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Research Article

Quality Risk Evaluation of Urban Rail Transit Construction Based on AHP–FCE Method

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The demand for urban transport is increasing globally, and urban rail transit is an important infrastructure for meeting this demand. The objectives of this study were to effectively control and prevent all types of risks in the construction of metro projects and improve the quality and safety control of urban metro project construction. First, 20 index factors were selected from the five dimensions of "man–machinery–materials–methods–environment" and constructed an index system for assessing urban metro construction quality risks. Second, the analytic hierarchy process (AHP) and fuzzy comprehensive evaluation (FCE) methods were used to comprehensively evaluate the construction quality risks of subway projects, and the weights of the secondary indices were determined. Finally, the importance of secondary indicators was evaluated using the integrated AHP–FCE method, and the model was applied to engineering practice for validation. The results indicated that the comprehensive AHP–FCE method has good adaptability and rationality and has practical application value for metro project construction quality and safety risk assessment. It can help prevent urban metro construction quality accidents and provides a novel idea for metro project construction quality risk assessment.

1. Introduction

With continuous urbanization throughout the world, the number of cities is gradually increasing, urban space is expanding, and the demand for urban transport is rising. Thus, urban rail transit is an important infrastructure that provides an effective solution for daily urban transport [1]. Since the world's first underground was constructed and put into operation in London in 1863 [2, 3], many large cities have accelerated the construction of similar efficient, safe, low-carbon, and sustainable infrastructure, which is expected to alleviate traffic congestion, reduce air pollution, and promote sustainable urban development. As of December 2022, 545 cities in 78 countries and regions around the world had urban rail transit, with a total mileage of >41,386.12 km. China (including Hong Kong, Macao, and Taiwan) had 61 cities with rail transit, corresponding to a total operating mileage of 10,857.17 km, which ranked first in the world and accounted for 26.2% of the global total mileage, while Germany, Russia, the United States, and Ukraine ranked 2nd to 5th, respectively [4]. Urban rail transit systems are a public good that has become an integral part of urban transport and will be increasingly used globally [5, 6].

Urban rail transport plays an important role in guiding the rational development of the spatial structure of cities, coordinating social resources, and improving people's lives, and it is an important way to solve the problem of urban traffic congestion [7]. However, most metro construction is underground, with a closed construction space and complex building structures and construction environments, often in densely populated areas. Thus, the occurrence of uncertain disaster events such as floods, fires, equipment failures, and other quality hazards during the construction process can lead to safety accidents and cause a social amplification effect [8, 9]. On January 12, 2007, seven people died as a direct result of a collapse at the construction site of Pinheiros station on yellow line 4 in São Paulo, Brazil [10]. On August 23, 2012, flooding during the construction of an underground tunnel in Warsaw, Poland, brought the city's traffic to a standstill [11]. In China, construction quality and safety accidents occur frequently during metro construction. On July 1, 2003, leakage in the tunnel liaison channel of Shanghai Metro Line 4 caused significant ground settlement and damage to several buildings, directly resulting in economic losses of RMB 150 million [12]. On February 5, 2007, an EBP shield construction accident occurred during the construction of Nanjing Metro Line 2, resulting in extensive subsidence and settlement on the road above the tunnel, which led to water, gas, and electricity outages for 2 days and caused considerable inconvenience to 5,400 residents [13]. On January 2, 2015, a combustible gas explosion occurred during the underground construction of Wuhan Metro Line 3, resulting in the death of two people [14]. Therefore, to promote the safe, rapid, and stable development of urban rail transit systems, it is necessary to effectively perform risk management in the construction phase of which risk assessment is an indispensable part [15]. The risk assessment of urban rail transit construction projects must be considered with regard to five aspects—construction man, machinery, materials, methods, and environment—to comprehensively sort the factors affecting the construction quality in the construction process; develop a practical, efficient, and systematic urban rail transit construction quality risk assessment system; implement risk prevention and control measures according to the assessment results; reduce the risk of loss; and ensure the smooth advancement of urban rail transit construction projects.

Scholars worldwide have conducted extensive research on risk assessment of urban rail transit construction and have made significant progress. Zhou et al. [16] identified metro construction collapse patterns with regard to scenarios, consequences, and causality and developed safety strategies and valuable countermeasures for metro construction practices to avoid varying degrees of quality risk in metro construction. Wu et al. [17] developed a risk assessment and safety decision-making methodology that can provide guidance for dynamic safety analyses of tunnel-induced pavement damage over time. Yan et al. [15] combined vague set and object-element theory to develop a vague fuzzy object-element model for risk assessment; the practicality and effectiveness of the model were verified through examples. Wu et al. [18] developed an intelligent monitoring system platform for urban rail transit project construction to realize project site monitoring and dynamic early warning management of sources of risk. Li et al. [19] proposed a BIM platform-based metro construction safety risk identification and early warning systems. Various methods for risk analysis and assessment of urban rail transit construction projects include probabilistic risk assessment (PRA) [20], the safety risk identification system (SRIS) [9], and risk-factor analysis (RFA) [13]. Among them, PRA and RFA use the questionnaire survey method to classify risk factors; then, practical countermeasures are identified for metro construction by identifying and evaluating key risk factors. The SRIS, by applying graphical recognition and risk identification automation technologies to risk assessment in the preconstruction period, can identify potential safety hazards and provide dynamic risk control and early warning during the construction of urban railways. Additionally, in engineering practice, fuzzy theory has been widely used to better identify uncertainties in the quality risk assessment of construction projects. Sari et al. [21] evaluated the urban rail system in Istanbul under different risk factors using the fuzzy analytic hierarchy process (FAHP) and conducted a multicriteria assessment of the existing rail system to allocate scarce resources. Al-Labadi et al. [22] proposed a fuzzy set model that can accurately assess the safety performance of grouting operations during metro tunnel construction. Zhang et al. [23] proposed a fuzzy decision analysis method to provide guidance for safety management in metro construction.

Most previous studies only focused on a particular aspect of metro construction through the research and development of monitoring platforms or the development of evaluation systems and the corresponding measures. There have been relatively few studies on construction quality risk evaluation of urban rail transit construction projects from the perspective of management science, and there are few methods for evaluating the quality risk in the actual construction process of metro projects. In the present study, we evaluated urban rail transit construction quality risks on the basis of the existing research. The three main contributions of the study are (1) methodological innovation: the integrated application of the analytic hierarchy process and fuzzy comprehensive evaluation (AHP–FCE) allows more scientific, reasonable, and practical quantitative evaluation of urban rail transit construction quality risks, and the results of the metro construction quality risk assessment can be expressed as both a vector and a value. (2) Innovative perspective: The "4M1E" management method was used to systematically explore the quality of urban rail transit construction with regard to the "man–machinery–materials–methods–environment" aspects. (3) Innovation in content: This study focused on the quality and safety risks in urban rail transit construction, which is conducive to identifying risks and helps to realize the management of metro construction quality risk evaluation. We propose a scientific and accurate evaluation method for enhancing metro construction quality control. The remainder of this paper is organized as follows: Section 2 presents the data sources and research methodology. Sections 3 and 4 present and discuss the results, respectively, Section 5 presents the main conclusions and discusses policy implications.

2. Methodology

2.1. Indicator System Construction

2.1.1. Introduction to Evaluation Methodology. In everyday production activities, decisions regarding various matters must be made. Decisions can be made according to subjective perceptions or experiences when evaluating simple matters. However, the subjective approach to decision-making is inadequate for complex system projects. Therefore, it is necessary to consider the whole picture, comprehensively consider the object under study, and grasp the general nature of the matter to obtain accurate and reasonable evaluation results. According to the relevant literature [24–27], methods

Table 1: Evaluation methods.

No.	Methods	Advantages	Disadvantages
1	Gray relational analysis	Easy to use, does not require a lot of sample data, and is suitable for filling gaps due to missing data	Subjective and difficult to determine the optimum value for some of the indicator data
2	TOPSIS	Objective and realistic reflection of reality and is intuitive and reliable	Specific data are needed for each evaluation indicator. Selection of quantitative indicators is difficult
3	Analytic hierarchy process (AHP)	Method is simple, and a small amount of quantitative data involved makes it a more systematic analysis method	Much subjective qualitative analysis and little objective quantitative data. Amount of data collation, statistics, and arithmetic makes solutions for decision-makers difficult
4	Fuzzy comprehensive evaluation (FCE)	Results of evaluation calculations are presented in vector form, which is rich in the information contained	Complex calculation process. Susceptible to subjective components in determining weights of vector indicators

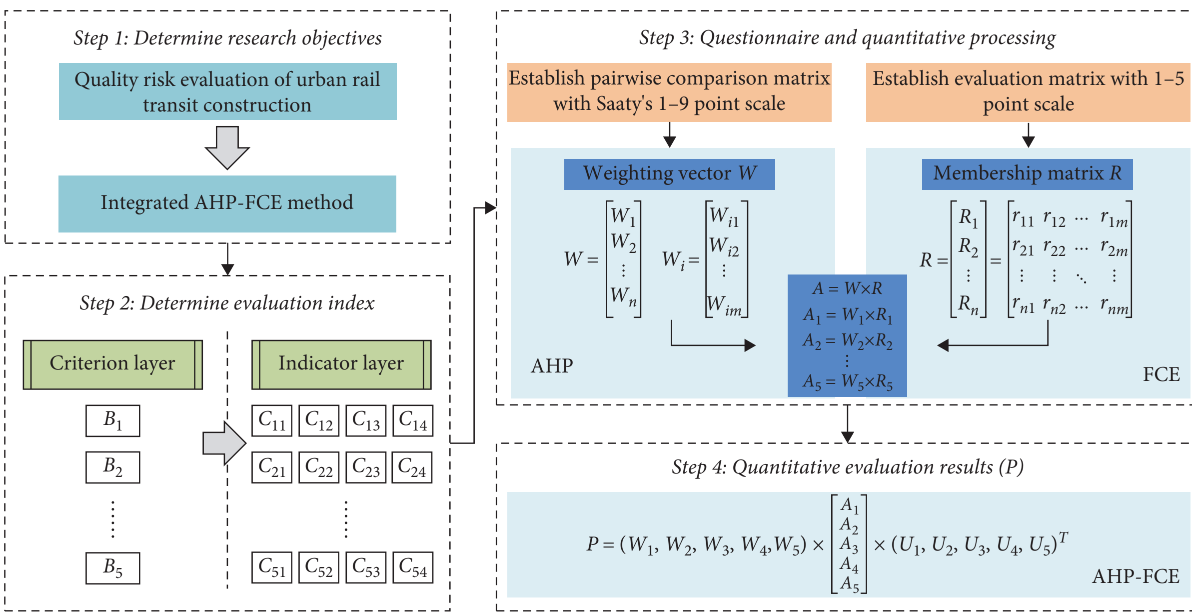

Figure 1: Steps for quality risk assessment during the construction period of urban rail transit.

widely used for construction risk evaluation are presented in Table 1.

Considering the various quality risk assessment indicators with obvious hierarchy during the construction of urban rail transit, in this study, the AHP method was used to determine the weight of each subgoal and subsystem and perform mathematical analysis based on expert semi-structured interviews to determine the weights of the indicators. FCE is a method based on fuzzy mathematics membership theory and can solve multivariable problems in complex decision-making processes [26, 28]. However, when dealing with complex problems and multiple evaluation indicators, it is difficult for FCE to directly provide the weight of each evaluation, for which the AHP is effective [29]. Therefore, combining the two methods can not only compensate for their respective shortcomings but also ensure the accuracy and comprehensiveness of the evaluation results [30, 31]. Figure 1 shows the application steps of the AHP–FCE method in the quality risk assessment of urban rail transit construction. The following are the specific steps of the AHP–FCE method.

Step 1: Determine the research objectives and use the integrated AHP–FCE method to evaluate the risk of urban rail transit construction quality.

Step 2: Using the "4M1E" management method, establish a quality risk assessment index system for urban rail transit construction with regard to five aspects: "man–machinery–materials–method–environment."

Step 3: Collect and calculate the weights (W) of the indicators at each level (using Saaty's 1–9 point scale). Comprehensively evaluate the comment set R (using a 1–5 point scale). Multiply the indicator weight set W by the fuzzy correlation matrix R to calculate the FCE vector A.

Step 4: Quantify the evaluation results for evaluating the risk level of urban rail transit construction quality.

2.1.2. Principles of Indicator System Construction. Depending on the study object, three principles should be followed for selecting an appropriate evaluation model to solve a practical problem:

(1) Principle of applicability. Different evaluation methods have different advantages and disadvantages, use conditions, and application scopes. Therefore, when selecting the method of the evaluation model, the most suitable solution should be selected according to the research problem.
(2) Principle of rationality. Research methods should be selected practically to ensure that they can support the research and are not cumbersome, and that the data are easy to collect.
(3) Principle of comprehensiveness. When a research method that cannot support the research results alone is selected, it should be sufficiently flexible to allow multiple methods to be combined to ensure the accuracy of the target results.

This study preferred the AHP and the FCE. In contrast, a comprehensive comparison and selection of evaluation methods and their combinations produced an evaluation model based on AHP–FCE. A construction quality risk index system for urban rail transit was constructed by integrating the construction quality risk factors in engineering construction. First, a structural model of metro construction quality risk influencing factors was constructed via the AHP, and the weights of different indicators were determined. Second, the fuzzy synthesis method was used to determine the evaluation index affiliation matrix according to the subjective scores of experts. Finally, the qualitative is transformed into quantitative, and the combination of qualitative and quantitative is adopted to comprehensively and systematically evaluate the urban rail transit construction quality risk.

2.1.3. Selection of the Evaluation System. Through systematic sorting and investigation of quality issues that occur during the construction of subway projects, it was found that construction quality issues are influenced by various factors, such as the construction man, machinery, materials, methods, and environment. In this study, to further investigate the factors that affect the quality of subway engineering construction and facilitate the development of improvement plans, risk prevention, and control measures for project management personnel, we systematically analyzed the quality factors that affect subway engineering construction with regard to five aspects, i.e., man–machinery–materials–methods–environment, and constructed a subway engineering quality risk assessment system.

(1) *Factors Related to Construction Man.* The participants in subway construction are not only the main people involved in project production and operation but also the main people in engineering construction quality control. The management level, technical ability, quality and safety awareness, and work experience of the participants all affect the construction quality of subway projects. Since the beginning of subway construction, the human factors that have triggered and caused quality incidents are mainly reflected in the technical level of subway engineering professionals and the standardization of construction personnel operations.

(2) *Factors Related to Construction Machinery.* A large amount of mechanical equipment is used in the construction of subway projects, and the practicality and efficiency of the mechanical equipment are prerequisites for ensuring construction progress and quality. In the construction of subway projects, the main factors related to the construction machinery and equipment include the performance of the machinery and equipment, the failure rate of the construction machinery, daily maintenance and upkeep of the machinery and equipment, and monitoring level of the machinery and equipment. Problems in different links have varying degrees of impact on the construction quality and safety. Therefore, monitoring involves reading machinery and equipment operating parameters in real time and understanding the state and performance of machinery and equipment can prevent all types of quality risk accidents caused by machinery and equipment.

(3) *Factors Related to Construction Materials.* In-depth visits and questionnaire surveys on the metro projects of the China Railway system under construction in 2016–2022 revealed that the construction of metro projects involves various engineering materials, such as steel reinforcement, concrete, prefabricated shield pieces, and electromechanical equipment. Therefore, the main factors related to construction materials that cause construction quality risks are the quality of incoming materials, whether the supply of primary (auxiliary) materials is timely, whether the management of materials in the station is standardized, and whether the waterproofing measures for materials are effective.

(4) *Factors Related to Construction Methods.* The construction of metro projects is characterized by long periods, high difficulty, and high technological requirements. The reasonableness of the construction plan and construction process design and whether they meet the actual needs impact the quality of the construction project. Owing to the concrete being poured from a great height during metro construction, a weak and unstable support system can potentially result in formwork deformation, which will have an incalculable negative impact on the project quality.

(5) *Factors Related to Construction Environment.* The construction of the metro is located in an urban area. Commercial and residential buildings surround the project. There are many construction units, and multiprofessional cross-construction is frequent. The construction and process connection increases the pressure on the schedule and necessitates highly skilled technical personnel. The concealed excavation project for the underground station is influenced by geological conditions. Therefore, the environmental impact of the construction quality risk is mainly caused by the geology of the construction site, the surrounding buildings, and the site construction environment, such as the undercutting of municipal pipelines.

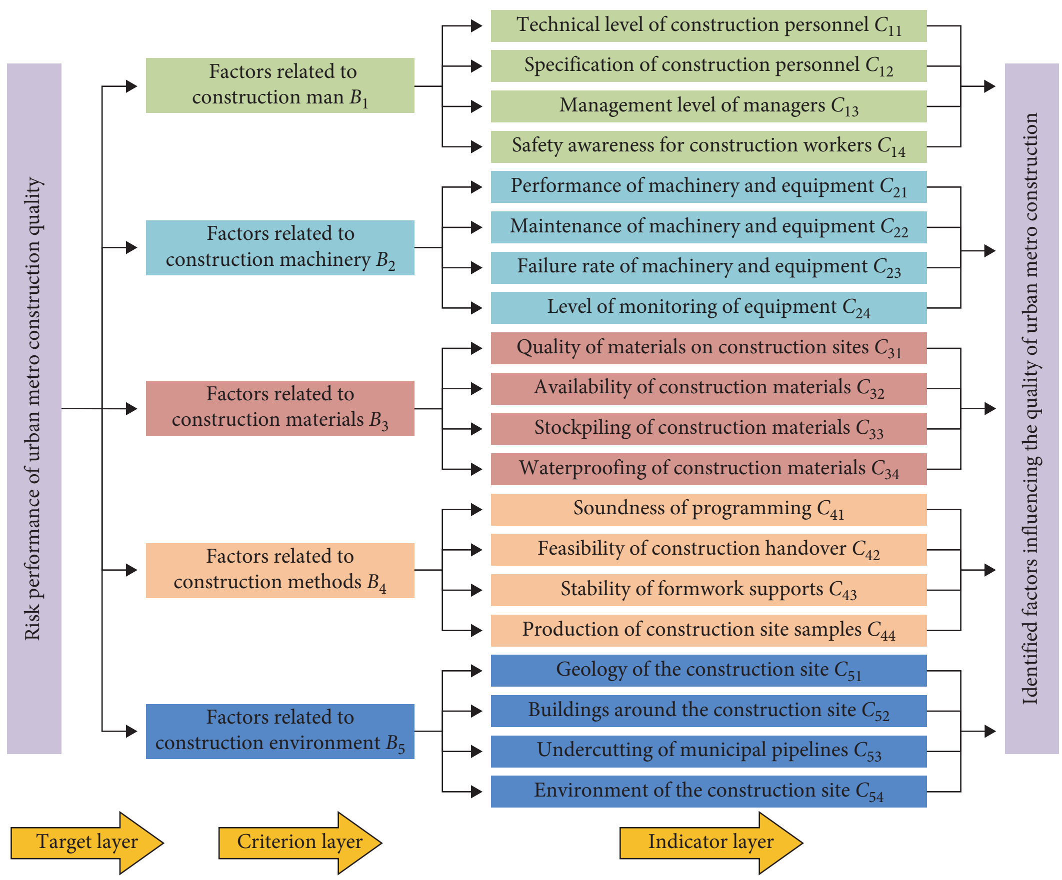

FIGURE 2: Indicator system establishment for the construction quality of urban subway.

The metro quality risk index system is constructed through the collation and analysis of the factors affecting the construction quality of metro projects, as shown in Figure 2.

2.2. Evaluation Models and Principles. The AHP–FCE evaluation method combines the two methods, taking into account their respective advantages, to overcome the shortcomings of subjective assumptions and better reflect the objective reality. The AHP and FCE are used to quantify the qualitative evaluation descriptions and construct a comprehensive evaluation model for urban rail transit construction quality risk, providing an alternative reference for construction quality risk evaluation in domestic urban rail transit engineering construction.

2.2.1. AHP Method. The objective of the AHP method is to translates experts' judgments of qualitative aspects into quantitative data and constructs a clear system by combining qualitative and quantitative aspects to build a hierarchy of complex problems for calculating the weight values of each indicator scientifically. The main steps are as follows:

(1) The main factors influencing the decision-making of the problem are analyzed at the criterion and indicator levels.
(2) The weights of the factors are calculated.
(3) The weights of the factors at different levels are analyzed analogously.

Step 1: Establishing a hierarchical ladder model.

Considering the quality risk influencing factors of the urban rail transit construction process, the objectives are graded, and each element is analyzed layer-by-layer.

Step 2: Constructing judgment matrix.

In the AHP, experts from relevant fields are invited to use the 1–9 scale method to determine the relative importance of influencing factors in the standard or indicator layer according to subjective and objective conditions and assign values according to the relative importance of different factors. The indicator vector of the standard layer is determined as $W = [W_1, W_2, \ldots, W_n]$, and the weight vector of the indicator layer is $W_i = [W_{i1}, W_{i2}, W_{i3}, \ldots, W_{im}]$, where $(i = 1, 2, 3, \ldots, n; j = 1, 2, 3, \ldots, m)$. In this study, the nine-level scale, presented in Table 2, was used as the scoring criterion. b_{ij} denotes the importance ratio of factor i to factor j. It is assumed that there are n schemes and i indicators in the indicator layer and indicator i is compared with indicator j with regard to importance. Then, the matrix is obtained via scoring by the experts.

Step 3: Consistency test.

After the scores for all the indicators were obtained, the value was used as the basis for judgment to clarify the importance of each indicator between each level, and the

Table 2: Nine-level scale method.

Degree of importance	Definition
1	Factor i is as important as factor j
3	Factor i is slightly more important than factor j
5	Factor i is more important than factor j
7	Factor i is significantly more important than factor j
9	Factor i is far more important than factor j
2, 4, 6, 8	Intermediate evaluation value
Reciprocal	If the judgement of factor i compared with factor j is b_{ij}, then $b_{ij} \cdot b_{ji} = 1$

eigenvector of the maximum eigenvalue $\lambda_{\max}$ of the judgment matrix was obtained. After the weights of each matrix are calculated, to avoid unreasonable results, the consistency indicator (*C.I.*) and average random consistency indicator (*C.R.*) values of the matrix are used to determine whether the matrix has *C.I.* as follows:

$$P_i = \prod_{j=1}^{n} b_{ij} \ (i = 1, 2, 3, \ldots, n), \tag{1}$$

$$W_i = \sqrt[n]{P_i}, \tag{2}$$

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(AW)_i}{W_i}, \tag{3}$$

$$C.I. = \frac{\lambda_{\max} - n}{n - 1}, \tag{4}$$

$$C.R. = \frac{C.I.}{R.I.}, \tag{5}$$

where i represents the number of rows in the matrix, j represents the number of columns in the matrix, W_i is the weight vector of the indicator, N represents the order of a matrix, and P_i represents the product of all indicator assignments in row i. When $C.R. < 0.1$, the matrix passes the consistency test and has good consistency.

2.2.2. FCE Method. The FCE method is based on fuzzy mathematical theory, which decomposes the total objective of the evaluation into a fuzzy set consisting of several indicators to deal with uncertain information. The operation process includes establishing sets of evaluation index factors and rubrics and constructing the affiliation and fuzzy relationship matrices.

Step 1: Establish a comprehensive evaluation index factor set.

This set consists of the construction quality risk guideline layer impact index factor $B = [B_1, B_2, B_3, B_4, B_5]$, indicator layer impact index factor $B_1 = [C_{11}, C_{12}, C_{13}, C_{14}]$, etc.

Step 2: Establishing a comprehensive evaluation rubric set.

From the literature review and expert interviews, the indicator evaluation criteria were classified into five levels with a rubric set of $V = [V_1, V_2, V_3, V_4, V_5]$ = [slightly low, low, average, medium, high].

Step 3: Determine the fuzzy relationship matrix.

r_{ij} was expressed as the degree of subordination between the evaluation factors and a specific evaluation level. When m elements are evaluated in a comprehensive analysis, a matrix R with m rows and n columns can be obtained as $R = [R_1, R_{2,} \ldots, R_n]^T$.

$$R = \begin{bmatrix} R_1 \\ R_2 \\ \cdots \\ R_n \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}. \tag{6}$$

Step 4: Calculation of FCE.

According to the AHP, the criterion layer indicator vector W and indicator layer weight vector W_i are obtained, and then the weight coefficients of each indicator are calculated. The final FCE vector is the operation between the fuzzy matrix R_i and the weight vector W_i, which is denoted as A_i.

$$\begin{aligned} A_i = W_i \times R_i &= (w_{i1}, w_{i2}, w_{i3}, \ldots, w_{in}) \\ &\times \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}, \\ &= (a_1, a_2, a_3, \ldots, a_m) \end{aligned} \tag{7}$$

$$S = W \cdot A, \tag{8}$$

$$P = S \cdot U^T. \tag{9}$$

In multifactor evaluation, the AHP–FEC comprehensive evaluation model S was obtained using Equations (6)–(9), and finally, the comprehensive evaluation score P was calculated using the scoring set.

3. Results

In this study, the construction project of a station in the first phase of Shaoxing city rail transit line 2 was considered as an example. The construction period of this project was short, covering a wide range of areas with high-quality requirements and frequent cross-processes. Thus, a quality and safety construction management team headed by the project manager was set up at the early stage of the project

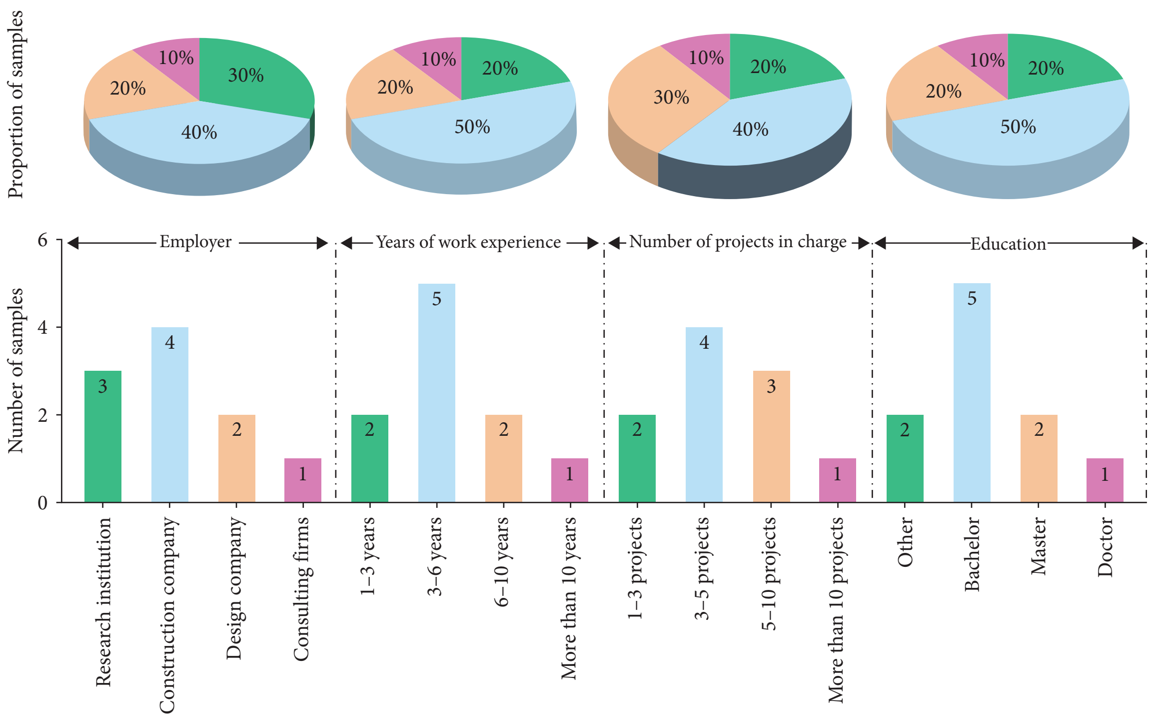

FIGURE 3: Details regarding the interviewees.

TABLE 3: Reliability analysis based on Cronbach's α coefficient for the indicators.

C	Cronbach α	C	Cronbach α	C	Cronbach α	C	Cronbach α
Technical level of construction personnel C_{11}	0.707	Maintenance of machinery and equipment C_{22}	0.833	Stockpiling of construction materials C_{33}	0.711	Production of construction site samples C_{44}	0.725
Specification of construction personnel C_{12}	0.812	Failure rate of machinery and equipment C_{23}	0.761	Waterproofing of construction materials C_{34}	0.901	Geology of the construction site C_{51}	0.783
Management level of managers C_{13}	0.760	Level of monitoring of equipment C_{24}	0.739	Soundness of programming C_{41}	0.930	Buildings around the construction site C_{52}	0.710
Safety awareness for construction workers C_{14}	0.753	Quality of materials on construction sites C_{31}	0.863	Feasibility of construction handover C_{42}	0.839	Undercutting of municipal pipelines C_{53}	0.828
Performance of machinery and equipment C_{21}	0.791	Availability of construction materials C_{32}	0.782	Stability of formwork supports C_{43}	0.759	Environment of the construction site C_{54}	0.804
Cronbach α: $0.789 > 0.7$							

Note: Cronbach α ($\alpha = 0.9$: excellent; $\alpha = 0.8$: good; $\alpha = 0.7$: acceptable; $\alpha = 0.6$: questionable; $\alpha = 0.5$: poor; $\alpha < 0.5$: unacceptable) [34, 35].

construction to ensure that the quality of the project would be "qualified" and that no general or above-project quality accidents would occur. First, a questionnaire was designed to assess the proposed evaluation indicators. During the questionnaire process, the interviewees were asked to rate the 20 quality risk influencing factors of urban rail transit construction, quantitatively process the obtained data to obtain the weights of each indicator in the evaluation index system, and comprehensively evaluate the quality risks of urban rail transit construction through calculation and analysis.

3.1. Data Sources and Tests. To ensure the objectivity and authority of the weights of the indicators, 10 experts engaged in different fields related to urban rail construction were invited to score the first- and second-level indicators in the indicator system, and the background information of the interviewees is shown in Figure 3.

To effectively avoid the occurrence of unreasonable scoring and strong human subjective factors in the recovered questionnaires, the Cronbach α coefficient test was used to evaluate the reliability of the indicator factors [32, 33], and the test results are shown in Table 3. The final standardized

Table 4: Evaluation model indicator weights.

C	Weight					$\lambda_{\max}$	C.I.	C.R.	Does it meet the test?	Combined weights	Sorting
	B_1 0.114	B_2 0.070	B_3 0.486	B_4 0.043	B_5 0.287						
Technical level of construction personnel C_{11}	0.564					4.117	0.039	0.043	Yes	0.064	5
Specification of construction personnel C_{12}	0.263									0.030	10
Management level of managers C_{13}	0.055									0.006	17
Safety awareness for construction workers C_{14}	0.118									0.013	15
Performance of machinery and equipment C_{21}		0.535				4.147	0.049	0.054	Yes	0.038	7
Maintenance of machinery and equipment C_{22}		0.130								0.009	16
Failure rate of machinery and equipment C_{23}		0.060								0.004	19
Level of monitoring of equipment C_{24}		0.275								0.019	12
Quality of materials on construction sites C_{31}			0.498			4.034	0.011	0.013	Yes	0.242	1
Availability of construction materials C_{32}			0.121							0.059	6
Stockpiling of construction materials C_{33}			0.068							0.033	8
Waterproofing of construction materials C_{34}			0.313							0.152	2
Soundness of programing C_{41}				0.482		4.121	0.040	0.045	Yes	0.021	11
Feasibility of construction handover C_{42}				0.057						0.002	20
Stability of formwork supports C_{43}				0.341						0.015	14
Production of construction site samples C_{44}				0.120						0.005	18
Geology of the construction site C_{51}					0.515	4.037	0.012	0.014	Yes	0.148	3
Buildings around the construction site C_{52}					0.067					0.019	13
Undercutting of municipal pipelines C_{53}					0.112					0.032	9
Environment of the construction site C_{54}					0.306					0.088	4

reliability coefficient α was 0.789. The value of $\alpha > 0.7$ indicating that the questionnaire and indicator data had high credibility.

3.2. Determination of Indicator Weights. Using the 1–9 point scale, 10 experts and technicians in metro engineering construction were invited to form an expert group to judge the importance of the indicators at the criterion level and then calculate the judgment matrix to obtain the final weights of each indicator and conduct consistency tests. According to the calculation method for the judgment matrix, the indicator weights of the evaluation model for all the factors influencing construction quality risk were determined, as shown in Table 4.

Here, the guideline layer has $\lambda_{\max} = 5.15$, $C.I. = 0.037$, $R.I. = 1.12$, and $C.R. = 0.033 < 0.1$, satisfying the consistency test. From Table 4, it can be seen that the index weights of the urban rail transit construction quality guideline layer are $B = \{B_1, B_2, B_3, B_4, B_5\} = \{0.114, 0.070, 0.486, 0.043, 0.287\}$. The construction materials have the largest weight, reflecting their key role in the evaluation of construction quality risks in urban rail transit engineering construction. Conversely, the construction method has the smallest weight. In the index layer, the quality of incoming construction materials, material waterproofing measures, construction site geology, and construction environment materials have higher weights. They should be given more attention during the construction of metro projects.

3.3. Construction Affiliation Matrix. To increase the accuracy of the evaluation results, members of the expert group were invited to evaluate the factors affecting the quality of metro construction, and an evaluation matrix was established according to the evaluation results. The evaluation results were divided into five levels, each corresponding to a different evaluation value. The comprehensive evaluation set of indicators was $V = \{V_1, V_2, V_3, V_4, V_5\} = \{$slightly low, low, average, medium, high$\}$; the evaluation set corresponded to the set of scores expressed as $U = \{U_1, U_2, U_3, U_4, U_5\} = \{50, 60, 70, 80, 90\}$. Using the expert determination of the level to which each indicator of metro construction quality risk belonged, the affiliation of each indicator was obtained according to the frequency, as shown in Table 5.

3.4. Evaluation of Construction Quality Risks. According to the affiliation weights of each indicator and using Equation (6) and Table 4, the participant affiliation matrix can be obtained as follows:

$$R_1 = \begin{bmatrix} 0.0 & 0.1 & 0.2 & 0.2 & 0.5 \\ 0.0 & 0.0 & 0.2 & 0.2 & 0.6 \\ 0.0 & 0.1 & 0.2 & 0.3 & 0.4 \\ 0.0 & 0.1 & 0.1 & 0.3 & 0.5 \end{bmatrix}. \quad (10)$$

In addition, according to the weights of each indicator in the indicator layer and Equation (7), the FCE results for indicator layer A_1 were obtained as follows:

Table 5: Summary of evaluation model indicator weights.

B	C	Weight	Risk level				
			V_1	V_2	V_3	V_4	V_5
Factors related to construction man B_1	C_{11}	0.564	0.0	0.1	0.2	0.2	0.5
	C_{12}	0.263	0.0	0.0	0.2	0.2	0.6
	C_{13}	0.055	0.0	0.1	0.2	0.3	0.4
	C_{14}	0.118	0.0	0.1	0.1	0.3	0.5
Factors related to construction machinery B_2	C_{21}	0.535	0.0	0.1	0.2	0.3	0.4
	C_{22}	0.130	0.1	0.1	0.2	0.3	0.3
	C_{23}	0.060	0.1	0.1	0.3	0.2	0.3
	C_{24}	0.275	0.0	0.0	0.0	0.3	0.7
Factors related to construction materials B_3	C_{31}	0.498	0.0	0.0	0.0	0.2	0.8
	C_{32}	0.121	0.0	0.0	0.2	0.3	0.5
	C_{33}	0.068	0.1	0.2	0.2	0.3	0.2
	C_{34}	0.313	0.0	0.0	0.1	0.2	0.7
Factors related to construction methods B_4	C_{41}	0.482	0.0	0.0	0.1	0.3	0.6
	C_{42}	0.057	0.1	0.1	0.3	0.3	0.2
	C_{43}	0.341	0.0	0.0	0.0	0.3	0.7
	C_{44}	0.120	0.0	0.0	0.0	0.2	0.8
Factors related to construction environment B_5	C_{51}	0.515	0.0	0.0	0.0	0.1	0.9
	C_{52}	0.067	0.1	0.1	0.3	0.3	0.2
	C_{53}	0.112	0.0	0.1	0.1	0.3	0.5
	C_{54}	0.306	0.0	0.0	0.0	0.3	0.7

$$\begin{aligned} A_1 &= W_1 \times R_1 \\ &= (0.564, 0.263, 0.055, 0.118) \\ &\quad \times \begin{bmatrix} 0.0 & 0.1 & 0.2 & 0.2 & 0.5 \\ 0.0 & 0.0 & 0.2 & 0.2 & 0.6 \\ 0.0 & 0.1 & 0.2 & 0.3 & 0.4 \\ 0.0 & 0.1 & 0.1 & 0.3 & 0.5 \end{bmatrix} \\ &= (0.000, 0.074, 0.188, 0.217, 0.521). \end{aligned} \tag{11}$$

Similarly, the results of the FCE of the other indicator layers are, in order: $A_2 = (0.019, 0.073, 0.151, 0.294, 0.464)$; $A_3 = (0.007, 0.014, 0.069, 0.219, 0.692)$; $A_4 = (0.006, 0.006, 0.065, 0.288, 0.635)$; $A_5 = (0.007, 0.018, 0.031, 0.197, 0.747)$. According to the principle of maximum affiliation and the solving rules and criteria, the scores were divided into five levels {50, 60, 70, 80, 90}, and the FCE of the metro target layer was performed.

$$\begin{aligned} P &= (W_1, W_2, W_3, W_4, W_5) \\ &\quad \times \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \end{bmatrix} \times (50, 60, 70, 80, 90)^T \\ &= (0.007, 0.025, 0.077, 0.2210.670) \times (50, 60, 70, 80, 90)^T \\ &= 85.21. \end{aligned} \tag{12}$$

The above solution process yielded a final FCE result of 85.21. Thus, the final score of the urban rail transit construction quality risk was 85.21, which is between 80 and 90. Therefore, the overall risk of metro construction quality is "medium," which is consistent with the results of the expert study. Accordingly, there is considerable room for optimization and improvement in project quality control.

4. Discussion

4.1. Index System Construction and Importance Analysis. Incorporating the advantages of the AHP into FCE and constructing the AHP–FCE integrated model for qualitative and quantitative analysis can achieve the purpose of identifying and evaluating risks. The main steps of the proposed method are risk-factor identification questionnaire survey and data processing, calculation of the weight coefficients of evaluation indices based on the AHP, and risk level evaluation based on FCE [30, 36]. As shown in Tables 4 and 5, the construction materials (B_3) had the largest weight coefficients among the five main indicators for the risk assessment of urban rail transit construction quality, followed by the construction environment (B_5), construction man (B_1), construction machinery (B_2), and construction methods (B_4). The five factors with the largest weight coefficients in the 20-indicator system were the quality of incoming materials (C_{31}), waterproofing measures for materials (C_{34}), geology of the construction site (C_{51}), onsite construction environment (C_{54}), and technical level of construction personnel (C_{11}). During the construction process, managers should focus on risk indicators with large weights and take targeted control measures to reduce quality risks.

4.2. Metro Construction Quality Risk Control Strategy. Metro construction is a complex project, and the entire construction process is usually conducted underground, presenting various risks [23]. To reduce the overall risk level of urban rail transit construction operations, managers should consider appropriate control of the five risk factors with the largest weights, i.e., the quality of incoming materials (C_{31}), waterproofing measures for materials (C_{34}), geology of the construction site (C_{51}), onsite construction environment (C_{54}), and technical level of construction personnel (C_{11}).

4.2.1. Incoming Construction Materials (C_{31}) and Material Waterproofing Measures (C_{34}). Quality problems with the selected construction materials, e.g., the steel or formwork, affect the quality of the entire metro station, and the construction materials should be placed in a ventilated and open place to ensure good waterproofing [8]. Additionally, if the concrete materials are not proportioned according to the design requirements and the construction process is not conducted according to the construction technology, the construction quality of the metro station will be negatively impacted.

4.2.2. Construction Site Geology (C_{51}). To ensure the excavation of the foundation pit and smooth tunneling of the metro station, the construction party must organize several field surveys involving technical personnel [13], invite experts to engage in risk studies and technical debates, formulate safe and efficient construction plans, and adopt new construction techniques according to the local conditions to accelerate the connection of work processes and increase the construction efficiency. Additionally, they must actively use information technology to monitor the geological environment and provide reasonable construction plans for poor-quality strata to ensure the quality of the project [15].

4.2.3. Onsite Construction Environment (C_{54}). Urban rail transit is generally near on the main road of the city, surrounded by a large number of existing buildings and underground pipelines (gas pipelines, lighting, and power cables) [9]. Thus, from the perspective of the construction environment, there are numerous uncertain factors. Therefore, in the process of metro construction, hidden dangers and risks associated with the construction environment should be carefully assessed to avoid ground subsidence, which can trigger the collapse of the surrounding buildings or the emergence of cracks.

4.2.4. Technical Level of Construction Personnel (C_{11}). The management of construction personnel, which constitute the main body of underground construction, must be strengthened to ensure that construction personnel have both professionalism and adequate technical level [37]. Additionally, it is necessary to improve training on the related equipment, including new technologies and maintenance [13]. Persons who do not satisfy the training and assessment requirements should be prohibited from participating in the construction process to avoid quality and safety accidents.

5. Conclusions

Quality risk identification and evaluation is a complex decision-making process affected by various factors. This study focused on the quality risk in the construction process of an underground station in Shaoxing. The elements of the construction quality risk were comprehensively analyzed through expert empirical judgment and assessment, and an AHP–FCE evaluation model was developed to quantitatively evaluate the quality risk of underground construction. Objective data were combined with subjective judgments to determine the ranges of the affiliation values and the importance ranking of the construction quality risk factors. According to the results of the study, the following conclusions are drawn:

(1) The "4M1E" management method based on five aspects ("man–machine–materials–methods–environment") of the construction of urban rail transit engineering construction quality risk assessment of the five categories of a total of 20-indicator system, a systematic analysis of the underground construction quality of the factors affecting the perspective of the study has a certain degree of innovation.

(2) The combined AHP–FCE-based method can quantitatively evaluate the risk of construction quality and simultaneously rank the importance of various risk factors of construction quality. The comprehensive selection of research methods not only plays the role of expert experience but also reduces the errors caused by human subjectivity and improves the objectivity and accuracy of the evaluation results. Among the factors affecting the construction quality risk, the construction materials have the largest weight (0.486), and the focus in the indicator layer is reflected in the quality of incoming materials, waterproofing measures of materials, the geology of the construction site, and the construction environment. The results of this study can help managers better understand the risks in the construction of underground projects and provide corresponding control recommendations.

(3) Using the AHP–FCE evaluation model, the final score of the metro construction quality risk was obtained as 85.21, corresponding to a "medium" risk level. The evaluation results match the actual situation of the selected project, confirming the practicality and effectiveness of the evaluation model. The results of the study provide a scientific basis and reference for the evaluation of the construction quality risk of domestic urban rail transit. The proposed method is also applicable to other types of risk assessment; however, it is necessary to replace the assessment indices according to the actual situation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Additional Points

Study Limitations. (1) Owing to the limitation of years of work and participation in the project, only one metro station under construction was studied. In future studies, other metro stations under construction will be studied for comprehensive comparative analyses from different perspectives, including cities with different levels of economic development in China, in areas such as the Yangtze River Basin, the Yellow River Basin, or plains areas. (2) The research data were mainly derived from experts' empirical judgment and assessment. Therefore, in future research, fuzzy mathematics will be introduced into hierarchical analysis to establish an FAHP–FCE evaluation model and the model will be applied to practical examples. Additionally, the number of questionnaire samples will be increased. (3) Measurable and objective data should be collected at the construction site of the metro project to validate the research framework.

Consent

Informed consent was obtained from all participants involved in the study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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