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Research Article

Risk Assessment of Building Foundation Pit Construction Based on Fuzzy Hierarchical Comprehensive Evaluation Method

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The safety of foundation pit construction is gaining widespread attention. In order to reduce the risks of foundation pit construction and avoid the safety problems brought by the pits, it is necessary to study the risks of foundation pit construction. This paper takes the actual construction of a building as the background. Firstly, the possible main risks of foundation pit construction were identified and summarized, and then, the evaluation index system was formed. Secondly, the risk levels of various types of foundation pit risks were derived through analytic hierarchy process (AHP). In the expert scoring session of the Delphi method, the influences of both the degree of risk consequences and the probability of occurrence are combined. The risk value of the risk event is obtained in combination, which overcomes the bias problem of the traditional single assignment. Finally, an affiliation matrix was established to judge the affiliation of risk indicators to the risk level. The comprehensive risk evaluation level of this foundation pit project construction was assessed as level II. It is the degree of general risk.

1. Introduction

A lot of projects, such as foundation pit, petroleum caverns, drainage tunnels, mines, and powerhouses, have been built or programmed in recent years [1–6]. Risk assessment of these projects is important for the safety construction. With the rapid development of urban construction, a large number of engineering constructions involve foundation pit projects. Due to the characteristics of many risk factors, construction conditions, and generally higher technical requirements, production safety accidents of different degrees are prone to occur, which not only cause delays in the construction schedule but also seriously threaten the personal safety of frontline construction workers. This makes it very important to identify and evaluate the various types of risks that may exist in foundation pit construction to determine the safety of foundation pit projects.

For the risks existing in foundation pit construction, Feng et al. [1] formed a multiview safety evaluation method specific to foundation pit construction by establishing the relationship between several factors such as safety evaluation index and safety level of construction plan. Wu et al. [2] developed an unmanned aircraft monitoring and analysis method based on pit slope in order to solve the problem of pit construction safety monitoring and evaluation and imported pit construction images in real time to evaluate and analyze the local safety status of the pit. Fan et al. [7] used the conceptual framework of BIM access to the Internet of Things in order to achieve risk assessment of deep foundation pit construction sites. In turn, the safety management efficiency of the construction site is improved to achieve the purpose of accident reduction. Zhai et al. [8] analyzed the risk factors of foundation pit construction in terms of geological conditions, building environment, geotechnical design, construction plan, and incidental risks. A risk evaluation method based on intuitionistic fuzzy set-dynamic weighting was proposed to obtain the system integrated risk level. Based on the model of AHP, Zhang et al. [9] proposed a quantitative risk assessment method for the whole objective process of foundation pit engineering. The main steps include constructing a hierarchical analysis model, building a foundation pit design base model, determining functional relationships, calculating risk factor weights, and ranking risk levels. Wei et al. [10] proposed a risk assessment method based on fuzzy evidence inference from the perspective of the engineering project as a whole. By this method, the risk level of all hazardous events involved can be obtained by this method, and then, the risk level of the project as a whole can be pooled. Meng et al. [11] used AHP for risk assessment of deep foundation pit construction. The analysis was carried out in terms of the possible consequences of the risks and the probability of their possible occurrence and was validated based on engineering examples. Shen et al. [12] analyzed the risk factors involved in foundation pit construction and established a subway station foundation pit construction risk evaluation index system. A comprehensive evaluation model was constructed, and the hazard levels of various types of risks were obtained. Zhang et al. [13] proposed an integrated method of dynamic risk analysis based on Fuzzy Bayesian Network (FBN) and Fuzzy Analytic Hierarchy Process (FAHP). Applying it to the risk evaluation analysis of foundation pit collapse to achieve quantitative risk reasoning of foundation pit collapse, which is essential for the prevention and control of foundation pit collapse accidents. Wu and Wang [14] proposed an integrated projection tracking model, particle swarm optimization, and interpolation algorithm to evaluate the in-flooding risk of deep foundation construction. Giannakos and Xenidis [15] focus on the relationship between overall and local risks and explored their intrinsic correlation using neural network models. It is pointed out that overall risk is not an aggregate of simple combinations of local risks and that the two are interdependent. Yang et al. [16] simulated the whole process of pit collapse and evacuation through a decision system model to minimize the safety problems caused by pit construction. Valipour et al. [17] combined stepwise and compound weight assessment methods to obtain five main risks of subway pit construction, which provides new ideas and references for controlling risks in pit excavation in subway projects. Zhou et al. [18] constructed support vector machine risk prediction model to predict and determine the safety risks that may occur during the construction of deep foundation pits.

In summary, many scholars have conducted various researches on foundation pit construction risks, mainly focusing on risk assessment, safety evaluation, dynamic analysis, and prediction. Among them, the hierarchical analysis method is a common class of methods for the risk assessment of foundation pit engineering. Since the risk of foundation pit has a certain fuzzy nature, by constructing a fuzzy hierarchical risk evaluation model, it can identify various risk factors of foundation pit construction more accurately. Therefore, the use of fuzzy hierarchical comprehensive evaluation method can effectively realize the risk assessment of foundation pit construction. This paper combines the fuzzy hierarchical comprehensive evaluation method and the Delphi method to establish a foundation pit construction risk index system. In turn, the weights of various types of risks are calculated to obtain various risk levels of foundation pit construction. The determination criteria of risk events are optimized, and targeted risk control measures are proposed.

2. Theoretical Bases

2.1. AHP. Hierarchical analysis is a practical and flexible system hierarchical evaluation method combining qualitative and quantitative approaches. The idea is to decompose the complex problem to be studied into multiple components and form a progressive multilevel analysis structure according to the interrelationship of each component. The complex problem is transformed into the lowest level unit relative to the highest level and determines the relative importance weights of each decomposition level. This method mathematizes the decision-making process with less quantitative information, processes and expresses subjective judgments in quantitative form, and provides a simple and scientific way to make decisions for complex problems with specific requirements.

The following are the steps for implementing the AHP. First, identify the nature of the research problem and the relevant influencing factors of the target, and construct a multilevel progressive hierarchical structure model. Second, establish a factor judgment matrix to determine the factor weights of each level. Finally, clarify the level of each influencing factor and obtain the factors with greater influence in the system. In this paper, we use AHP to determine the relative importance weights of risk events relative to the total risk of pit construction and the relative importance weights of the four risk consequence degree indicators.

2.2. Fuzzy Theory. There are various risks and safety hazards in the process of construction of foundation pits. The complexity of the operating conditions, processes, and equipment of foundation pit construction makes it difficult to describe the risk events in a quantitative manner. Therefore, most risk judgments are realized based on expert opinions or historical experiences. Based on fuzzy sets, fuzzy theory takes the object of study to deal with uncertain things and accepts the objective existence of fuzzy phenomena. The theory translates numerical variables into linguistic variables for thing description, providing an effective method for analyzing complex things or systems with uncertainty.

Among them, the affiliation function, which is extremely important in fuzzy theory, is an effective way to characterize a fuzzy set. The affiliation function is designed to describe the affiliation of an element u to a fuzzy set of U. Due to the uncertainty of this relationship, the values obtained in [0,1] will be used instead of the fixed values to characterize. It can be considered that $U : u \longrightarrow [0, 1]$, $u \longrightarrow U(u)$, by calling U a fuzzy set of u and $U(u)$ is an affiliation function of the fuzzy set u.

2.3. Fuzzy Hierarchical Integrated Evaluation Method. Fuzzy hierarchical comprehensive evaluation method combines hierarchical analysis and fuzzy mathematics. The relevant factors of the evaluation object are classified according to certain rules to form a progressive hierarchical structure with multiple types. The evaluation method consists of a target layer, a criteria layer and a factor layer in order from top to bottom. It provides a more comprehensive and integrated assessment of the evaluation object.

The following are the steps of this risk assessment. Firstly, the risk index evaluation system is constructed in a hierarchical manner, and the weights of each risk factor are calculated by using the AHP. Secondly, determine the affiliation degree of evaluation risk factors, apply fuzzy theory to conduct comprehensive evaluation of the evaluation object, and get the level of evaluation risk factors. Finally, get the risk consequence level by the Delphi method, so as to get the comprehensive risk level of the whole evaluation target. The fuzzy hierarchical comprehensive evaluation process of foundation pit construction risk is shown in Figure 1.

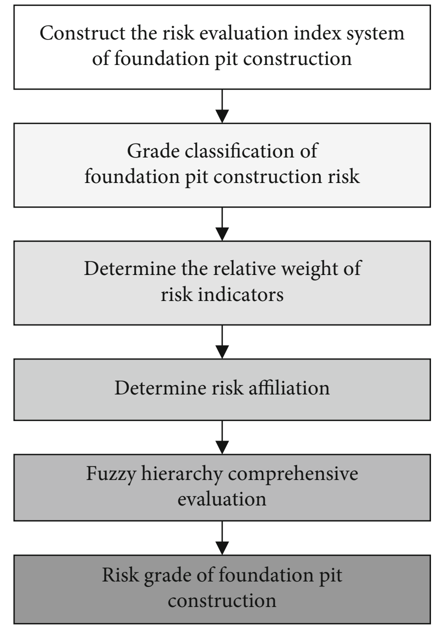

Figure 1: Fuzzy hierarchy comprehensive evaluation process of foundation pit construction risk.

2.4. Consequence Level. According to the report on production safety accident and regulations of investigation and treatment [19], the consequences of accidents cover four aspects: casualties, economic losses, environmental impacts, and social impacts. The above four consequence level indicators are used to judge the severity of risk consequences. The consequence degree level index is shown in Table 1.

Based on the above indicators, the risk consequence judgment matrix was constructed. The corresponding weights of the four indicators are calculated using hierarchical analysis, and the risk consequence degree is divided into four levels. The consequence degree levels are shown in Table 2.

2.5. Occurrence Probability Level. The probability of occurrence of foundation pit construction risk is divided into four levels using the likelihood of risk events as an indicator [20]. The risk occurrence probability levels are shown in Table 3.

Based on the above indicators, the judgment matrix of risk occurrence probability is constructed. The corresponding weights of the four indicators are calculated using hierarchical analysis, and finally, the risk occurrence probability is divided into four levels. The consequence degree levels are shown in Table 4.

2.6. Risk Grading Criteria. According to different risk consequence level and occurrence probability level, it constitutes the risk grading evaluation standard. The risk grading evaluation standard of foundation pit construction is shown in Table 5.

From Table 5, it can be seen that the pit construction risk is divided into four levels. However, the risk assessment combined with the Delphi method has a certain subjectivity, and the assessment results and the delineation of risk level boundaries are often vague. Therefore, it is necessary to introduce the affiliation function for analysis, using the affiliation function to effectively determine the pit construction risk value. According to the principle of maximum affiliation, the risk level of each risk index is determined.

In this paper, the value of pit construction risk is derived by constructing a trapezoidal affiliation function [21, 22]. The trapezoidal affiliation function is shown in Figure 2.

Let $u_1, u_2, u_3, \ldots, u_6$ are the linear values of the proximity threshold of each index, and $U_1, U_2, U_3,$ and U_4 are the values of the derived risk factor levels. Preceding part of the text divides the foundation pit construction risk into 4 levels. The affiliation function of each level is as follows:

The functional equation for Grade I (slightly risk) is as follows:

$$U_1 = \begin{cases} 1, & u_i \le u_1, \\ \dfrac{u_2 - u_i}{u_2 - u_1}, & u_1 < u_i < u_2, \\ 0, & u_i \ge u_2. \end{cases} \tag{1}$$

The functional equation for Grade II (general risk) is as follows:

$$U_2 = \begin{cases} 0, & u_i \le u_1 \text{ or } u_i \ge u_4, \\ \dfrac{u_i - u_1}{u_2 - u_1}, & u_1 < u_i < u_2, \\ 1, & u_2 \le u_i \le u_3, \\ \dfrac{u_4 - u_i}{u_4 - u_3}, & u_3 < u_i < u_4. \end{cases} \tag{2}$$

The functional equation for Grade III (significant risk) is as follows:

$$U_3 = \begin{cases} 0, & u_i \le u_3 \text{ or } u_i \ge u_6, \\ \dfrac{u_i - u_3}{u_4 - u_3}, & u_3 < u_i < u_4, \\ 1, & u_4 \le u_i \le u_5, \\ \dfrac{u_6 - u_i}{u_6 - u_5}, & u_5 < u_i < u_6. \end{cases} \tag{3}$$

Table 1: Degree of consequence grade index.

Serious injury (SI), death (D)/person	Direct economic loss/10,000,000 RMB	Environmental impact	Social impact	Assignment
$SI < 3$ or $D < 10$	<1	Small	Consider	1
$SI \in [3, 10)$ or $D \in [10, 50)$	[1, 5)	Big	Serious	2
$SI \in [10, 30)$ or $D \in [50,100)$	[5, 10)	Very big	More serious	3
$SI \geq 30$ or $D \geq 100$	≥10	Large	Terrible	4

Table 2: Degree of consequence.

Grade	*A*	*B*	*C*	*D*
Degree	Things to consider	Serious	More serious	Disastrous
Assignment	1	2	3	4

Table 3: Index of the probability level of risk occurrence.

Risk event description	Rarely happens	Happens occasionally	May happen	Frequently
Things to consider/%	<0.1	[0.1, 1)	[1, 10)	≥10

The functional equation for Grade III (highly risk) is as follows:

$$U_4 = \begin{cases} 0, & u_i \leq u_5, \\ \dfrac{u_i - u_5}{u_6 - u_5}, & u_5 < u_i < u_6, \\ 1, & u_i \geq u_6. \end{cases} \quad (4)$$

The risk value of each risk event is input into equations (1)–(4); the affiliation r_{ij} of each pit construction risk factor index to the risk level is calculated. According to the principle of maximum affiliation in fuzzy mathematics, the risk level of each risk event is determined by comparing the calculation results. Among them, the risk value R is specifically expressed as follows:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}. \quad (5)$$

3. Foundation Pit Construction Risk Assessment Model

According to the engineering characteristics of pit construction, operation equipment, and other aspects, risk identification needs not only to grasp the overall situation of the project but also to take into account the specific details of engineering construction. The WBS-RBS engineering risk identification method can meet the above requirements, so this paper uses this method for the identification of pit construction risks [23, 24]. In order to obtain richer foundation pit risk assessment content and more accurate risk judgment, the Delphi method is used to obtain the scores of each index of the probability of occurrence and consequences of foundation pit construction risks. At the same time, the bias of some nonprofessional risk assessment on the risk judgment results is reduced as much as possible. AHP is effectively used to calculate the weight of each index of the consequences of risk. In turn, the risk value of each risk factor of the pit construction risk is obtained from the risk value calculation formula. The final total risk value of the whole pit construction is obtained by the relative weight of each local item. In order to avoid the fuzzy definition between risk levels, risk grading is carried out with the help of the affiliation function, and the affiliation degree is calculated by using the affiliation functions corresponding to different risk levels. According to the relevant principles, the affiliation degree is compared, and the risk level of the risk event is obtained. In this paper, the risk assessment of foundation pit construction is realized step by step through the above three main steps. The risk assessment model of foundation pit construction is shown in Figure 3 [25].

4. Case Study

4.1. Project Profile. A central hospital in X city has a new outpatient surgery building with a total construction area of 20560 m^2, of which the above-ground ten-story construction area is 17420 m^2 and the underground one-story construction area is 3140 m^2. The foundation treatment adopts graded sandstone bedding whole piece treatment, the bottom elevation of the foundation pit is 795.730 m and 796.330 m, and the excavation volume is 32500 m^3. The parameters of the main soil layer of the foundation pit related are shown in Table 6. There are existing buildings around the upper entrance of the foundation pit, and the minimum distance is 3 m, and the maximum distance is 13 m. According to the geological survey report and design drawings, the pit bottom elevation was obtained below the groundwater level. Therefore, the excavation of the pit involves pit precipitation works.

Table 4: Probability level of risk occurrence.

Grade	*a*	*b*	*c*	*d*
Description	Things to consider	Serious	More serious	Disastrous
Assignment	1	2	3	4

Table 5: Grading criteria for risk.

Scale	Risk value	Grade	Acceptance criteria	Control measures
I	[1, 3]	Slightly risk	Permissible	Strengthen daily management and timely changes
II	(3, 6]	General risk	Acceptable	Focused attention for prevention and control
III	(6, 9]	Significant risk	Unwilling to accept	Develop countermeasures for timely resolution
IV	(9, 16]	Highly risk	Unacceptable	Stop immediately, rectify, circumvent

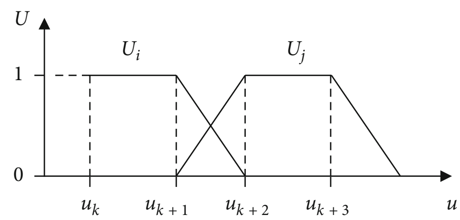

Figure 2: General form of trapezoidal membership function.

4.2. Risk Evaluation Index System. There are many risk factors in the construction of foundation pit projects, and in order to better realize the risk assessment of foundation pit construction, an exclusive evaluation index system should be established before the risk assessment. The selection of evaluation indicators generally follows the principles of completeness, independence, and typicality. Completeness means that the evaluation indicators must be selected in a scientific and comprehensive manner, reflecting all aspects involved as far as possible. Independence means that when constructing the evaluation index system, each index is independent of each other, and the content is clearly directed. Try to select indicators with less linkage to avoid the negative impact of the duplication of indicators on the final evaluation results. Typicality means that among many related evaluation factors, the most closely related and representative indexes should be selected, instead of simply appropriating all related contents to form a noncohesive index.

The construction of risk evaluation index system in this paper is based on the actual foundation pit construction project. Combined with the WBS-RBS method and the content of total safety management to sort out and identify the risk factors step by step. After identifying the foundation pit construction risks through WBS-RBS, the risks of foundation pit project are divided into 5 categories, which are personnel risks, construction risks, geological conditions, geotechnical design, and management risks. The risks in construction are screened out as comprehensively as possible and constitute the index system for evaluating the risks of foundation pit construction. It includes 5 primary indicators and 16 secondary indicators, as shown in Figure 4.

4.3. Risk Indicator Scores. The risk evaluation index system was obtained by combining the affiliation of each risk factor for pit construction. From Sections 2.4 and 2.5, it can be concluded that the scoring rules for risk events are divided into two aspects. On the one hand, the degree of risk consequences (r) is divided into four levels: A, B, C, and D, corresponding to scores of 1, 2, 3, and 4. On the other hand, the probability of risk occurrence (p) is similarly divided into four levels: a, b, c, and d, corresponding to scores of 1, 2, 3, and 4. From this, the risk value of each risk event can be quantified, and the calculation of the risk value (v) can be performed with the help of the following equation [26].

$$v = r \times p. \tag{6}$$

The Delphi method was used to score the construction risks, and eight experts in the industry were invited to participate in the scoring. Each expert was provided with the special construction plan, excavation drawings, and other relevant background information for the risk assessment project, and the experts rated each risk in terms of the degree of consequence and probability of occurrence. The scores of each risk factor are derived from the review and evaluation, and each expert score will form a corresponding score sheet, where the rating scale of expert (E_1) is shown in Table 7.

The weights of the degree of consequence of risk were obtained from the AHP, and then, the individual risk values were calculated. The weights of the degree of consequence obtained after expert (E_1) scoring are shown in Table 8.

A total of five indicators of risk consequence degree and risk occurrence probability were matched with corresponding scores. The risk value obtained for each risk event after expert scoring was calculated according to formula (6). The scores of eight experts were summarized to form an expert rating scale and a rating summary chart, as shown in Table 9 and Figure 5.

4.4. Indicator Weights. Establish a judgment matrix of indicators at all levels and use hierarchical analysis to determine the weight of foundation pit construction risk indicators

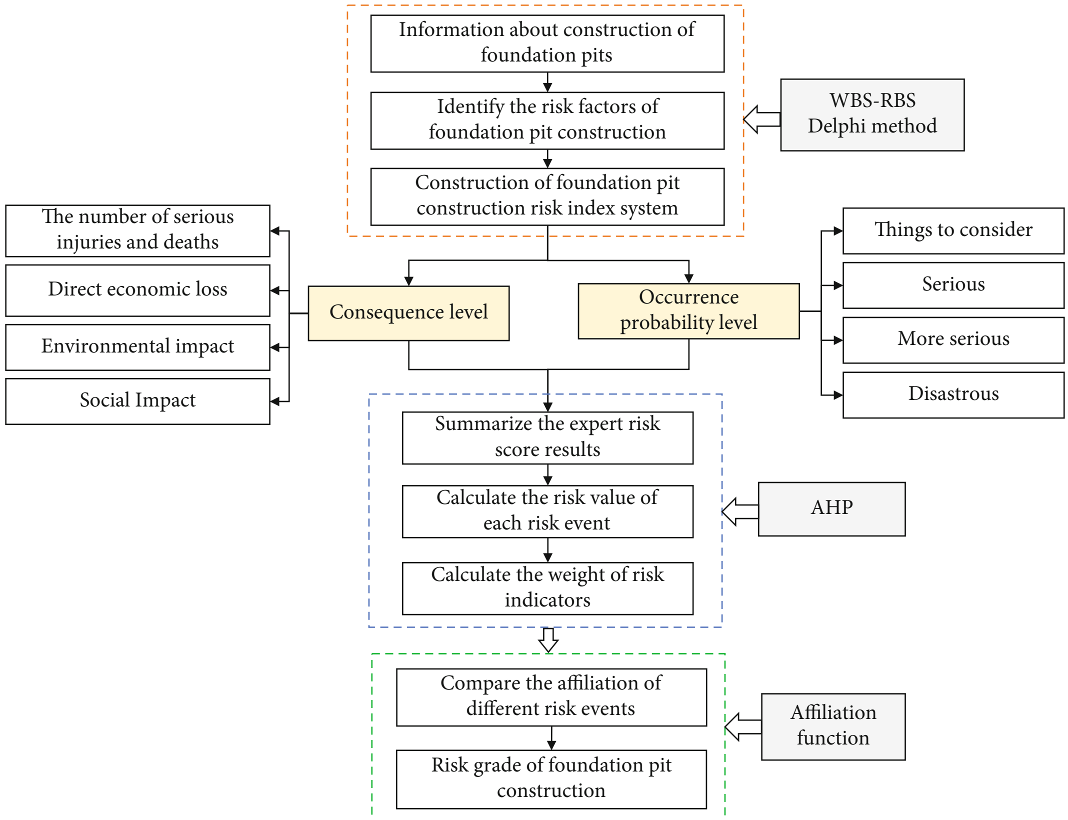

Figure 3: Risk assessment model of foundation pit construction.

Table 6: The main parameters of the rock.

Soil layer name	Soil thickness (m)	Layer bottom depth (m)	Floor elevation (m)	Carrying capacity (kPa)
Mixed fill	0.70-1.10	0.70-1.10	801.60-803.02	—
Vegetative fill	0.70-0.80	0.70-0.80	802.58-802.62	—
Loess	2.50-3.80	3.20-4.50	798.20-800.00	160
Pebbles	0.90-3.80	5.30-7.70	795.68-798.13	250
Strongly weathered mudstone	11.50-13.50	18.50-19.80	783.20-785.11	330

$(w_i, 0 \le w_i \le 1)$, and the weight of each risk factor indicator is shown in Table 10.

4.5. Affiliation Matrix. Based on the affiliation function formulas (1)–(4), the values of u_1, u_2, $u_3,\cdots,u_6$ in the formula are taken as 1, 2, 3,⋯,6, respectively. The affiliation degree of foundation pit construction risk index to each risk level is calculated. The calculation results are shown in Table 11.

4.6. Risk Level Fuzzy Evaluation

4.6.1. One-Level Fuzzy Integrated Evaluation. In the process of foundation pit construction risk evaluation, the fuzzy comprehensive evaluation formula is $B_i = w_i{}^\circ R_i = (b_1, b_2, b_3 \cdots b_n)$, and for personnel risk U_1, the evaluation process is as follows:

$$B_1 = w_1{}^\circ R_1 = (0.109, 0.309, 0.582)^\circ \begin{bmatrix} 0.125 & 0.375 & 0.250 & 0.250 \\ 0 & 0.250 & 0.125 & 0.625 \\ 0 & 0.250 & 0.625 & 0.125 \end{bmatrix} = (0.014, 0.264, 0.429, 0.293). \quad (7)$$

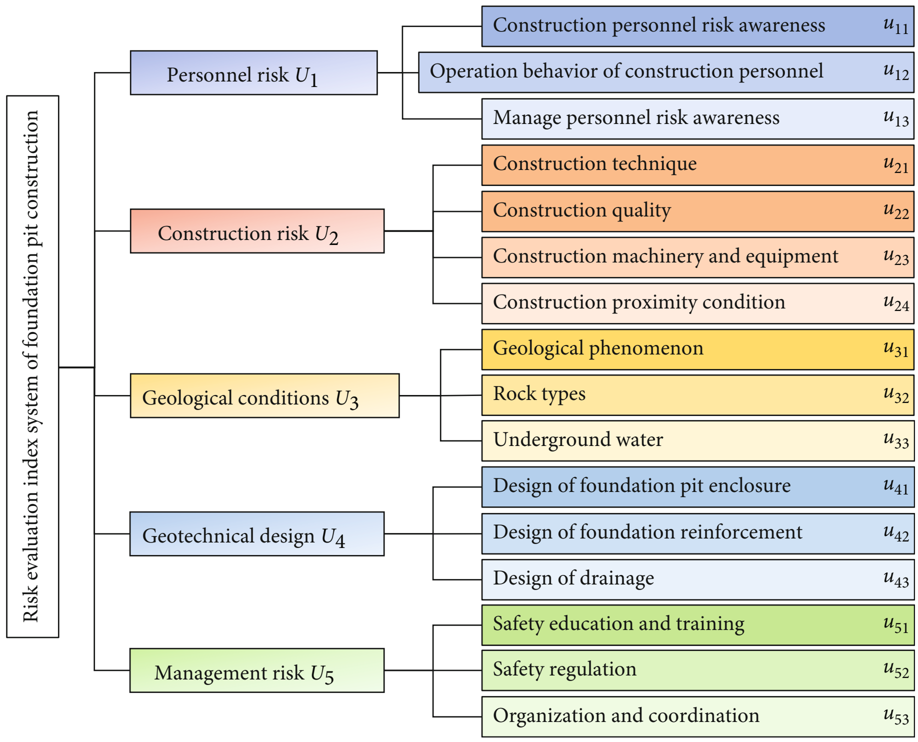

FIGURE 4: Risk evaluation index system of foundation pit construction.

TABLE 7: Rating scale (expert E_1).

Risk indicators	Personnel casualties	Economic loss	Environmental impact	Social impact	Occurrence probability
Construction personnel risk awareness u_{11}	4	3	1	3	4
Operation behavior of construction personnel u_{12}	4	4	2	4	4
Manage personnel risk awareness u_{13}	4	2	2	3	4
Construction technique u_{21}	3	1	3	1	2
Construction quality u_{22}	3	2	4	1	1
Construction machinery and equipment u_{23}	2	3	3	1	1
Construction proximity condition u_{24}	2	1	3	3	2
Geological phenomenon u_{31}	2	3	3	2	2
Rock types u_{32}	2	2	1	1	1
Underground water u_{33}	3	3	2	3	2
Design of foundation pit enclosure u_{41}	3	3	3	1	2
Foundation reinforcement design u_{42}	3	3	2	1	2
Drainage design u_{43}	3	2	3	1	2
Safety education and training u_{51}	4	2	1	2	3
Safety regulation u_{52}	4	2	1	2	3
Organization and coordination u_{53}	2	1	1	1	3

Table 8: Consequence degree index weight (expert E_1).

Index	Personnel casualties	Economic loss	Environmental impact	Social impact
Weights	0.452	0.057	0.197	0.294

Based on the principle of maximum affiliation, it is known that the personnel risk is at level III, which is a significant risk.

For construction risk U_2, the evaluation process is as follows:

$$B_2 = w_2{}^{\circ} R_2 = (0.126, 0.078, 0.326, 0.469)^{\circ} \begin{bmatrix} 0.375 & 0.625 & 0 & 0 \\ 0.250 & 0.500 & 0.250 & 0 \\ 0.375 & 0.375 & 0.125 & 0.125 \\ 0.375 & 0.375 & 0.250 & 0 \end{bmatrix} = (0.365, 0.416, 0.178, 0.041). \quad (8)$$

Based on the principle of maximum affiliation, it is known that the construction risk is at level II, which is a general risk.

For geological conditions U_3, the evaluation process is as follows:

$$B_3 = w_3{}^{\circ} R_3 = (0.168, 0.484, 0.349)^{\circ} \begin{bmatrix} 0.250 & 0.625 & 0.125 & 0 \\ 0.375 & 0.625 & 0 & 0 \\ 0.250 & 0.500 & 0.250 & 0 \end{bmatrix} = (0.310, 0.581, 0.108, 0). \quad (9)$$

Based on the principle of maximum affiliation, it is known that the geological condition is at level II, which is a general risk.

For geotechnical design U_4, the evaluation process is as follows:

$$B_4 = w_4{}^{\circ} R_4 = (0.364, 0.537, 0.099)^{\circ} \begin{bmatrix} 0 & 0.625 & 0.375 & 0 \\ 0.125 & 0.500 & 0.375 & 0 \\ 0.125 & 0.500 & 0.125 & 0.250 \end{bmatrix} = (0.079, 0.546, 0.350, 0.025). \quad (10)$$

Based on the principle of maximum affiliation, it is known that the geotechnical design is at level II, which is a general risk.

For management risk U_5, the evaluation process is as follows:

$$B_5 = w_5{}^{\circ} R_5 = (0.320, 0.558, 0.122)^{\circ} \begin{bmatrix} 0 & 0.375 & 0.625 & 0 \\ 0.125 & 0.125 & 0.375 & 0.375 \\ 0.250 & 0.750 & 0 & 0 \end{bmatrix} = (0.100, 0.281, 0.409, 0.209). \quad (11)$$

Based on the principle of maximum affiliation, it is known that the management risk is at level III, which is a significant risk.

4.6.2. Two-Level Fuzzy Integrated Evaluation. For the comprehensive risk of foundation pit construction, the evaluation process is as follows:

$$B = w^{\circ} R = (0.057, 0.158, 0.096, 0.276, 0.412)^{\circ} \cdot \begin{bmatrix} 0.014 & 0.264 & 0.429 & 0.293 \\ 0.365 & 0.416 & 0.178 & 0.041 \\ 0.310 & 0.581 & 0.108 & 0 \\ 0.079 & 0.546 & 0.350 & 0.025 \\ 0.100 & 0.281 & 0.409 & 0.209 \end{bmatrix} = (0.152, 0.403, 0.328, 0.116). \quad (12)$$

According to the principle of maximum affiliation, $B_{max} = 0.403$, so the comprehensive risk of foundation pit construction is at level II, which is a general risk.

5. Analysis and Discussion

The risk value of each risk factor is calculated by obtaining the score of foundation construction risk factors in terms of consequence degree and probability of occurrence through the Delphi method. In order to more intuitively reflect the risk level corresponding to each risk index of foundation construction, the risk level intervals are correlated with the risk values of the indicators, as shown in Figure 6. The comparison shows that the risk level of u_{32} (rock types) is I, and the degree is slightly risk, which needs to strengthen daily management and timely change. u_{21} (construction technique), u_{22} (construction quality), u_{23} (construction machinery and equipment), u_{24} (construction proximity condition), u_{31} (geological phenomenon), u_{33} (underground water), u_{42} (foundation reinforcement design), and u_{53} (organization and coordination) are level II; the degree of general risk should focus on and timely prevention and control. u_{11} (construction personnel risk awareness), u_{13} (manage personnel risk awareness), u_{41} (design of foundation pit enclosure), u_{43} (drainage design), u_{51} (safety education and training), and u_{52} (safety regulation) are level III, the degree is

Table 9: Summary of expert evaluation scales.

Expert	Evaluation indicators															
	u_{11}	u_{12}	u_{13}	u_{21}	u_{22}	u_{23}	u_{24}	u_{31}	u_{32}	u_{33}	u_{41}	u_{42}	u_{43}	u_{51}	u_{52}	u_{53}
E_1	9.2	13.3	12.8	4.6	2.6	2.0	4.9	4.5	1.5	5.6	4.8	4.4	4.7	8.1	8.1	4.4
E_2	5.3	10.5	6.8	5.9	9.9	2.7	3.1	6.1	1.5	2.2	6.4	1.9	1.5	5.9	10.3	5.2
E_3	9.9	11.6	7.9	16.0	7.8	11.6	8.0	3.1	3.1	8.2	6.6	7.6	6.0	7.0	13.3	8.1
E_4	6.1	3.9	5.4	2.5	6.4	6.2	2.2	2.9	3.4	2.0	5.8	5.7	4.5	8.1	9.5	4.7
E_5	8.9	8.7	5.5	4.7	3.0	3.3	2.0	4.2	3.6	5.4	8.4	8.4	4.3	4.6	6.7	1.3
E_6	2.4	10.1	6.9	3.0	3.7	4.0	3.0	3.6	3.2	5.9	7.6	7.0	9.4	7.2	2.1	3.0
E_7	5.3	11.7	7.1	2.1	3.2	5.9	6.9	5.1	1.5	5.8	4.5	4.8	9.4	3.4	4.6	3.9
E_8	4.3	4.0	7.0	4.7	5.8	2.1	3.7	2.8	6.0	6.6	6.3	5.9	9.5	8.0	6.1	3.9
Risk value	6.4	9.2	7.4	5.4	5.3	4.7	4.2	4.0	3.0	5.2	6.3	5.7	6.2	6.5	7.6	4.3

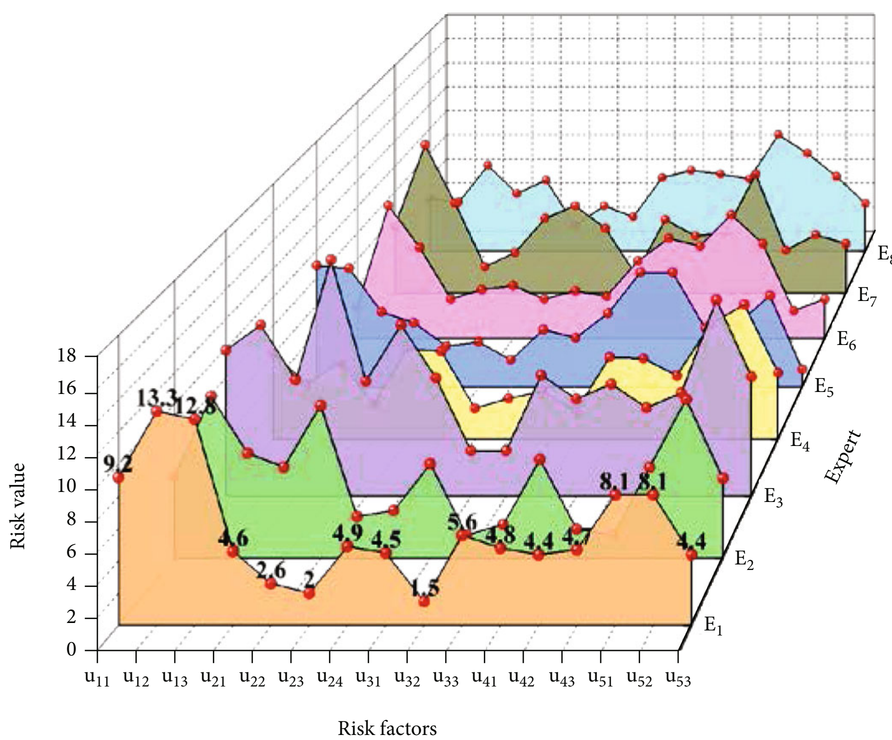

Figure 5: Expert rating summary figure.

Table 10: Weighting of foundation pit construction risk indicators.

Risk factors	Weights				
Personnel risk u_{1i}	0.109	0.309	0.582	—	—
Construction risk u_{2i}	0.126	0.078	0.326	0.469	—
Geological conditions u_{3i}	0.168	0.484	0.349	—	—
Geotechnical design u_{4i}	0.364	0.537	0.099	—	—
Management risk u_{5i}	0.320	0.558	0.122	—	—
Comprehensive risks of foundation pit construction U_i	0.057	0.158	0.096	0.276	0.412

Table 11: Risk level affiliation.

Indicators	Grade			
	Slightly risk I	General risk II	Significant risk III	Highly risk IV
Construction personnel risk awareness u_{11}	0.125	0.375	0.250	0.250
Operation behavior of construction personnel u_{12}	0	0.250	0.125	0.625
Manage personnel risk awareness u_{13}	0	0.250	0.625	0.125
Construction technique u_{21}	0.375	0.625	0	0
Construction quality u_{22}	0.250	0.500	0.250	0
Construction machinery and equipment u_{23}	0.375	0.375	0.125	0.125
Construction proximity condition u_{24}	0.375	0.375	0.250	0
Geological phenomenon u_{31}	0.250	0.625	0.125	0
Rock types u_{32}	0.375	0.625	0	0
Underground water u_{33}	0.250	0.500	0.250	0
Design of foundation pit enclosure u_{41}	0	0.625	0.375	0
Foundation reinforcement design u_{42}	0.125	0.500	0.375	0
Drainage design u_{43}	0.125	0.500	0.125	0.250
Safety education and training u_{51}	0	0.375	0.625	0
Safety regulation u_{52}	0.125	0.125	0.375	0.375
Organization and coordination u_{53}	0.250	0.750	0	0

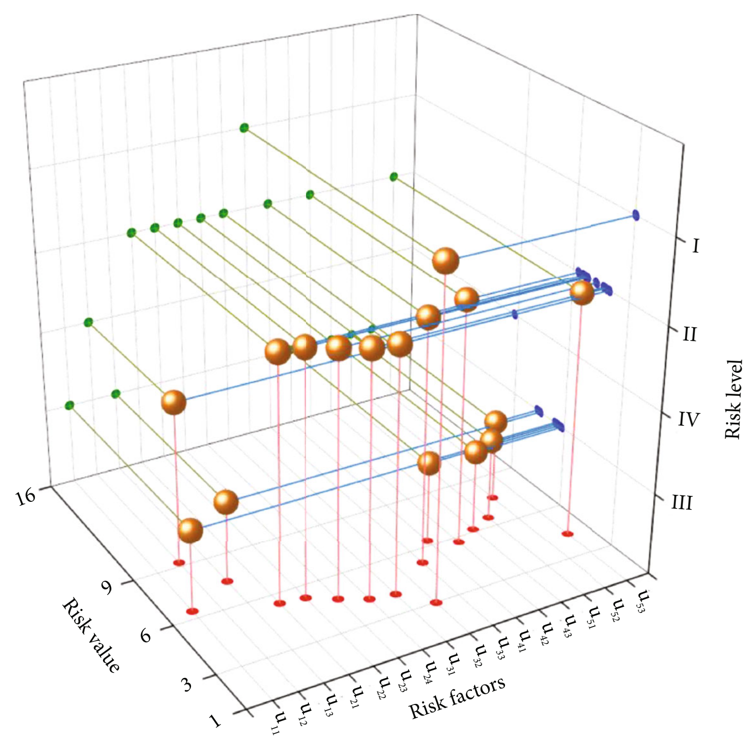

Figure 6: Risk factor, risk value, and risk level interval comparison.

significant risk, and the corresponding solution should be developed. The risk level of u_{12} (operation behavior of construction personnel) is IV, and the degree of highly risk should focus on and timely start the plan or implementation of the program to avoid unnecessary losses and injuries caused by risk.

From the risk assessment of the project example, it is known that the risk level of U_1 (personnel risk) is III, and the degree is significant risk. Therefore, in the process of foundation pit construction, we should cultivate the risk consciousness of construction personnel and regulate their operation behavior. At the same time, the management personnel should also have a strong awareness of risk and supervise the safety of personnel from the control level. The risk levels of U_2 (construction risk), U_3 (geological conditions), and U_4 (geotechnical design) are II, and the degree is general risk. According to the actual situation of underground facilities and neighboring buildings at the construction site, a scientific and reasonable construction plan is formulated and strictly followed, with a view to avoiding construction risks. The geological conditions and geotechnical design are important risk factors affecting construction safety during the construction of the foundation pit, and a reasonable and perfect real-time monitoring program and safety measures program must be adopted. The risk level of U_5 (management risk) is III, the degree of significant risk. In the process of carrying out safety management, the construction unit needs to optimize the entire construction process and reasonably allocate resources to ensure the quality and safety of construction. And the comprehensive risk evaluation of the system is level II, the degree of general risk. The pit is generally in a safe state, but there are still certain safety hazards. It is necessary to take appropriate monitoring measures and early warning means for major risk sources to ensure construction safety.

6. Conclusion

In the process of foundation pit construction risk assessment, the risk consequence degree index is refined and divided into five aspects: human casualty, economic loss, environmental impact and social impact, and the probability of occurrence. In the expert scoring session of the Delphi method, the risk value of the risk event is obtained by combining the influence of both the degree of risk consequences and the probability of occurrence.

The pit construction risks are summarized and analyzed from five perspectives: personnel, construction, geology, geotechnical, and management, and a comprehensive risk evaluation index system is constructed, which includes 5 primary indicators and 16 secondary indicators.

The results of the case study showed that the risk level of "personnel risk" is III and the degree of significant risk. The risk levels of "construction risk," "geological conditions," and "geotechnical design" are level II and the degree of general risk. The risk level of "management risk" is level III, and the degree is significant risk. The comprehensive risk evaluation of the system is level II, and the degree is general risk. This method has some practical engineering significance and can provide preliminary reference for similar foundation pit construction projects.

Data Availability

The data sets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Lei Li contributed to the conceptualization, supervision, and funding acquisition. Ruihan Li contributed to the methodology, software, and writing—original draft. Mei Zhi contributed to the investigation, supervision, and writing—review and editing. Siwei Wang contributed to the investigation and writing—review and editing. Lirong Cao contributed to the supervision and writing—review and editing.

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