

Research on the Green Construction Evaluation System for Urban Underground Utility Tunnels

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Abstract: To address issues such as the numerous factors and unreasonable weight allocation in existing green construction evaluation systems for urban underground utility tunnels, this paper systematically reviews relevant domestic and international research and, considering the unique characteristics of underground utility tunnels, proposes evaluation factors encompassing four dimensions: resource utilization, environmental impact, construction management, and technological innovation. Through the Delphi method, the evaluation factors were screened and refined, ultimately leading to the identification of six core indicators: application of trenchless construction techniques, recycling and utilization of spoil, innovation in green construction techniques, application of information technology, conservation of energy and material resources, and integrated control of dust and noise pollution. These core indicators collectively embody the intensive nature, circularity, technological innovation, and environmental sensitivity inherent in the green construction of utility tunnels. Validation results using the fuzzy comprehensive evaluation method demonstrate that the proposed system can effectively assess the green construction performance of different construction methods. This study provides a scientific basis for standardizing and promoting the sustainable development of green construction practices for urban underground utility tunnels, thereby advancing the green transformation of urban infrastructure development.

1. Introduction

In recent years, green construction has been facilitating the transformation of the building industry towards low-carbon, environmentally friendly, and sustainable development through energy conservation, emission reduction, and eco-friendly management. Against this backdrop, the urban utility tunnel, as a critical component of modern urban infrastructure, has witnessed increasingly prominent construction demands^[1-2]. However, the construction of utility tunnels involves complex construction processes and substantial resource consumption, thus their green construction performance directly impacts both ecological and economic benefits. Therefore, establishing a scientific and systematic green construction evaluation system serves not only as an essential tool for accurately measuring the degree of greening, but also as a key instrument for promoting construction standardization and normalization. This system can provide clear guidance for green construction practices, thereby advancing utility tunnel development towards higher levels of sustainable development^[3-4].

Scholars have developed specialized green construction evaluation systems and proposed systematic design principles for such assessments^[5], spanning diverse infrastructure domains including highways, rail transit, and railway passenger stations. These research

efforts have further advanced the field by quantitatively analyzing green construction performance through fuzzy mathematics and validating system applicability via case study methodologies^[6-8].

From the above analysis, the existing research mostly focuses on general building projects or single construction links, while the research on green construction evaluation of underground utility tunnels, a special infrastructure, is still relatively lacking and is still in the exploratory stage. Building upon this foundation, this study systematically reviews existing green evaluation frameworks from both domestic and international research. With particular emphasis on the inherent characteristics of urban underground utility tunnels, it employs the Delphi method to screen evaluation factors, thereby establishing an assessment system comprising both universal and specific indicators. The applicability of this system is subsequently validated through the fuzzy comprehensive evaluation method. The ultimate objectives are to standardize construction practices, mitigate the negative environmental impacts of engineering projects, and facilitate the transition of traditional construction modes towards green and low-carbon alternatives. Furthermore, this research offers practical guidance for advancing the green transformation of urban infrastructure development in China.

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2. Analysis of Green Construction Evaluation Factors for Utility Tunnels

Based on a review of existing literature, prevailing green construction evaluation systems commonly adopt a three-tiered structure comprising the objective level, criterion level, and indicator level. These systems are developed around the core objectives of "Four Savings and One Environmental Protection" (energy, land, water, and material conservation, along with environmental protection). The framework primarily encompasses four key dimensions^[9-12]: resource utilization, environmental protection, integrated management, and social benefits. However, since different projects possess distinct characteristics, the green construction evaluation of specialized projects must incorporate project-specific factors to enhance its accuracy—namely, it must satisfy the principle of targeted focus on critical elements.

The construction of utility tunnels differs significantly from conventional building construction due to distinguishing features such as extensive underground operations and substantial geological influences. First, conventional construction of urban

underground utility tunnels typically employs open-cut excavation methods, which inevitably cause disruption to the local ecological environment and adversely affect residents' daily lives and urban traffic. Second, in terms of resource utilization, soil balance and the recycling of construction waste are particularly critical, as underground projects involve large volumes of earthwork and require effective management of generated waste. Therefore, compared with conventional above-ground construction, the adoption of trenchless technologies and the resource recovery of construction waste have become distinctive and critical criteria in the green construction evaluation of urban underground utility tunnels.

Based on the aforementioned analysis of green construction evaluation factors and drawing upon references^[7,13,14], this study develops a set of evaluation criteria specifically for the green construction of urban underground utility tunnels. These factors are concentrated in four main aspects: resource utilization, environmental impact, construction management and technological innovation. The specific evaluation factors are shown in Table 1

Table 1. Evaluation factor table

Dimension	Evaluation factors	Key Measures	Expected effect
Resource utilization	Material Resource Saving	Prioritize the use of green materials (e.g. recycled building materials, high-strength concrete), accurate procurement and scientific storage management.	Reduce resource consumption, minimize pollution, improve utilization rate and save costs.
	Efficient utilization of water resources	Adopt water-saving equipment (e.g. rainwater collection system) and optimize drainage design.	Enhance the recycling rate, reduce the waste of water resources, and ensure sustainable utilization.
	Efficient use of energy	Use of energy-saving equipment (electric machinery), optimization of equipment operation, use of natural light and energy-saving light fixtures	Reduce energy consumption and improve energy efficiency
	Intensive land use	Rationally plan the layout of construction sites, optimize the temporary storage and transfer of soil and waste.	Reduce land occupation, harmonize urban functions, and reduce environmental interference.
Environmental Impact	Dust control	Spraying to reduce dust, closed transportation, road sweeping	Improve air quality and reduce the impact on residents and ecology.
	Noise control	Low-noise equipment, time-restricted construction (avoiding nighttime), noise barriers	Reduce noise pollution and protect the surrounding environment
	Waste Disposal	Separate recycling (e.g. steel, concrete recycling), harmless treatment (incineration/landfill)	Reduce pollution, realize resourcefulness and minimization
	Resourceful utilization of slag	Dirt backfill, processed into recycled building materials (bricks, aggregates), safe landfill	Reduce land occupation, save resources, reduce pollution and project costs
Construction management	Scientific organization and design	Optimize the construction process, incorporate green goals, reduce repeated operations	Improve efficiency and reduce waste of resources
	Personnel Quality Improvement	Green construction training, establish environmental protection assessment and incentive mechanism.	Enhance environmental awareness, standardize operation and reduce waste
	Quality and Safety Management	Strict quality control and perfect safety protection system	Avoid rework, reduce accidents, and ensure project stability
Technological Innovation	Application of information technology	BIM technology optimizes full-cycle management, while the Internet of Things supports real-time monitoring of equipment and environmental conditions.	Improve construction precision and efficiency, reduce error rate
	Green construction technology	Promote assembly construction (reduce wet work), research and develop environmentally friendly materials and processes.	Reduce pollution and energy consumption, improve construction efficiency
	Non-excavation Technology	Apply pipe jacking and directional drilling technology to reduce surface damage.	Reduce environmental interference and protect ecology

3. Establishment of green construction evaluation system for comprehensive pipeline corridor

To develop a practical and innovative green evaluation system for utility tunnels, a scientific framework must follow four core principles^[15-16](Fig. 1).

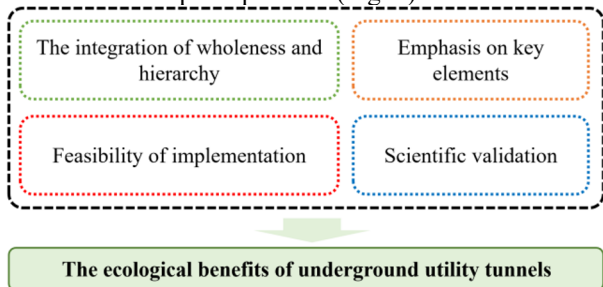


Fig. 1. Four Core Principles of Green Evaluation for Comprehensive Utility Tunnels.

3.1. Factor screening based on Delphi method

From the above analysis, it can be seen that the evaluation factors for the green construction of underground urban utility tunnels are numerous, covering multiple aspects such as construction materials, energy consumption, waste treatment, ecological protection, noise control, and dust suppression, forming

a complex and extensive evaluation system. However, the application of multiple factors in practice presents several challenges: first, it increases evaluation difficulty and complexity, consuming substantial time and resources for data collection and reducing work efficiency; second, unreasonable weight allocation dilutes the importance of critical factors, compromising evaluation accuracy; third, non-specialists find it difficult to comprehend fully, potentially leading to misunderstandings or improper application. Consequently, there is a pressing need to optimize and integrate evaluation factors by removing redundant or weakly correlated elements, retaining the most representative and critical indicators, and constructing a streamlined, efficient, and practical evaluation system.

This study employs the Delphi method to screen and refine evaluation factors, identifying core elements that reflect the distinctive characteristics of green construction in urban underground utility tunnels. Through scientific analysis, a concise and effective evaluation framework will be established to provide a scientific basis for research and practice, thereby promoting the standardization and sustainable development of green construction practices for urban underground utility tunnels.

The detailed process of screening and simplifying the evaluation factors is illustrated in Fig. 2. The outcomes of the initial consultation round are presented in Table 2.

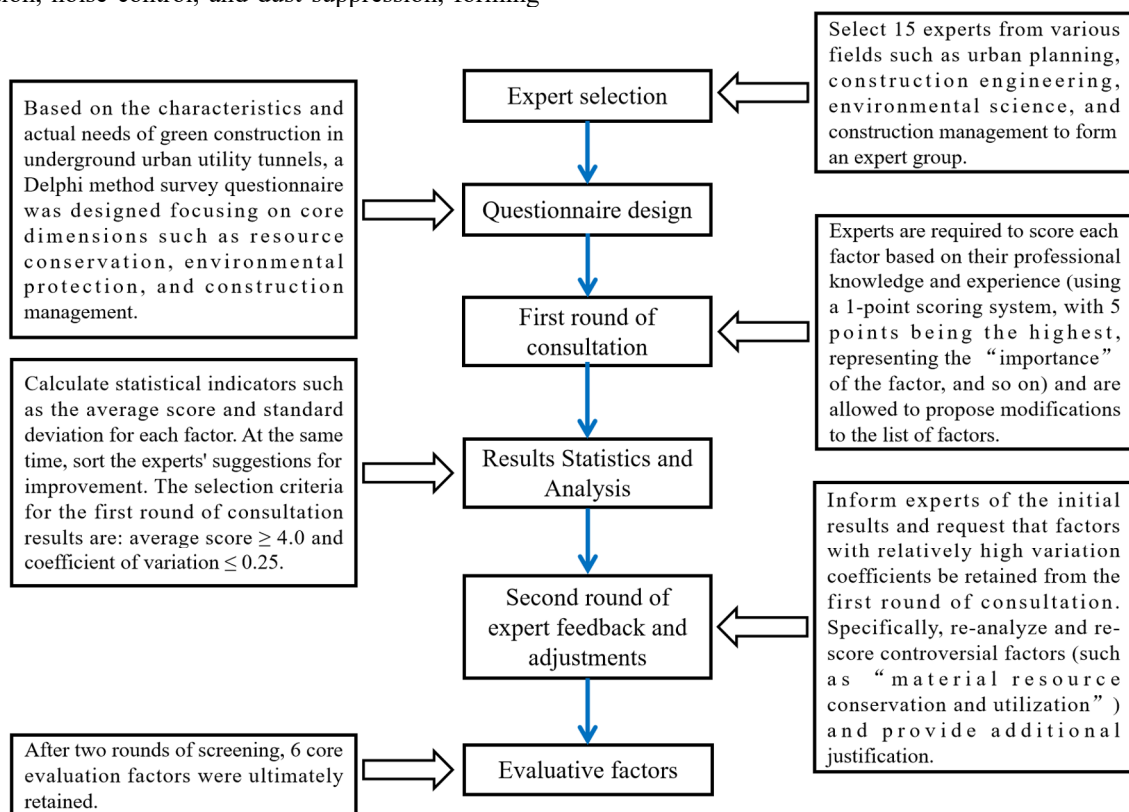


Fig. 2. Flow chart of screening and streamlining of evaluation factors.

Table 2. Evaluation factor table

Factor Number	Factor	Mean Score	Standard deviation	Coefficient of variation (CV)	Whether to retain
A_1	Application of non-excavation construction technology	4.73	0.45	0.095	Yes
A_2	Resource utilization of sludge	4.67	0.49	0.105	Yes
A_3	Green construction process innovation	4.53	0.62	0.137	Yes
A_4	Application of information technology	4.40	0.74	0.168	Yes
A_5	Energy Resource Conservation and Utilization	4.33	0.72	0.166	Yes
A_6	Material resource conservation and utilization	4.27	0.80	0.187	Yes
A_7	Dust pollution	4.13	0.83	0.201	Yes
B_1	Noise pollution	3.93	0.92	0.234	No
B_2	Waste Emission	3.87	1.02	0.263	No
B_3	Construction Organization Design	3.80	1.05	0.276	No
B_4	Land resource conservation and utilization	3.60	1.12	0.311	No
B_5	Water resource conservation and utilization	3.53	1.15	0.326	No
B_6	Quality and safety management	3.40	1.18	0.347	No
B_7	Personnel management	2.93	1.24	0.423	No

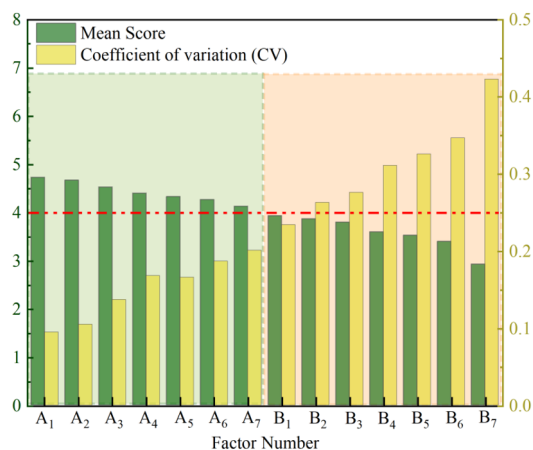


Fig.3 Analysis and Screening Diagram of Evaluation Factors

In Figure 3, the Delphi method was employed in two rounds of screening, utilizing criteria of an average score of ≥ 4 and a coefficient of variation (CV) of ≤ 0.25 . This process identified core factors within the green zone (A_1 to A_7). Factors A_6 and A_7 were subsequently consolidated, resulting in the determination of six core factors, as detailed in Table 3. These six core factors collectively encapsulate the principles of intensiveness, circularity, technological innovation, and environmental sensitivity inherent to green construction practices for underground utility tunnels. This aligns with the defining characteristics of such projects, including spatial confinement, resource intensity, and significant ecological impact.

Table 3. Final core factors and their basis

Core factors	Rationale for screening (underground pipe corridor characteristics)
Application of non-excavation construction technology	Reducing surface damage and adapting to urban underground space limitations
Resource utilization of sludge	Waste recycling, reduce landfill pollution
Green construction technology innovation	Technological innovation to drive resource efficiency and environmental protection
Application of Information Technology	BIM and Internet of Things optimize construction process and resource management
Energy and Material Resource Saving	Underground construction has high energy consumption and requires targeted measures to reduce consumption.
Dust and noise pollution prevention and control	Enclosed environment needs to strengthen pollution diffusion control

3.2. Establishment of green evaluation index system for underground urban comprehensive pipeline corridor

Based on the comprehensive analysis above, an established green evaluation index system for urban underground utility tunnels is presented in Figure 4.

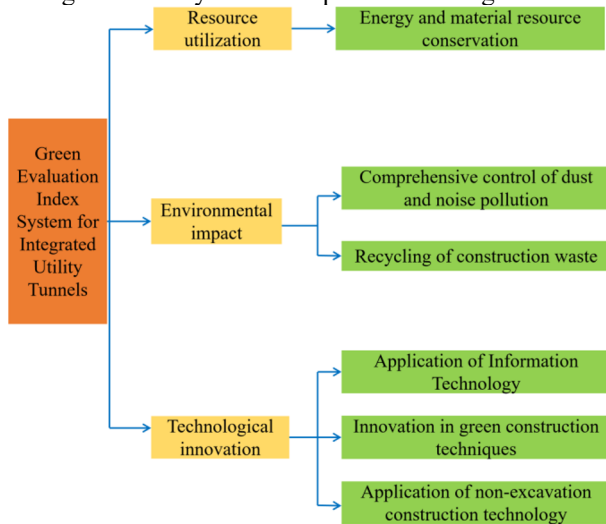


Fig.4 Green evaluation index system of underground urban comprehensive pipeline corridor

As shown in the figure above, the final green evaluation index system for utility tunnels consists of two components: universal indicators and project-specific indicators. While referencing the composition of green building indicator systems, this study also proposes two additional indicators tailored to the characteristics of utility tunnels: the application of trenchless construction techniques and the resource utilization of excavated spoil, thus highlighting their distinctive nature.

4. Feasibility Verification

To validate the applicability of the proposed green evaluation index system for urban underground utility tunnels in assessing green construction methods, three representative construction methods were specifically selected for evaluation.

(1)Method 1-Traditional Open-Cut Method: By excavating a working pit from the ground surface, support structures are installed to reinforce the pit walls. Cast-in-place concrete construction is then sequentially carried out for the utility tunnel's base plate, wall panels, and roof plate, followed by final backfilling and surface restoration. This method relies heavily on extensive wet trades, is characterized by an extended construction period, substantial material consumption, and significant environmental impacts.

(2)Method 2-Construction Method of Composite Prefabricated Pipe Gallery^[17]: By prefabricating components such as the base plate, top plate and double-skin wall panels in the factory, the on-site construction volume and time are reduced. High-precision positioning technology is utilized to ensure the accurate installation of components. An independent support system is adopted to guarantee installation safety. Segmented pouring and waterproof treatment are carried out to ensure the integrity of the structure and waterproof performance

(3)Method 3-BIM-Based Integrated Construction Method for Utility Tunnels^[18]: This method establishes a BIM model for the utility tunnel to integrate design and construction information, enabling 3D visual management. It employs clash detection to resolve design conflicts, utilizes 4D simulation to optimize construction scheduling, and operates a collaborative management platform for data sharing, thereby enhancing efficiency and quality while reducing costs and environmental impact.

Table 4 shows the comparison of the three construction methods in dimensions such as construction period, material consumption and environmental impact.

Table 4. Comparison table of construction methods

Comparison dimension	Traditional open cut method	Stacked assembly pipe corridor technology	BIM technology integration method
Construction period	12 days for 30m section	Only 5 days for 30m section (58% increase in efficiency)	Construction period shortened by 20
Material Consumption	A large quantity of formwork and steel pipes results in a substantial waste of timber resources.	Tool-type support + prefabricated components, saving 70% of timber	Accurate calculation optimization, material saving 10%
Labor demand	Staff-intensive, relying on skilled workers	40% reduction in labor, mainly mechanized installation	Reduced rework, lower labor coordination requirements
Environmental impact	Heavy dust and noise pollution	Factory prefabrication reduces on-site pollution (60% reduction in dust)	Optimization of sponge facilities, 40% increase in rainwater reuse rate
Quality control	Large cast-in-place error ($\geq 10\text{mm}$), easy to leakage	Axial deviation $\leq 3\text{mm}$, reliable Sealing of joints	Collision detection solves 95% of conflicts, Rework rate $\leq 3\%$
Collaboration efficiency	Multidisciplinary communication is inefficient and prone to delay	Mechanized process reduces human intervention	Real-time data sharing on collaboration platform improves decision-making efficiency by 50%.
Cost-effectiveness	High material loss, high rework cost	Turnable formwork reduces material costs by 30%.	Reduced rework and waste, reducing overall costs by 15%.

Comparison dimension	Traditional open cut method	Stacked assembly pipe corridor technology	BIM technology integration method
Environmental Benefits	Sloppy rainwater management and high carbon emissions	50% reduction in carbon emissions	Sponge city design reduces carbon emissions by 25
Resource Management Efficiency	Low site utilization and high resource waste	Turnable formwork and support system (30% reduction in material cost)	BIM optimized site layout (utilization rate increased by 30%), dynamic adjustment of resource allocation

As evidenced by the table, under prevailing green construction principles, both Method 2 (composite precast) and Method 3 (BIM-based integration) demonstrate superior performance across all evaluated criteria—including construction efficiency, resource conservation, and environmental impact—when compared to the traditional open-cut method. Regarding technological innovation and intelligent construction, Method 3, due to its digital and intelligent features, clearly stands out as the optimal green construction method among the three approaches.

To scientifically verify the above analysis, this study applies the established green evaluation index system for urban underground utility tunnels, utilizing the fuzzy comprehensive evaluation method to assess the green construction performance of the three aforementioned methods and identify the optimal green construction approach.

4.1. Establishment of factor index set U and construction method alternative set V

According to the proposed green evaluation index system for urban underground utility tunnels, the factor indicator set U is defined as: $U =$ (conservation of energy and material resources, integrated control of dust and noise pollution, recycling and utilization of spoil, application of information technology, innovation in green construction techniques, trenchless construction techniques)

And the green construction method alternative set is:
 $V =$ (method 1, method 2, method 3)

4.2. Establish judgment matrix K

In the process of constructing the judgment matrix K based on the factor indicator set U , a scientifically determined evaluation scale is essential to ensure the reliability of pairwise comparison results. Therefore, to reduce subjectivity in expert judgment, this study

innovatively employs a five-level scale to establish the fuzzy evaluation system, as detailed in Table 5.

Table 5. Fuzzy evaluation scale

Scale	Definition
1	Factor u_i is equally important as factor u_j
2	Factor u_i is slightly more important than factor u_j .
3	Factor u_i is significantly more important than factor u_j .
4	Factor u_i is more strongly important than factor u_j
5	Factor u_i is significantly more important than factor u_j
The reciprocal of the above values	When factor u_i is compared with factor u_j , if it is assigned one of the above scaled values, then The weight of factor u_j when compared to factor u_i should be the reciprocal of that scale value.

As shown in the factor indicator set U , these factors contribute differently to evaluating green construction of urban underground utility tunnels. Urban underground utility tunnels are predominantly located in densely populated areas. Due to complex construction environments and stringent ecological protection requirements, their green construction must prioritize resolving issues that directly affect resident health and the urban environment, while simultaneously incorporating resource recycling and technological innovation. In summary, the order of influence for each factor on the evaluation results should be: Integrated Control of Dust and Noise Pollution > Conservation of Energy and Material Resources > Trenchless Construction Techniques > Recycling and Utilization of Spoil > Innovation in Green Construction Techniques > Application of Information Technology. Based on this ranking, factors are compared pairwise to generate the binary comparison ranking assignment table, as presented in Table 6.

Table 6. Binary comparison assignment of each factor

Factor	u_j					
	Energy and Material Resource Conservation	Comprehensive Prevention and Control of Dust and Noise Pollution	The Resource Utilization of Construction Waste	The application of information technology.	Innovation in Green Construction Techniques	Trenchless Construction Technology
u_i Energy and Material Resource Conservation	1	1/2	3	5	4	2
Comprehensive Prevention and Control of Dust and Noise Pollution	2	1	3	5	4	3
The Resource	1/3	1/3	1	3	2	1/2

Utilization of Construction Waste							
The application of information technology.	1/5	1/5	1/3	1/3	1/2	1/4	
Innovation in Green Construction Techniques	1/4	1/4	1/2	2	1	1/3	
Trenchless Construction Technology	1/3	1/3	2	1/3 2	3	1	

From Table 6, the judgment matrix K can be constructed

$$K = (k_{ij})_{m \times n} = \begin{bmatrix} 1 & 1/2 & 3 & 5 & 4 & 2 \\ 2 & 1 & 3 & 5 & 4 & 3 \\ 1/3 & 1/3 & 1 & 3 & 2 & 1/2 \\ 1/5 & 1/5 & 1/3 & 1 & 1/2 & 1/4 \\ 1/4 & 1/4 & 1/2 & 2 & 1 & 1/3 \\ 1/2 & 1/3 & 2 & 4 & 3 & 1 \end{bmatrix} \quad (1)$$

and the judgment matrix K satisfies $k_{ij} > 0$, $k_{ij}=1/k_{ji}$, $k_{ii}=1$ ($i, j=1,2,3,4,5,6$)

4.3. Establish the factor weight set A

Calculate the weight value of each factor

$$\alpha_i = \left(\prod_{j=1}^m k_{ij} \right)^{\frac{1}{m}} = (i, j 1,2,3,4,5,6, m =6) \quad (2)$$

The weight value for each factor can be derived from Equation (2).

$\alpha_1= 1.98, \alpha_2= 2.67, \alpha_3= 0.83, \alpha_4= 0.34, \alpha_5= 0.52, \alpha_6= 1.26$.

The above weight values were normalized according to equation (3).

$$\bar{\alpha}_i = \frac{\alpha_i}{\sum_{i=1}^6 \alpha_i} \quad (3)$$

The final set of weights can be obtained
 $A=(0.26, 0.35, 0.11, 0.05, 0.07, 0.17)$

4.4. Consistency test

To ensure calculation accuracy, a consistency check must be conducted to prevent excessive deviations caused by subjective judgments. The consistency of the judgment matrix is determined by the consistency ratio (CR): when $CR < 0.1$, the evaluation demonstrates satisfactory consistency; when $CR > 0.1$, the judgment matrix requires revision. The formula for calculating CR is as follows:

$$CR = \frac{CI}{RI} \quad (4)$$

Where:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (5)$$

$$\lambda_{max} = \sum_{i=1}^n \frac{(K \cdot A^T)_i}{n \cdot A^T_i} \quad (6)$$

The consistency index CI is defined as follows; n represents the order of the judgment matrix; RI denotes the average random consistency index, which varies according to the size of n , with specific values available in Table 7; λ_{max} refers to the maximum eigenvalue of the judgment matrix. The remaining symbols are consistent with those previously mentioned.

By substituting the determined judgment matrix K and weight set A into Equations (4) through (6), we find that $\lambda_{max} = 6.18$; $CI = 0.036$; $CR = 0.029 < 0.1$. This indicates that the consistency test meets established requirements, thereby confirming that its weight allocation is more rational and justifiable

Table 7. Average random consistency index

n	1	2	3	4	5	6	7
RI	0	0	0.58	0.96	1.12	1.24	1.32

4.5. Determine the affiliation function and build the fuzzy matrix

To achieve more accurate results, it is recommended to use distribution functions as membership functions for representing fuzzy sets. With reference to [19], the right semi-trapezoidal distribution is suggested as the membership function for factors in the indicator set U , as shown in Fig. 5.

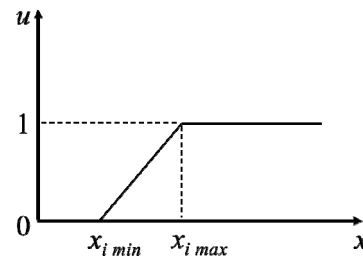


Fig. 5 Biased large semi-trapezoidal distribution

The affiliation degree is calculated as:

$$\mu_{ij} = \begin{cases} 1 & x_{ij} \geq x_{i \max} \\ \frac{x_{ij} - x_{i \min}}{x_{i \max} - x_{i \min}} & x_{i \min} < x_{ij} < x_{i \max} \\ 0 & x_{ij} \leq x_{i \min} \end{cases} \quad (7)$$

where μ_{ij} is the affiliation degree of factor i of program j ; $x_{i\min}$ is the measured minimum value of factor i ; and $x_{i\max}$ is the measured maximum value of factor i ;

According to Equation (7) and Tables 5 and 6, the affiliation degree of each factor index corresponding to the three green construction methods can be determined as follows: $r_{1j}=(0.25, 0.5, 0.75)$; $r_{2j}=(0.25, 0.75, 1.0)$; $r_{3j}=(0, 0.25, 0.5)$; $r_{4j}=(0.25, 0.5, 0.75)$; $r_{5j}=(0, 0.75, 1.0)$; $r_{6j}=(0, 0.5, 1.0)$, where j represents the indices $\{1,2,3\}$.

Then the fuzzy judgment matrix R is:

$$R = \begin{bmatrix} 0.25 & 0.5 & 0.75 \\ 0.25 & 0.75 & 1.0 \\ 0 & 0.25 & 0.5 \\ 0.25 & 0.5 & 0.75 \\ 0 & 0.75 & 1.0 \\ 0 & 0.5 & 1.0 \end{bmatrix} \quad (8)$$

4.6. Fuzzy Comprehensive Judgment Model

Using the basic principles and methods of fuzzy mathematics, the fuzzy comprehensive judgment uses the following model:

$$B = A \cdot R = (0.17 \quad 0.58 \quad 0.88) \quad (9)$$

Normalizing the results of Equation (9) with reference to Equation (3) yields $B = (0.10, 0.36, 0.54)$.

Following the fuzzy comprehensive evaluation, the final assessment results were interpreted according to the maximum membership principle. The analysis identifies Method 3 (BIM-based integrated technology) as the optimal green construction approach among the three alternatives, followed by Method 2 (composite precast method), with Method 1 (traditional open-cut method) ranking last. This finding theoretically validates the aforementioned comparative analysis. Thus, the green evaluation index system proposed in this study can be considered to possess practical applicability in the comprehensive assessment of green construction methods for urban underground utility tunnels.

4.7. Weight sensitivity analysis

This paper conducts a systematic sensitivity analysis on the index weights, Using the initial weight set A as reference, adjusts the weights of each core indicator by $\pm 10\%$ in sequence, recalculates the fuzzy comprehensive evaluation result B , and observes whether the optimal method changes. As shown in Table 8.

Table 8 Sensitivity Analysis Table.

Scene	Method 1	Method 2	Method 3	Optimal method
Original weight	0.10	0.36	0.54	Method 3
+10% disturbance	0.102	0.359	0.540	Method 3
-10% disturbance	0.102	0.359	0.540	Method 3

From Table 8, none of the weight adjustments have changed the optimal position of Method 3. This demonstrates that the proposed evaluation system can reliably identify the optimal green construction method across varying parameter scenarios, thereby providing operational resilience for practical applications.

4.8. A comparative analysis of three construction methods

To further verify the effectiveness of the green construction evaluation system proposed in this paper, a detailed comparative analysis was conducted using the fuzzy evaluation matrix R from Equation (8) combined with the actual performance data of the three construction methods across core indicators from Table 4.

(1) Method 1 (Traditional Open-Cut Method): It performs the worst in indicators such as "Conservation of Energy and Material Resources" and "Integrated Control of Dust and Noise Pollution," with a membership degree of only 0.25. Specifically it exhibited the longest construction period (12 days for a 30-meter section), significant material wastage (particularly timber), and severe dust and noise pollution, rendering it the least effective in green construction performance.

(2) Method 2 (Composite Precast Method): This approach demonstrated superior performance in "Innovation in Green Construction Techniques" (membership degree 0.75) and "Conservation of Energy and Material Resources" (membership degree 0.5) compared to Method 1. Specifically, its construction efficiency is increased by 58%, and wood is saved by 70%. However, there are still improvements in "application of information technology" and "trenchless construction technology".

(3) Method 3 (BIM-based Integrated Technology): It scored the highest in most indicators, especially in "Conservation of Energy and Material Resources" (membership degree 0.75), "Application of Information Technology" (membership degree 0.75) and "Trenchless Construction Techniques" (membership degree 1.0). Specific achievements include a 20% reduction in construction period, 10% material savings, 60% dust reduction, and 50% improvement in collaborative efficiency, representing the optimal overall green construction performance.

To sum up, the ranking of the green construction effects of the three methods is: Method 3 > Method 2 > Method 1, which is consistent with the above fuzzy comprehensive evaluation results and further verifies the scientificity and applicability of this evaluation system.

5. Discussion

Although the evaluation system constructed in this paper is universal, it still faces the following challenges when implemented in different urban contexts:

(1) Diversity of geological conditions: In soft soil, rock or high water level areas, the application of

trenchless construction technologies (such as pipe jacking method) may be restricted, and the technology selection and weights need to be adjusted according to the geological exploration results.

(2) Differences in economic development levels: Disparities in economic development levels: Economically underdeveloped regions may demonstrate inadequate investment in areas such as "application of information technology" and "innovation in green construction techniques," which affects the applicability of the evaluation results. It is necessary to flexibly adjust the threshold values of the indicators in combination with local economic conditions.

(3) Inconsistent policies and standards: The implementation of policies in areas such as green construction and waste soil treatment varies among different cities, which may lead to difficulties in standardizing indicators such as "recycling and utilization of spoil" and "dust control"

6. Conclusion

(1) Addressing issues such as excessive factors and unreasonable weight allocation in existing evaluation systems, this study employed the Delphi method to screen and refine the evaluation factors, ultimately identifying six core indicators. These core indicators - including trenchless construction techniques, spoil recycling and utilization, and innovative green construction methods - collectively embody the intensive nature, circularity, technological innovation, and environmental sensitivity characteristic of utility tunnel construction. This establishes a streamlined, efficient, and practical evaluation system, thereby providing a scientific basis for standardizing and advancing sustainable development in green construction of urban underground utility tunnels.

(2) Validation through the fuzzy comprehensive evaluation method confirms that the proposed green evaluation index system for urban underground utility tunnels effectively assesses the green construction performance of different construction methods, thereby providing a scientific basis for selecting optimal green construction approaches.

References

1. Xiao Yuting, Huang Shunyu, Wu Xiaogang. Research on Green Construction Technology of Urban Underground Comprehensive Pipe Conduits [J]. *New Urban Construction Technology*, 2024, 33(11): 53-55.
2. Xu Xiaoli. Application Framework of Green Construction Technology in Urban Underground Comprehensive Pipe Conduits [J]. *Housekeeping*, 2021, (23): 73-74.
3. Dong Yingjian. Application of Green Construction Technology in Urban Underground Comprehensive Pipe Conduits [J]. *Municipal Technology*, 2020, 38(06): 234-236+258.
4. Zhao Yongli, Jiang Xinxin, Wu Zongpeng. Discussion on Green Construction Technology of Underground Comprehensive Pipe Conduits [J]. *China Building Decoration & Renovation*, 2023, (17): 89-91.
5. Wang Shuang, Dong Jing, Ji Xingyu. Research on the Construction of Green Construction Evaluation Index System Based on Analytic Hierarchy Process [J]. *Journal of Jilin Jianzhu University*, 2016, 33(03): 93-96.
6. Jia Keyang. Research on the Construction of Green Construction Evaluation System and Model for Highways [J]. *Science and Technology Innovation*, 2022, (24): 113-116.
7. Xiao Guangfa. Research on Green Construction Evaluation of Metro Based on Fuzzy Matter-Element [D]. *Shijiazhuang Tiedao University*, 2017.
8. Guo Zhenwei, Guo Dandan. Research on the Construction Method of Green Construction Evaluation System for Railway Passenger Stations [J]. *Urban Development Studies*, 2013, 20(05): 5-8+16.
9. Wang Jing, Chen Li, Liu Mengxi. Research on Green Construction Evaluation of Metro Engineering Based on Matter-Element Method [J]. *Modern Urban Mass Transit*, 2024, (12): 67-73.
10. Chen Wei. Research on Green Construction Evaluation of a Substation Based on Grey Relational Analysis [J]. *Construction Machinery & Maintenance*, 2024, (12): 97-99.
11. Ding Zhuanzuan. Research on Comprehensive Evaluation of Green Construction in Construction Projects Based on Extension Model [D]. *Henan University of Technology*, 2024.
12. Zhao Yuqing. Research on Green Construction Evaluation of Metro Projects under the Trend of Refinement [D]. *Changchun Institute of Technology*, 2023.
13. Jia Zhenmin. Comprehensive Evaluation Method of Green Construction Level for Prefabricated Residential Buildings [J]. *Construction Technology*, 2024, (20): 55-57.
14. Tong Wenjun. Research on Comprehensive Evaluation Model of Green Construction for Construction Projects [J]. *Housing and Real Estate*, 2024, (32): 99-101.
15. Wang Lei. Research on Green Evaluation of Comprehensive Pipe Conduits Based on Fuzzy Comprehensive Evaluation Method [D]. *Xihua University*, 2019.
16. Yu Peng. Research on Green Construction of Urban Comprehensive Pipe Conduits Based on Evolutionary Game [D]. *Southeast University*, 2022.
17. Shen Xinhua. Research on Prefabricated Composite Assembly Construction Technology of Underground Comprehensive Pipe Conduits [J]. *Shanxi Architecture*, 2020, 46(17): 97-98.

18. Han Shiyu, Guo Xiujuan. Application of BIM Technology in the Construction of Urban Underground Comprehensive Pipe Conduits [J]. Northern Architecture, 2021, 6(01): 67-71.
19. Liu Chunyang. Research on Safe and Rapid Construction Technology of Long and Extra-long Tunnels in Plateau [D]. Beijing: Beijing Jiaotong University, 2012.