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Research Article

Risk Assessment of EPB Shield Construction Based on the Nonlinear FAHP Method

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There are many risk factors in EPB shield construction. The traditional fuzzy analytic hierarchy process (FAHP) method usually uses a linear analysis method to determine the risk level, but there are often some risk factors with prominent influence, which will reduce the accuracy of the evaluation results. In this paper, a new risk assessment model of Earth pressure balance (EPB) shield construction based on a nonlinear FAHP method is established by introducing nonlinear factors into the comprehensive calculation of the traditional FAHP. First, the new model establishes the framework of EPB shield construction risk analysis based on the work breakdown structure (WBS) and risk breakdown structure (RBS) methods. Then, it constructs an EPB shield construction risk index system by coupling the units of the WBS and RBS. The model constructs a fuzzy consistent judgment matrix, which replaces the 1~9 scale. Finally, the nonlinear operator is introduced into the FAHP comprehensive calculation, considering the influence of some prominent risk factors, which improves the accuracy of the risk assessment. By applying the new model to the risk analysis of the EPB shield construction section of a tunnel project in Hangzhou, the effectiveness of the model is further verified.

1. Introduction

In China, with the continuous development of urbanization, the contradiction between limited land resources and the growing urban population has become increasingly prominent. To solve the problems of urban ground traffic congestion and land energy shortages, the development and utilization of urban underground space has become an inevitable trend of urban development to a certain stage [1, 2]. EPB shields are widely used in the underground tunnel construction of urban rail transit, utility tunnel, and other projects because of their advantages of high safety, fast excavation speed, automatic operation throughout the excavation process, and low construction labor intensity. However, EPB shield construction has the risks of water permeability, sand gushing, mud bursting, and collapse, which can easily cause large-scale surface collapse and damage to underground pipelines or surrounding buildings. Therefore, the risk assessment of urban underground space engineering has important theoretical significance to ensure the safety of construction and the surrounding environment.

In 1980, Saaty proposed analytic hierarchy process, which is a multiobjective system decision-making method combining qualitative and quantitative aspects. It is widely used in social, economic, management, military, and other fields. In 1996, Einstein outlined the basic aspects of risk analysis and decision-making, and then discussed in detail three typical rock engineering applications of risk analysis: (1) slope design, (2) fractured medium flow, and (3) tunnel excavation [3]. Fuzziness and uncertainty are one of the characteristics of risk assessment. Various uncertain factors can be expressed quantitatively by membership function, so as to realize the transformation of risk assessment from qualitative to quantitative. Based on the uncertainty model of fuzzy mathematics, Choi et al. established a standardized underground engineering evaluation method and applied this method to the Seoul metro project in South Korea for subway construction risk evaluation, which verified its effectiveness [4]. In addition, in the field of civil engineering, the factors to be considered in risk assessment can be divided into three parts: preconstruction preparation, main construction process, and auxiliary construction process according to the construction characteristics. In this regard, many scholars have carried out corresponding research according to different engineering characteristics. Dağdeviren and Yüksel studied the safety risk of TBM construction by using the FAHP and proposed an evaluation model for the TBM dynamic performance [5]. Zhou and Cao established the comprehensive evaluation index system of the foundation pit support scheme by analyzing the influencing factors of urban deep foundation pit support in soft soil area, obtained the weight value of each risk factor by using analytic hierarchy process, determined the relative superior degree matrix by logical operation, and put forward the FAHP model suitable for the optimization of urban deep foundation pit support scheme in soft soil area [6]. Liu et al. established the construction risk evaluation index system of deep foundation pit by the WBS-RBS method and established the fuzzy level assessment model of construction risk based on the theory of triangle fuzzy mathematics [7]. Deng et al. studied the construction risk of tunnel portal based on Fuzzy AHP and analyzed the Wuguangyi highway tunnel as a case study [8]. Lu et al. used the FAHP to build a model that can be used to evaluate the probability of tunnel collapse accidents [9]. Samantra et al. proposed a comprehensive risk assessment method for urban construction projects based on the fuzzy set theory [10]. Kuchta and Ptaszyńska proposed a fuzzy risk registration method to identify risks in construction projects and evaluate their attributes [11] based on the existing risk assessment theory of urban rail transit project infrastructure. According to the translational velocity and angular velocity characteristics of the TBM, Yu et al. established the dynamic performance evaluation model of the TBM by using the FAHP to determine the weight of the evaluation model [12]. Nezarat et al. used the fuzzy analytic hierarchy process (FAHP) to rank the geological risks of Golab tunnel construction in northwestern Isfahan (Iran) [13]. Lyu et al. proposed an improved trapezoidal fuzzy analytic hierarchy process (FAHP) to evaluate the risk of infrastructure related to land subsidence in megacities and evaluated the risk of infrastructure related to land subsidence in Shanghai [14]. Hu et al. used the analytic hierarchy process and fuzzy principle to determine the weight of each index in the index system, and on this basis, finally established an evaluation system and a classification standard for the highway tunnel structure safety grade state [15]. Based on the fuzzy comprehensive evaluation theory, Zhu et al. proposed a multilevel comprehensive evaluation method for tunnel construction organizations and applied it to an example [16]. Wang et al. took surface vertical settlement, structural stress, crack displacement, and contact pressure as the early warning indicators of the underground comprehensive pipe gallery structure in the active period of ground cracks and gave the safety control value and early warning standard on the basis of the analysis results [17, 18]. Zheng et al. combined triangular fuzzy number (TFN) and analytic hierarchy process (AHP) into the geographic information system (GIS) to evaluate geological disasters along the Zhengkun railway, which not only effectively predicted the risk distribution of geological disasters in the study area in recent 10 years but also put forward risk prevention management measures [19]. Obviously, the abovementioned scholars have made different contributions to the development of underground engineering risk management, but there is less risk analysis related to EPB shield construction.

Generally, FAHP can be divided into FAHP based on fuzzy number and FAHP based on fuzzy consistent matrix [20]. FAHP based on fuzzy numbers includes interval FAHP, triangular FAHP, and trapezoidal FAHP [21]. Interval FAHP uses interval numbers to represent the relative importance of factors[22~24], while triangular/trapezoidal FAHP uses a triangle/trapezoid number to represent the relative importance in pairwise comparison [22, 23]. After constructing the judgment matrix, if the expert's reply to the questionnaire adopts the method of pairwise comparison [24], the consistency check needs to be carried out. The consistency check mainly includes three steps: (1) calculation of consistency index; (2) determination of the average random consistency index; and (3) consistency ratio calculation[25]. When the judgment matrix does not have consistency, the factors of the judgment matrix need to be adjusted to make it consistent. This does not rule out that it needs several times of adjustment and inspection to make the judgment matrix consistent. The process is cumbersome, and the amount of calculation will increase accordingly. Therefore, Lyu et al. proposed a new questionnaire, which is composed of a comprehensive table. The first column lists all factors, and the other columns list 9 scores representing the relative importance of a factor's contribution to construction risk (from 1 = lowest importance to 9 = highest importance). The fuzzy number is determined by scoring all factors directly by experts, and a consistent judgment matrix is established [26]. When experts consider a small number of factors, this method has higher efficiency and greater accuracy, but when experts must consider a large number of factors, the importance of some factors may not be more accurate than pairwise comparison. The FAHP based on the fuzzy consistent matrix first establishes the fuzzy complementary matrix, and then transforms it into the fuzzy consistent judgment matrix for risk assessment. Because the fuzzy consistent judgment matrix transformed from the fuzzy complementary judgment matrix meets the additive consistency condition, that is, the difference between the factors of any two rows is constant, so there is no need to do consistency test [27]. Therefore, by combining this method with pairwise comparison, it can not only ensure the accuracy of experts' scoring of factors but also meet the consistency conditions.

In this paper, the WBS-RBS method is introduced into the system decomposition of the tunnel construction work structure and construction risk source, and the framework structure of EPB shield construction risk analysis is constructed. By coupling the tunnel construction work breakdown structure and construction risk breakdown structure, the risk factors reflecting EPB shield construction are determined, and the EPB shield construction risk index system is built. On this basis, the expert questionnaire is collected by a pairwise comparison method, and the fuzzy consistency judgment matrix is established by transforming the fuzzy complementarity matrix, which not only meets the accuracy and consistency requirements of expert scoring but also avoids the cumbersome consistency test. Finally, the nonlinear operator is introduced into the FAHP comprehensive calculation to improve the accuracy of the risk assessment, and a new EPB shield construction risk assessment model based on the nonlinear fuzzy analytic hierarchy process is established. The new model is applied to the risk analysis of EPB shield construction section of a tunnel project in Hangzhou, and the validity of the model is verified. It also provides ideas and experience for risk assessment in the shield construction field by using nonlinear FAHP.

2. Risk Identification of EPB Shield Construction Based on the WBS-RBS Method

The WBS (work breakdown structure) is a method to divide project tasks into different levels. The basic principle of the WBS is to decompose project tasks into different levels by top-down, bottom-up, or analogy methods. The RBS (risk breakdown structure) is a method to decompose various major risk factors into the most basic risk factors by taking risk management theory as the basic theory and combining quantitative and qualitative risk grading. Hillson and Grimaldi and others first began to integrate the WBS and RBS [28]. The basic principle of the WBS-RBS method is to organically combine the specific risk factors defined in the RBS with the effective scope of work defined in the WBS to construct the risk identification coupling matrix to identify the risk of each underlying unit and establish the risk index system of the engineering project. The steps of WBS-RBS method are as follows [25]: (1) construct the WBS work breakdown structure; (2) build the RBS risk decomposition structure; and (3) associate WBS with RBS, establish WBS-RBS coupling matrix with the work package set at the bottom of WBS and the risk element set at the bottom of RBS, and then analyze the existing risks.

2.1. Establishment of the EPB Shield Construction Work Breakdown Structure. According to the WBS principle, the EPB shield construction process is decomposed into two levels.

(1) According to the main construction stages of the EPB, the first-level WBS is divided into three stages: preparation before EPB shield construction, EPB shield tunneling construction, and EPB ancillary equipment construction.

(2) Combined with the characteristics of each stage of EPB shield construction, the first-level WBS is decomposed into different second-level WBSs by distinguishing different processes.

According to the WBS method, the EPB shield construction work breakdown structure is shown in Figure 1.

2.2. Establishment of the EPB Shield Construction Risk Decomposition Structure. According to the RBS principle, the risk sources of EPB shield construction are decomposed into two levels.

(1) According to the characteristics of EPB shield construction, the first-level RBS can be divided into three types: geological condition risk source, environmental risk source along the line, and other risk sources.

(2) On the basis of the first-level risk decomposition source, the EPB shield construction risk is analyzed in detail, and the first-level risk structure is decomposed into the second-level risk structure.

The risk decomposition structure of EPB shield construction based on the RBS method is shown in Figure 2.

2.3. Establishing the Coupling Matrix of EPB Shield Construction Risk Identification. By coupling the bottom units of the WBS (Figure 1) and RBS (Figure 2), the coupling matrix of EPB shield construction risk identification can be obtained, as shown in Table 1. The result is "0" when the two couplings do not produce risk and "1" when the two couplings produce risk. The results of the EPB shield construction risk identification coupling matrix are classified as follows: (1) $W_{11}R_{11}$, $W_{11}R_{14}$, $W_{11}R_{31}$, and $W_{11}R_{33}$: end reinforcement failure of shield shaft; (2) $W_{12}R_{11}$, $W_{12}R_{14}$, $W_{12}R_{31}$, and $W_{12}R_{33}$: tunnel portal collapsed; (3) $W_{13}R_{31}$, and $W_{13}R_{33}$: backup system failure; (4) $W_{14}R_{31}$, $W_{14}R_{32}$, and $W_{14}R_{33}$: bracket deformation and instability; (5) $W_{15}R_{31}$ and $W_{15}R_{33}$: deviation of the shield tunneling route; (6) $W_{16}R_{31}$, $W_{16}R_{32}$, and $W_{16}R_{33}$: failure of the shield machine assembly and commissioning; (7) $W_{21}R_{11}$, $W_{21}R_{31}$, and $W_{21}R_{32}$: collapse of the tunnel face; (8) $W_{21}R_{21}$, $W_{23}R_{21}$, and $W_{24}R_{21}$: settlement of surface buildings; (9) $W_{21}R_{22}$, $W_{23}R_{22}$, and $W_{24}R_{22}$: buried pipelines damage; (10) $W_{21}R_{23}$, $W_{23}R_{23}$, and $W_{24}R_{23}$: deformation of underground buildings or structures; (11) $W_{21}R_{24}$, $W_{23}R_{24}$, and $W_{24}R_{24}$: road surface heave or settlement; (12) $W_{22}R_{11}$ and $W_{22}R_{14}$: water and sand gushing in tunnel face; (13) $W_{22}R_{13}$, $W_{22}R_{32}$, and $W_{31}R_{13}$: harmful gas accumulation in tunnel; (14) $W_{22}R_{31}$ and $W_{22}R_{33}$: discontinuous transportation of muck; (15) $W_{25}R_{11}$, $W_{25}R_{12}$, $W_{25}R_{31}$, and $W_{25}R_{33}$: cutting tools damage; (16) $W_{31}R_{31}$ and $W_{31}R_{33}$: poor ventilation and dust collection in the tunnel; (17) $W_{32}R_{31}$ and $W_{32}R_{33}$: tunnel lighting system failure; (18) $W_{33}R_{14}$, $W_{33}R_{31}$, and $W_{31}R_{33}$: water accumulation in tunnel; and (19) $W_{34}R_{31}$, $W_{33}R_{32}$, and $W_{31}R_{33}$: leakage of lining segment.

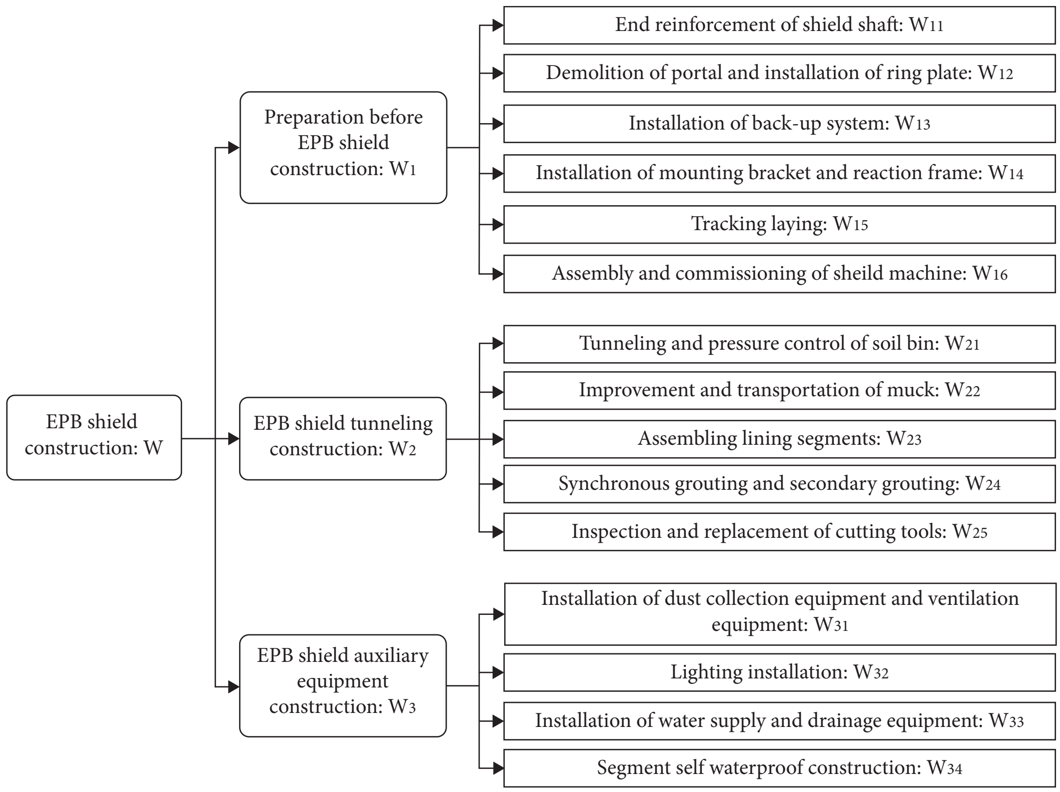

Figure 1: EPB shield construction work breakdown structure.

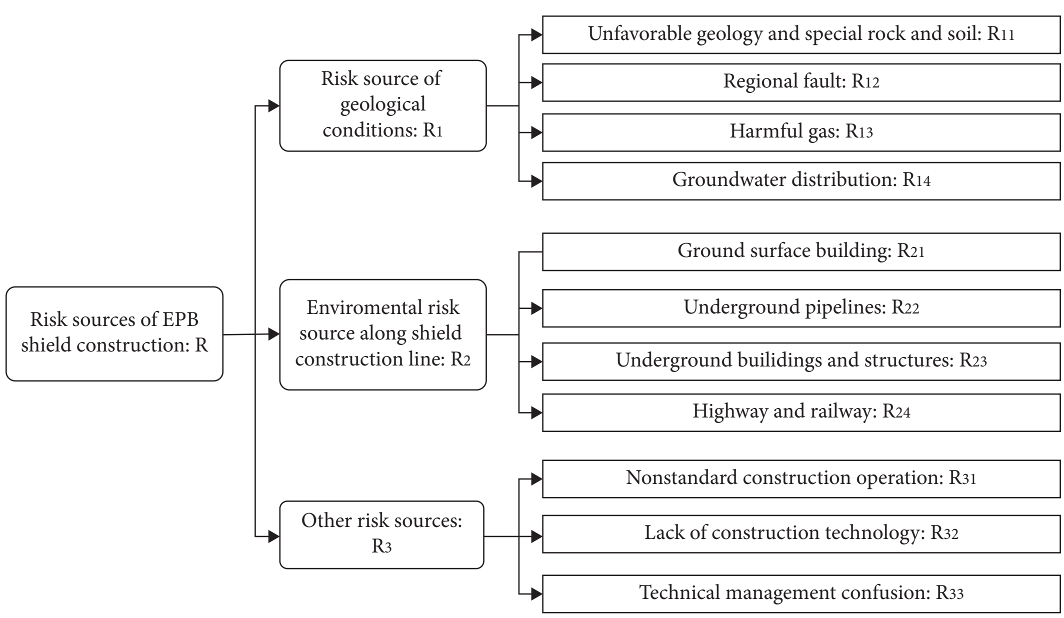

Figure 2: EPB shield construction risk decomposition structure.

2.4. Establishment of the EPB Shield Construction Risk Index System. By combining the results of the EPB shield construction risk identification coupling matrix with the experience of onsite management personnel and expert suggestions and sorting out and classifying the risks that can reflect EPB shield construction, the final EPB shield construction risk index system is shown in Figure 3.

3. EPB Shield Construction Risk Assessment

3.1. Establishment of the Fuzzy Relation Matrix

3.1.1. Establishment of the Risk Assessment Set. Risk evaluation refers to the description of risk evaluation indicators by using qualitative language. The evaluation set in this

Table 1: Coupling matrix of EPB shield construction risk identification.

		W_1						W_2					W_3			
		W_{11}	W_{12}	W_{13}	W_{14}	W_{15}	W_{16}	W_{21}	W_{22}	W_{23}	W_{24}	W_{25}	W_{31}	W_{32}	W_{33}	W_{34}
R_1	R_{11}	1	1	0	0	0	0	1	1	0	1	1	0	0	0	0
	R_{12}	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
	R_{13}	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
	R_{14}	1	1	0	0	0	0	0	1	0	0	0	0	0	1	0
R_2	R_{21}	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0
	R_{22}	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0
	R_{23}	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0
	R_{24}	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0
R_3	R_{31}	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
	R_{32}	0	0	0	1	0	1	1	1	0	0	0	0	0	0	1
	R_{33}	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1

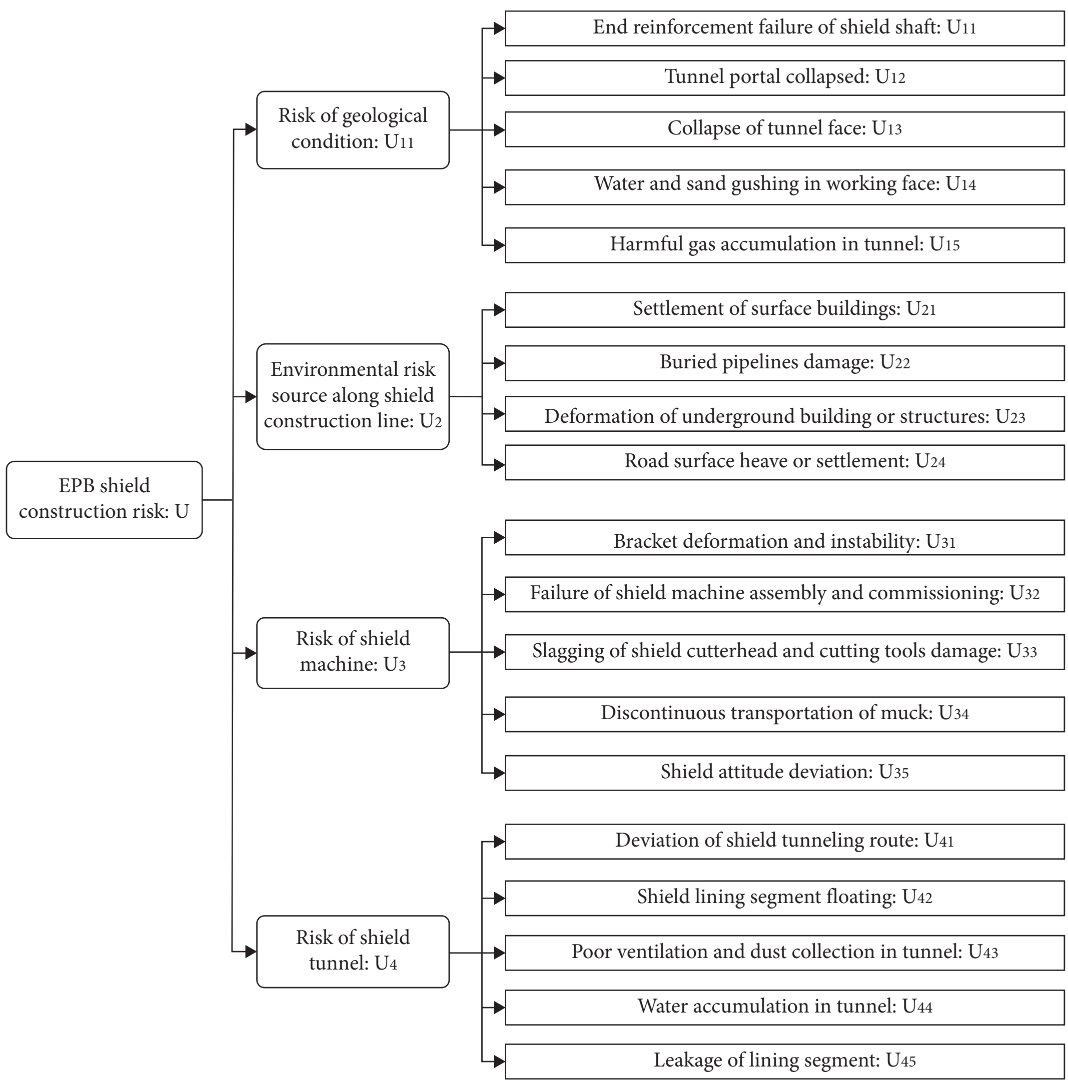

Figure 3: EPB shield construction risk index system diagram.

paper refers to the collection of comments made by judges on various construction risks of EPB shields. According to the characteristics of EPB shield construction, the comments can be divided into five levels:

$$V = \{ v_1 \ \ v_2 \ \ v_3 \ \ v_4 \ \ v_5 \} = \{ \text{Lowest risk} \ \ \text{low risk} \ \ \text{medium risk} \ \ \text{high risk} \ \ \text{highest risk} \}. \quad (1)$$

3.1.2. Establishment of the Risk Factor Set. The factor set involved in this paper is based on the EPB shield construction risk index system. The first-level index risk factor set is as follows: $U = \{U_1, U_2, U_3, U_4\}$; the second-level index risk factor set is as follows: $U_1 = \{u_{11}, u_{12}, u_{13}, u_{14}, u_{15}\}$, $U_2 = \{u_{21}, u_{22}, u_{23}, u_{24}\}$, $U_3 = \{u_{31}, u_{32}, u_{33}, u_{34}\}$, $U_4 = \{u_{41}, u_{42}, u_{43}, u_{44}, u_{45}\}$.

3.1.3. Establishment of the Membership Vector. The expert evaluation method is a quantitative evaluation method based on quantitative and qualitative analysis, through which the target events are scored by experts. The expert group consists of 10 experts who have worked in the field of tunnel construction safety for more than 8 years, including 6 doctors and 4 masters. According to the grade of the risk evaluation, the evaluation index of each risk factor is scored, and the membership vector of EPB shield construction risk evaluation is constructed [29]. The membership vector of any risk factor concentration evaluation index u_i in the EPB shield construction risk evaluation index u to v_{ij} in the risk evaluation set V is as follows: $R_i = [r_{i1}, r_{i2}, r_{i3}, r_{i4}, r_{i5}]$.

3.1.4. Establishment of the Fuzzy Relation Matrix. According to the construction principle of the membership vector, the membership vector of each risk index to the evaluation set in the EPB shield construction risk assessment is obtained. The fuzzy relation matrix between the risk evaluation set and the factor set is obtained by combining the membership vectors corresponding to each risk index as follows:

$$R = \begin{bmatrix} r_{11} & \cdots & r_{1j} & \cdots & r_{1m} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ r_{i1} & \cdots & r_{ij} & \cdots & r_{im} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ r_{n1} & \cdots & r_{nj} & \cdots & r_{nm} \end{bmatrix}. \quad (2)$$

where $0 \leq r_{ij} \leq 1$ and r_{ij} is the membership of the i-th factor to the j-th risk level.

3.2. Determination of the Weight Vector. According to the established EPB shield construction risk evaluation index system, the weight of each risk factor in the EPB shield construction risk evaluation is calculated by using the analytic hierarchy process [30].

3.2.1. Establishment of the Fuzzy Complementary Judgment Matrix. The fuzzy complementary judgment matrix R represents a comparison of the relative importance of the factors related to a certain factor in the previous level. Assuming that the factor of the upper level is C and the related factor of the lower level is $a_1, a_2, \cdots, a_n$, the fuzzy complementary judgment matrix can be expressed as in Table 2.

Factor r_{ij} means that when factor a_i and factor a_j are compared with the upper level factor C, factor a_i and factor a_j have a membership degree of "more important than." By using the 0.1~0.9 scale method [31], the relative importance of any two factors in this layer to the upper layer is quantitatively described, as shown in Table 3.

Table 2: Fuzzy complementary judgment matrix.

C	a_1	a_2	$\cdots$	a_n
a_1	r_{11}	r_{12}	$\cdots$	r_{1n}
a_2	r_{21}	r_{22}	$\cdots$	r_{2n}
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
a_n	r_{n1}	r_{n2}	$\cdots$	r_{nn}

After a quantitative description with the 0.1~0.9 scale method, the following fuzzy complementary judgment matrix can be obtained by comparing the upper factor C with the related factor $a_1, a_2, \ldots, a_n$ of this layer.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}. \quad (3)$$

3.2.2. Construction of the Fuzzy Consistent Judgment Matrix. By using the following formula to transform the fuzzy complementary judgment matrix obtained in step (1), the fuzzy consistent matrix is obtained [20]:

$$r_{ij} = \frac{r_i - r_j}{2n} + 0.5,$$
$$\begin{cases} r_i = \sum_{k=1}^{n} r_{ik} & i = 1, 2, \cdots, n, \\ r_j = \sum_{j=1}^{n} r_{jk} & j = 1, 2, ...n. \end{cases} \quad (4)$$

3.2.3. Weight Calculation and Ranking of the Fuzzy Consistent Judgment Matrix. The weight value has a direct impact on the final result. Let the weight values of factor $a_1, a_2, \ldots, a_n$ in the fuzzy consistent judgment matrix R be $w_1, w_2, \ldots, w_n$; then, the following relation can be obtained from the above discussion:

$$r_{ij} = a\left(w_i - w_j\right) + 0.5, \ (i, j \in K) \quad (5)$$

In the formula, a refers to a measure of the difference degree of the evaluated objects, which is related to the number and difference degree of the evaluated objects. When the number or difference degree of the evaluated objects is larger, the value of a is larger, $0 a \leq 0.5$.

When the factors in the fuzzy consistent judgment matrix R and the corresponding weights satisfy $n_j = a(w_i - w_j) + 0.5$ and $a \geq (n-1)/2$, the weights can be obtained by the following formula:

$$w_i = \frac{1}{n} - \frac{1}{2a} + \frac{1}{na} \sum_{k=1}^{n} r_{ik}, \ (i \in K). \quad (6)$$

Table 3: Coupling matrix of EPB shield construction risk identification.

Scale	Definition	Explanation
0.5	Equally important	The two factors are equally important.
0.6	Slightly more important	One factor is slightly more important than the other.
0.7	Obviously important	One factor is clearly important than the other.
0.8	Much more important	One factor is much more important than the other.
0.9	Extremely important	One factor is extremely important than the other.
0.1, 0.2, 0.3, 0.4	Converse comparison	If factor a_i is compared with factor a_j to get judgment r_{ij}, then factor a_j is compared with factor a_i to get judgment $r_{ji} = 1 - r_{ij}$

When the fuzzy complementary judgment matrix is not transformed into a fuzzy consistent matrix or a $(n-1)/2$, the least square method can be used to solve the weight vector, that is, to solve the following constrained programming problem:

$$\begin{cases} \min z = \sum_{i=1}^{n}\sum_{j=1}^{n}\left[a\left(w_i - w_j\right) + 0.5 - r_{ij}\right]^2, \\ s.t. \sum_{i=1}^{n} w_i = 1, w_i \geq 0, (i \in K). \end{cases} \quad (7)$$

By means of the Lagrange multiplier method, the constrained programming problem can be solved as follows: unconstrained programming problem:

$$\min L(w,T) = \sum_{i=1}^{n}\sum_{j=1}^{n}\left[a\left(w_i - w_j\right) + 0.5 - n_j\right]^2 + 2T\left(\sum_{i=1}^{n} w_i - 1\right). \quad (8)$$

where T is the Lagrange multiplier. The weight vector $W = [w_1, w_2, \ldots, w_n]^T$ can be obtained by solving the equations by taking the partial derivative of (L, w, T) with respect to $W_i\,(i \in K)$ and making it zero.

3.3. Nonlinear Comprehensive Evaluation. The fuzziness and uncertainty of the EPB shield construction process render the risk assessment nonlinear. However, in the existing fuzzy evaluation methods of the EPB shield construction risk analysis, the calculation is usually carried out by combining a linear fuzzy operator, which makes it difficult to solve the influence of the prominent index factors on the evaluation results. Therefore, this paper combined nonlinear fuzzy operator analysis to render the evaluation results more practical [32]. The nonlinear fuzzy matrix composition operator is defined as follows:

$$f(W, X, \Lambda) = \left(w_1 x_1^{\lambda_1} + w_2 x_2^{\lambda_2} + \ldots + w_n x_n^{\lambda_n}\right)^{\frac{1}{\lambda}}, \quad \lambda_i \geq 1, \quad i = 1, 2, \ldots, n, \quad (9)$$

where $W = (w_1, w_2, \ldots, w_n)$ is the risk index weight vector, $w_i \geq 0, \sum_{i=1}^{n} w_i = 1$; $X = (x_1, x_2, \ldots, x_n)$ is the factor membership vector, $x_i \in [0,1]$; Λ is the index prominent influence degree coefficient vector, denoted as $\Lambda = (\lambda_1, \lambda_2, \ldots, \lambda_n)$, and $\lambda = \max(\lambda_1, \lambda_2, \ldots, \lambda_n)$. When the risk factors have a more prominent influence on the EPB shield construction risk assessment, the index prominent influence coefficient λ_i is larger; when the risk factors have no prominent influence on the EPB shield construction risk assessment, the index prominent influence coefficient λ_i is 1. The value method of the index prominent influence coefficient is determined according to the 1~9 scale method and λ_i value principle, and the specific value standard is shown in Table 4 [25].

In addition, when using a nonlinear operator to synthesize a fuzzy matrix, to facilitate calculation, each value of the single factor evaluation matrix should be greater than 1. Therefore, formula (8) can be used for fuzzy transformation:

$$r'_{ij} = 10 \times r_{ij} \quad (10)$$

where r_{ij} is the value of the initial fuzzy evaluation matrix and r'_{ij} is the value of the transformed nonlinear fuzzy evaluation matrix. To keep the same proportion relationship between the evaluation matrix and the initial matrix of the nonlinear fuzzy matrix, when $r_{ij} = 0.05$, $r'_{ij} = 0$ is taken; when $0.05 \leq r_{ij} = 0.1$, $r'_{ij} = 1$ is taken.

3.4. New Risk Assessment Model for EPB Shield Construction. Based on the above analysis, on the basis of the EPB shield construction risk index system obtained by the WBS-RBS method, the traditional fuzzy analytic hierarchy process (FAHP) and nonlinear operator are combined for comprehensive calculation, and a new EPB shield construction risk assessment model based on the nonlinear fuzzy analytic hierarchy process is established. The specific risk assessment and analysis process of the new model is shown in Figure 4.

The new risk assessment model of EPB shield construction based on a nonlinear fuzzy analytic hierarchy process can more objectively reflect the outstanding impact of adverse risk factors on the risk assessment of EPB shield construction. By using the pairwise comparison method to collect the expert questionnaire and establishing the fuzzy complementary matrix and transforming it into the fuzzy consistent judgment matrix, it not only meets the accuracy and consistency requirements of the expert score but also avoids the complex consistency test. When this model is

Table 4: Value standard of the index prominent influence degree coefficient.

Scale	Definition
1.5	The index factors almost have no prominent influence
2.5	Index factors have a slightly prominent impact
3.5	Index factors have a significant impact
4.5	Index factors have a strong prominent impact
5.5	Index factors have extremely prominent influence
2.0, 3.0, 4.0, 5.0	The median value of adjacent scales represents the scale between two adjacent scales

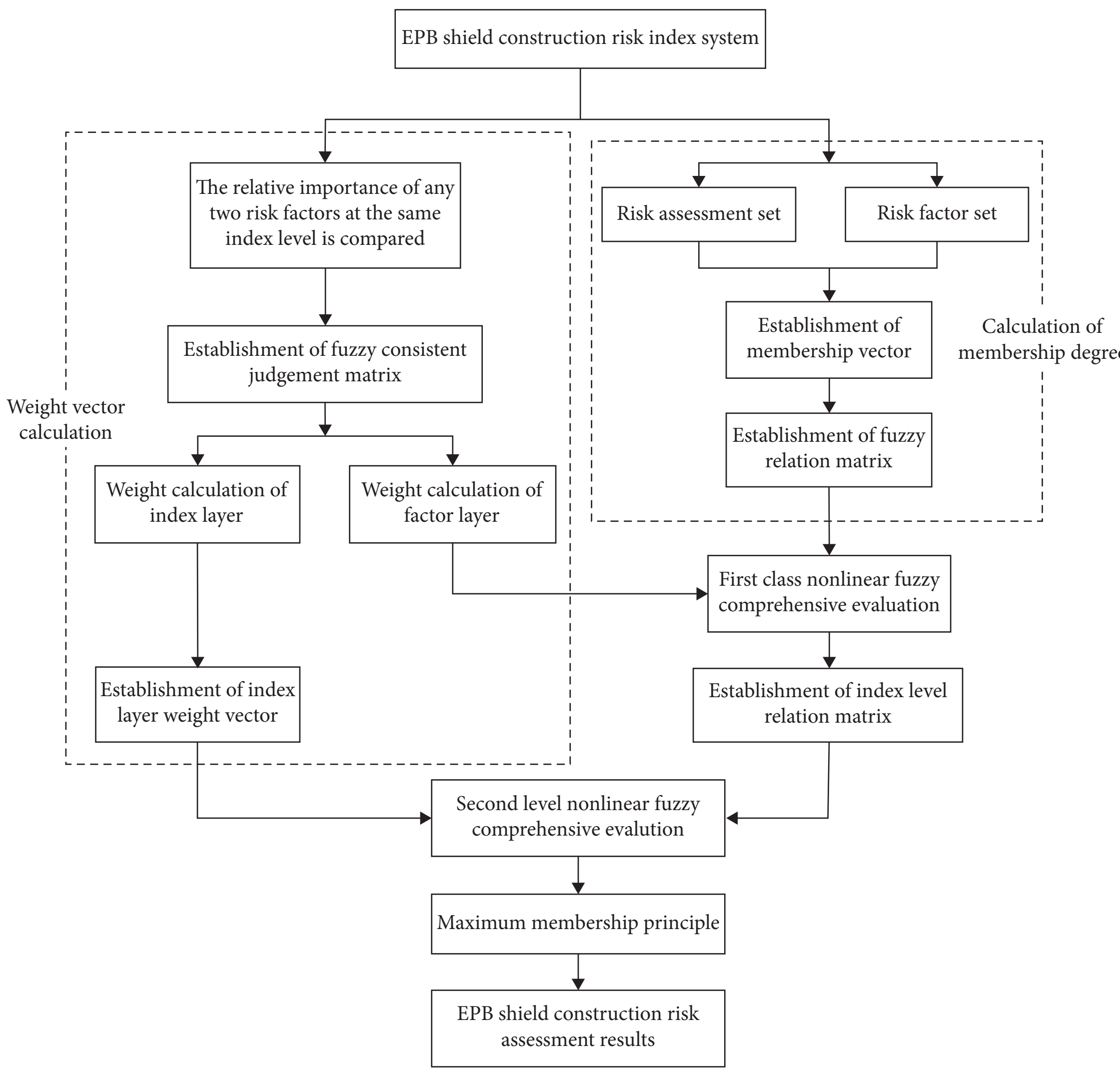

Figure 4: EPB shield construction risk assessment model.

applied to the risk assessment of EPB shield construction, the analysis results are more reasonable, feasible, and operatable.

4. Project Case Analysis

4.1. Project Overview. To verify the rationality and effectiveness of the model, it is applied to the EPB shield construction section of a tunnel project in Hangzhou. The EPB shield section is mainly located in muddy silty clay stratum. The shield passes under a DN610 mm high-pressure natural gas pipeline once, with a buried depth of approximately 5.5~8.6 m; passes under a DN500 mm medium pressure natural gas pipeline once, with a buried depth of approximately 2.2 m; passes under a 400 ∗ 200 mm optical fiber military optical cable twice, with buried depth of approximately 0.74~0.9 m. In addition, there are small and medium-sized buildings along the construction line, and the nearest building is only 10 m away from the tunnel centerline. The geological formation of the tunnel project in Hangzhou is shown in Figure 5.

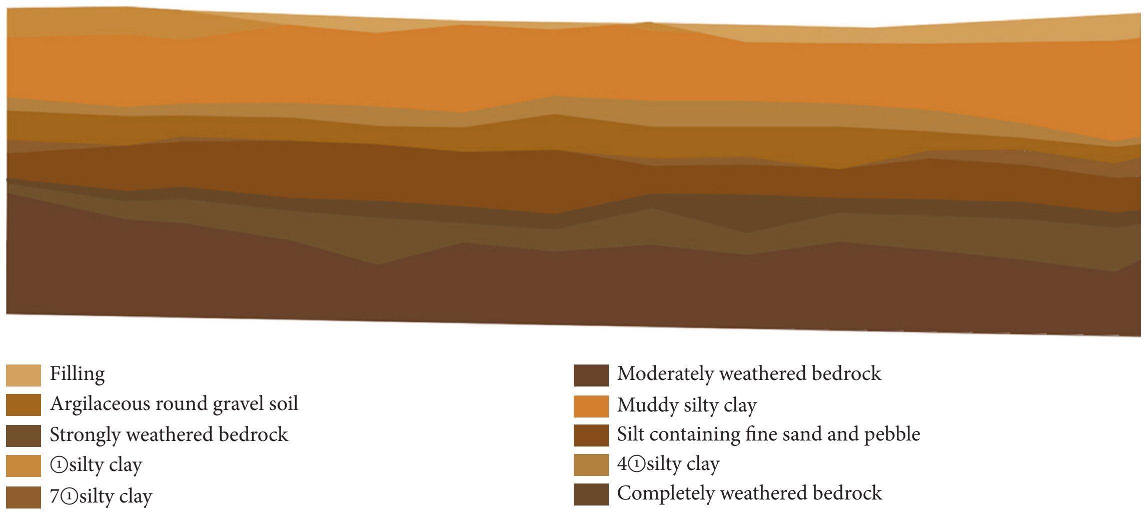

FIGURE 5: Geological formation of the tunnel project in Hangzhou.

4.2. Weight Vector Calculation.

Step 1: The fuzzy complementary matrix is established by using the 0.1~0.9 scale method. According to the established risk index system, the matrix between the first layer and the second layer is set as $A-B$, the matrix between the second layer and the third layer is set as $B_1-C, B_2-C, B_3-C, B_4-C$. Take $A-B$ as an example.

Step 2: The fuzzy complementary matrix is transformed into a fuzzy consistent judgment matrix according to formulas (1) and (2). (Table 5)

Step 3: Calculate the weight value of each factor in the fuzzy consistent matrix of each level through formula (4). To improve the resolution of sorting, take $a=(n-1)/2$. Then, the weight value of each factor of layer B relative to layer A is given in Table 6.

$$\begin{aligned}
w_1^1 &= \frac{1}{4}-\frac{1}{2\times 4-1/2}+\frac{1}{4\times 4-1/2}\times(0.500+0.350+0.538+0.413)=0.217,\\
w_2^1 &= \frac{1}{4}-\frac{1}{2\times 4-1/2}+\frac{1}{4\times 4-1/2}\times(0.650+0.500+0.688+0.563)=0.317,\\
w_3^1 &= \frac{1}{4}-\frac{1}{2\times 4-1/2}+\frac{1}{4\times 4-1/2}\times(0.462+0.312+0.500+0.375)=0.192,\\
w_4^1 &= \frac{1}{4}-\frac{1}{2\times 4-1/2}+\frac{1}{4\times 4-1/2}\times(0.587+0.437+0.625+0.500)=0.275,\\
w_1 &= \left(w_1^1, w_2^1, w_3^1, w_4^1\right)=(0.217, 0.317, 0.192, 0.275).
\end{aligned} \tag{11}$$

Similarly, the weight value of each factor of layer C relative to layer B is as follows:

(i) Risk of the geological condition:

$$\begin{aligned} w_{21} &= \left(w_1^{21}, w_2^{21}, w_3^{21}, w_4^{21}, w_5^{21}\right)\\ &= (0.319, 0.288, 0.256, 0.219, 0.231). \end{aligned} \tag{12}$$

(ii) Environmental risk sources along the shield construction line:

$$\begin{aligned} w_{22} &= \left(w_1^{22}, w_2^{22}, w_3^{22}, w_4^{22}\right)\\ &= (0.309, 0.259, 0.233, 0.200). \end{aligned} \tag{13}$$

(iii) Risk of the shield machine:

$$\begin{aligned} w_{23} &= \left(w_1^{23}, w_2^{23}, w_3^{23}, w_4^{23}, w_5^{23}\right)\\ &= (0.269, 0.288, 0.238, 0.219, 0.300). \end{aligned} \tag{14}$$

(iv) Risk of the shield tunnel:

$$\begin{aligned} w_{24} &= \left(w_1^{24}, w_2^{24}, w_3^{24}, w_4^{24}, w_5^{24}\right)\\ &= (0.343, 0.305, 0.199, 0.218, 0.249). \end{aligned} \tag{15}$$

According to the calculated weight value, the environmental risk along the line and the risk of the tunnel itself are the two factors that affect the safety of EPB shield

Table 5: *A-B* fuzzy complementary matrix.

A	B_1	B_2	B_3	B_4
B_1	0.500	0.200	0.600	0.300
B_2	0.800	0.500	0.900	0.600
B_3	0.400	0.100	0.500	0.300
B_4	0.700	0.400	0.700	0.500

Table 6: *A-B* fuzzy consistent matrix.

A	B_1	B_2	B_3	B_4
B_1	0.500	0.350	0.538	0.413
B_2	0.650	0.500	0.688	0.563
B_3	0.462	0.321	0.500	0.375
B_4	0.587	0.437	0.625	0.500

construction, and the other two risk factors cannot be ignored. Among the environmental risk factors along the line, the risk of surface building settlement and underground pipeline damage is greater. Among the risk factors for the tunnel itself, the risk of excavation route deviation and segment floating is greater.

4.3. Calculation of the Membership Degree. The expert evaluation method is used to score the secondary risk factors in the EPB shield construction risk assessment of a tunnel project in Hangzhou. The membership degree values of the risk factors are as shown in Table 7:

By combining the membership value of secondary risk factors for the EPB shield construction risk assessment with formula (8), the fuzzy evaluation matrix AA of the geological condition risk, the fuzzy evaluation matrix BB of the environmental risk along the line, the fuzzy evaluation matrix cc of the shield equipment risk, and the fuzzy evaluation matrix DD of tunnel risk are constructed, which can be used for the nonlinear fuzzy comprehensive calculation and are constructed as follows

$$R_1 = \begin{bmatrix} 0 & 0 & 8 & 2 & 0 \\ 0 & 2 & 7 & 1 & 0 \\ 0 & 3 & 6 & 1 & 0 \\ 0 & 2 & 7 & 1 & 0 \\ 0 & 2 & 7 & 1 & 0 \end{bmatrix},\quad R_2 = \begin{bmatrix} 0 & 0 & 2 & 6 & 2 \\ 0 & 0 & 3 & 6 & 1 \\ 0 & 1 & 5 & 4 & 0 \\ 0 & 2 & 6 & 2 & 0 \end{bmatrix},\quad R_3 = \begin{bmatrix} 0 & 5 & 5 & 0 & 0 \\ 0 & 4 & 5 & 1 & 0 \\ 1 & 4 & 5 & 0 & 0 \\ 2 & 3 & 5 & 0 & 0 \\ 0 & 2 & 6 & 2 & 0 \end{bmatrix},\quad R_4 = \begin{bmatrix} 0 & 0 & 1 & 7 & 2 \\ 0 & 0 & 2 & 7 & 1 \\ 2 & 5 & 3 & 0 & 0 \\ 0 & 3 & 6 & 1 & 0 \\ 0 & 3 & 6 & 1 & 0 \end{bmatrix}. \tag{16}$$

4.4. Determination of the Risk Index Prominent Influence Degree Coefficient. According to the actual situation of the EPB shield construction section of a tunnel project in Hangzhou and by combining the 1~9 scale method and λ_i value principle, the values of the prominent influence coefficient of the first-level risk factors and the prominent influence coefficient of the second-level risk factors are determined as follows in Table 8:

According to the prominent influence coefficient values of the risk factors determined in Table 9, the corresponding prominent influence coefficient vectors of risk indicators of nonlinear fuzzy evaluation matrix R_1, R_2, R_3, R_4 are constructed as follows:

$$\begin{aligned} \Lambda_1 &= (3.0, 3.0, 2.5, 3.0, 2.5), \\ \Lambda_2 &= (4.5, 4.0, 3.5, 3.0), \\ \Lambda_3 &= (1.52.0, 2.5, 2.5, 3.5), \\ \Lambda_4 &= (4.5, 4.0, 1.5, 1.5, 2.0). \end{aligned} \tag{17}$$

4.5. First-Level Nonlinear Fuzzy Comprehensive Evaluation. By substituting the obtained weight value of secondary risk factors, nonlinear fuzzy evaluation matrix, and prominent influence coefficient vector of risk index into formula (7), the following results can be obtained:

$$\begin{aligned} N_1 &= \mathrm{f}\left(W_1, R_1, \Lambda_1\right) \\ &= (0.319, 0.288, 0.256, 0.219, 0.231) \begin{bmatrix} 0 & 0 & 8^{3.0} & 2^{3.0} & 0 \\ 0 & 2^{3.0} & 7^{3.0} & 1^{3.0} & 0 \\ 0 & 3^{2.5} & 6^{2.5} & 7^{2.5} & 0 \\ 0 & 2^{3.0} & 7^{3.0} & 1^{3.0} & 0 \\ 0 & 2^{2.5} & 7^{2.5} & 1^{2.5} & 0 \end{bmatrix}^{1/3.0} \\ &= [0, 2.1070, 7.3046, 3.3165, 0]. \end{aligned} \tag{18}$$

After normalization, the results can be obtained as follows: $N_1 = [0, 0.1655, 0.5739, 0.2606, 0]$

In the same way, the following result is obtained:

$$\begin{aligned} N_3 &= [0.1194, 0.2444, 0.4812, 0.1550, 0], \\ N_2 &= [0, 0.1075, 0.2802, 0.4663, 0.1460], \\ N_4 &= [0.0519, 0.1000, 0.1405, 0.5968, 0.1108]. \end{aligned} \tag{19}$$

4.6. Second-Level Nonlinear Fuzzy Comprehensive Evaluation. According to the above results, a new single factor evaluation matrix $R_N = [N_1 N_2 N_3 N_4]^T$ is constructed

Table 7: Membership value table of the risk factors.

Risk level risk factor	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{41}	C_{42}	C_{43}	C_{44}	C_{45}
Level 1	0	0	0	0	0	0	0	0	0	0	0	0.1	0.2	0	0	0	0.2	0	0
Level 2	0	0.2	0.3	0.2	0.2	0	0	0.1	0.2	0.5	0.4	0.4	0.3	0.2	0	0	0.5	0.3	0.3
Level 3	0.8	0.7	0.6	0.7	0.7	0.2	0.3	0.5	0.6	0.5	0.5	0.5	0.5	0.6	0.1	0.2	0.3	0.6	0.6
Level 4	0.2	0.1	0.1	0.1	0.1	0.6	0.6	0.4	0.2	0	0.1	0	0	0.2	0.7	0.7	0	0.1	0.1
Level 5	0	0	0	0	0	0.2	0.1	0	0	0	0	0	0	0	0.2	0.1	0	0	0

Table 8: Prominent influence coefficient of the first-level risk factors.

Evaluating indicator	B_1	B_2	B_3	B_4
Λ	3.0	4.0	2.5	3.5

Table 9: Prominent influence coefficient of the second-level risk factors.

Evaluating indicator	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{41}	C_{42}	C_{43}	C_{44}	C_{45}
λ	3.0	3.0	2.5	3.0	2.5	4.5	4.0	3.5	3.0	1.5	2.0	2.5	2.5	3.5	4.5	4.0	1.5	1.5	2.0

and transformed by formula (8) to meet the requirements of the nonlinear fuzzy evaluation calculation. The conversion results are as follows:

$$R_N' = \begin{bmatrix} 8.486 & 16.358 & 22.990 & 97.669 & 18.157 \\ 0 & 1.075 & 2.802 & 4.663 & 1.460 \\ 1.194 & 2.444 & 4.812 & 1.550 & 0 \\ 0.519 & 1 & 1.405 & 5.968 & 1.108 \end{bmatrix}. \quad (20)$$

According to the above steps, the prominent influence coefficient matrix vector corresponding to the first-level risk factors is $\Lambda = [3.0, 4.0, 2.5, 3.5]$, and the weight vector of the first-level risk factors is $\Lambda = [3.0, 4.0, 2.5, 3.5]$. The above results are substituted into formula (7), and the results of the second-level nonlinear fuzzy comprehensive evaluation are determined as follows:

$$\begin{aligned} N &= f\left(W_{A-B}, R_N', \Lambda\right) \\ &= (0.217, 0.317, 0.192, 0.275) \circ \begin{bmatrix} 8.486 & 16.358 & 22.990 & 97.669 & 18.157 \\ 0 & 1.0755 & 2.802 & 4.663 & 1.460 \\ 1.194 & 2.444 & 4.812 & 1.550 & 0 \\ 0.519 & 1 & 1.405 & 5.968 & 1.108 \end{bmatrix}^{\frac{1}{4.0}} \\ &= [2.2134, 4.6349, 7.1873, 24.6111, 4.7076]. \end{aligned} \quad (21)$$

After normalization, the total risk evaluation vector of EPB shield construction of a tunnel project in Hangzhou is obtained as follows:

$$N = [0.0510, 0.1069, 0.1658, 0.5677, 0.1086]. \quad (22)$$

Finally, combined with the principle of the maximum membership degree, it can be judged that the overall construction risk level of the EPB shield of the tunnel project in Hangzhou is grade 4, which indicates high risk. Among them, the greater risk is the environmental risk along the line and the risk of the tunnel itself. At the same time, the risks of the geological conditions and the shield equipment cannot be ignored, which is in line with the actual situation of the EPB shield construction of the tunnel project in Hangzhou.

5. Discussion

To verify the effectiveness of the EPB shield construction risk assessment model based on the nonlinear fuzzy analytic hierarchy process, the linear fuzzy analytic hierarchy process is used to calculate the data provided by the same group of field managers and experts, that is, the prominent influence coefficient of each risk factor at all levels is 1. The fuzzy comprehensive evaluation vector of the calculation results is as follows:

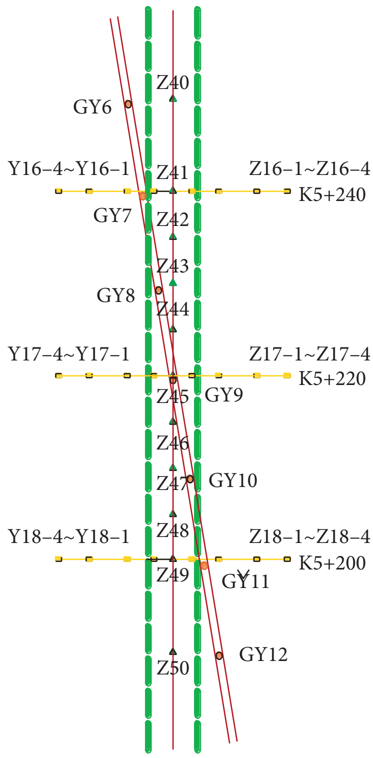

Figure 6: Layout of the surface monitoring points.

$$N' = [0.0261, 0.2347, 0.5804, 0.3242, 0.0505]. \quad (23)$$

According to the principle of maximum membership degree, the overall construction risk level of EPB shield construction section of the tunnel project in Hangzhou is grade 3, which belongs to medium risk. However, the nonlinear FAHP considers the influence of outstanding index factors on the risk level, so the risk level obtained by the nonlinear FAHP is higher than that obtained by the linear FAHP.

The surface displacement monitoring data above the pipeline of the EPB shield obliquely crossing the construction section of the high-pressure natural gas pipeline are selected for verification. The layout of surface monitoring points in the selected construction section, the surface monitoring displacement above the pipeline, and the surface monitoring displacement above the shield tunnel are shown in Figures 6–8:

This section is a construction section of EPB shield tunneling under a natural gas high-pressure pipeline at a small intersection angle of 11.4° and is mainly located at the underpass mileage of $K5 + 240 \sim K5 + 200$. According to the undercrossing range of the new tunnel in the existing pipeline, monitoring points are arranged on the surface of the upper part of the pipeline at a distance of 10 m before and after undercrossing the pipeline. It can be seen from Figures 7 and 8 that during the period of the EPB shield crossing the high-pressure natural gas pipeline obliquely, the ground surface above the pipeline and above the tunnel is greatly disturbed by the shield, showing an uplift state as a whole. Among them, the maximum uplift of the surface

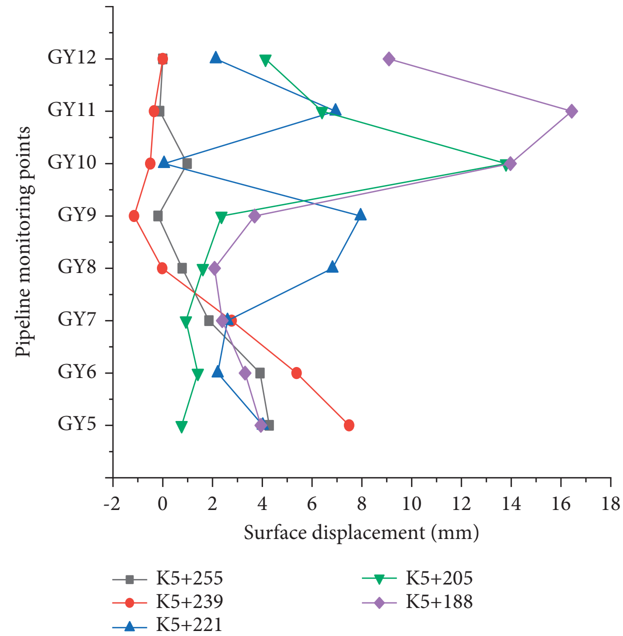

Figure 7: Surface monitoring displacement above the pipeline.

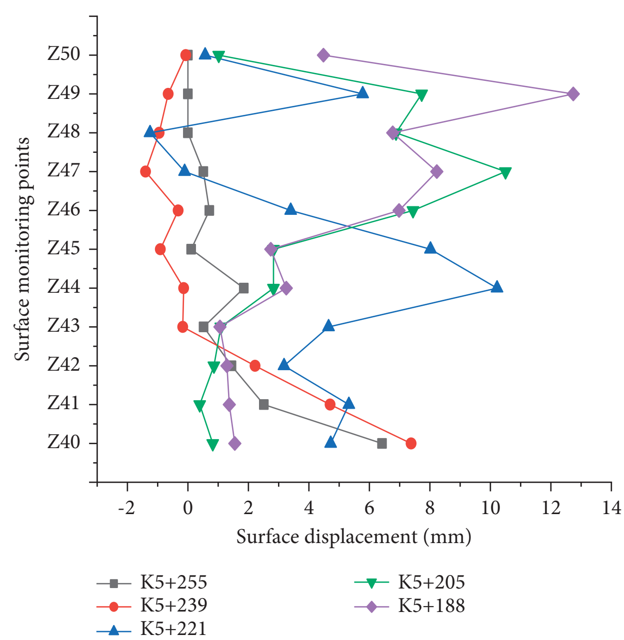

Figure 8: Surface monitoring displacement above the shield tunne1.

above the pipeline is 16.43 mm, which exceeds the control value of displacement ≤10 mm required by the control index of the underground pressure pipeline, and the maximum uplift of the surface above the shield tunnel is 12.74 mm. This finding proves that the EPB shield construction risk assessment model based on a nonlinear fuzzy analytic hierarchy process can well reflect the actual risk situation of construction and has a certain reliability and effectiveness.

6. Conclusion

The construction risk index system of an EPB shield in a soft soil area is constructed by the WBS and RBS methods, the judgment matrix is constructed by a fuzzy consistent matrix, and a nonlinear fuzzy mathematics theory is introduced to discuss the construction risk of the EPB shield:

(1) Based on the WBS-RBS method, the risk index system of EPB shield construction is constructed, which makes up for possible risk omission or incomplete identification in the expert evaluation method so that the constructed risk index system can more comprehensively reflect various risk factors and the actual situation of all levels of risk in EPB shield construction.

(2) By using pairwise comparison method to collect expert questionnaires and transforming fuzzy complementary matrix to establish fuzzy consistency judgment matrix, it not only meets the accuracy and consistency requirements of expert scoring but also avoids the cumbersome consistency test.

(3) Combining the nonlinear operator with the traditional fuzzy analytic hierarchy process, a new risk assessment model for EPB shield construction in soft soil areas based on a nonlinear fuzzy analytic hierarchy process is constructed. The outstanding influence of the risk factors is considered, and the nonlinear characteristics of the assessment process are reflected, which makes the EPB shield construction risk assessment results more reasonable. The validity of the model is verified by nonlinear calculation and linear calculation of the data provided by the same group of experts, and the results are compared with the measured data [33–35].

Data Availability

The data for the final analysis in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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