Risk Assessment of Underground Utility Tunnel Projects in Q City Using the Analytic Hierarchy Process

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Abstract: The rapid urbanization and economic development in China have led to increasing demand for infrastructure systems such as utilities, water, gas, and communication networks, exacerbating urban challenges like land scarcity and congestion. Previous studies have highlighted the potential of underground space development as a means to address these issues. Underground utility tunnel construction has been identified as a key solution for efficient pipeline maintenance and the advancement of smart city initiatives. However, as the scale of such projects continues to grow, so does the associated risk. Traditional risk assessment frameworks have often overlooked the significance of intelligent operation and maintenance (O&M) in the context of the digital transformation of infrastructure. This study proposes an updated risk assessment approach that integrates smart O&M into the evaluation framework, reflecting the adoption of technologies such as Building Information Modeling (BIM), digital twins, and big data in construction processes. The Analytic Hierarchy Process (AHP), expert consultations, questionnaire surveys, and fuzzy evaluation methods are applied to identify and assess risks in an underground utility tunnel project in Q City. The results indicate that the overall risk level of the project is above average, with the most significant risks occurring during the construction and operational phases. Risk mitigation measures have been proposed for the identified high-risk areas, tailored to the specific characteristics of the project. This study underscores the importance of incorporating smart operation and information technology risks into traditional risk management frameworks. The findings emphasize the need for a paradigm shift in the risk management of underground utility tunnel projects, particularly in light of the ongoing digital transformation of infrastructure. Such an approach would enhance the safety and efficiency of project management across the entire life cycle of the tunnel system.

Keywords: Risk assessment; Risk identification; Analytic Hierarchy Process; Underground utility tunnel; Smart operation and maintenance; Fuzzy evaluation; Digital transformation; Building Information Modeling

1 Introduction

China's urbanization has accelerated dramatically over the past decades, with the proportion of the urban population rising from less than 20% in 1978 to approximately 70% by 2030 [1]. This rapid expansion has driven substantial economic and spatial restructuring. Urban per capita residential land area has continued to grow, and the scale of urban construction land has expanded at a rate that surpasses population growth [2]. Nevertheless, the ongoing urbanization process has also intensified a series of structural challenges, including land scarcity [3], growing traffic congestion [4], delays in infrastructure provision [5], and increasing environmental pressures [6]. In response to these constraints, the strategic development and utilization of underground space have emerged as an important pathway to ease resource limitations associated with dense urban development [7]. Existing research has adopted approaches such as integrating Geographic Information Systems with the AHP and overlay analysis to support risk evaluation and site selection for underground projects [8, 9]. These methodological advances have enhanced the scientific basis for planning, developing, and managing urban underground space and have significant implications for promoting more coordinated and resilient urban development.

The construction of urban underground utility tunnels has become a key strategy for optimizing urban spatial structure and strengthening the carrying capacity of municipal infrastructure [10]. China introduced the initiative

of piloting utility tunnels in 2015, followed by a series of policies aimed at accelerating their deployment and standardizing their development [11]. Driven by the advancement of new urbanization and the national "dual-carbon" objectives, utility tunnels have gradually evolved into an essential component of contemporary urban infrastructure. By 2024, more than 5,100 kilometers of utility tunnels had been completed nationwide, and exemplary projects—such as those in the Xiong'an New Area—had achieved comprehensive underground integration and intelligent O&M.

As the "nervous and vascular system" of urban subsurface space, the safe and stable operation of utility tunnels is fundamental to enhancing urban resilience. Yet, under the ongoing digital transformation, traditional risk assessment frameworks are encountering new limitations. The application of technologies such as BIM and digital twin systems has shifted utility tunnels from isolated physical facilities to cyber–physical integrated infrastructures. This transition has introduced a series of emerging risk types—such as data manipulation, system intrusion, and failures in intelligent algorithms—posing new challenges to the lifecycle risk management of smart utility tunnels. Developing a risk governance framework that is compatible with the digital and intelligent operating environment, and that ensures the reliability and efficiency of utility tunnel systems, has therefore become an important research frontier.

As the scale of comprehensive utility tunnels continues to expand, the risks associated with their construction and operation have become increasingly multifaceted. The inherent complexity and dynamic nature of underground engineering further exacerbate the challenges of ensuring effective safety risk management [12]. Existing studies have contributed valuable insights in this regard. In the research on the location planning of urban underground pipe galleries, Oh et al. [13] evaluated the method of selecting the best route of underground pipe galleries in urban areas based on the priority of the feasibility and economy of the project. In the risk study of urban underground pipe galleries, different scholars have different perspectives. Zhou et al. [14] analyzed the risk of water pipe, Wang et al. [15] paid attention to the impact of its structure on shock mitigation and disaster mitigation, Ma et al. [16] focused on the rainy climate in the south, and explored the influence of the ventilation system on the underground pipe galleries. Scholars' risk analysis on the site selection and material structure of underground pipe galleries can effectively improve the safety of underground engineering projects and ensure urban safety.

In terms of risk assessment methods, traditional methods are unable to meet the requirements of complex systems, and scholars have begun to explore emerging technologies. Bai et al. [17] assessed the risk of urban underground pipe galleries by analyzing the coupled energy model (CRA), and concluded that the fire protection and drainage system of urban underground pipe galleries with coupling effect could not reduce the risk; Chen et al. [18] conducted a risk assessment based on the Bayesian network (BN) through the collected data of the Beijing underground pipe galleries to reduce the probability of risk occurrence; Wu et al. divided the risk assessment of the underground pipe galleries into two steps. In the worst case, dynamic hazard scenario identification (DHSI) and the BN method were used to model, forming a comprehensive risk assessment method [19]; Xue et al. [20] used machine learning to predict the risk of underground pipe galleries, solved the problems in traditional expert decision-making, and improved the accuracy of risk prediction; Min et al. [21] evaluated the worst-case and vulnerability of urban underground pipe galleries by establishing a mathematical model.

With the popularization of science and technology, researchers can use digital technology to assess the risk of engineering projects. Many scholars use BIM technology to study the risk identification of the whole life cycle of bridges [22–24]. Remote sensing technology can also help scholars build digital maps to identify the risk of corrosion in coastal cities on steel structures and optimize the use of available resources [25]. In the field of construction enabled by intelligent detection equipment, it can help identify the degradation of railway arch bridges [26], solve the safety problems of power grid lines caused by artificial ground wire crimping errors [27] and accurately identify the fire location in the tunnel [28]. Digital technology can not only enable project participants to realize the risk identification of the whole life cycle of the engineering project and take safeguard measures in advance, but also optimize the use of resources and improve the accuracy of risk prediction to ensure the feasibility and safety of the project.

The above research has improved the accuracy of underground pipe galleries' risk analysis through probabilistic risk assessment and data-driven models, but there are still shortcomings in the integration of multidimensional indicators: from a traditional perspective, the risk assessment of comprehensive pipe galleries mainly focuses on risks such as physical equipment failures and human operational errors, while the introduction of new technologies such as the Internet of Things, digital twins, and AI decision-making will lead to the emergence of intelligent O&M risk dimensions. Existing research has paid insufficient attention to this aspect. Meanwhile, the results of traditional AHP largely rely on the experience and subjective judgment of experts. If the opinions of experts are inconsistent or biased, it may lead to distorted evaluation results.

Therefore, we take the underground comprehensive utility tunnel in Q City as its empirical case. Using the Delphi method, experts were consulted to obtain an initial understanding of the categories of risks that may arise during the project's implementation. By integrating theoretical insights with the practical characteristics of engineering projects, the relevant risks were systematically identified, analyzed, and evaluated. On the basis of the developed survey instrument, experts further assessed the relative importance of each risk factor, and the collected data were organized and analyzed to provide a robust empirical foundation for constructing the risk assessment model. Finally,

the AHP was employed to evaluate the project's risk indicators, and targeted risk mitigation strategies were proposed in accordance with the assessment results.

Today is the era of rapid development of digital technology, and the construction of large-scale projects has relied on the help of digital technology. However, the current mainstream digital risk assessment is mostly applied in Internet companies and high-tech fields. The research on the risk assessment of underground pipe galleries still focuses on the traditional dimensions and the complexity of technology, and does not mature the digital O&M into the evaluation system. Therefore, this paper takes digital O&M into account in the selection of primary indicators. Through literature review and expert discussion, it is concluded that in the digital risk, the main risks of engineering projects come from: O&M Cost Risk, Accuracy Rate Risk of Monitoring Equipment, Failure of Intelligent Decision-making and Data Security Issues. In terms of case selection, we also choose the 2022 underground pipe galleries project with the help of digital technology, which not only conforms to the development of engineering project construction in the digital era, but also enhances the theoretical and practical value of the research results.

At the theoretical level, we broaden the analytical lens of infrastructure risk management within smart-city contexts by integrating data security, algorithmic reliability, and other digital-era risk factors into the AHP–based framework. This integration enriches the theoretical foundation for evaluating risks in complex cyber–physical systems. At the practical level, the development of an intelligent evaluation system for utility tunnels can mitigate unexpected incidents, strengthen urban safety governance, and reduce the cost of smart O&M through more accurate risk identification. Such advancements contribute to the standardized development of emerging infrastructure and support the high-quality, resilient growth of smart cities.

2 Methodology

2.1 Delphi Method

We reviewed the literature on urban comprehensive pipe galleries, considering the inevitability of digital transformation in the information technology era [29–33]. We incorporated smart O&M into the risk assessment system of urban underground comprehensive pipe galleries and synthesized the views of different scholars to obtain a preliminary risk factor classification table. This study conducted the Delphi method for the initial risk system, including expert consultation, revision, and simplification of the indicator system. We used the expert authority coefficient to classify the expert's familiarity with the problem (C_s) into very familiar, familiar, average, somewhat unfamiliar, and unfamiliar; the judgment is based on four aspects: theoretical basis, practical experience, understanding of domestic and foreign peers, and intuition [34]. We chose the judgment coefficient (C_a) is divided into three levels.

$$C_r = \frac{C_a + C_s}{2} \tag{1}$$

2.2 AHP

According to the hierarchical structure model, create weighted relationships between layers based on their relationships, and construct a judgment matrix.

Step 1: Use Saaty's 1–9 ratio scaling method, as shown in Table 1. For elements in the same level, pairwise comparisons are made and a judgment matrix is constructed based on the scale (1–9) [35].

Table 1. Judgment matrix scaling and its meaning

Number	Importance Level	C_{ij}
1	i and j are equally important	1
2	i is slightly more important than j	3
3	i is more important than j	5
4	i is strongly more important than j	7
5	i is extremely more important than j	9
6	i is slightly less important than j	1/3
7	i is less important than j	1/5
8	i is strongly less important than j	1/7
9	i is extremely less important than j	1/9

Note: $C_{ij} \in \{1/8, 1/6, 1/4, 1/2, 2, 4, 6, 8\}$ indicates that its importance lies between the adjacent levels in $C_{ij} \in \{1/9, 1/7, 1/5, 1/3, 1, 3, 5, 7, 9\}$.

Thus, the judgment matrix A is constructed:

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix}$$

Step 2: Get the value of the consistency evaluation index (CI) by using the maximum characteristic root λ_{max} value, so as to check the consistency of the decision-maker's judgment.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

Step 3: Compare CI with the random consistency standard value (RI) to obtain the random consistency ratio (CR). If CR < 0.10, it indicates that the consistency test of matrix A is passed; If it fails, it is necessary to adjust the values of each element of the judgment matrix and recalculate.

$$CR = \frac{CI}{RI} \tag{3}$$

The value of RI is shown in Table 2.

Table 2. Reference value of average random consistency index (RI)

Matrix Order	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Step 4: Calculate the relative importance of an element at level i to an element at level $i - 1$. This sort is called a hierarchical single sort. This hierarchical single sort can be used to find the maximum eigenvalue and eigenvector of the judgment matrix.

(1) Product of element values in each row of the judgment matrix A:

$$M_i = \prod_{i=1}^{m} A_{ij}(i = 1, 2, \ldots m) \tag{4}$$

(2) Find the root of M power:

$$P_i = \sqrt[m]{M_i} \tag{5}$$

(3) Calculate the subjective weight of index i:

$$W_i = \frac{P_i}{\sum P_i} \tag{6}$$

It can be obtained that $W_i = [W_1, W_2, \cdots W_i]^T$ is the obtained eigenvector.
(4) Find the maximum eigenvalue of the judgment matrix:

$$\lambda_{\max} = \sum_{i=1}^{m} \frac{(BW)_i}{nW_i} \tag{7}$$

where, $(BW)_i$ represents the element i of vector BW.

2.3 Risk Fuzzy Evaluation

Step 1: According to the risk level of the project, establish the project risk evaluation set J = $\{J_1, J_2, J_3, J_4, J_5\}$, which are five risk levels: higher risk $J_1 \in [80, 100]$, high risk $J_2 \in [60, 80)$, medium risk $J_3 \in [40, 60)$, low risk $J_4 \in [20, 40)$, lower risk $J_5 \in [0, 20)$.

Table 3. Probability of risk occurrence (P)

Probability of Occurrence	Description
Risks have a probability of 80%–100%	Highest
Risks have a probability of 60%–80%	Higher
Risks have a probability of 40%–60%	Medium
Risks have a probability of 20%–40%	Lower
Risks have a probability of 0%–20%	Lowest

Step 2: Fuzzy evaluation is carried out by using the occurrence probability (P) of risk factors and the consequences (S). The definition of occurrence probability (P) and consequence (S) is shown in Table 3 and Table 4.

Table 4. Consequence of risk (S)

Consequence of Risk	Description
The loss is more than 10 million yuan, and the construction period is affected for 1 year, resulting in death and injury, which has a great impact on the overall project quality.	Tragedy
The loss is 5–10 million yuan, affecting the construction period for 6–12 months, causing injury to 10 or more people, which has a great impact on the quality of key projects.	Serious
The loss is 3–5 million yuan, affecting the construction period for 3–6 months, causing 5–10 injuries, which has a relatively large impact on the overall quality of the project.	Medium
The loss is 1–3 million yuan, affecting the construction period for 1 to 3 months, causing 3–5 injuries, which has a great impact on the overall quality of secondary projects.	Slight
The loss is less than 1 million, affecting the construction period for 1 month, causing injury to less than 3 people, which has a small impact on the quality of the project.	Negligible

Step 3: Establish a risk classification evaluation matrix according to the occurrence probability (P) of risk factors and the consequences (S), as shown in Table 5.

Table 5. Risk classification evaluation matrix

		Consequence of Risk S				
		Tragedy	Serious	Medium	Slight	Negligible
	Highest	5 level	5 level	4 level	4 level	2 level
	Higher	5 level	5 level	4 level	3 level	2 level
Probability of occurrence P	Medium	4 level	4 level	3 level	3 level	1 level
	Lower	4 level	3 level	3 level	2 level	1 level
	Lowest	2 level	2 level	1 level	1 level	1 level

Step 4: Normalize the occurrence probability (P) of risk factors and the consequence (S) data, and establish the membership matrix respectively:

$$D_{ij} = \frac{d_{ij}}{\sum d_{ij}} \tag{8}$$

Step 5: Risk fuzzy evaluation calculation:
(1) Fuzzy evaluation matrix U_{ij}:

$$U_{ij} = P_{ij} \times S_{ij} (i, j = 1, 2, 3, 4, 5) \tag{9}$$

(2) Combine with the risk classification assessment matrix, the risk grade membership L_{ij}:

$$L_{ij} = [R_{l1}, R_{l2}, R_{l3}, R_{l4}, R_{l5}] \tag{10}$$

where, R_{li} is the membership of the i-th risk level.
(3) Fuzzy value of each risk factor (N):

$$N = L \times J \tag{11}$$

In order to better evaluate the weight of each risk factor, this paper uses the weighted average to calculate the fuzzy value of the risk factor, taking the median of the risk evaluation set for calculation, that is $J = [10, 30, 50, 70, 90]$.

2.4 Sample Steps of Risk Fuzzy Evaluation

This section selected the secondary risk index: result destruction as an example to show the complete process of membership calculation, fuzzy synthesis and risk grade judgment.

Step 1: Get the original matrix through the questionnaire.

$$P_{\text{base} \cdot R_{74}} = [20, 33, 26, 8, 4]$$
$$S_{\text{base} \cdot R_{74}} = [12, 21, 31, 19, 8]$$

Step 2: Construct membership matrix.

$$D_{P \cdot R_{74}} = [0.220, 0.363, 0.286, 0.889, 0.044]$$
$$D_{S \cdot R_{74}} = [0.132, 0.231, 0.341, 0.209, 0.088]$$

Step 3: Construct fuzzy evaluation matrix.

$$U_{R_{74}} = D_{P \cdot R_{74}} \times D_{S \cdot R_{74}}{}^{T}$$

$$U_{R_{74}} = \begin{bmatrix} 0.029 & 0.051 & 0.075 & 0.046 & 0.019 \\ 0.048 & 0.084 & 0.124 & 0.076 & 0.032 \\ 0.038 & 0.066 & 0.097 & 0.060 & 0.025 \\ 0.012 & 0.020 & 0.030 & 0.018 & 0.008 \\ 0.006 & 0.010 & 0.015 & 0.009 & 0.004 \end{bmatrix}$$

Step 4: Calculate risk membership $L_{(R_{74})}$ according to Table 5.

$$R_{l1 \cdot R_{74}} = 0.025 + 0.008 + 0.015 + 0.009 + 0.004 = 0.061$$
$$R_{l2 \cdot R_{74}} = 0.019 + 0.032 + 0.018 + 0.006 + 0.010 = 0.085$$
$$R_{l3 \cdot R_{74}} = 0.076 + 0.097 + 0.060 + 0.020 + 0.030 = 0.085$$
$$R_{l4 \cdot R_{74}} = 0.075 + 0.046 + 0.124 + 0.038 + 0.066 + 0.012 = 0.359$$
$$R_{l5 \cdot R_{74}} = 0.029 + 0.051 + 0.048 + 0.084 = 0.211$$

The risk membership of structural damage is:

$$L_{R_{74}} = [0.061, 0.085, 0.283, 0.359, 0.211]$$

Step 5: Calculate the final fuzzy risk value.

$$L_{R_{74}} \times J = [0.061, 0.085, 0.283, 0.359, 0.211] \times [10, 30, 50, 70, 90]$$
$$N_{R_{74}} = 61.494$$

Therefore, $N_{R_{74}} = 61.494 \in [60, 80)$ belongs to a 4-level risk.

3 Risk Identification of Underground Comprehensive Pipe Gallery Project in Q City

The underground comprehensive pipe gallery project of Q High-speed Railway New City extends east to Jinxi Avenue, west to Shihua Line, north to Ke'an Third Road, south to Changshan River and National Highway 320. The engineering layout of the project mainly includes the underground comprehensive pipe galleries of the new Minjiang Avenue, Qianjiang Avenue, Qinjiang West Road, Mount Sanqing Avenue and Chuangzhi Road, with a total length of about 14.6 km.

The general contractor for this project was determined through open bidding in 2020 as a consortium consisting of China Railway Fourth Bureau Co., Ltd. and East China Survey and Design Institute Co., Ltd. of China Power Construction Group. The contract period is 610 days, and the project started in November 2020 and was completed and accepted on June 15, 2022.

3.1 Delphi Method Risk Identification Results

3.1.1 Basic information of experts

We carried out the Delphi method for the initial risk system, carried out expert consultation, revision and simplification of the index system. The new index system was confirmed by issuing questionnaires to experts. At this stage, seven experts who have been engaged in the construction industry for many years were invited to participate in the consultation work, as shown in Table 6.

Table 6. Composition of experts

Basic Information		Number of People	Percentage
	Engineer	1	0.14
	Construction worker	2	0.29
Career	Scientific researchers	1	0.14
	Safety Officer	1	0.14
	Inspector	2	0.14
	More than 8 years	3	0.43
Length of work	5–8 years	3	0.43
	2–5 years	1	0.14
	Specialist	2	0.29
Educational background	Undergraduate course	4	0.57
	Master	1	0.14

We invited 7 professionals in the fields of design, construction and O&M. Among them, there are 6 professionals with more than five years' experience and 3 professionals with more than eight years' experience. They have participated in many engineering projects, such as the construction of a subway in Fujian and the construction of a tunnel project in Fujian. Their professional knowledge and rich practical experience make the research results more reliable and authentic.

3.1.2 Expert authority coefficient results

Table 7. Expert authority coefficient results

	Judgment Coefficient	Familiarity	Authority Coefficient
Environmental risk	0.79	0.86	0.82
Design risk	0.85	0.83	0.84
Construction risk	0.73	0.87	0.80
Social risk	0.80	0.78	0.79
Intelligent O&M risk	0.78	0.75	0.77
Management risk	0.82	0.86	0.84
Operation risk	0.88	0.80	0.84

Table 8. Project risk index system table for this study

First Level Indicator	Second Level Indicator
Environmental risk (R_1)	Natural disaster (R_{11})
	Hydrogeology (R_{12})
	Poor construction environment (R_{13})
Design risk (R_2)	Survey geological risk (R_{21})
	Poor feasibility of the design and planning scheme (R_{22})
	Unreasonable waterproof and fireproof design (R_{23})
Construction risk (R_3)	Inadequate inspection and maintenance of materials and equipment (R_{31})
	Construction progress risk (R_{32})
	Inaccurate alignment of the utility tunnel splicing (R_{33})
Social risk (R_4)	Government's financial affordability (R_{41})
	Legal and policy risks (R_{42})
	Project financing risk (R_{43})
Intelligent O&M risk (R_5)	O&M cost risk (R_{51})
	Accuracy rate risk of monitoring equipment (R_{52})
	Failure of intelligent decision-making (R_{53})
	Data security issues (R_{54})
Management risk (R_6)	Poor experience level of technical management personnel (R_{61})
	The rights, responsibilities, interests of the contract are not clear (R_{62})
	HSE risk (R_{63})
Operation risk (R_7)	Human risk (R_{71})
	Risk of fire and drainage equipment failure (R_{72})
	Damage to internal pipelines (R_{73})
	Structural damage (R_{74})

According to Eq. (1), the expert authority coefficient is shown in Table 7. The results of the expert authority coefficient show that experts' familiarity with the seven first-class indicators is basically between very familiar and familiar, and the influence of judgment based on experts is between medium and large, and the average value of the authority coefficient is higher than 0.8, indicating that the experts selected in the study have high authority.

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3.1.3 Index determination

Through two rounds of expert scoring and consultation, the risk index system of this study was finally determined, as shown in Table 8. Their professional knowledge and rich practical experience make the research results more reliable and authentic.

3.2 Application of AHP

After identifying and analyzing the risks of the underground pipe gallery project in Q city, a hierarchical analysis model is established to classify and analyze the risk categories and factors. The AHP has good applicability and a wide range of applications, and can calculate the influence weights between levels.

The core of AHP is to construct a judgment matrix, and obtain various data of the judgment matrix based on the filling results of each expert.

Comparison results of primary risk category indicators:

$$A_0 = \begin{bmatrix} 1 & 0.227 & 0.239 & 0.844 & 0.555 & 0.577 & 0.481 \\ 4.407 & 1 & 0.569 & 0.577 & 2.625 & 1.631 & 0.325 \\ 4.190 & 1.756 & 1 & 0.791 & 2.500 & 0.824 & 0.515 \\ 1.185 & 1.732 & 1.265 & 1 & 0.643 & 0.457 & 0.326 \\ 1.803 & 0.381 & 0.400 & 1.556 & 1 & 0.295 & 0.487 \\ 1.733 & 0.613 & 1.213 & 2.190 & 3.390 & 1 & 0.369 \\ 2.079 & 3.074 & 1.941 & 3.067 & 2.052 & 2.709 & 1 \end{bmatrix}$$

Comparison results related to environmental risk factors:

$$A_1 = \begin{bmatrix} 1 & 0.365 & 0.516 \\ 2.741 & 1 & 0.568 \\ 1.937 & 1.762 & 1 \end{bmatrix}$$

Comparison results related to design risk factors:

$$A_2 = \begin{bmatrix} 1 & 0.918 & 0.415 \\ 1.089 & 1 & 0.931 \\ 2.407 & 1.074 & 1 \end{bmatrix}$$

Comparison results related to construction risk factors:

$$A_3 = \begin{bmatrix} 1 & 0.364 & 0.479 \\ 2.746 & 1 & 0.762 \\ 2.089 & 1.313 & 1 \end{bmatrix}$$

Comparative results related to social risk factors:

$$A_4 = \begin{bmatrix} 1 & 0.570 & 0.326 \\ 1.756 & 1 & 0.482 \\ 3.067 & 2.074 & 1 \end{bmatrix}$$

Comparison results related to risk factors in smart O&M:

$$A_5 = \begin{bmatrix} 1 & 0.482 & 0.574 & 0.515 \\ 2.074 & 1 & 0.727 & 0.508 \\ 1.741 & 1.376 & 1 & 0.259 \\ 1.941 & 1.968 & 3.857 & 1 \end{bmatrix}$$

Comparison results related to managing risk factors:

$$A_6 = \begin{bmatrix} 1 & 0.711 & 0.514 \\ 1.407 & 1 & 0.439 \\ 1.946 & 2.279 & 1 \end{bmatrix}$$

Comparison results related to operational risk factors:

$$A_7 = \begin{bmatrix} 1 & 0.368 & 0.895 & 0.524 \\ 2.710 & 1 & 0.901 & 0.324 \\ 1.117 & 1.110 & 1 & 0.626 \\ 1.909 & 3.089 & 1.598 & 1 \end{bmatrix}$$

Calculate the weight values of each indicator in the judgment matrix A_0–A_7 and perform consistency tests on the indicators. The calculation results are shown in Tables 9, 10, 11, 12, 13, 14, 15, and 16, respectively:

Table 9. Consistency test and weight results of matrix A_0

R_1	R_2	R_3	R_4	R_5	R_6	R_7
6.64%	14.89%	16.26%	10.92%	8.94%	15.45%	26.91%
$\lambda_{\mathbf{max}}$	CI	CR				
7.771	0.129	0.095				

After calculation, the CR of A_0 is $0.095 < 0.1$, and the consistency test has passed.

Table 10. Consistency test and weight results of matrix A_1

R_{11}	R_{12}	R_{13}
18.02%	35.83%	46.15%
$\lambda_{\mathbf{max}}$	CI	CR
3.094	0.047	0.090

After calculation, the CR of A_1 is $0.090 < 0.1$, and the consistency test has passed.

Table 11. Consistency test and weight results of matrix A_2

R_{21}	R_{22}	R_{23}
23.54%	32.44%	44.02%
$\lambda_{\mathbf{max}}$	CI	CR
3.058	0.029	0.056

After calculation, the CR of A_2 is $0.056 < 0.1$, and the consistency test has passed.

Table 12. Consistency test and weight results of matrix A_3

R_{31}	R_{32}	R_{33}
17.37%	39.47%	43.16%
$\lambda_{\mathbf{max}}$	CI	CR
3.033	0.017	0.032

After calculation, the CR of A_3 is $0.032 < 0.1$, and the consistency test has passed.

Table 13. Consistency test and weight results of matrix A_4

R_{41}	R_{42}	R_{43}
16.95%	28.09%	54.97%
$\lambda_{\mathbf{max}}$	CI	CR
3.003	0.002	0.003

After calculation, the CR of A_4 is $0.003 < 0.1$, and the consistency test has passed.

Table 14. Consistency test and weight results of matrix A_5

R_{51}	R_{52}	R_{53}	R_{54}
14.17%	21.37%	20.47%	43.99%
λ_{max}	CI	CR	
4.212	0.071	0.079	

After calculation, the CR of A_5 is $0.079 < 0.1$, and the consistency test has passed.

Table 15. Consistency test and weight results of matrix A_6

R_{61}	R_{62}	R_{63}
22.37%	26.62%	51.01%
λ_{max}	CI	CR
3.028	0.014	0.027

After calculation, the CR of A_6 is $0.027 < 0.1$, and the consistency test has passed.

Table 16. Consistency test and weight results of matrix A_7

R_{71}	R_{72}	R_{73}	R_{74}
15.75%	22.97%	21.14%	40.15%
λ_{max}	CI	CR	
4.229	0.076	0.086	

After calculation, the CR of A_7 is $0.086 < 0.1$, and the consistency test has passed. The weight ranking of primary indicators is shown in Table 17.

Table 17. Ranking of first level indicator weights

Serial Number	First-Level Indicator	Weight
1	Operation risk	26.91%
2	Construction risk	16.26%
3	Management risk	15.45%
4	Design risk	14.89%
5	Social risk	10.92%
6	Intelligent O&M risk	8.94%
7	Environmental risk	6.64%

As can be seen from Table 17, the weight of operation risk is the highest, accounting for 26.91%, indicating that the operation link plays a very important role in the success of the underground utility tunnel project. Construction risk, management risk and design risk are also relatively important. While the weights of intelligent O&M risk and environmental risk are relatively low, as decision-makers, their roles cannot be ignored either. These weights can provide decision-making guidance for the project.

The weight ranking of secondary indicators is shown in Table 18.

The results show that the overall weight of the structural damage risk exceeds 10%, indicating that the project manager needs to strictly control the structural quality of the project during the construction period and conduct regular inspections and maintenance in the later stage to ensure the structural stability of the utility tunnel; while the risks of HSE risk and inaccurate alignment of the utility tunnel exceed 7%, indicating that the project decision-makers need to pay attention to the HSE indicators during construction to ensure the health, safety of employees and a

good environment. Although the impact ratios of the risks of monitoring equipment accuracy, government financial affordability, intelligent decision-making failure, O&M cost, and natural disaster risks are the lowest, all lower than 2%, the project decision-makers still need to pay attention to these indicators.

Table 18. Weight ranking of secondary indicators

Serial Number	Secondary Indicator	Overall Weight
1	Structural damage	10.80%
2	HSE risk	7.88%
3	Inaccurate alignment of pipe gallery splicing	7.02%
4	Unreasonable waterproof and fireproof design	6.55%
5	Construction progress risk	6.42%
6	Risk of fire protection and drainage equipment failure	6.18%
7	Project financing risk	6.00%
8	Damage to internal pipelines	5.69%
9	Poor feasibility of design and planning scheme	4.83%
10	Human risk	4.24%
11	Unclear rights, responsibilities and interests in the contract	4.11%
12	Data security issues	3.94%
13	Survey geological risk	3.51%
14	The experience and level of technical management personnel are poor	3.46%
15	Legal and policy risks	3.07%
16	Poor construction environment	3.06%
17	The inspection and maintenance of materials and equipment are not in place	2.82%
18	Hydrogeology	2.38%
19	Risk of inaccurate monitoring equipment	1.91%
20	The government's financial affordability	1.85%
21	Intelligent decision-making failure	1.83%
22	O&M cost risk	1.27%
23	Natural disasters	1.20%

3.3 Fuzzy Evaluation of Risk Factors

3.3.1 Membership matrix

To ensure the authenticity and credibility of the data, employees in the field of construction were invited to evaluate the probability of occurrence (P) and the consequences (S) of various risk factors of the underground pipe gallery project in Q city through the network. 91 questionnaires were effectively recovered. According to the results of questionnaire collection, the data are normalized and the membership matrix of risk factor occurrence probability (P) and consequence (S) is established, as shown in Table 19 and Table 20.

Table 19. Membership matrix of occurrence probability of each risk factor

Risk \ Probability	Highest	Higher	Medium	Lower	Lowest
R_{11}	0.110	0.308	0.286	0.209	0.088
R_{12}	0.231	0.253	0.264	0.209	0.044
R_{13}	0.264	0.253	0.275	0.143	0.066
R_{21}	0.209	0.385	0.242	0.121	0.044
R_{22}	0.209	0.308	0.275	0.143	0.066
R_{23}	0.286	0.286	0.253	0.110	0.066
R_{31}	0.330	0.231	0.242	0.132	0.066
R_{32}	0.165	0.264	0.396	0.121	0.055
R_{33}	0.198	0.297	0.385	0.099	0.022
R_{41}	0.194	0.308	0.330	0.165	0.022
R_{42}	0.176	0.374	0.253	0.154	0.044
R_{43}	0.242	0.308	0.209	0.154	0.088
R_{51}	0.187	0.253	0.396	0.132	0.033
R_{52}	0.198	0.330	0.286	0.132	0.055
R_{53}	0.176	0.352	0.275	0.176	0.022
R_{54}	0.198	0.352	0.319	0.110	0.022
R_{61}	0.242	0.297	0.308	0.154	0.000
R_{62}	0.231	0.275	0.385	0.088	0.022
R_{63}	0.213	0.308	0.297	0.121	0.088
R_{71}	0.220	0.308	0.319	0.132	0.022
R_{72}	0.226	0.253	0.319	0.198	0.022
R_{73}	0.176	0.319	0.308	0.143	0.055
R_{74}	0.220	0.363	0.286	0.088	0.044

Table 20. Consequences caused by risk factors S membership matrix

Risk \ Consequences	Tragedy	Serious	Medium	Slight	Negligible
R_{11}	0.099	0.154	0.374	0.264	0.110
R_{12}	0.055	0.275	0.286	0.297	0.088
R_{13}	0.110	0.165	0.418	0.242	0.066
R_{21}	0.209	0.220	0.385	0.176	0.110
R_{22}	0.044	0.209	0.385	0.275	0.088
R_{23}	0.077	0.209	0.297	0.330	0.088
R_{31}	0.121	0.187	0.396	0.176	0.121
R_{32}	0.088	0.275	0.341	0.198	0.099
R_{33}	0.121	0.220	0.319	0.253	0.088
R_{41}	0.077	0.198	0.330	0.319	0.077
R_{42}	0.099	0.209	0.363	0.220	0.110
R_{43}	0.088	0.176	0.429	0.209	0.099
R_{51}	0.132	0.220	0.330	0.264	0.055
R_{52}	0.088	0.187	0.297	0.297	0.132
R_{53}	0.110	0.176	0.330	0.231	0.154
R_{54}	0.121	0.253	0.297	0.209	0.121
R_{61}	0.066	0.242	0.319	0.297	0.077
R_{62}	0.099	0.253	0.275	0.286	0.088
R_{63}	0.132	0.209	0.286	0.275	0.099
R_{71}	0.110	0.209	0.297	0.352	0.033
R_{72}	0.121	0.242	0.275	0.297	0.066
R_{73}	0.099	0.275	0.374	0.220	0.033
R_{74}	0.132	0.231	0.341	0.209	0.088

3.3.2 Fuzzy evaluation calculation of risk factors

Calculation shows that the fuzzy evaluation risk value of the surveyed geological risk is the highest, followed by structural damage and human risk; the fuzzy evaluation risk value of natural disasters is the lowest. At the same time, among the 23 risk factors, 8 factors are of level 4 risk, that is, relatively high risk, and 15 factors are of level 3 risk, that is, medium risk. The results are shown in Table 21.

Table 21. Fuzzy risk value table of each risk factor

Risk Factors	Fuzzy Risk Value	Risk Level	Risk Ranking
R_{11}	52.514	Third level	23
R_{12}	57.258	Third level	18
R_{13}	58.340	Third level	14
R_{21}	68.115	Fourth level	1
R_{22}	56.391	Third level	20
R_{23}	58.154	Third level	16
R_{31}	58.441	Third level	13
R_{32}	57.702	Third level	17
R_{33}	59.950	Third level	9
R_{41}	58.896	Third level	11
R_{42}	58.221	Third level	15
R_{43}	56.671	Third level	19
R_{51}	59.772	Third level	10
R_{52}	55.630	Third level	22
R_{53}	56.313	Third level	21
R_{54}	60.371	Fourth level	7
R_{61}	60.429	Fourth level	6
R_{62}	60.308	Fourth level	8
R_{63}	58.610	Third level	12
R_{71}	61.112	Fourth level	3
R_{72}	60.665	Fourth level	5
R_{73}	61.105	Fourth level	4
R_{74}	61.494	Fourth level	2

According to Eq. (11), the fuzzy risk value of the first-level index can be calculated, where L is the weight of each factor within the layer, and J is the fuzzy risk value of each factor. The fuzzy risk value of the first-level index is shown in Table 22.

Table 22. Fuzzy risk value table of first-level risk index

Risk Factor	Fuzzy Risk Value	Risk Level	Risk Ranking
R_1	55.948	Third level	7
R_2	61.129	Fourth level	1
R_3	58.502	Third level	4
R_4	58.043	Third level	5
R_5	57.870	Third level	6
R_6	59.946	Third level	3
R_7	61.045	Fourth level	2

Calculation shows that the fuzzy risk value of the design risk is the highest, followed by the operation risk, both of which are level-four risks, that is, relatively high risks; while the fuzzy risk value of the environmental risk is the lowest, which is a level-three risk, that is, a medium risk; the remaining four first-level risk indicators are also medium risks.

Further calculate the overall risk of the project, and the calculation results are shown in Table 23.

Table 23. Overall project risk table

Risk Classification	Risk Factor	Fuzzy Risk Value		Overall Weight		Weighted Risk Value		Risk Ranking	
	R_{11}		52.514		0.012		0.630		23
R_1	R_{12}	55.948	57.258	0.0664	0.024	3.778	1.363	7	18
	R_{13}		58.340		0.031		1.785		16
	R_{21}		68.115		0.035		2.391		12
R_2	R_{22}	61.129	56.391	0.1498	0.048	8.923	2.724	4	9
	R_{23}		58.154		0.066		3.809		4
	R_{31}		58.441		0.028		1.648		17
R_3	R_{32}	58.502	57.702	0.1626	0.064	9.561	3.704	2	6
	R_{33}		59.950		0.070		4.209		3
	R_{41}		58.896		0.019		1.090		19
R_4	R_{42}	58.043	58.221	0.1092	0.031	6.278	1.787	5	15
	R_{43}		56.671		0.060		3.400		8
	R_{51}		59.772		0.013		0.759		22
R_5	R_{52}	57.870	55.630	0.0894	0.019	5.225	1.063	6	20
	R_{53}		56.313		0.018		1.031		21
	R_{54}		60.371		0.039		2.379		13
	R_{61}		60.429		0.035		2.091		14
R_6	R_{62}	59.946	60.308	0.1545	0.041	9.188	2.479	3	11
	R_{63}		58.610		0.079		4.618		2
	R_{71}		61.112		0.042		2.591		10
R_7	R_{72}	61.045	60.665	0.2691	0.062	16.460	3.749	1	5
	R_{73}		61.105		0.057		3.477		7
	R_{74}		61.494		0.108		6.641		1
Overall risk value									59.413

The calculated overall fuzzy risk value of the underground utility tunnel project in Q City is $59.413 \in [40, 60)$, which belongs to a risk level above medium and is close to a relatively high risk. The project party should attach importance to project risks and formulate corresponding plans to deal with the occurrence of risks.

4 Results and Discussion

4.1 Analysis of First-Level Risk Indicators

Figure 1 and Figure 2 are respectively the radar chart of risk values after weighting of first-level indicators and the radar chart of overall weights of first-level indicators. The changing trends presented by the two radar charts are basically the same, indicating that the importance of indicators determined by the AHP has a greater impact on the final risk value. As can be seen from Figure 1, the risk value of operation risk is the highest, and decision-makers need to focus on it. Followed by construction risk and management risk; the risk values of intelligent operation risk and environmental risk are relatively low, indicating that their impact on the overall risk is limited and belongs to the controllable range; the risk values of the remaining design risk and social risk are in the middle position.
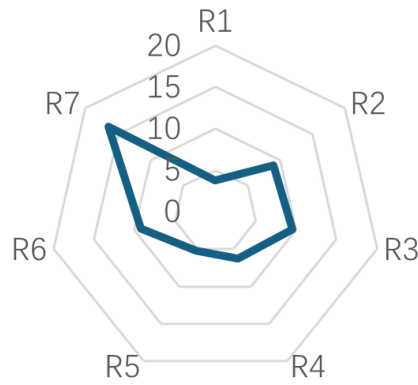
Figure 1. Radar chart of risk values after weighting of first-level indicators
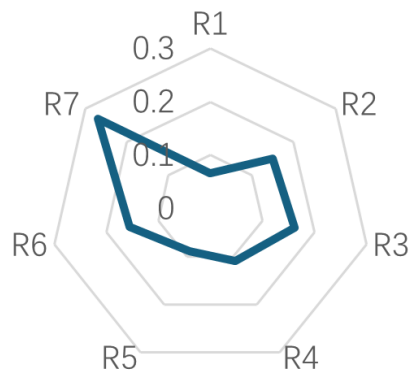

Figure 2. Radar chart of overall weights of first-level indicators

(1) Reasons for high operational risk value

The expert rating shows that the operational risk weight and fuzzy risk value are both the highest, belonging to the 4-level risk. The risks mainly come from equipment failures, human errors, and environmental factors. Underground equipment is exposed to high humidity and corrosive environments, making it prone to aging; 35% of accidents are caused by illegal operations, involving a large number of temporary workers and insufficient training; the lower-than-expected actual returns have also compressed safety investment, resulting in a higher overall operational risk value.

(2) Reasons for high construction risk value

The weight of "inaccurate positioning of pipe gallery splicing" in construction risks is high, which increases the overall risk value. When multiple sections are constructed in parallel, the disconnection between BIM models and schedules can easily lead to collisions and delays; construction quality issues are often caused by non-standard design, execution, material management, and personnel operations, increasing risks.

(3) Reasons for high management risk value

The project operations in Q city are complex and require reasonable arrangement of cross construction to avoid resource conflicts; Contract management involves multi-party coordination, which can easily lead to unclear rights and responsibilities; The HSE risk in the cross-operation area is high, and the emergency response is lagging behind. In addition, during the epidemic control period, the management difficulty is further exacerbated.

(4) The reasons for the low-risk values of intelligent O&M and environmental risks

Due to the low fuzzy values and indicator weights, the weighted risk value is low. In terms of intelligent O&M, the project is implemented by experienced Shujian Technology. The platform integrates GIS, BIM, IoT and other technologies, equipped with a complete set of monitoring equipment and systems, to achieve 24/7 intelligent supervision and reduce O&M risks. In terms of environment, Q city has stable geology, and a comprehensive environmental impact assessment was conducted before construction. Pollution control and ecological protection

measures were strictly implemented, resulting in minimal construction interference and overall low environmental risks.

4.2 Secondary Risk Index Analysis

The weighted risk values and overall weights of the secondary risk indicators are shown in Figure 3 and Figure 4, respectively. The distribution states of the weights occupied by the risk indicators and the weighted risk values are basically the same, indicating that the size of the weighted risk value is highly related to the weight size determined by the AHP. After weighting, the risk value of the structural damage risk is the highest, followed by the risk and the risk of the corridor splicing and positioning. The above risk indicators not only rank high in terms of weight but also show a relatively high level in the fuzzy risk evaluation value. And the natural disaster risk and the O&M cost risk are relatively small, and the risk values of other risk factors are in the middle.
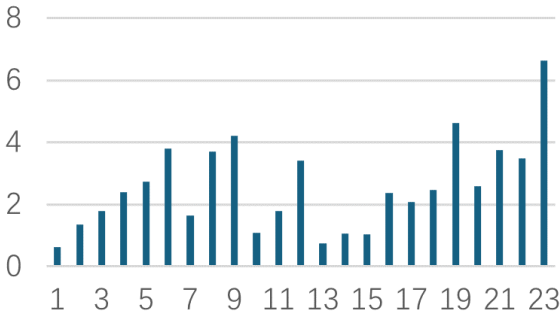
Figure 3. Weighted risk values of secondary indicators
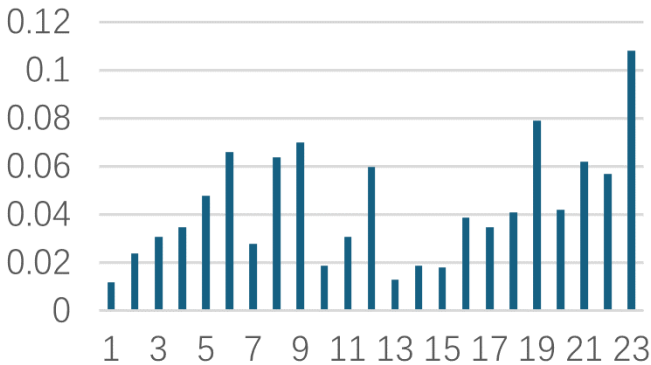
Figure 4. Overall weights of secondary indicators

(1) The reason for the high-risk value of structural damage

The risk of structural damage is mainly affected by internal defects and external loads. The concrete structure is in the environment of underground moisture and acid-base erosion for a long time, which makes it prone to chemical erosion. At the same time, the reinforced structure is also prone to corrosion, which will accelerate the risk of structural stiffness degradation. The external loads mainly include the dead weight of the covering soil, the ground traffic load, and the internal pipeline load. Due to the uneven geological conditions, the fluctuation of groundwater level or the disturbance of surrounding foundation pit excavation, the differential deformation of the foundation may be caused, resulting in structural damage.

The project has a total length of 14.6 kilometers and involves multiple structural forms with significant geological differences, which can easily cause structural deformation. Quality control is difficult in EPC mode, and cast-in-place concrete is prone to cracking and waterproofing failure. The entrance rate is only 28.63%, and the unused space causes stress concentration. As a long-term municipal infrastructure, once the structure of the pipe galleries is damaged, it will seriously affect the operation of the city and have significant consequences.

In addition to paying attention to the risk of structural damage in the operation stage, as a project-related party, it should also pay attention to the risk in the whole life cycle of the project to reduce the possibility and consequences

of the risk. In the construction stage, improper formwork erection, insufficient concrete vibration and poor joint treatment will form initial defects, laying hidden dangers for later damage; in the O&M stage, inadequate patrol inspection and insufficient maintenance of the alarm system may lead to the delayed discovery of problems such as ponding and corrosive gas leakage, which may evolve into safety accidents or equipment damage events.

(2) Reasons for high HSE risk value

HSE risks are driven by three factors—organizational management capabilities, execution capabilities, and personnel behavior—forming a chain reaction mechanism. The project execution process involves numerous uncertainties, leading to deviations from established protocols, such as unclear responsibilities, insufficient supervision, and missing records, which contribute to continuous risk accumulation. Additionally, due to the confined, elongated space within utility tunnels and the enclosed environment, high demands are placed on workers' adherence to behavioral standards and emergency response capabilities. Failure to correctly identify and address risks can easily trigger hazardous incidents. Moreover, the complex and dynamic nature of construction environments, coupled with the impact of leakage, water level fluctuations, and gas accumulation on the internal conditions of utility tunnels, can transform potential environmental risks into accident scenarios if monitoring and alarm systems are inadequate or if management responses are delayed.

Under the EPC mode, subcontractors have insufficient safety investment and have experienced major safety accidents. During the epidemic, construction was hindered, and health and environmental safety were affected. The multi-departmental collaboration mechanism is not perfect. Although the "Q City Management Measures for Pipe Corridors" clearly define responsibilities, the cost management and dynamic response mechanism still need to be strengthened.

In addition, HSE risks will have different impacts on different stages of the project. During the construction phase, limited space operations, inadequate ventilation, and lax management of welding operations can increase the risks of fire, poisoning, and falling. During the operation phase, inadequate inspections and inadequate maintenance of alarm systems may result in delayed detection of issues such as water accumulation and corrosive gas leaks, which could escalate into safety accidents or equipment damage incidents.

(3) The reason for the high-risk value of inaccurate alignment of the utility tunnel splicing

The process of pipe gallery splicing often involves component hoisting, alignment, temporary support, and joint construction, and its risks are mainly determined by construction accuracy, stress state, and process conversion. Pipe gallery components are generally large in size and heavy in weight. If the lifting points are improperly arranged or disturbed by wind and vibration, they are prone to swinging and displacement, affecting the positioning accuracy and even causing damage to the components. And due to limited space on the construction site, possible slight deformation of the foundation, and equipment accuracy limitations, the difficulty of alignment is relatively high. Considering the reliance on temporary support structures to control the position and stability of components during the splicing process. If the supporting bearing capacity or arrangement is not reasonable, displacement may occur during unloading and rotation, causing displacement and structural damage.

There are many splicing sections in the project, and the splicing technology requirements for the three-cabin structure are high. The foundation boundary area is prone to uneven settlement, and the conversion section is prone to misalignment. The project is divided into six sections, each using different splicing techniques, with poor interface compatibility, which increases the difficulty of construction and coordination.

The risk of pipe gallery splicing during the construction phase will affect the overall integrity of the structure and also affect the later operation phase. The quality problems of pipe gallery joints will expand under long-term loads and environmental effects, leading to structural cracks, water leakage, or abnormal stress on auxiliary pipelines. This also increases the difficulty of repairing joints in the later stage, and often only local reinforcement methods can be adopted, which cannot completely eliminate the cumulative impact of initial deviations. Therefore, the risk value of this risk is relatively high.

(4) The reason for the low-risk value of O&M costs

The project introduces a professional company to integrate O&M data using BIM, and optimizes cost control by combining it with a full lifecycle model. The asset management system can predict the replacement cycle of spare parts, reduce inventory, and improve resource allocation efficiency, so the risk is relatively low.

(5) The reason for the low-risk value of natural disasters

Q city has stable geology, no active fault zones, and few typhoons and floods. The weight of natural disaster indicators is low, and dynamic monitoring and early warning systems can timely identify risks, such as slope stability prediction models to further reduce the risk of landslides and debris flows.

4.3 Overall Risk Analysis

The overall weighted risk value of the project belongs to the medium risk category. The main sources are construction risks and operation risks, and the operation risk accounts for a relatively large proportion, especially the risk value of structural damage. Decision-makers should strengthen their attention to the operation stage of the

utility tunnel, consider the O&M requirements in advance, and take into account factors such as structural safety, maintenance convenience, and equipment operation environment during the construction process.

5 Conclusions

We introduce the project overview of the underground pipe gallery project in Q city. Through the previous risk identification and analysis of the underground engineering project, the risk factors of the urban underground pipe gallery project are preliminarily sorted out. Using the Delphi method and two rounds of amendments by experts, 7 risk categories and 23 risk factors of the project are determined. The comprehensive weight of engineering risk is determined by questionnaire survey, AHP and fuzzy evaluation method. We normalized the data and processed the membership, and finally concluded that the comprehensive risk of the underground comprehensive pipe gallery project in Q city was medium to high risk. The high-risk categories are operation risk and construction risk, and the high-risk factors are structural damage risk and HSE risk. Countermeasures are proposed according to each index.

We show that in the risk management and control of the underground pipe gallery project, although the environmental, design, social factors, intelligent O&M and management-related risks cannot be ignored, the risks in the construction and operation stages should be paid more attention by the decision-makers. In the actual construction process, special attention should be paid to the overall stability of the pipe gallery structure to reduce the possibility of damage to internal components; in the later stage of operation, we should also continue to strengthen the monitoring of structural status to prevent the accumulation of potential hazards. In addition, decision-makers should further improve the level of construction management, improve the construction organization system, strengthen HSE management and safety control at the operation site, and ensure the institutionalization and standardization of construction and decision-making implementation, so as to improve the overall safety and reliability of the project.

We not only help to clarify the key risk points of the underground pipe gallery project in different stages, but also provide more targeted management guidance for relevant governance subjects. By emphasizing the importance of the construction and operation stages, decision makers can form a more focused decision orientation in resource allocation, management system improvement and security mechanism construction, so as to improve the effectiveness of risk prevention and control.

We also have a certain promotion value, which can provide a reference for the risk identification and management of other similar infrastructure projects, and help to further improve the overall safety level and operation reliability of urban underground space construction. For example, the construction of Xi'an underground comprehensive pipe gallery pays great attention to the anti-cracking technology and later maintenance because of the wide occurrence of ground fissure geological disasters. At the same time, more and more underground pipe gallery projects reduce the risk probability by using digital technology. For example, the construction and development group promote the intelligent and digital construction of the comprehensive pipe galleries in Shenzhen, and creates the intelligent construction O&M based on BIM + GIS.

Therefore, the conclusion of this study is not only practical, but also in line with the development trend of the times. We take smart O&M into consideration of the first-class risk indicators, which conforms to the trend of development in the field of engineering construction in the era of big data. However, the use of digital technology still has problems such as data security, equipment failure, and smart decision-making failure. This also provides a new perspective for the risk assessment system of urban underground comprehensive pipe galleries in the future, and promotes the development of smart cities.

Although the study has achieved some results, there are still some limitations. (1) Limitations of sample sources. The sample size of this study is relatively limited, and mainly from the southeast coastal area. Although the distribution is consistent with the geographical characteristics of Q City, it limits the applicability of the research conclusions in similar projects in other regions to a certain extent, which is not conducive to a broader risk comparison and analysis. (2) The limitation of the Delphi method. The Delphi method used in the research process largely relies on expert judgment, which makes it difficult to completely avoid subjectivity, which may affect the objectivity and robustness of risk identification and index determination. (3) Future research prospects. In view of the strong subjectivity of the Delphi method, the follow-up study can consider introducing large model analysis and building a data-driven big data prediction model through the training of a large number of engineering cases, so as to improve the objectivity and accuracy of risk identification. At the same time, cross-regional comparative studies of projects in different regions can be carried out to identify common risks and regional-specific risks of engineering projects, and help managers formulate more targeted construction and management strategies in different regions, so as to break through the limitations of risk identification in regions and project types.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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