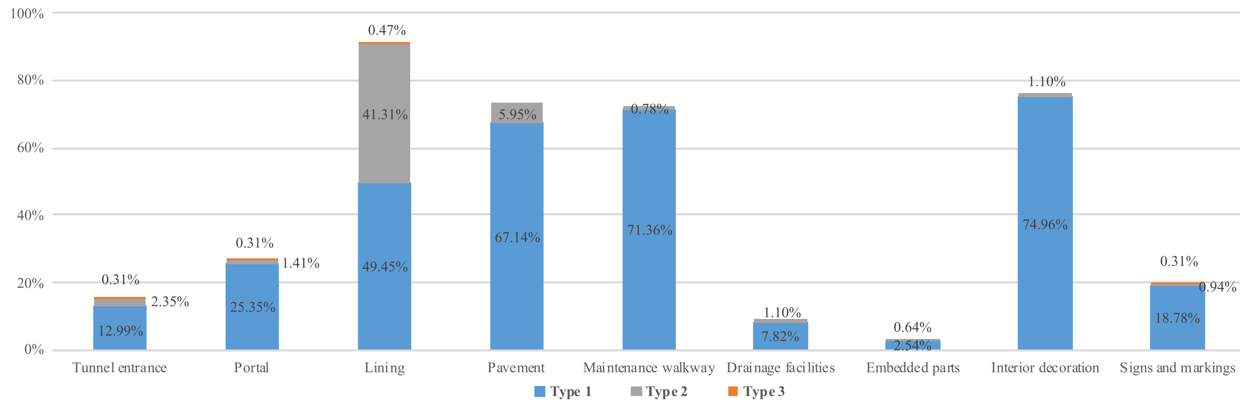

Figure 8. Percentage chart of sub-item status values for tunnel civil engineering structures.

Upon further analysis of the types and causes of defects, it was found that the lining often experiences leakage due to local failure of the waterproofing system, as well as cracks and damages caused by tunnel surrounding rock load, concrete deterioration, structural thermal expansion and contraction, and vehicle scratching; the pavement often suffers from cracks and potholes due to the load of heavy vehicles, broken tunnel base, or construction quality issues; the maintenance walkways often experience panel chipping, damage, and cracking due to insufficient strength of the cover plate, improper lifting and covering during maintenance construction, as well as side wall damage caused by vehicle collisions and scrapes; the interior decoration and sign markings often suffer from damage and dirt due to long operating hours and heavy traffic. Among these, lining and pavement may develop from small defects into large ones. It is recommended to prioritize the inspection and repair of lining and pavement during daily maintenance. At the same time, for high-frequency minor defects such as those on maintenance walkways and interior decoration, daily maintenance plans or preventive maintenance plans should be formulated to ensure the operational and structural safety of the tunnel.

5. Conclusion

Through statistical analysis of the most recent regular inspections of the civil structures of 639 highway tunnels in Hebei Province, this study reveals the relationship between the technical condition of tunnel civil structures and the tunnel road technical grade and tunnel type, and identifies the sub-items of tunnel civil structures that are prone to diseases, as well as common types of defects and their risk causes. The conclusions help tunnel management units optimize maintenance strategies, improve tunnel safety and service life, and reduce operational risks. Through this review, the main conclusions and recommendations of this thesis are as follows:

(1) The technical condition of the civil structure of national expressway tunnels is significantly better than that of national and provincial trunk line tunnels. Tunnel maintenance units should, while continuously consolidating the high-standard maintenance management achievements of national expressway tunnels, proactively and effectively take measures to improve the relatively weak technical aspects of national and provincial trunk line tunnels.

(2) As the tunnel length increases, the overall technical condition of the tunnel's civil structures tends to

decline, but it can be partially improved through resource allocation or management optimization. Maintenance units need to focus on enhancing the upkeep of medium- and long-length tunnels.

(3) Lining, pavement, maintenance access, and interior decoration are the main sub-items where civil engineering structural defects are concentrated in highway tunnels in Hebei Province. In particular, lining damage and water leakage are the most frequent and most influential defects in civil engineering structures. The maintenance unit needs to pay attention to inspection and repair, and strive to ensure the operation and structural safety of the tunnel.

Disclosure statement

The authors declare no conflict of interest.

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Building Carbon Emission Accounting and Whole Life Cycle Decarbonization Pathways for Green Buildings

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Abstract: As one of the world's primary sources of carbon emissions, the building sector's decarbonization progress directly affects the realization of "dual carbon" goals. Based on life cycle theory, this paper systematically analyzes the technical logic and limitations of carbon emission accounting methods for buildings, and elaborates on innovative pathways for green building decarbonization technologies, including passive design, active energy systems, and BIM-based digitalization. The Technology Acceptance Model (TAM) and a tripartite evolutionary game framework are introduced to analyze the barriers and driving mechanisms for technology diffusion from a socio-technical perspective. Using practical cases from China Construction Science and Technology Group Co., Ltd. (CSCSTC), the paper quantifies emission reduction performance. Finally, a coordinated implementation framework integrating policy regulation, technological innovation, and market incentives is proposed. Results show that combining Life Cycle Assessment (LCA) with the emission factor method can improve accounting accuracy by over 30%; integrating passive design and renewable energy technologies reduces building energy consumption by 50–64%; and scaled application of the "Photovoltaics + Energy storage + Direct current + Flexibility" (PEDF) system achieves renewable energy self-consumption rates above 80%. Furthermore, modular construction reduces carbon emissions from the construction phase by 30%, while green financial instruments such as preferential loans can raise project internal rates of return (IRR) by approximately 2–3 percentage points. This study provides theoretical support and practical guidance for low-carbon transition in the building industry.

Keywords: Building carbon emissions; Green buildings; Life cycle assessment; Zero-carbon technologies; Decarbonization policies; Evolutionary game

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1. Introduction

1.1. Research background

Against the backdrop of intensifying global climate change, the building sector has become a critical focus of carbon emission control. Data from the International Energy Agency (IEA) indicate that the building sector accounts for 38% of global energy-related carbon emissions and approximately 50% of raw material consumption, covering the entire life cycle of material production, construction, operation, and maintenance [1]. In China, carbon emissions from the building sector constitute a growing share of the national total. According to the *2023 China Building Energy Consumption and Carbon Emission Research Report*, the total whole-life-cycle carbon emissions of China's building sector reached 5.01 billion tons of CO_2 in 2021, accounting for 47.1% of the national total [2]. The "14th Five-Year Plan" for Building Energy Efficiency and Green Building Development* explicitly identifies the building sector as a core battlefield for achieving the "dual carbon" goals, setting the binding target that all newly built urban buildings shall achieve green certification by 2025 [3]. In this context, clarifying the logic of building carbon accounting, overcoming technical bottlenecks in green building decarbonization, and constructing feasible emission reduction pathways are crucial for realizing the "dual carbon" goals.

1.2. Research significance

1.2.1. Theoretical significance

Existing research mostly focuses on emission reduction technologies at individual stages, lacking a systematic whole-life-cycle perspective. By integrating carbon accounting methodologies and green building technology systems, this paper constructs a complete theoretical framework spanning "carbon accounting → decarbonization technologies → regional adaptation → diffusion mechanisms". In particular, through the introduction of an evolutionary game model, this study reveals the strategic interactions and equilibrium formation mechanisms among local governments, developers, and consumers in the promotion of green buildings, addressing gaps in existing research including technological fragmentation, weak regional specificity, and the absence of multi-agent interaction analysis, thereby enriching the theoretical system of green and low-carbon buildings.

1.2.2. Practical significance

Using practical cases of zero-carbon buildings from leading enterprises such as CSCSTC, this paper quantifies the emission reduction benefits and economic feasibility of different technology portfolios, providing replicable technical solutions for construction companies and supporting key economic decisions such as payback periods and incremental cost allocation. In response to practical challenges including data deficiencies and technology diffusion difficulties (especially the design of green financial products), this paper offers policy recommendations for decision-makers.

1.3. Domestic and international research status

Internationally, the European Union has promoted nearly-zero-energy building standards through the *Energy Performance of Buildings Directive* (EPBD IV, 2024 revision requiring zero carbon emissions for all new buildings by 2030), and has developed software such as SimaPro and One Click LCA for LCA applications [4,5]. The German Passivhaus standard achieves energy consumption reductions of more than 80% compared to conventional buildings through optimized envelope and natural ventilation. The U.S. LEED certification system incorporates carbon footprint as a core indicator and has developed the dynamic carbon tracking platform Arc for existing buildings. Domestically, research represented by the Building Energy Research Center of Tsinghua University has clarified the structural characteristics of China's building carbon emissions, 70% from the operational phase and 20% from material production, but further progress is needed in regionally adaptive technologies (e.g., integrated ventilation and insulation for hot-summer/cold-winter zones) and market-based incentive mechanisms (e.g., integration of carbon inclusion, green power trading, and building carbon trading) [6].

2. Building carbon emission accounting and baseline setting for energy saving

2.1. Carbon emission accounting methods and application scenarios

Table 1 summarizes the key characteristics of the three core accounting methods for ease of comparison and application.

Table 1. Comparison of building carbon emission accounting methods

Method	Core logic and formula	Applicable stages	Advantages	Disadvantages	Accuracy & cost
LCA	"Cradle-to-grave" full-process inventory	Design, whole-life-cycle assessment	Identifies key mitigation nodes; prevents emission leakage	High data demand; boundary inconsistency; long cycle	High (accuracy), high (cost)
Emission factor method	Emissions = Σ(activity data × emission factor)	Planning, preliminary estimation, operation	Simple calculation; standardized; rapid screening	Temporal lag in factors; regional variability	Medium (accuracy), low (cost)
Measurement method	Real-time monitoring (smart meters/sensors)	Operation; effect validation	Authentic and reliable data; verifiable	High equipment cost; high technical/data platform requirements	High (accuracy), medium-high (cost)

2.1.1. Life cycle assessment (LCA)

LCA follows the "cradle-to-grave" logic, covering six stages: raw material extraction, production, transportation, construction, operation, and demolition/recycling. It involves three steps: inventory analysis, impact assessment, and interpretation. Its core advantage lies in identifying key mitigation nodes such as material production (cement production accounts for 60% of building material carbon emissions, of which clinker calcination process emissions constitute 60–65% of total cement emissions—a "hard-to-abate" component) and operational energy use. For the Shanghai Tower, LCA revealed that optimizing envelope materials could reduce whole-life-cycle emissions by 18%. However, challenges remain, including difficulty in data acquisition and long accounting cycles; in developing countries, data gaps for building material production energy consumption can exceed 40%.

2.1.2. Emission factor method

Based on the formula "Emissions = Energy consumption × Emission factor", this method uses emission factor databases from the IPCC *Guidelines for National Greenhouse Gas Inventories* or China's *Guidelines for Provincial Greenhouse Gas Inventories* to enable rapid accounting. It is suitable for initial project screening. For the operational phase of a building, for example, carbon emissions can be estimated by multiplying electricity consumption by 0.5703 $kgCO_2/kWh$ (the national average grid emission factor published by China's Ministry of Ecology and Environment in 2023). However, accuracy is significantly affected by the timeliness of emission factors; increasing shares of renewable energy have widened regional variations in grid factors, leading to potential biases of 20–30%.

2.1.3. Measurement method

By installing smart monitoring devices inside buildings (e.g., smart meters, gas meters, carbon concentration sensors), this method collects real-time energy consumption data and carbon emission concentrations, combined with on-site environmental parameters (temperature, humidity, illumination) to calculate actual emissions. It is suitable for verifying energy saving and emission reduction effects during the operational phase. For example, at a green office building in Beijing, an IoT-based monitoring system identified "excessive cooling" by the air conditioning system; optimizing the temperature control strategy reduced cooling energy consumption by 28%, representing an annual reduction of 12 tons CO_2. The advantage of the measurement method is its authentic and reliable data, but it requires additional investment in monitoring equipment (approximately 50–100 RMB/m^2) and high data transmission and analytical capabilities. It is currently used mainly in large public buildings.

2.2. Practical challenges and optimization directions for accounting

2.2.1. Main challenges

(1) Data

Building material manufacturers lack standardized carbon emission ledgers; dynamic data such as transport distances and construction machinery energy use are difficult to track.

(2) Methodological

Lack of consistent integration standards between LCA and the emission factor method reduces comparability of results across projects.

(3) Institutional

Absence of mandatory building carbon information disclosure systems prevents market mechanisms (e.g., green finance, carbon trading) from delivering effective price signals for low-carbon buildings.

(4) Standardization

Significant differences exist between domestic and international accounting boundaries; China focuses on operational-stage emissions (referred to as "operational carbon"), while the EU requires whole-life-cycle coverage.

2.2.2. Optimization pathways

Establish a national-level building carbon emission database integrating key data on building materials production and energy supply; Guangdong Province has piloted a traceability platform for building material carbon emissions. Develop intelligent, SaaS-based accounting tools that bridge BIM and LCA data interfaces, enabling "one-click accounting" and multi-scenario comparison at the design stage. Align domestic accounting standards with international norms by referencing the ISO 14040 series and actively participating in the localization of international building carbon accounting standards (e.g., CRREM, GRESB).

3. Whole-life-cycle decarbonization technology system for green buildings

3.1. Passive design: Foundational energy saving reconstruction

Passive energy-saving technologies maximize the use of natural energy sources (solar, natural ventilation, geothermal) by optimizing the building's intrinsic performance, reducing reliance on active energy systems, the foundation for energy saving and emission reduction in green and low-carbon buildings.

3.1.1. Spatial form and envelope optimization

Using Computational Fluid Dynamics (CFD) simulation to optimize building form increases natural ventilation efficiency by 20–30%. Beijing Daxing International Airport uses streamlined design and ventilated atriums, with natural ventilation covering 60% of office areas in summer. For the envelope, vacuum insulation panels combined with aerogel composites achieve a thermal conductivity below 0.015 W/(m·K). However, current aerogel costs are approximately 5–8 times those of traditional insulation materials, limiting its application in ordinary residential projects, and urgent development of low-cost precursors and continuous production processes is needed. After adopting this technology, CSCSTC's Baoding Yanhuacheng project reduced winter heating energy consumption by 58%.

3.1.2. Smart shading and microclimate regulation

Photovoltaic-integrated shading systems achieve dual "shading + power generation" functions. A design combining cadmium telluride thin-film modules with louvers enabled the Shanghai Zhongli Science and Technology Park's façade PV to generate 120 kWh/m^2 per year. Phase change materials (PCM, e.g., paraffin-based or salt hydrate-based materials) integrated with building components reduce indoor temperature fluctuations by 4–6 °C. The passive building at Qingdao Sino-German Eco-Park uses PCM floor slabs (with a phase change temperature of approximately 23–26 °C), reducing air conditioning operation time by 40%.

3.2. Active energy systems: Renewable energy integration

Active systems achieve deep emission reductions through clean energy substitution and intelligent control. Key technologies include renewable energy utilization, heat pumps, and energy storage.

3.2.1. Photovoltaic and wind energy applications

Building-integrated photovoltaics (BIPV) replace conventional building materials. Current crystalline silicon modules achieve efficiencies of 22–24%, while thin-film modules (e.g., CIGS) can reach 18–20% with better low-light performance and architectural formability. Using BIPV curtain walls, CSCSTC's Guangzhou New Town Construction Demonstration Park generates an average of 802,300 kWh per year, reducing carbon emissions by 347 tons. In regions with abundant wind resources, small vertical-axis wind turbines complement PV to reduce the sole dependence on energy storage; in the Xiong'an New Area, energy microgrids achieve renewable energy penetration rates exceeding 80%.

3.2.2. Heat pumps and energy storage technologies

Ground-source heat pumps achieve a COP ≥ 4.0 (i.e., 1 unit of electricity input delivers 4 units of heat), saving 70% energy compared to conventional gas boilers. Air-source heat pumps achieve COP ≥ 2.5 at –25 °C (using inverter and vapor injection technologies), solving the clean heating challenge for northern regions. The "Photovoltaics + Energy storage + Direct current + Flexibility" (PEDF) system enables flexible energy supply. At the CSCSTC Green Industrial Park, this technology achieved a PV self-consumption rate of 85% and a 40% reduction in peak-to-valley grid load difference.

3.3. Digital support: BIM-enabled whole-process empowerment

BIM technology enables whole-life-cycle carbon control across design, construction, and operation, optimizing emission reduction outcomes through multi-dimensional simulation.

3.3.1. Precise accounting at design stage

Integrating GIS with BIM to analyze terrain and wind environment improves energy simulation accuracy to over 90%. Through BIM-based PV layout optimization, CSCSTC's CMC R&D headquarters achieved a renewable energy utilization rate of 50%. Moreover, parametric design tools based on BIM can automatically generate hundreds of facade alternatives and rapidly compare their whole-life-cycle carbon emissions and costs, enabling "low-carbon-economic" dual-objective optimization.

3.3.2. Intelligent construction and operation

During construction, clash detection reduces material waste by 15%, while modular construction (prefabricating standardized units in factories) increases efficiency by 30%. Using modular construction, CSCSTC's Shanghai Brilliant City Exhibition Center shortened its construction period by 40%. During operation, an emission monitoring platform combined with digital twin technology enables real-time control and fault prediction, with the smart management system achieving over 20% energy savings for air conditioning and lighting, while equipment fault prediction accuracy exceeds 85%.

4. Case study analysis of green building decarbonization practice

4.1. Modular zero-energy building case

CSCSTC's Shanghai Brilliant City Zero-Carbon Building Exhibition Center is China's first modular zero-energy building, integrating BIPV curtain walls, PV-driven air conditioning, and other core technologies. The building's own power generation fully covers its energy demand, achieving an annual emission reduction of 52 tons and a payback period of approximately 8 years. Its technological innovation lies in factory prefabrication of modular components, achieving an on-site assembly rate of 95% and reducing construction-phase carbon emissions by 30% (mainly from reduced material cutting waste, lower wet-work energy use, and decreased on-site transportation machinery usage).

4.2. Nearly zero-carbon park case

The CSCSTC Green Industrial Park, the world's first "PEDF" nearly zero-carbon park, integrates rooftop PV (1.5 MW), energy storage (0.5 MWh), and a smart distribution network, reducing annual carbon emissions by over 47% and energy consumption by more than 50% compared to national standards. Through Vehicle-to-Grid (V2G) technology, the park enables bidirectional interaction between electric vehicles and the grid, smoothing PV output fluctuations and maintaining a renewable energy penetration rate above 75%. Economic analysis indicates that its incremental cost is approximately 350 RMB/m², and relying on saved electricity costs, demand response subsidies, and carbon trading revenues, the dynamic payback period is about 7.5 years.

4.3. Comparison of case study emission reduction outcomes

The comparison results are shown in **Table 2**.

Table 2. Comparison of emission reduction and economic performance of benchmark green building projects

Project name	Core technologies	Energy reduction rate	Annual emission reduction (t)	Renewable energy utilization rate	Incremental cost (RMB/m²)	Estimated payback period (years)
Shanghai brilliant city center	Modular + BIPV + carbon monitoring	60% +	52	100%	600–800	8
Guangzhou new town construction demo park	PEDF + BIPV curtain wall	60% +	347	50%	400–550	7–8
Baoding Yanhuacheng	High-performance insulation + HRV	50% +	106	35%	250–350	6–7
CSCSTC green industrial park	PEDF + V2G	50% +	189	80%	300–450	7.5

5. Policy and economic incentive mechanisms

5.1. Policy system evolution and current status

China has formed a “1 + N” building low-carbon policy system. The Zero-Carbon Building Technical Standard (draft for comments) requires whole-life-cycle net-zero carbon and mandates indicators such as low-carbon materials and renewable energy into compulsory evaluation. At the local level, Guangdong Province promotes advanced technologies through carbon reduction case selections; CSCSTC was the only construction enterprise selected. Xiong’an New Area enforces mandatory green building standards, with 100% of new buildings achieving ultra-low energy levels. Beijing provides a reward of 200 RMB/m² for ultra-low energy buildings, up to a maximum of 30 million RMB per project.

5.2. Economic incentives and market mechanisms

5.2.1. Fiscal and financial support

The central government provides subsidies of 200–300 RMB/m^2 for ultra-low energy buildings; Shandong Province exempts 50% of urban infrastructure surcharges for zero-carbon building projects. Financial institutions offer special green building loans with interest rates 10–15% lower than benchmark. Through green credit, Shanghai Zhongli Science and Technology Park reduced its financing cost by 3 million RMB. In addition, channels for green building projects to issue REITs (Real Estate Investment Trusts) are gradually opening, facilitating the activation of existing low-carbon assets.

5.2.2. Carbon trading and value realization

The building sector is being gradually incorporated into the national carbon market. The Shenzhen pilot includes public building carbon emission quotas in its trading system, with excess emitters required to purchase quotas, incentivizing energy-saving retrofits. Through carbon trading, CSCSTC turned emission reductions into economic benefits, generating an annual carbon asset revenue of 280,000 RMB for its Guangzhou project. In the future, with the refinement of building-sector methodologies for CCER (China

Certified Emission Reduction), more new and existing building retrofit projects can be developed as carbon assets and enter the voluntary emission reduction trading market.

6. Challenges and countermeasures

6.1. Core challenges

6.1.1. Technical level

High-performance building materials remain expensive: vacuum insulation panels cost 3–5 times conventional materials. Cross-system coordination technologies are immature; BIM and LCA data interfaces are incompatible (e.g., the IFC standard lacks a complete carbon information expression model), leading to low accounting efficiency.

6.1.2. Economic level

Initial incremental investment reaches 15–25% (for ordinary residential projects, consumers are highly price-sensitive). Small and medium-sized construction enterprises face significant capital pressure. Carbon accounting costs are high (for projects requiring full life-cycle data auditing, single project accounting fees exceed 100,000 RMB).

6.1.3. Institutional and market level

Regional standards are inconsistent: northern regions focus on heating energy efficiency, while southern regions lack normative regulation for cooling emission reduction (e.g., mandatory requirements for external shading, ventilation, high-reflectivity coatings, etc.). Supervision mechanisms are insufficient; data falsification for operational-phase carbon emissions frequently occurs. The incremental cost and premium of green buildings are difficult to realize in secondary market transactions, suppressing consumers' willingness to pay for low-carbon features.

6.2. Countermeasures

6.2.1. Technological innovation and cost control

Increase R&D investment in low-carbon building materials, aiming for a 50% cost reduction for aerogel by 2030. Establish a BIM-LCA integrated platform and develop open-source accounting tools to lower application barriers. Promote lightweight, standardized renewable energy products such as "PV + storage + charging" integrated canopies to reduce system integration costs.

6.2.2. Policy optimization and market activation

Formulate a national unified zero-carbon building standard and incorporate it into compulsory energy efficiency assessments. Expand the coverage of the carbon market and establish a building carbon emission traceability system. Explore the inclusion of green performance (energy consumption, carbon emissions) as "one certificate with visibility" in the real estate registration certificate to enhance market information transparency. Strengthen carbon emission responsibilities of construction enterprises through national policy guidance and regulatory improvements. Simultaneously improve the carbon trading mechanism and encourage enterprise participation in carbon trading markets.

6.2.3. Industry coordination and talent training

Form "industry-university-research-application" innovation alliances; CSCSTC has collaborated with universities to develop PV-integrated shading technologies. Establish specialized green building courses to train multidisciplinary low-carbon professionals. Create cross-sector collaboration platforms to promote data sharing and coordinated emission reduction among the building, power, and transportation sectors (e.g., building flexible loads participating in power demand response).

7. Conclusions and outlook

7.1. Conclusions

(1) Building carbon emission accounting should adopt a combined "LCA + emission factor" model. Through database construction and intelligent tools, accuracy can be improved, and data deficiency and standard inconsistency problems can be solved. The measurement method is used for verifications at key nodes. Integrating the three methods creates a closed-loop accounting and validation system, supporting policy-making and corporate decisions.

(2) The synergistic application of passive design and active energy systems is the core pathway for emission reduction, achieving building energy savings of 50–64% and renewable energy self-consumption rates exceeding 80%. The costs of high-performance envelopes and "PEDF" systems are falling rapidly and are expected to approach conventional solutions economically by 2030.

(3) The integration of modular construction, PEDF technologies, and digital management is moving zero-carbon buildings from demonstration to scale. The CSCSTC cases verify their technical feasibility and economic viability. Modular construction is particularly suitable for standardized building types such as affordable housing, schools, and hotels, enabling rapid diffusion.

(4) Combining mandatory policies with market incentives is key to diffusion. A long-term mechanism must be built through standard refinement, carbon trading, and fiscal subsidies. The evolutionary game model indicates that when the ratio of penalties to subsidies for developers exceeds a certain threshold and consumer low-carbon preference reaches 30%, green buildings can achieve spontaneous market diffusion even without mandatory policies.

7.2. Outlook

Future low-carbon building development will feature three major trends: First, the technology system is evolving toward deep integration of "passive prioritization, active optimization, smart operation, and digital empowerment". The integration rate of photovoltaics with building envelopes will exceed 60%. The maturation of perovskite PV technology will significantly reduce BIPV costs and increase power generation. Second, the accounting system will achieve "full-cycle, high-precision, and intelligent" capabilities. Blockchain technology will solve data traceability problems, and AI algorithms can dynamically optimize operational strategies based on historical data and climate forecasts. Third, the industrial model will transition toward the synergy of "zero-carbon parks + smart grids + virtual power plants", forming an integrated building-transportation-energy-waste management system for emission reduction. Through technological innovation, institutional safeguards, and the application of full-life-cycle carbon sequestration and offsetting technologies, the building sector has the potential to achieve full-sector carbon neutrality by 2060.

Disclosure statement

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Practice and Improvement of Quality Inspection System for Highway Engineering

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Abstract: Highway engineering construction involves numerous processes and has a long construction cycle, making it challenging to control the construction quality. The quality inspection system for highway engineering serves as an important basis for engineering quality inspection and safety management, providing clear standards and parameter ranges for engineering inspections. Therefore, the completeness of the inspection quality system directly impacts the effectiveness of engineering quality control. This paper mainly analyzes the composition of the quality inspection system for highway engineering, summarizes the current practice status of the system, and proposes optimization paths for its practical implementation, thereby providing references for the high-quality development of highway engineering.

Keywords: Quality inspection system for highway engineering; Inspection equipment; Inspection process; Practical assessment

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1. Introduction

Against the backdrop of the rapid development of China's transportation sector, the number and scale of highway engineering projects continue to expand. Meanwhile, driven by the dual forces of increasing car ownership and the vigorous development of the logistics industry, the quality standards for highway engineering have further risen. The quality inspection system for highway engineering serves as the standard basis for quality inspection, closely related to the overall quality of highway projects. However, there are still numerous shortcomings in the implementation of the quality inspection system in highway engineering construction, such as insufficient quality control awareness among construction personnel and non-standard equipment calibration, which are widespread issues. These problems subsequently reduce the regulatory and restrictive effectiveness of the quality inspection system for highway engineering [1]. Based on this, this article attempts to explore practical optimization paths for the quality inspection system for highway engineering by referencing the current implementation status of the system.

2. Composition of the quality inspection system for highway engineering

The quality inspection system for highway engineering is a quality specification and management system aimed at ensuring comprehensive, authentic, and reliable engineering inspections. According to the content of its specifications, it can be divided into different modules such as inspection personnel management, equipment management, process management, and supervision methods [2]. Firstly, inspection personnel management. Quality inspection personnel are the main entities responsible for implementing the quality inspection system and are tasked with advancing and controlling the inspection process. Therefore, the professional competence and experience of inspection personnel are closely related to the practical effectiveness of inspection work. As China's highway engineering projects gradually become more complex, encompassing not only road construction but also special engineering contents such as tunnels and bridges, quality inspection personnel need to comprehensively master professional knowledge and inspection skills related to highway construction techniques and quality standards to ensure the scientific nature of engineering quality inspections [3]. Secondly, inspection equipment management. In the quality inspection system for highway engineering, clear requirements are proposed for various inspection equipment, covering the entire process of inspection and management from equipment procurement to decommissioning. Thirdly, the inspection process for highway engineering is the implementation process of quality inspection. Based on specific practical processes, the quality inspection system divides it into five stages: inspection planning, sample collection, sample testing, data processing, and report generation, and sets corresponding standards for operations in each stage. Fourthly, supervision of highway engineering inspections is a fundamental guarantee for inspection quality. To ensure the objectivity and impartiality of supervision, both internal and external supervision mechanisms are stipulated. Internal supervision involves quality control of inspection work within the inspection unit, while external supervision involves supervision and inspection work conducted by superior management departments or third-party organizations. At the same time, clear punishment measures are proposed for engineering projects and responsible persons who fail supervision assessments [4].

3. Current implementation status of the quality inspection system for highway engineering

3.1. Mismatch between professional competence and practical operations of inspection personnel

The implementation of highway engineering inspection work relies on the operations of inspection personnel, highlighting their important role in the practical implementation of the quality inspection system. However, the current construction of the inspection personnel team for highway engineering in China is still imperfect, and the quality of the inspection personnel team needs improvement. On one hand, some experienced inspection personnel are accustomed to relying on experience to conduct inspection work and do not participate in training and learning in a timely manner, resulting in insufficient understanding of new construction techniques, materials, and inspection technologies, which seriously affects the quality of engineering inspections. On the other hand, some young inspection personnel have sufficient theoretical knowledge but limited practical experience, making it difficult for them to effectively combine theory with practice in inspection work, thereby reducing inspection efficiency and potentially causing distortion of inspection results [5]. In addition, some inspection personnel have low professional ethics and do not realize the true significance of inspection work for engineering quality control, exhibiting laxity and perfunctory attitudes in their work, thereby challenging the authority of inspection work. The root cause of these problems is the mismatch between the professional competence of inspection personnel and their practical operations, which limits the implementation of the engineering quality inspection system.

3.2. Non-standard implementation methods for equipment operation, maintenance, and calibration

Highway engineering inspections rely on the assistance of inspection equipment, so the condition and accuracy of inspection equipment are crucial for ensuring inspection quality. However, there are problems with non-standard equipment operation, maintenance, and calibration in the practical application of inspection equipment. Firstly, the quality control at the procurement source of inspection equipment for highway engineering is inadequate. Due to cost considerations, inspection agencies do not choose high-quality equipment during procurement, leading to significant errors in equipment application and making it difficult to detect quality issues [6]. Secondly, the work of equipment operation, maintenance, and calibration is inadequate. During the operation of inspection equipment, performance and accuracy may decrease due to equipment wear and tear, requiring regular maintenance and calibration by operators. However, operators do not effectively implement equipment maintenance systems, resulting in equipment not receiving timely maintenance and operating under high loads for extended periods, which can easily create hidden dangers in equipment application and subsequently affect equipment inspection results. In addition, failure to calibrate equipment in a timely manner or inaccurate calibration before application can lead to distortion of subsequent inspection results.

3.3. Poor connection and unreasonable control nodes in the inspection process

The construction of the quality inspection system for highway engineering should ensure the standardization of the inspection process. However, problems such as unreasonable node settings and poor connection in the inspection process are widespread in current inspection work. The problems with the inspection process can be summarized as follows: Firstly, no scientific inspection plan is formulated before the inspection work begins, resulting in inspection process settings that do not meet engineering inspection requirements and easily causing issues such as repeated inspections or missed inspections. Secondly, there is insufficient linkage between engineering inspection stages. Poor communication between stages in engineering inspections can easily lead to issues such as unreasonable timing for sample collection and improper management of sample transportation and storage, affecting the performance or information verification of samples and subsequently causing significant deviations in subsequent inspection results [7]. Thirdly, the setting of inspection points in the inspection process is unscientific. Control in some stages of inspection work is particularly important and directly related to subsequent inspection results, such as the sample collection stage. Sample collection needs to be typical to ensure that it can represent the overall construction quality of the project. However, some collectors do not evaluate collection points during sample collection but blindly collect samples, resulting in inspection results that are detached from reality and difficult to truly reflect engineering quality.

3.4. Inadequate supervision mechanisms and implementation assessments for system operation

The practical implementation of the quality inspection system for highway engineering requires supervision and assessment mechanisms as effective constraints and fundamental guarantees for inspection work. However, some inspection agencies have insufficient awareness of inspection work, leading to inadequate implementation of supervision and assessment mechanisms. Firstly, there are gaps in the supervision mechanisms of highway engineering inspection units, resulting in a lack of effective normative guidance for inspection personnel in their work and easily leading to non-compliant operations [8]. At the same time, the lack of effective supervision mechanisms can create a sense of luck among some inspection personnel, leading to perfunctory behaviors such as improper attitudes and inadequate execution in their work, thereby affecting the detection and correction of engineering quality issues. Secondly, the problem of external supervision deficiencies in highway engineering inspections is severe. Currently, highway engineering inspection supervision agencies lack proactive supervision awareness and have issues such as narrow supervision scope and low inspection frequency during the supervision process, resulting in limited effectiveness of external supervision. Inadequate external supervision work not only affects the detection of quality issues but also provides opportunities for data falsification within inspection departments, thereby preventing the effective detection and elimination of engineering quality issues and creating hidden dangers for highway engineering.

4. Practical optimization paths for the quality inspection system in highway engineering

4.1. Strengthening the construction of the inspection team

In the practical optimization of the quality inspection system for highway engineering, it is essential to build upon the optimization, adjustment, and restructuring of the inspection team to solidify their execution capabilities and enhance their professional competence. Firstly, it is crucial to strengthen the control over the source of the inspection team. During the recruitment process, comprehensive consideration should be given to candidates' professional theoretical knowledge, practical operational skills, inspection experience, and personal character. Meanwhile, to ensure that the recruited talent matches the needs of the inspection organization, reduce the acclimation period for talent in their roles, and lower training costs, enterprises can establish an order-based talent cultivation system with higher vocational colleges. The inspection organization provides talent cultivation requirements, while the colleges tailor the talent pool for the organization, thereby ensuring the quality of the talent in the highway inspection industry [9]. Secondly, effective on-the-job training for inspection personnel should be implemented. Regular training should be conducted for existing employees in inspection units, incorporating personalized training based on the characteristics of the inspectors to precisely match the training content with their growth needs. The training should cover the latest construction techniques, materials, inspection technologies, and equipment to ensure that inspectors' capabilities keep pace with the times. Thirdly, it is essential to enhance the professional ethics of inspection personnel. Currently, there is a tendency in talent cultivation within inspection organizations to prioritize skills over ethics, leading to violations such as abuse of power for personal gain among some inspectors. Therefore, in constructing the inspection team, it is also necessary to provide ideological guidance to enhance their sense of professional responsibility, enabling them to consciously adhere to ethical standards and ensure the objectivity and impartiality of inspection work. Additionally, an incentive mechanism can be established to externally motivate inspectors to fulfill their duties diligently, thereby fostering a culture of integrity within the inspection organization.

4.2. Standardizing the full-cycle management of inspection equipment

Inspection equipment primarily plays a supportive role in highway engineering inspections, enabling comprehensive, rapid, and precise detection of engineering quality through modern technological means, which is conducive to the timely identification of engineering hazards. However, if equipment performance deteriorates or is not calibrated in a timely manner, it can affect inspection results. Therefore, it is necessary to standardize the use and maintenance procedures for inspection equipment. Firstly, adopt a proactive approach to equipment quality control, starting with the procurement process. During equipment procurement, strictly adhere to the inspection requirements of engineering projects and screen equipment suppliers accordingly. The procurement department of the inspection unit can establish a supplier resource pool for comprehensive comparison of suppliers' credibility and qualifications and establish long-term cooperative relationships with high-quality suppliers to ensure the stability of equipment quality and cost. Secondly, inspect the specifications, range, and performance of the equipment to ensure it meets the inspection requirements of the engineering project, and conduct a re-inspection before the equipment enters the site to prevent substandard equipment from being used. Thirdly, establish a scientific equipment maintenance and calibration mechanism. Clearly define the maintenance and upkeep procedures and frequency for the equipment. Each piece of equipment should have an assigned responsible person who is in charge of daily maintenance, upkeep, and record-keeping to ensure full traceability of equipment maintenance and upkeep. Finally, for equipment calibration, establish a dedicated calibration process to provide reference for subsequent equipment users. Record the results after each calibration to assess equipment performance and condition. Additionally, equipment that cannot be calibrated should be promptly retired and replaced to avoid affecting inspection results.

4.3. Optimizing the inspection process for highway engineering

In the practical implementation of the quality inspection system for highway engineering, the control of the inspection process is particularly important. Firstly, before commencing inspection work, comprehensively review the engineering characteristics and key inspection points, and based on this, develop a comprehensive inspection plan. The inspection plan should cover inspection methods, sequence, frequency, and items to ensure that inspectors can efficiently carry out inspection work and avoid redundant or missed inspections [10]. Simultaneously, the inspection plan should be dynamically adjustable to adapt to changes in the construction progress of the project and ensure synchronization between inspection work and the project. Secondly, ensure smooth links in the inspection process. Each stage of highway engineering inspection should have corresponding management procedures, and an effective links system should be established between stages. For example, sample collection should be precisely judged based on collection time, specifications, and area to ensure reasonable sample collection. Communication with transportation control personnel should occur before sample collection to ensure timely transportation after collection and avoid prolonged exposure affecting sample performance. Sample storage personnel should maintain contact with transportation personnel to prepare for sample storage in advance and ensure compliance with storage environment and methods during storage.

4.4. Improving the system supervision and assessment mechanism

An effective supervision and assessment mechanism can provide a guarantee for the operation of the quality inspection system in highway engineering. Therefore, it is necessary to strengthen the improvement of the supervision and assessment mechanism. Firstly, establish a comprehensive internal supervision and assessment mechanism. The inspection organization should set up an independent supervision position directly under the highest management level of the organization to avoid supervision being influenced by other departments. A comprehensive internal supervision process should be developed to normalize internal supervision work. Any inspection issues discovered should be promptly reported, and corrective measures with deadlines should be taken to ensure that supervision effectively urges inspectors and enhances their self-management awareness. Secondly, strengthen external supervision and control. External supervision and assessment work should reasonably set supervision frequencies and adopt a combination of regular and irregular supervision methods to enhance the sense of responsibility among inspectors. Simultaneously, severe penalties should be imposed for behaviors such as tampering with inspection reports or fraud to enhance the binding force of supervision work and ensure the effectiveness of implementing the inspection system.

5. Conclusion

In summary, the original intention of constructing a quality inspection system for highway engineering is to provide a basis for engineering inspections, enabling orderly conduct of inspection work and ensuring the accuracy of inspection results. However, numerous issues persist in practical implementation, leading to inadequate inspection work, which can easily result in engineering quality defects and affect the safe operation and service life of highways. Therefore, it is necessary to further optimize the implementation paths of the engineering inspection quality system from aspects such as personnel team construction, equipment control, process optimization, and supervision and assessment to ensure the high-quality development of highway engineering construction.

Disclosure statement

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Research on Traffic Volume Transfer Forecasting for Expressway Reconstruction and Expansion under the Condition of Regional Road Network Linkage

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Abstract: Against the backdrop of the concurrent advancement of China's expressway network development and large-scale reconstruction and expansion projects, the reconstruction and expansion of a single road section can trigger a redistribution of the overall traffic flow within the regional road network, with significant characteristics of traffic volume transfer across routes, corridors, and regions. Traditional traffic volume analysis methods, which focus on individual road sections, struggle to meet the practical demands of regional road network linkage, multi-path competition, and dynamic traffic organization. To scientifically grasp the traffic transfer patterns within the road network during reconstruction and expansion and ensure the safety and efficiency of road network operations during construction, this paper adopts a perspective of regional road network linkage to systematically analyze the internal mechanisms and spatiotemporal distribution characteristics of traffic volume transfer during expressway reconstruction and expansion. Furthermore, it proposes a traffic volume transfer forecasting and analysis system suitable for reconstruction and expansion scenarios. Through this analysis, the paper aims to provide theoretical support and practical references for formulating traffic assurance plans for expressway reconstruction and expansion projects, optimizing the allocation of regional road network resources, and preventing and controlling traffic operation risks. This research holds significant importance for enhancing the service level of the road network during expressway reconstruction and expansion.

Keywords: Regional road network linkage; Expressway reconstruction and expansion; Traffic volume transfer; Traffic forecasting; Road network coordination

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1. Introduction

As China's transportation infrastructure network continues to improve, early-built expressways are gradually entering the reconstruction and expansion cycle, with reconstruction and expansion becoming the primary means of enhancing quality and capacity for expressways [1]. Coastal core corridors such as the southern section of the Ningbo-Taizhou-Wenzhou Expressway in Wenzhou face challenges due to their long construction history and saturated traffic volumes, making the dual four-lane standard insufficient to meet passenger and freight transportation demands, thereby necessitating large-scale reconstruction and expansion projects. Unlike new construction projects, expressway reconstruction and expansion must be carried out without interrupting traffic flow. Measures such as construction lane occupation, lane reduction, and speed restrictions directly reduce the mainline capacity. In the context of a highly interconnected regional road network, construction disturbances in localized sections can rapidly propagate to parallel expressways, national and provincial highways, and urban arterial roads, triggering large-scale traffic diversion. Current traffic volume forecasts often focus on individual projects, neglecting the synergistic effects and dynamic transfer characteristics of the road network, leading to issues such as congestion on diversion routes, failure of mainline traffic preservation, and regional traffic paralysis. In a networked transportation landscape, only by adopting a regional road network interconnection perspective, clarifying the driving mechanisms, path patterns, and spatiotemporal patterns of traffic volume transfer, and constructing an accurate transfer prediction system can scientific bases be provided for construction traffic organization, road network diversion control, and traffic safety assurance. This represents a core issue that urgently needs to be addressed in current expressway reconstruction and expansion traffic management.

2. Analysis of traffic volume transfer mechanisms and characteristics in expressway reconstruction and expansion

2.1. Primary impacts of reconstruction and expansion projects on road network operations

Expressway reconstruction and expansion alter existing traffic conditions through methods such as lane occupation, half-closure, speed-restricted passage, and interchange modifications, producing multi-level impacts on regional road network operations [2]. Firstly, there is a reduction in mainline capacity. The decrease in the number of lanes, insufficient lateral clearance, and degraded alignment indicators in construction sections, combined with speed restrictions, result in a 10–35% decrease in capacity compared to normal sections. Core sections such as the southern Wenzhou to Ruian segment easily degrade from Level III to Level V service during peak hours, forming chronic bottlenecks. Secondly, there is a redistribution of road network traffic. With the decline in mainline capacity, long-distance transit, medium-distance interval, and short-distance intra-regional traffic flows are forced to transfer to parallel expressways and national and provincial highways. The Yongguan Expressway, Wenzhou Ring Expressway, and National Route G104 become primary carriers, with previously unsaturated road network nodes rapidly approaching saturation. Finally, there is an increase in traffic organization complexity. Reconstruction and expansion involve cross-construction of multiple processes such as subgrade, pavement, bridges, and interchanges, with dynamic adjustments to traffic preservation plans at different stages and frequent traffic conversions, further exacerbating road network traffic fluctuations and amplifying traffic operation risks.

2.2. Core driving factors for traffic volume transfer under regional road network interconnection

Under regional road network interconnection, traffic volume transfer results from the combined effects of supply-side constraints and demand-side choices, with core driving factors categorized into four types. The first is the decline in capacity caused by construction. Half-closure, speed restrictions, and ramp closures directly reduce mainline supply capacity, serving as the fundamental inducement for traffic volume transfer. During the Wenzhou Bridge closure construction, mainline traffic decreased by over 30%, with the transfer effect being most pronounced. The second factor is the supply conditions of alternative routes in the road network. The technical grade, capacity, and service level of parallel expressways and national and provincial highways determine transfer capacity [3]. The Yongguan Expressway, with its dual six-lane configuration and Level I service, becomes the preferred diversion route for long-distance freight vehicles; while certain sections of National Route G104, already saturated, can only accommodate short-distance traffic transfers. The third factor is traveler path selection preferences. Passenger vehicles prioritize paths with higher speeds and shorter distances, while freight vehicles focus on transportation costs and restriction policies. Concentrated travel by passenger vehicles during holidays amplifies transfer traffic, with holiday traffic volumes reaching 1.5 times the usual levels. The fourth factor is traffic control and guidance measures. Measures such as remote guidance, vehicle-type restrictions, and entrance controls actively guide traffic flow transfers. Restrictions on vehicles with five or more axles and mandatory diversions at hub interchanges directly alter traffic flow distribution. These four factors interact to form the traffic volume transfer mechanism under regional road network interconnection.

2.3. Primary paths and modes of traffic volume transfer

Based on the traffic flow composition in reconstruction and expansion projects, traffic volume transfer forms three types of paths and three modes, covering all regional traffic travel. Transfer paths are divided into long-distance transit paths, medium-distance interval paths, and short-distance intra-regional paths [4]. Long-distance transit primarily involves directions such as Ningbo-Fujian and Hangzhou-Fujian, achieving long-distance detours via the Yongguan Expressway and Zhuyong Expressway + Wenzhou Ring Expressway. Medium-distance intervals primarily involve travel from the main urban area of Wenzhou to Cangnan and Pingyang, relying on the Ouyue Avenue and National Route G322 for conversions. Short-distance intra-regional travel primarily involves travel by towns along the route, with transfers completed through local roads and interchange connections. Transfer modes include active diversion mode, passive transfer mode, and mandatory control mode. Active diversion involves travelers autonomously selecting alternative paths based on road condition information, often occurring during the initial stages of construction. Passive transfer involves forced detours due to mainline congestion, concentrated during peak hours. Mandatory control involves management departments guiding traffic flow through restrictions and closures, applicable to core bottleneck sections. The combination of these three modes constitutes a complete traffic volume transfer system for the regional road network.

2.4. Spatiotemporal distribution characteristics of traffic volume transfer

Traffic volume transfer exhibits significant spatiotemporal imbalance, serving as a key basis for predictive analysis. In terms of temporal distribution, annual variations are influenced by construction stages, with smaller transfer volumes during subgrade construction and peak transfer volumes during pavement construction and bridge splicing periods. Monthly variations exhibit a "double-peak, double-valley" pattern, with February (Chinese New Year) and September representing traffic valleys, and August and November representing peaks. Daily distributions peak during 7:00–9:00 and 16:00–17:00, with transfer volumes accounting for over 13% of the daily total. In terms of spatial distribution, there is a north-high, south-low, and core-concentrated characteristic. The southern Wenzhou to Feiyun section serves as the core transfer area, with transfer volumes accounting for over 60% of the entire route, gradually decreasing from north to south. In terms of road network dimensions, expressways account for 45% of transfers, national and provincial highways account for 35%, and urban roads account for 20%. Freight vehicles prioritize diversion to expressways, while passenger vehicles disperse to urban roads. In terms of vehicle type distribution, the transfer rate for vehicles with five or more axles exceeds 80%, while the transfer rate for small passenger vehicles is less than 30%, exhibiting differentiated transfer characteristics by vehicle type.

3. Prediction and analysis system for traffic volume transfer under regional road network linkage

3.1. Overall prediction approach and principles

Against the backdrop of regional road network linkage, the prediction of traffic volume transfer is guided by the core principles of "priority for unimpeded traffic flow, road network coordination, dynamic adaptation, and precise quantification". This approach breaks away from the limitations of isolated predictions for single projects, treating the reconstructed or expanded road sections and the entire regional road network as an integrated whole. During the prediction process, emphasis is placed on simulating changes in road network capacity during construction, the effectiveness of various traffic control measures, and the dynamic adjustment patterns of traveler route choices. This enables precise calculation of the scale of traffic volume transfer among different routes, time periods, and vehicle types, providing support for maintaining unimpeded traffic flow during construction [5].

In line with practical engineering needs, the prediction work strictly adheres to four core principles: First, the principle of road network integrity ensures a comprehensive consideration of all road resources, including expressways, national and provincial trunk roads, and urban roads, covering all potential routes for traffic volume transfer to avoid prediction deviations caused by partial considerations. Second, the principle of stage-specific adaptability involves dynamically adjusting prediction parameters according to traffic maintenance plans at different construction stages, such as subgrade construction, pavement laying, and traffic engineering installation, ensuring that prediction results align with construction progress. Third, the principle of vehicle type differentiation fully considers the differences in travel purposes, driving characteristics, and route choices between passenger cars and freight vehicles, constructing separate prediction models for each to enhance prediction accuracy. Fourth, the principle of practical orientation ensures that prediction results directly serve the formulation of diversion plans and optimization of traffic control measures, balancing scientific rigor with on-site operability to ensure direct applicability of prediction outcomes.

3.2. Basic data requirements and collection analysis

The accuracy of traffic volume transfer predictions relies on multi-dimensional, comprehensive basic data support, necessitating the establishment of a robust data collection system that primarily covers four core categories of data: road network, traffic, construction, and control.

Road network data includes the topological structure of the regional road network, technical grades of various road sections, number of lanes, design speeds, and key parameters of interchange hubs. Focus is placed on core routes such as the Ningbo-Taizhou-Wenzhou Expressway, Ningbo-Dongguan Expressway, Wenzhou Ring Expressway, and National Highways G104, G228, and G322, with comprehensive collection of basic information on these routes to lay the foundation for linked road network analysis [6]. Traffic data encompasses historical cross-sectional traffic volumes, entrance and exit traffic volumes, vehicle type composition ratios, peak hour factors, and directional imbalance factors. Using 2021 as the base year, continuous observational data from the past five years is collected, strictly distinguishing between weekday and holiday traffic characteristics, as well as between passenger cars and freight vehicles, to fully grasp regional traffic operation patterns. Construction data requires clarification of construction stage divisions, road occupation methods, speed limit standards, closure periods, and interchange reconstruction plans to accurately grasp the impact of different construction stages on road network capacity. Control data includes traffic restriction policies, locations of diversion points, traffic guidance measures, and emergency control plans, providing a basis for simulating traffic volume transfer routes. During data collection, a combination of methods such as drone aerial photography, on-site observations, toll system statistics, and traffic model calibration is employed to verify data authenticity and completeness from multiple sources, ensuring that basic data can support accurate predictions.

3.3. Traffic volume transfer prediction and analysis process

Combining the characteristics of regional road network linkage, a prediction process of "four-stage method + construction disturbance correction" is adopted, completing the entire prediction and analysis process in four sequential steps to ensure that prediction results align with actual engineering conditions.

The first step involves current situation analysis and benchmark calibration. This includes a comprehensive review of the overall structure of the regional road network, systematic analysis of current traffic volume distribution, road network service levels, and traffic volume transfer potential, precise calibration of key parameters such as road network capacity and flow coefficients, and clarification of traffic volume distribution characteristics in the base year to provide a foundational reference for subsequent predictions. The second step quantifies construction impacts. Based on specific measures such as road occupation scope, speed limit requirements, and closure durations at different construction stages, scientific calculations are made to determine capacity reduction coefficients for mainlines and construction areas, clearly defining changes in road network supply and the extent of construction impact on road network capacity. The third step involves traffic volume generation and distribution. Combining regional economic development trends and vehicle ownership growth patterns, future trend traffic volumes, construction-induced traffic volumes, and transferred traffic volumes are reasonably predicted. Using TransCAD software, a provincial road network model is constructed to allocate future year Origin-Destination (OD) flows reasonably to various road sections within the regional road network. The fourth step calculates transfer volumes and allocates routes. Based on established diversion principles and vehicle type-specific traffic restriction policies, precise calculations are made to determine the scale of traffic volume transfer on each route, clarifying the transfer ratios for long-distance, medium-distance, and short-distance traffic volumes, ultimately outputting traffic volume transfer prediction results for different time periods, road sections, and vehicle types. Throughout the prediction process, dynamic corrections are made to account for the impacts of construction disturbances, adjustments in control measures, and changes in traveler choices, continuously optimizing prediction results to ensure they align with actual on-site operation conditions.

3.4. Evaluation indicators for prediction results

To verify the reasonableness and practicality of traffic volume transfer prediction results, a multi-dimensional evaluation indicator system is established, comprehensively validating prediction results from four core aspects: traffic volume, service level, transfer efficiency, and operational risk, providing a basis for optimizing prediction models and adjusting diversion plans [7].

Traffic volume indicators primarily include total traffic volume transfer, transfer volumes by road section, transfer rates by vehicle type, and peak hour transfer traffic volumes, comprehensively measuring the overall scale and distribution characteristics of traffic volume transfer. Service level indicators cover the V/C ratio (traffic volume to capacity ratio) of construction road sections, service levels of diversion routes, and the overall service level of the road network, with explicit requirements that the service level of construction road sections should not be lower than Level 4 and that of diversion routes should not be lower than Level 3, ensuring basic traffic needs are met during construction. Transfer efficiency indicators include transfer balance, route utilization rates, and increases in detour distances, with the core aim of avoiding excessive load on single routes and achieving balanced distribution of road network traffic volumes. Operational risk indicators include the number of bottleneck road sections, congestion durations, and predictions of accident-prone points, providing precise support for traffic safety control and emergency response during construction. Through comprehensive evaluation using these indicators, prediction model parameters are promptly optimized, and diversion plans are adjusted to achieve optimal allocation of regional road network resources, ensuring safe, orderly, and efficient traffic flow during construction.

4. Conclusion

In the context of the networked development of expressways and the normalization of reconstruction and expansion projects, regional road network linkage has become a core feature of traffic volume transfer, rendering prediction methods from a single-project perspective inadequate for meeting traffic maintenance needs during construction. Through mechanistic analysis, this paper clarifies the multi-level impacts of reconstruction and expansion projects on the road network, identifies the driving factors, route patterns, and spatiotemporal distribution characteristics of traffic volume transfer, and constructs a traffic volume transfer prediction system adapted to regional road network linkage, achieving a transition from single-project to whole-network analysis and from static to dynamic simulation. Research indicates that traffic volume transfer during expressway reconstruction and expansion is the result of the combined effects of construction supply constraints, road network alternative conditions, traveler choice preferences, and traffic control measures, exhibiting significant spatiotemporal imbalances and vehicle type-specific differentiation characteristics. The prediction system, based on the four-stage method and construction disturbance correction, can accurately quantify transfer scales and distributions, providing scientific support for construction traffic organization, road network diversion control, and traffic safety guarantees. Future research can further integrate vehicle-road coordination and real-time traffic sensing technologies to achieve dynamic traffic volume transfer prediction and real-time control linkage, continuously improving the operational efficiency and service levels of regional road networks during expressway reconstruction and expansion, providing replicable and transferable theoretical and practical experience for similar projects nationwide.

Disclosure statement

The author declares no conflict of interest.

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Research on Aging Detection of Asphalt Mixture

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Abstract: With the continuous growth of China's national economy, the diverse travel demands of people have led to greater pressure and challenges on roads. Asphalt mixture, as the main material for road construction, has received increasing attention in terms of aging detection. Aging tests on asphalt mixtures ensure that their performance is not affected after long-term use and that they do not negatively affect road safety. This paper first presents an overview of asphalt mixtures and asphalt mixture aging, and then conducts an in-depth study of asphalt mixture aging detection from multiple perspectives. This study aims to provide a valuable reference for future research.

Keywords: Asphalt; Mixture; Aging test

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1. Introduction

In the context of the new era, asphalt mixtures, as a new type of high-quality pavement material, have very high application advantages and value. However, due to the fact that it is easily affected by air, moisture and other factors during actual use, attention should also be paid to the detection of aging. The detection of asphalt mixture aging is conducive to a deeper understanding of its aging mechanism and influencing factors, enabling the asphalt mixture to have higher application value. This also requires a thorough understanding of the asphalt mixture and its specific aging conditions in order to conduct more detailed detection studies.

2. Asphalt mixture

Asphalt mixture is a kind of composite material used in road construction, which requires aggregates and fillers to be mixed together in certain proportions to ensure its true value in different application scenarios. The classification of asphalt mixtures is very diverse. According to the composition and structure of the materials, asphalt mixtures can be divided into discontinuous graded mixtures and continuous graded mixtures. There are also differences in the properties of different types of asphalt mixtures. In practical applications, it is necessary to make a choice based on the actual situation to ensure that it can meet the standard construction requirements. For example, a mixture with a nominal maximum particle size greater than 37.5 mm is an extra-coarse mixture, which can be used to build impermeable walls. By taking advantage of its impermeability and low-temperature resistance, problems such as deformation of the impermeable walls can be effectively avoided.

The most commonly used asphalt mixtures in engineering can be mainly divided into the following two types:

(1) Asphalt concrete mixture, which is a mixture of mineral materials with a specified gradation composed of coarse aggregates, fine aggregates and fillers in appropriate proportions and asphalt mixture, with a residual porosity of less than 10% after compaction.

(2) Asphalt-crushed stone mixture, which is made by mixing and extruding the appropriate proportion of coarse aggregates, fine aggregates and other fillers with concrete, with a porosity of more than 10%.

The main types include road petroleum asphalt, soft coal tar pitch and liquid petroleum asphalt, emulsified petroleum asphalt, etc. In practical applications, various types of asphalt should be selected based on actual conditions such as road traffic volume, climate environment, construction technology, type of asphalt surface layer, and source of materials. When using asphalt for each layer, it is generally advisable to use thicker asphalt on the upper part and thinner asphalt on the lower part and at the junctions. Emulsified petroleum asphalt can be classified into three types based on setting rate: fast setting, medium setting and slow setting. It is mainly used in asphalt surface treatment, asphalt penetration pavement, or the surface of normal-temperature asphalt mixture, as well as prime coat, tack coat and seal coat.

3. Overview of aging of asphalt mixtures

3.1. Definitions

Asphalt mixture aging is a very common phenomenon, an irreversible change in chemical composition and deterioration of physical properties, which can have a very serious impact on the service performance of asphalt. Asphalt mixture aging mainly occurs during the mixing process and the application of asphalt mixture on the road surface. Once it is exposed to factors such as oxygen, ultraviolet light or moisture, it is inevitable that its softening point, brittle point and other properties will change. As the road surface is in use, it is easily affected by external factors, causing cracking or damage to the asphalt mixture road surface [1].

3.2. Performance

Asphalt mixture aging can be affected in multiple processes, resulting in changes in its properties and internal structure. Such as enhanced high-temperature performance, changes in flow characteristics, weakened water stability, etc., are the main performance characteristics of asphalt mixture after aging, which will eventually lead to the asphalt mixture being difficult to meet the requirements of traffic load, and will also cause serious consequences due to cracking. For the performance of the asphalt mixture, test items such as penetration, viscosity and ductility can be evaluated. And since the degree of the asphalt mixture is closely related to aspects such as porosity and pavement density, once the penetration drops to 30, the asphalt mixture reaches its service limit. There are two types of asphalt mixtures: discontinuous graded asphalt mixtures and continuous graded asphalt mixtures. Discontinuous graded asphalt mixtures are more susceptible to the effects of oxygen and ultraviolet light, which can lead to evaporation and oxidation. In addition, since the road surface is subjected to greater pressure on a daily basis, appropriately increasing the density of the asphalt mixture can also effectively optimize its performance.

4. Research on aging detection of asphalt mixtures

4.1. Methods for aging detection of asphalt mixtures

4.1.1. Softening point detection method

The softening point test method is to test the temperature stability of the asphalt mixture, as the softening point of the asphalt mixture can reflect the high-temperature viscosity of the asphalt. The procedure is as follows: First, prepare the test specimen, prepare the external environment required for the test, and control the temperature between 80 and 135 °C. The specimens are then cured to adjust the temperature to approximately 5 °C. Finally, place the specimen properly to ensure there are no air bubbles on its surface. Once these preparations are done, you can start the test and record the temperature increase per minute during the test.

4.1.2. Methods for measuring ductility

Specimen preparation should also be carried out first, using the same method for temperature and softening point testing. But when curing the specimens later, they need to be placed in water for about 1 hour. When placing the test piece later, make sure it is free of air bubbles and that it is about 20 mm above the water surface. During the subsequent test, stretch about 5cm per minute to obtain accurate test results.

4.1.3. Method for detecting penetration

This method involves not only temperature control but also sieving and mold filling during the initial specimen preparation. During the subsequent curing of the specimens, keep the temperature at 15 °C to 30 °C and ensure that the temperature does not change much within 1 hour. During the subsequent placement of the specimen, make sure the load is 100 g so that the specimen and the needle cone are in perfect contact. During the test, the time to drop the cone should be controlled within about 5 seconds to obtain the corresponding test results.

4.2. Evaluation of asphalt mixture aging test

By evaluating the aging test of asphalt mixtures, it is possible to effectively understand the specific causes of their aging and achieve a more comprehensive and scientific evaluation and analysis of them. This aspect of the evaluation is mainly done from several aspects.

4.2.1. Chemical composition

In road asphalt mixtures, the factors that cause aging are due to the chemical composition within them. Because the chemical composition of the asphalt mixture changes with aging, oxidation reactions occur, etc. Evaluating from the chemical composition aspect can provide a deeper understanding of its aging mechanism.

4.2.2. Physical properties

The physical properties of asphalt mixtures include aspects such as softening point, viscosity and degree of polymerization. Evaluating from the aspect of physical properties can effectively understand the impact of physical properties on asphalt concrete. Under normal circumstances, the lower the density of the asphalt mixture and the lower the degree of polymerization, the lower the probability of aging.

4.2.3. Microappearance

The evaluation of this aspect requires observations based on both optical microscopes and scanning electron microscopes to achieve more detailed analysis and evaluation. This aspect of the evaluation can provide a clear understanding of the internal cracks and fragmentation of the asphalt mixture, and can determine the specific extent of its aging. As shown in **Figure 1**, it is the basic appearance of the asphalt mixture under a microscope. By observing it, one can understand the specific situation of the asphalt mixture. The evaluation in this aspect still needs to be based on a comprehensive assessment of experimental data and theoretical models, so as to clarify the mechanism and degree of asphalt mixture, and provide a basic technical guarantee for the construction and maintenance of roads [2].

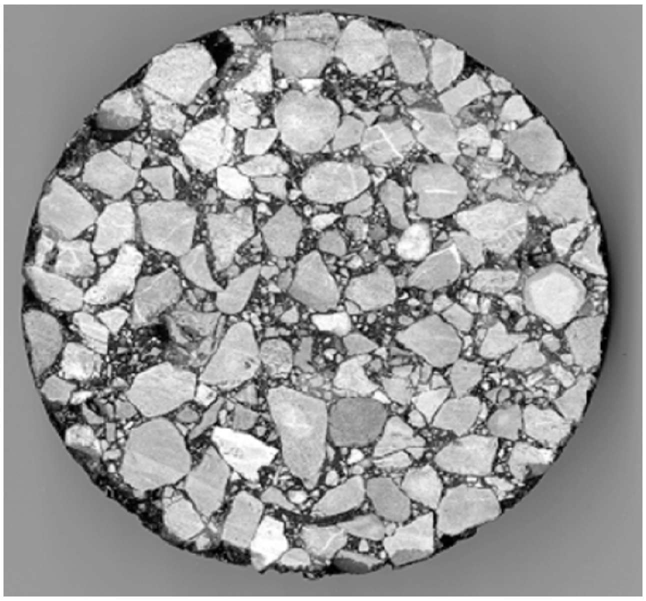

Figure 1. Basic appearance of the asphalt mixture under a microscope.

4.3. Data from asphalt mixture aging tests

Asphalt mixtures age to varying degrees both in use and in the process of use. To study the aging detection of asphalt mixtures, it is important to focus on the study of detection data. By studying the possible effects on the asphalt mixture, analyze the actual causes of its aging. Because the asphalt mixture becomes brittle and hard after aging, the analysis of the test data is more accurate. For the data on aging detection of asphalt mixtures, it should mainly be analyzed from the following aspects.

One aspect is the geographical aspect. By analyzing the aging of the asphalt mixture by testing the region and measuring the specific test indicators, the specific impact can be analyzed. The analysis of this aspect of data can effectively understand the specific causes of asphalt mixture aging. Among them, the eastern region is the area with the highest precipitation and the temperature is relatively low. The west, on the other hand, has less precipitation and, due to its drought, has relatively higher temperatures. Analysis of **Figure 2** shows that the softening point of the asphalt mixture is the highest in the central region.

On the other hand, in terms of service life. This also has an impact on the aging of the asphalt mixture, which, over time, affects aspects such as the hardness and softening point of the asphalt mixture. It is known from the investigation of the service life of most pavements that the initial change in softening point is more obvious as the service life increases, and the subsequent change is more significant. The rate of pavement aging also shows a pattern of rapid aging in the first few years and slow aging in the subsequent years. From this, it can be seen that service life also has an impact on it. The lifespan of asphalt concrete is typically around 18 years, and the exact lifespan depends on a variety of factors, including materials, construction methods, and usage environments. Under normal usage conditions, asphalt concrete will age over time, and cracks and potholes will become more prominent.

4.4. Stability of asphalt mixture aging tests

Stability is also part of the asphalt mixture aging test. Studying this aspect helps to clarify the changes in the asphalt mixture under the influence of external factors and analyze its performance changes. The following aspects of stability need to be studied specifically.

4.4.1. High-temperature stability

Dynamic stability was used as an evaluation index by aging permeable asphalt mixtures with different porosities of 19%, 21%, and 24% and conducting rutting tests. The greater increase in permeable asphalt mixture may be due to its higher porosity, such as: the increase in asphalt mixture with a porosity of 24% is much greater than that of asphalt mixture with a porosity of 19%.

4.4.2. Low-temperature stability

By conducting trabecular low-temperature bending tests, it is possible to test permeable asphalt mixtures aged with void ratios of 19%, 21%, and 24% to determine their low-temperature resistance to deformation. According to the test results, the asphalt mixture shows different properties at different aging periods. For example, the flexural tensile strength and maximum flexural tensile strain of the permeable asphalt mixture will change, but the 24% porosity sample is more stable than the 19% low porosity sample. To optimize the low-temperature stability of the asphalt mixture, it is necessary to control the construction process well. By strictly controlling the construction time and temperature, the probability of rapid aging of the asphalt can be effectively reduced. Construction personnel should try to shorten the high-temperature storage time and transportation distance of the mixture, thereby effectively reducing the influence of external factors.

4.4.3. Water stability

The splitting strength of permeable asphalt mixtures increases with aging and decreases significantly within four hours. Observations showed that the 24 percent porosity test mold had local loose cracking due to long-term aging. For samples with porosity of 19%, 21%, and 24%, the initial freeze-thaw splitting ratios were 93.9%, 64.1%, and 79.9%, respectively. With different porosity measurements, the samples took on different shapes over time. Notably, when the time was extended to ten hours, the ratio of freeze-thaw splitting in samples with a porosity of 19% decreased by 14.9%. It can be concluded that the higher the asphalt concentration, the faster the aging rate.

4.5. Structure for aging detection of asphalt mixtures

A variety of different results are included in the asphalt mixture. By studying the structure of asphalt mixture aging detection, it is possible to clarify the impact of different structures on it, and it can also serve as one of the bases for detection. There are mainly the following types of structures.

4.5.1. Compact skeleton structure

Asphalt mixture is a composite material made by blending asphalt and aggregates (such as sand, crushed stone, etc.). The dense framework structure refers to the arrangement of aggregate particles in the asphalt. It is generally divided into two types: porous and unsaturated. The porous structure can effectively improve the stability and durability of the mixture. The dense structure of the asphalt mixture skeleton is one of the important factors affecting its performance and service life. Optimizing its dense skeleton structure can enhance the stability, durability and crack resistance of the mixture.

4.5.2. Skeleton void structure

The skeleton void structure of asphalt concrete refers to the void structure formed by the aggregate particles in the asphalt adhesive, which includes the voids between the aggregate particles, the voids between the cements formed after the asphalt adhesive fills the voids of the aggregate particles, and the voids between the molecules of the asphalt adhesive. The skeletal voids structure of asphalt concrete is closely related to its mechanical properties. The mechanical properties of asphalt concrete depend on the construction techniques at each stage and the characteristics of the aggregate particles.

4.5.3. Suspended compact structure

The suspended dense structure of asphalt mixtures refers to a three-dimensional spatial arrangement structure formed by asphalt with aggregates, air and other components. In this structure, the asphalt has colloidal properties, and its presence forms an asphalt colloid; Aggregates, air, etc. are dispersed in the asphalt colloid. The suspended and dense structure of the asphalt mixture has a significant impact on its performance. Better stability, durability and load-bearing capacity of the mixture can be achieved by reasonably controlling features such as the distribution of asphalt colloid, air porosity, porosity and particle arrangement [4].

5. Conclusion

To sum up, by conducting research on aging detection of asphalt mixtures, a more accurate analysis of the causes of aging of asphalt mixtures can be made, thus facilitating the subsequent adoption of scientific and effective anti-aging measures. This will effectively enhance the anti-aging performance of asphalt mixtures, thus making it a driving force for the sustainable development of roads in our country. Because asphalt is exposed to complex climate conditions for a long time, thermal oxidative aging leads to hardening of asphalt, which is an inevitable problem. Detection of aging can provide a reliable driving force for the development of roads in our country.

Disclosure statement

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Study on Design Quality Evaluation Model of Radiation Protection Engineering in General Hospitals Based on Life Cycle Concept

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Abstract: With the continuous expansion of radiological diagnostic equipment in Chinese general hospitals, the design quality of radiation protection engineering directly affects the radiation safety of medical staff, patients and the surrounding public. This study introduces the concept of the entire life cycle into the field of assessment of the design quality of radiation protection engineering. By identifying the quality influencing factors in each stage including planning and design, construction implementation, operation and maintenance iteration, as well as decommissioning disposal, an assessment index system was constructed, the model application scenarios in different stages were clarified, and a guarantee mechanism was proposed from three dimensions: organizational system, technical data, and personnel capability. The research results can provide some reference for the whole life cycle management of the design quality of radiation protection engineering in general hospitals, so as to reduce the radiation safety risk and improve the long-term effectiveness of radiation protection engineering.

Keywords: General hospital; Radiation protection engineering; Design quality assessment; Entire life cycle; Evaluation model

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1. Introduction

Radiation protection engineering in a general hospital is a systematic engineering, covering the design of shielding structures in radiation diagnosis and treatment areas, the configuration of protective facilities, and the deployment of radiation monitoring systems. Its design involves numerous elements, and scholars at home and abroad have conducted extensive research on the quality assessment system for such designs [1]. However, most studies only focus on the design stage. Based on this, this paper comprehensively analyzes the design quality assessment in the whole life cycle of hospital radiation protection project, forms an index system, and provides some reference for improving the design quality.

2. Factor identification and evaluation index system construction

2.1. The entire life cycle of the radiation protection project

The entire life cycle of the radiation protection project can be divided into four stages. The first stage is the planning and design stage, which includes the layout planning of the radiology department, the calculation of shielding parameters, the selection of protective materials, and the design of radiation monitoring points. This is the source stage that determines the overall quality of the protection project; the second stage is the construction and implementation stage, involving the construction of shielding structures, the installation of protective doors, and the sealing treatment of pipe intersections, which is the implementation stage of converting the design intention into a practical project; the third stage is the operation and iterative stage, including daily radiation monitoring, the maintenance of protective facilities, and the adjustment of protective measures during equipment updates and renovations, which is an important stage for ensuring that the project continuously meets the protection requirements over the long term; the fourth stage is the decommissioning and disposal stage, including the decommissioning of radiation equipment, the removal of protective facilities, and the detection and cleaning of radioactive contamination on the site, which is the closing stage for preventing radiation risks during the decommissioning phase. Based on the concept of project life cycle management, the impact of the quality of radiation protection project design has obvious lag. As the equipment ages and the structure is damaged, the parameter deviation from the design and construction phase will gradually become apparent, leading to the risk of radiation leakage [2]. Once a radiation leak occurs, it will not only affect the personnel within the hospital but also have an impact on surrounding buildings and the public. Therefore, the design quality assessment of the radiation protection project requires strict compliance review. The design must comply with the mandatory requirements of relevant national regulations, such as the Health Review Regulations for Diagnostic Radiology Projects and the Radiation Protection Requirements for Medical X-ray Diagnosis. It must match the equipment configuration planning, diagnostic process and spatial layout characteristics of the hospital radiology department, and also take into account the equipment renewal needs in the next 5 to 10 years. The feasibility of construction, the convenience of operation and maintenance, and the environmental friendliness of decommissioning disposal are fully considered to reduce the overall cost and safety risk during the whole life cycle [3].

2.2. Identification and screening of factors affecting design quality

To identify the factors that affect design quality, it is necessary to consider various factors comprehensively. This article mainly screens relevant materials through literature research. From 2018 to 2025, authoritative journal articles and industry reports on radiation protection engineering design and radiation safety assessment from both domestic and international sources were collected, and national and industry standards such as “Radiation Protection Regulations” and “Construction Specifications for Hospital Radiology Departments” were sorted out. The factors affecting quality and various indicators corresponding to mandatory provisions were extracted [4]. Comparisons were made with the practices of various hospitals, and common design quality influencing factors in practice were supplemented. Through deduplication and integration, a pool of 53 indicators affecting factors was initially formed. Among them, the planning and design stage includes 21 indicators such as the rationality of shielding parameter calculations and the adaptability of protective material selection; the construction implementation stage contains 13 indicators, such as the feasibility of design implementation and the completeness of protective design at pipe intersection points; the iterative operation and maintenance stage contains 12 indicators, such as the rationality of radiation monitoring point design and the reserved space for protective facility maintenance; the decommissioning disposal stage contains 7 indicators, such as the convenience of protective facility removal and the completeness of pollution prevention design [5]. See **Table 1**.

Table 1. Expert categories and experience background

No.	Expert category	Number	Years of experience	Professional background
1	Radiation protection evaluation experts	7	≥ 10 years	1. 3 senior experts in radiation health monitoring/evaluation from provincial/municipal CDC 2. 2 technical directors of third-party radiation protection testing institutions 3. 2 senior engineers specializing in radiation protection evaluation in environmental impact assessment institutions
2	Hospital radiology department administrator	5	≥ 10 years	1. 3 directors/deputy directors of radiology departments in tertiary first-class hospitals (in charge of radiation protection) 2. 2 responsible persons for radiation protection management in nuclear medicine departments of tertiary general hospitals
3	Medical building designers from Class-A design institutes	4	≥ 10 years	1. 2 senior engineers specializing in radiation protection design from medical building specialized design institutes 2. 2 chief designers from medical building departments of comprehensive Class-A design institutes
4	Hospital infrastructure management personnel	4	≥ 10 years	1. 2 project leaders from infrastructure departments of tertiary first-class hospitals (have presided over radiology department reconstruction and expansion projects) 2. 2 specialists in charge of radiation protection projects in public hospital infrastructure management departments
Total	–	20	–	All experts have full-process experience in radiation protection engineering, covering the entire professional chain of design, evaluation, management and implementation

As shown in **Table 1**, in order to ensure the scientifically and practicability of the indicators, this study used the Delphi method to screen the 53 indicators initially extracted. 20 experts with over 10 years of working experience were invited to evaluate the importance of the indicators. The evaluation used a Likert 5-point scale, where 1 indicated completely unimportant and 5 indicated very important [6]. After two rounds of expert consultation, a total of 26 indicators are eliminated, the average importance scores below 3.5, the variation coefficient is greater than 0.25. These indicators, such as the qualification level of the construction unit and the professional level of operation and maintenance personnel, belong to the control content of the subsequent stage, as well as the popularity of the design unit and the working life of the designer. These indicators cannot directly reflect the quality of the design scheme itself, and are ultimately retained. Eventually, they were retained. A total of 27 core evaluation indicators were ultimately retained. The specific contents of these indicators are as follows. See **Table 2**.

Table 2. Evaluation index system for design quality of radiation protection engineering in general hospitals

Criterion layer	Index layer code	Index name	Index description
Planning and design adaptability (A)	A1	Scenario adaptability of shielding calculation parameters	The degree of fit between calculation parameters and actual scenarios such as hospital diagnosis and treatment processes, equipment usage frequency, etc., on the basis of meeting mandatory requirements
	A2	Design margin of main shielding layer thickness	The proportion of shielding layer thickness exceeding the minimum requirement, reflecting the redundant safety level and balancing safety and economy
	A3	Integrity of secondary shielding protection design	The full coverage degree of protection design for walls, floors, ceilings, etc. in non-main irradiation directions, without omitted areas
	A4	Sealing performance of protection design for pipeline crossing points	The rationality of sealing protection design at positions where water and electricity pipelines, exhaust ducts pass through the shielding layer
	A5	Adaptability of protection material selection	The adaptation degree of protection materials to application scenarios (e.g., whether high atomic number materials are selected for high-energy rays)
	A6	Rationality of radiology department layout and workflow	The clarity of the division of controlled areas and supervised areas, and the degree to which personnel streamline design avoids unnecessary radiation exposure
	A7	Reserved Space for future equipment upgrade	The redundant protection design reserved for equipment update in the next 5-10 years, reducing the difficulty of subsequent transformation
Construction feasibility (B)	B1	Technical feasibility of shielding structure construction	The degree to which the construction difficulty of the designed shielding structure is within the scope of existing technical capabilities
	B2	Market availability of protection materials	The degree to which the protection materials selected in the design belong to conventional purchasable categories in the market, avoiding supply risks of special materials
	B3	Rationality of fault tolerance design for construction errors	The degree to which the design considers the impact of construction errors and reserves reasonable parameter margin
	B4	Clarity of coordination design for cross construction	The clarity of protection requirements for construction intersection points between radiation protection engineering and HVAC, electrical and other specialties
	B5	Clarity of construction quality acceptance points	The detail degree of acceptance standards and testing methods for each key process specified in the design documents
	B6	Safety protection design for construction process	The perfection degree of temporary radiation protection measures during the construction stage considered in the design scheme
	B7	Controllability of construction cost	The degree to which the construction cost is controlled within a reasonable range under the premise of meeting protection requirements

Operation and maintenance sustainability (C)	C1	Rationality of radiation monitoring point design	The integrity degree of fixed radiation monitor positions covering all potential leakage points
	C2	Reserved maintenance space for protection facilities	The degree to which sufficient maintenance operation space is reserved around protection doors, interlock devices and other facilities
	C3	Redundant design of radiation interlock devices	The perfection degree of redundant backup design for safety devices such as door-machine interlock and working status warning
	C4	Interface design for operation and maintenance data collection	The perfection degree of reserved system interfaces for remote transmission of radiation monitoring data, automatic alarm, etc.
	C5	Compatibility design for local transformation	The rationality of design that does not require large-scale demolition of the original shielding structure when replacing local equipment
	C6	Life matching of protection facilities	The matching degree between the design life of protection facilities and the expected service cycle of radiation equipment
	C7	Supporting design of emergency response plan	The perfection degree of emergency disposal operation procedures and facility configuration in case of radiation accidents
Decommissioning environmental friendliness (D)	D1	Convenience design for dismantling of protection facilities	The degree to which shielding structures, protection doors and other facilities are convenient for safe dismantling, reducing pollution risk during dismantling
	D2	Radioactive pollution prevention and control design for decommissioning	The perfection degree of pollution detection points and decontamination operation space considered during decommissioning in the design
	D3	Proportion of recyclable protection materials	The proportion of recyclable materials among the protection materials selected in the design
	D4	Guidance for classified disposal of decommissioning waste	The detail degree of classified disposal requirements for different types of protection waste specified in the design documents
	D5	Adaptability for site reuse after decommissioning	The degree to which the site is convenient to be transformed into other non-radiation uses after decommissioning, reducing secondary transformation costs
	D6	Pre-assessment design for decommissioning environmental impact	The perfection degree of pre-assessment of the impact of the decommissioning process on the surrounding environment considered in the design stage
	D7	Controllability of decommissioning treatment cost	The degree to which the decommissioning treatment cost is controlled within a reasonable range from the perspective of the whole life cycle in the design scheme

The admission review is a necessary prerequisite step. Only after passing the review can one proceed to the scoring stage. The scoring is conducted on a 100-point scale. The weights of the four criterion layers remain as originally set in the research: planning and design compatibility 0.48, construction feasibility 0.18, operation and maintenance sustainability 0.24, and decommissioning environmental friendliness 0.10. The scoring criteria still use a 5-level classification: 90–100 (excellent), 75–89 (good), 60–74 (qualified), 40–59 (unqualified and requires rectification), 0–39 (serious defects require redesign).

2.3. Quantification of indicators and data collection

The scoring system adopts a 100-point scale. These indicators are classified into 5 grades based on the degree to which they meet the requirements: 90–100 points indicate excellent performance, fully meeting the requirements with a high degree of redundancy; 75–89 points indicate good, meet the requirements of the specification and adapt to the actual needs of the project; 60–74 points indicate qualified performance, basically meeting the minimum requirements of the specification; 40–59 points indicate unqualified performance, with some non-compliance with the specification requirements, requiring rectification; 0–39 points indicate poor performance, with serious radiation safety hazards, and the design must be redone. In order to complete the quality assessment, in the evaluation of design document review indicators, documents such as design specifications, shielding calculation documents and construction drawings will be reviewed to obtain the specific degree of completion of the indicators [7]. Calculate the design margin of the main shielding layer thickness, the shielding level of the protective door, and other adaptability indicators, and recalculate the deviation between the design parameters and the theoretical requirement values. Simulation analysis and simulation derivation were also used to evaluate the feasibility of construction and the ease of demolition, and experts in the fields of construction, operation and decommissioning disposal were invited to score [8].

3. Evaluation results and model application

3.1. Indicator evaluation and weight calculation

In this study, the subjective and objective fusion weight assignment method combining analytic hierarchy process (AHP) and entropy weight method was used. According to the results of expert consultation, the judgment matrix of each level index was constructed, and 20 experts were invited to compare the relative importance of the indicators at the same level, and the 1–9 scale method was used to score. The subjective weights of each indicator were calculated using the YAAHP software and consistency tests were conducted. The results showed that the consistency ratio CR of all judgment matrices was less than 0.1, meeting the consistency requirements. The weight distribution is based on the dual logic of expert consensus and the analysis of the risk contribution throughout the entire life cycle. The subjective weights of the four criterion layers were as follows: planning and design adaptability 0.48, construction feasibility 0.18, operation and maintenance sustainability 0.24, and decommissioning environmental protection 0.10. It can be seen that the quality of the planning and design stage has the greatest impact on the overall project quality [9].

The design data of 30 radiation protection projects in general hospitals completed in the past three years were collected as samples. The scoring results of 27 indicators were standardized, and the information entropy of each indicator was calculated. The objective weight was determined according to the information entropy. The smaller the information entropy, the higher the discrimination of the indicator and the greater the weight.

Finally, the comprehensive weight was obtained through linear weighted combination, and the calculation formula is:

$$w_i = \alpha \cdot w_{i1} + \left(1-\alpha\right) \cdot w_{i2}$$

Where is the subjective weight obtained by analytic hierarchy process, is the objective weight obtained by entropy weight method, α represents the preference coefficient of subjective weights. Based on literature analysis and industry consensus, in this study, the coefficient is set at 0.6., that is, the subjective weight accounts for 60%, and the objective weight accounts for 40%, taking into account both expert experience and actual data characteristics. The calculation results of the comprehensive weights for each indicator are shown in **Table 3**.

Table 3. Comprehensive weight table of evaluation indicators

Criterion layer (Weight)	Index	Subjective weight	Objective weight	Comprehensive weight
Planning and design adaptability (0.48)	A1	0.152	0.138	0.146
	A2	0.136	0.142	0.138
	A3	0.124	0.118	0.122
	A4	0.118	0.125	0.121
	A5	0.095	0.087	0.092
	A6	0.087	0.092	0.089
	A7	0.076	0.081	0.078
	A8	0.072	0.068	0.07
	A9	0.065	0.073	0.068
	A10	0.075	0.076	0.076
Construction feasibility (0.18)	B1	0.285	0.262	0.276
	B2	0.212	0.228	0.218
	B3	0.198	0.205	0.201
	B4	0.175	0.183	0.178
	B5	0.13	0.122	0.127
Operation and maintenance sustainability (0.24)	C1	0.224	0.236	0.229
	C2	0.186	0.178	0.183
	C3	0.175	0.182	0.178
	C4	0.142	0.135	0.139
	C5	0.121	0.128	0.124
	C6	0.088	0.095	0.091
	C7	0.064	0.046	0.056
Decommissioning environmental friendliness (0.10)	D1	0.312	0.298	0.306
	D2	0.265	0.278	0.27
	D3	0.174	0.182	0.177
	D4	0.135	0.146	0.139
	D5	0.114	0.096	0.108

The design quality of radiation protection engineering to be evaluated is taken as the matter element R, which is composed of three elements: evaluation object N, evaluation feature C and characteristic quantity V, namely $R=(N,C,V)$. Among them, C corresponds to 27 evaluation indicators, and V corresponds to the score values of each indicator. The evaluation grades are divided into five levels: excellent（N_1）、good（N_2）、qualified（N_3）、poor （N_4）、very poor（N_5）, with the corresponding value ranges being < 90, 100 >, < 75, 89 >, < 60, 74 >, < 40, 59 >, and < 0, 39 >, respectively. The evaluation range is the total range of indicator values for all evaluation grades, that is, < 0, 10 0>. The correlation degree reflects the degree to which the evaluated object belongs to a certain evaluation grade. The calculation formula is:

$$K_j(v_i)=\begin{cases} -\dfrac{\rho(v_i,X_{ji})}{|X_{ji}|}, & v_i\in X_{ji} \\ \dfrac{\rho(v_i,X_{ji})}{\rho(v_i,X_P)-\rho(v_i,X_{ji})}, & v_i\notin X_{ji} \end{cases}$$

Here, $\rho(v_i,X_{ji})$ represents the distance from point v_i to the interval X_{ji}, $\rho(v_i,X_P)$ represents the distance from point v_i to the sub-interval X_P, and $|X_{ji}|$ is the length of the interval X_{ji}. Calculate the comprehensive correlation degree: Based on the comprehensive weights of each indicator, calculate the comprehensive correlation degree of the evaluated object to each evaluation level:

$$K_j(N)=\sum_{i=1}^{n} w_i\cdot K_j(v_i)$$

Where w_i represents the comprehensive weight of the i-th indicator.

Determine the evaluation level: If $K_{j0}(N)=max\{K_j(N)\}$, then the evaluated object belongs to level j_0. To further reflect the position of the evaluated object within the corresponding level, the characteristic value of the level variable can be calculated:

$$j^*=\frac{\sum_{j=1}^{m} j\cdot|K_j(N)|}{\sum_{j=1}^{m}|K_j(N)|}$$

The closer j^* is to a certain level's value, the more the evaluated object is close to the level's standard.

In order to verify the actual application effect of the model, five radiation protection projects that had completed the completion acceptance and had more than 3 years of operation and maintenance data were selected as verification samples. The model constructed in this study was evaluated by the traditional compliance review method, and the matching degree between the two evaluation results and the actual operation effect was compared [10].

The verification results show that the traditional compliance review method rated all five samples as "excellent", while the evaluation results of the proposed model indicate that 3 samples were rated as "excellent" and 2 samples were rated as "good". It can be seen that compared with the traditional method, this research model can more accurately identify potential risks.

4. Conclusion

This paper constructs a design life cycle assessment model based on the concept of the entire life cycle. It assesses the design quality from comprehensive perspectives such as compliance and long-term effectiveness. The research results can provide scientific quality monitoring tools for relevant departments, enhance the overall level of protective engineering, and ensure safety.

Disclosure statement

The author declares no conflict of interest.

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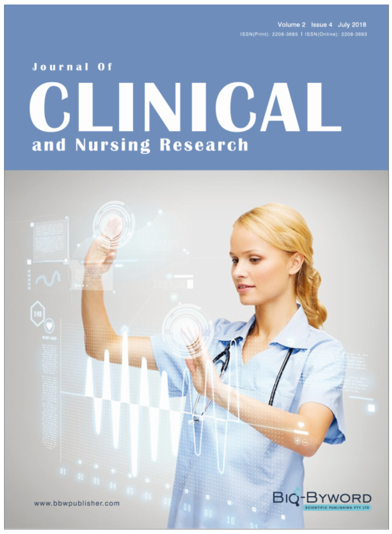

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