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Research Article

A Novel Approach for Risk Assessment of Building Damage via Metro Tunnel Construction

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The impact of shield construction on the surrounding buildings involves numerous factors, and the factors are uncertain and ambiguous, which have a great impact on the progress and safety of the project. Therefore, this paper developed a systematic approach for the risk assessment of existing buildings adjacent to tunneling excavation. Firstly, a risk assessment system for adjacent buildings in shield tunneling environments was proposed. Secondly, the weighting of factors was calculated by Pythagorean fuzzy AHP. Then, the VIKOR method was used to divide the risk of existing buildings adjacent to tunneling excavation into five uneven levels. Finally, the extended VIKOR with interval numbers was first introduced in risk assessment of building adjacent to tunneling environment to determine a specific building risk level. The proposed approach was successfully applied to the risk assessment of several buildings adjacent to tunnel construction of Metro Line 4 of Changsha. The accuracy and effectiveness of the constructed new approach were verified by comparing the obtained evaluation results with the actual situation on-site. This work provides a new method for similar engineering risk assessment.

1. Introduction

Due to an increase in urbanization all over the world, urban population density increases and road traffic pressure becomes severe, a large number of metro tunnels are being constructed or planned in urban areas, especially in China [1]. Many subway tunnels in China have been constructed using the shield tunneling technique because of their distinct advantages over other conventional methods [2–4]. However, shield tunneling excavation through soft soils are tend to produce surface settlements due to disturbance to the soil layers around tunnels and the volume loss of the tail void, which may cause adjacent buildings deformation, and then threaten the safety and security of urban inhabitants [5–14]. Therefore, to reduce the impact of subway shield construction on surrounding buildings, it is very important to analyze and evaluate the safety of existing buildings and to perceive and anticipate the potential safety risks in tunnel-induced building damages.

Numerous studies have been conducted for risk assessment of adjacent buildings around the tunnel and can be categorized into the following methods: empirical formula method [15, 16], analytical theoretical method [17, 18], and numerical analysis method [19, 20]. These methods have several advantages in analyzing tunnel-soil-building interaction, however, some limits have been found in application. The empirical formula method and analytical theoretical method are based on greenfield scenarios, the effect of surface buildings has been mostly neglected in these previous studies. Meanwhile, many parameters in the empirical formula method and the theoretical analysis method are more difficult to obtain accurate values, so the calculation results have certain deviations. The numerical analysis method can fully consider the building-tunnel-soil interaction and save time and effort through computer calculations, but different parameter settings can lead to excessive differences in the final results due to model construction. To address those issues, multicriteria decision making (MCDM) approaches, which is capable of taking all relevant information into account, are presented to facilitate risk assessment in a complex project environment.

MCDM provides a broad range of methodologies to decision-makers and experts that can work out the complexity of risk assessment problems. The commonly used MCDM methods include analytical hierarchy process (AHP) [21, 22], analytical network process (ANP) [23], technique for order preference by similarity to an ideal solution (TOPSIS) [24, 25], VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR) [26, 27], and multiplicative form of multiobjective optimization by ratio analysis (MULTIMOORA) [28]. AHP is one of the most important methods in MCDM, which can transform uncertain information or concepts into quantitative expressions and is often used to determine indicator weights. However, the criteria of hierarchical analysis are too fixed when calculating the weights, which cannot reflect the experts' ideas well and are influenced by the subjective factors of the researcher. Pythagorean fuzzy sets are extensions of intuitionistic fuzzy sets that can better deal with ambiguity and uncertainty in decision making. Therefore, this paper combines Pythagorean fuzzy sets with hierarchical analysis and transforms them into Pythagorean fuzzy hierarchical analysis (PFAHP). PFAHP converts the linguistic descriptions of experts into fuzzy numbers better and reflects the opinions of experts more accurately, which in turn makes up for the shortcomings of traditional hierarchical analysis and makes the obtained index weights more reasonable and reliable. The VIKOR method is developed to solve the discrete multicriteria problem with conflicting criteria, and aims to determine a compromise ranking and selection scheme taking into account conflicting criteria. The interval number improvement VIKOR method is based on the VIKOR method by replacing specific values with interval numbers. Due to the complexity of underground engineering and the uncertainty of factor values, the interval number is used to improve the VIKOR method, which can better reflect the actual engineering situation, and thus improve the accuracy and objectivity of risk assessment.

In this paper, we combine PFAHP and interval number improved VIKOR method for the first time and applied it to the risk assessment of shield tunnel in the engineering field. Firstly, based on relevant literature and expert experience, this paper proposed a risk assessment system for adjacent buildings in shield tunneling environments. Secondly, according to experts' judgments and in-site geological conditions, the weighting of factors was calculated by PFAHP. Then, the VIKOR method was used to divide the risk of existing buildings adjacent to tunneling excavation into five uneven levels. Meanwhile, the extended VIKOR with interval numbers was first introduced in the risk assessment of building adjacent to tunneling environment to determine a specific building risk level. Finally, the proposed approach was applied to the risk assessment of several buildings adjacent to tunnel construction of Metro Line 4 of Changsha. The accuracy and effectiveness of the constructed new approach were verified by comparing the obtained evaluation results with the actual situation on-site. This work provides a new method for similar engineering risk assessment.

The paper is organized as follows: in section 2, we describe the methodology used in this paper, including PFAHP method, VIKOR method, and extended VIKOR method with interval number. In section 3, we introduce the construction process of risk assessment of adjacent buildings in shield tunneling environment. In section 4, the proposed approach is applied to a case study. In section 5, we discuss the results and provide some managerial comments. In section 6, conclusions are drawn.

2. Methodology

2.1. PFAHP Method

2.1.1. Pythagorean Fuzzy Sets. Ever since Zadeh first introduced the concept of fuzzy sets, these sets have been used by many researchers in various fields to express uncertainty. Fuzzy sets have developed into a variety of forms. Intuitionistic fuzzy sets are one of these that was proposed. In intuitionistic fuzzy sets, membership function, nonmembership function, and hesitancy degree can be determined by decision-makers. However, in some cases, it cannot express the accuracy of membership and nonmembership function. For example, the sum of membership and nonmembership degrees is over 1, which dissatisfies the requirement of intuitionistic fuzzy sets. As a result, Yager [29] proposed Pythagorean fuzzy sets. These sets are the generalization of intuitionistic fuzzy sets in some conditions. Pythagorean fuzzy sets can address uncertainty and reduce vagueness. These achievements make Pythagorean fuzzy sets a powerful and flexible tool to solve problems about uncertainty.

2.1.2. Notations of Pythagorean Fuzzy Sets. In Pythagorean Fuzzy sets, the sum of membership and nonmembership degrees can exceed 1, but the sum of squares cannot. This situation is described below in Definition 1.

Definition 1. Let a set X be a universe of discourse. A Pythagorean fuzzy set P is an object having the form [30].

$$P = \{\langle x, P(\mu_P(x), \nu_P(x))\rangle \mid x \in X\}, \tag{1}$$

where the function $\mu_P(x)\colon X \longrightarrow [0,1]$ defines the degree of membership and $\nu_P(x)\colon X \longrightarrow [0,1]$ defines the degree of nonmembership of the element $x \in X$ to P, respectively, and for every $x \in X$, it holds that

$$(\mu_P(x))^2 + (\nu_P(x))^2 \le 1. \tag{2}$$

For any PFS P and $x \in X$, $\pi_p(x) = \sqrt{1 - \mu_P^2(x) - \nu_P^2(x)}$ is called the degree of indeterminacy of x to P.

Definition 2. Let $\beta_1 = P(\mu_{\beta 1}, \nu_{\beta 1})$ and $\beta_2 = P(\mu_{\beta 2}, \nu_{\beta 2})$ be two Pythagorean fuzzy numbers, and $\lambda > 0$, then the operations on these two PFNs are defined as follows [30]:

$$\beta_1 \oplus \beta_2 = P\left(\sqrt{\mu_{\beta 1}^2 + \mu_{\beta 2}^2 - \mu_{\beta 1}^2\mu_{\beta 2}^2}, \nu_{\beta 1}\nu_{\beta 2}\right),$$
$$\beta_1 \otimes \beta_2 = P\left(\mu_{\beta 1}\mu_{\beta 2}, \sqrt{\nu_{\beta 1}^2 + \nu_{\beta 2}^2 - \nu_{\beta 1}^2\nu_{\beta 2}^2}\right),$$
$$\lambda\beta = P\left(\sqrt{1-\left(1-\mu_\beta^2\right)^\lambda}, \left(\nu_\beta\right)^\lambda\right), \tag{3}$$
$$\beta^\lambda = P\left(\left(\mu_\beta\right)^\lambda, \sqrt{1-\left(1-\nu_\beta^2\right)^\lambda}\right).$$

Definition 3. Let $\beta_1 = P(\mu_{\beta 1}, \nu_{\beta 1})$ and $\beta_2 = P(\mu_{\beta 2}, \nu_{\beta 2})$ be two Pythagorean fuzzy numbers, a nature quasi-ordering on the Pythagorean fuzzy numbers is defined as follows [30]:

$\beta_1 \geq \beta_2$ if and only if $\mu_{\beta 1} \geq \mu_{\beta 2}$ and $\nu_{\beta 1} \leq \nu_{\beta 2}$.

2.1.3. Steps of PFAHP. In this section, the steps of the PFAHP method will be introduced [31, 32].

Step 1. Construct the compromised pairwise comparison matrix $R = (r_{ik})_{m\times m}$ based on the linguistic evaluation of experts using the scale in Table 1.

Step 2. Calculate the difference matrix $D = (d_{ik})_{m\times m}$ between the lower and upper values of the membership and nonmembership functions using the following equations:

$$d_{ikL} = \mu_{ikL}^2 - \nu_{ikU}^2, \tag{4}$$

$$d_{ikU} = \mu_{ikU}^2 - \nu_{ikL}^2. \tag{5}$$

Step 3. Calculate the interval multiplicative matrix $S = (s_{ik})_{m\times m}$ using the following equations:

$$S_{ikL} = \sqrt{1000^{d_L}}, \tag{6}$$

$$S_{ikU} = \sqrt{1000^{d_U}}. \tag{7}$$

Step 4. Calculate the determinacy value $\tau = (\tau_{ik})_{m\times m}$ using the following equation:

$$\tau_{ik} = 1 - \left(\mu_{ikU}^2 - \mu_{ikL}^2\right) - \left(\nu_{ikU}^2 - \nu_{ikL}^2\right). \tag{8}$$

Step 5. Multiply the determinacy value $\tau = (\tau_{ik})_{m\times m}$ and the interval multiplicative matrix for obtaining the matrix of weights, obtain $T = (t_{ik})_{m\times m}$ before normalization using the following equation:

$$t_{ik} = \left(\frac{S_{ikL} + S_{ikU}}{2}\right)\tau_{ik}. \tag{9}$$

Step 6. Calculate the normalized weights w_i using the following equation:

$$w_i = \frac{\sum_{k=1}^m t_{ik}}{\sum_{i=1}^m \sum_{k=1}^m t_{ik}}. \tag{10}$$

2.2. VIKOR Method. The VlseKriterijumska Optimizacija I Kompro-misno Resenje (VIKOR) is an effective method in MCDM. This method focuses on solving discrete decision problems with conflicting criteria and determining a compromise solution for a problem with conflicting criteria, which can help the decision-makers to optimize complex systems to get a final solution. In this article, the VIKOR method is used for determining risk levels based on the value of Q_i.

The VIKOR method started with the following form of L_p*-metric* [33, 34]:

$$L_{p,j} = \left\{\sum_{j=1}^m \left[w_j\left(f_j^* - f_{ij}\right)/\left(f_j^* - f_j^-\right)\right]^p\right\}^{1/p}.1 \leq p \leq \infty j = 1, 2, \cdots, m, \tag{11}$$

where f_{ij} means the value of j-th criterion function for the alternative A_i, n is the number of criteria, f_j^* is the best value of criterion j, f_j^- is the worst value of criterion j, and w_j means the weight of criterion j.

The procedure of the VIKOR method is described as follows:

Step 1. Normalize quantities by using the following equation:

$$f_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^n x_{ij}^2}}, i = 1, 2, \ldots, n; j = 1, 2, \ldots, m. \tag{12}$$

Step 2. Determine the best value f_j^* and the worst value f_j^- of each criterion. If the j-th function represents a benefit then: $f_j^* = \max_i f_{ij}$ and $f_j^- = \min_i f_{ij}$. If the j-th function represents a cost then: $f_j^* = \min_i f_{ij}$ and $f_j^- = \max_i f_{ij}$.

Step 3. Calculate the values S_i and R_i by using the following equations:

$$S_i = \sum_{j=1}^m \left[\frac{w_j\left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)}\right], \tag{13}$$

$$R_i = \max_j \left[w_j\left(f_j^* - f_{ij}\right)/\left(f_j^* - f_j^-\right)\right]. \tag{14}$$

Step 4. Calculate the value Q_i by using the following equation:

$$Q_i = \frac{\nu\left(S_i - S^*\right)}{\left(S^- - S^*\right)} + \frac{(1-\nu)\left(R_i - R^*\right)}{\left(R^- - R^*\right)}, \tag{15}$$

where $S^* = \min_i S_i, S^- = \max_i S_i, R^* = \min_i R_i$, and $R^- = \max_i R_i$, and ν represents the weight of the strategy of "the majority of Criteria" (or "the maximum group utility"), usually $\nu = 0.5$.

Step 5. Rank the value Q_i by increasing order, the minimum Q_i is the best option.

2.3. Extended VIKOR Method with Interval Number. In some cases, due to incomplete and uncertain data, it is difficult to obtain accurate values, and the interval numbers are more

Table 1: Weighting scale for PAHP [31].

Linguistic term	Pythagorean fuzzy number			
	Lower value of membership degree (μ_L)	Upper value of membership degree (μ_U)	Lower value of nonmembership degree (ν_L)	Upper value of nonmembership degree (ν_U)
Certainly low important (CLI)	0.00	0.00	0.90	1.00
Very low important (VLI)	0.10	0.20	0.80	0.90
Low important (LI)	0.20	0.35	0.65	0.80
Below average important (BAI)	0.35	0.45	0.55	0.65
Average important (AI)	0.45	0.55	0.45	0.55
Above average important (AAI)	0.55	0.65	0.35	0.45
High important (HI)	0.65	0.80	0.20	0.35
Very high important (VHI)	0.80	0.90	0.10	0.20
Certainly high important (CHI)	0.90	1.00	0.00	0.10
Exactly equal (EE)	0.1965	0.1965	0.1965	0.1965

probable to deal with problems. Using interval numbers can make decision-makers make a better judgment. In the risk assessment area, VIKOR with interval number is first used for determining the specific building risk level.

The procedure of the extended VIKOR method is described as follows [35]:

Step 1. Construct a decision matrix M using the interval numbers:

$$M = \begin{bmatrix} \left[f_{11}^L, f_{11}^U\right] & \left[f_{12}^L, f_{12}^U\right] & \cdots & \left[f_{1m}^L, f_{1m}^U\right] \\ \left[f_{21}^L, f_{21}^U\right] & \left[f_{22}^L, f_{22}^U\right] & \cdots & \left[f_{2m}^L, f_{2m}^U\right] \\ \cdots & \cdots & \cdots & \cdots \\ \left[f_{n1}^L, f_{n1}^U\right] & \left[f_{n2}^L, f_{n2}^U\right] & \cdots & \left[f_{nm}^L, f_{nm}^U\right] \end{bmatrix}, \tag{16}$$

where $i = 1,2, \ldots, n$; $j = 1,2, \ldots, m$.

Step 2. Determine the best value f_j^* and the worst value f_j^- for each criterion using the following equations:

$$f_j^* = \left\{\left(\max_i f_{ij}^U \mid j \in I\right) \text{or} \left(\min_i f_{ij}^L \mid j \in J\right)\right\}, \tag{17}$$

$$f_j^- = \left\{\left(\min_i f_{ij}^L \mid j \in I\right) \text{or} \left(\max_i f_{ij}^U \mid j \in J\right)\right\}, \tag{18}$$

where I is associated with the benefit criterion and J is associated with the cost criterion.

Step 3. Calculate the values $[S_i^L, S_i^U]$ and $[R_i^L, R_i^U]$ by using the following equations:

$$S_i^L = \sum_{j\in I} w_j \left(\frac{f_j^* - f_{ij}^U}{f_j^* - f_j^-}\right) + \sum_{j\in J} w_j \left(\frac{f_{ij}^L - f_j^*}{f_j^- - f_j^*}\right), \tag{19}$$

$$S_i^U = \sum_{j\in I} w_j \left(\frac{f_j^* - f_{ij}^L}{f_j^* - f_j^-}\right) + \sum_{j\in J} w_j \left(\frac{f_{ij}^U - f_j^*}{f_j^- - f_j^*}\right), \tag{20}$$

$$R_i^L = \max \left\{ w_j \left(\frac{f_j^* - f_{ij}^U}{f_j^* - f_j^-}\right) \middle| j \in I, w_j \left(\frac{f_{ij}^L - f_j^*}{f_j^- - f_j^*}\right) \middle| j \in J \right\}, \tag{21}$$

$$R_i^U = \max \left\{ w_j \left(\frac{f_j^* - f_{ij}^L}{f_j^* - f_j^-}\right) \middle| j \in I, w_j \left(\frac{f_{ij}^U - f_j^*}{f_j^- - f_j^*}\right) \middle| j \in J \right\}. \tag{22}$$

Step 4. Calculate the value $[Q_i^L, Q_i^U]$ by using the following equations:

$$Q_i^L = \nu \frac{\left(S_i^L - S^-\right)}{\left(S^* - S^-\right)} + (1-\nu) \frac{\left(R_i^L - R^-\right)}{\left(R^* - R^-\right)}, \tag{23}$$

$$Q_i^U = \nu \frac{\left(S_i^U - S^-\right)}{\left(S^* - S^-\right)} + (1-\nu) \frac{\left(R_i^U - R^-\right)}{\left(R^* - R^-\right)}, \tag{24}$$

where $S^- = \min_i S_i^L$; $S^* = \max_i S_i^U$; $R^- = \min_i R_i^L$; $R^* = \max_i R_i^U$; an d ν is the weight of "the majority of criteria" (or "the maximum group utility"), usually $\nu = 0.5$.

3. Risk Assessment of Adjacent Buildings in Shield Tunneling Environments

According to the PFAHP method, VIKOR method, and extended VIKOR method with interval number mentioned in section 2, the new method of risk assessment of adjacent buildings in the tunnel environment is established in this section.

3.1. The Process of Risk Assessment of Adjacent Buildings. The process of risk assessment of adjacent buildings can be divided into four phases. Firstly, a risk assessment system for adjacent buildings in shield tunneling environments is constructed by referring to relevant literature and code for risk management of underground engineering construction of urban rail transit. Secondly, the PFAHP method is used to transfer the expert's linguistic judgment into quantitative numbers, then factors weighting is determined. Thirdly, a risk level classification standard is constructed using the VIKOR method. Finally, the extended VIKOR method is used to determine a specific building risk level. The full flowchart of the process is given in Figure 1.

3.2. Influence Variables. Risk factor identification is crucial for risk assessment. Shield tunneling is a very complicated process where various factors are involved. Tunnel-induced building damage happens more and more frequently. Based on relevant literature [36–41] and code for risk management of underground engineering construction of urban rail transit, four types of variables are proposed, and a risk assessment system for adjacent buildings in shield tunneling environments was established, as shown in Figure 2.

3.2.1. Geotechnical Variables. Geotechnical variables play a crucial role during tunneling progress. The tunneling excavation inevitably causes soil displacement or subsidence, which can subsequently affect the surface or subsurface buildings. The parameters, such as friction angle (X1), soil cohesion (X2), compression modulus (X3), groundwater table (X4), compound stratum (X5), soft hard stratum junction (X6), and special stratum (X7) are seven variables frequently used to illustrate the geological conditions [42, 43].

3.2.2. Building Variables. The ability of buildings to resist external loads is important for the safety of adjacent buildings in tunneling environments. Different buildings have different abilities to resist external loads. Some old buildings are too aging to resist deformation. Some typical variables such as foundation configuration (X8), structure configuration (X9), important value (X10), and building intact conditions (X11) are all concerned about building conditions [12, 44].

3.2.3. Tunnel Variables. The variables related to the tunnel have a strong influence on adjacent buildings in the tunneling environment. Such as tunnel diameter (X12) and covering depth (X13). Besides, the horizontal distance (X14) between buildings and tunnels is also crucial for risk assessment [17, 45].

3.2.4. Machine Variables. Shield tunneling has a great impact on the surrounding environment. During tunneling progress, soil excavation inevitably causes ground settlement. To minimize the impact, some sensors are installed in tunneling machines. These monitored parameters include driving speed (X15), thrust force (X16), cutter torque (X17), grouting amount (X18), and soil pressure (X19). These parameters can reflect the geological condition admirably and are very sensitive to stratum change [9, 46].

3.3. Risk Level Gradation. Among the proposed 19 influence variables, some are objective but some are subjective. To better describe these variables, objective variables are evaluated by practical values in real projects, such as X1, X2, . . ., X4 and X12, X13, . . ., X19. Other subjective variables, such as X5, X6, . . ., and X11, are evaluated by judgments from domain experts using a hundred-mark scale (0–100). Due to the complexity of the tunneling environment, each variable contributes to the final risk. The influence variables are divided into five different levels, I (safe), II (low risk), III (medium risk), IV (high risk), and V (extreme risk). The index classification is mainly based on the even distribution according to previous research in security risk perception [36–40]. The specific risk level of each influence variable is shown in Table 2.

4. Case Study

This paper takes the tunnel construction on Metro Line 4 of Changsha as an example and applies the new approach constructed in Section 3 to this actual project, which effectively verifies the scientific and practicality of the new approach.

4.1. Background. In this study, tunnel construction on Metro Line 4 of Changsha, China, was investigated. The buildings along the tunnel route are dense, and the geological environment is complicated. It is necessary to carry out risk assessment for the buildings. Among hundreds of buildings around tunnels, five buildings were randomly selected for the case study. Figure 3 shows the layout of five buildings adjacent to tunnels, denoted by $1^{\#}$, $2^{\#}$, $3^{\#}$, $4^{\#}$, and $5^{\#}$.

The whole geological profile along these five buildings is shown in Figure 4. In this tunnel section, the cover depth of the tunnel ranges from 16 m to 22 m. On top of the ground is a backfill layer with a thickness of about 1.3 to 2 m. Under the backfill layer is a silt clay layer, to the depth of about 5 m. The following is the sandstone layer, with a thickness of 6 to 25 m, and a marlite layer mixed with mudstone and carbonaceous mudstone.

The tunnel was constructed by the Earth pressure balanced (EPB) shield-driven method. The cutter head diameter and length of EPB shields used in this project are 6.28

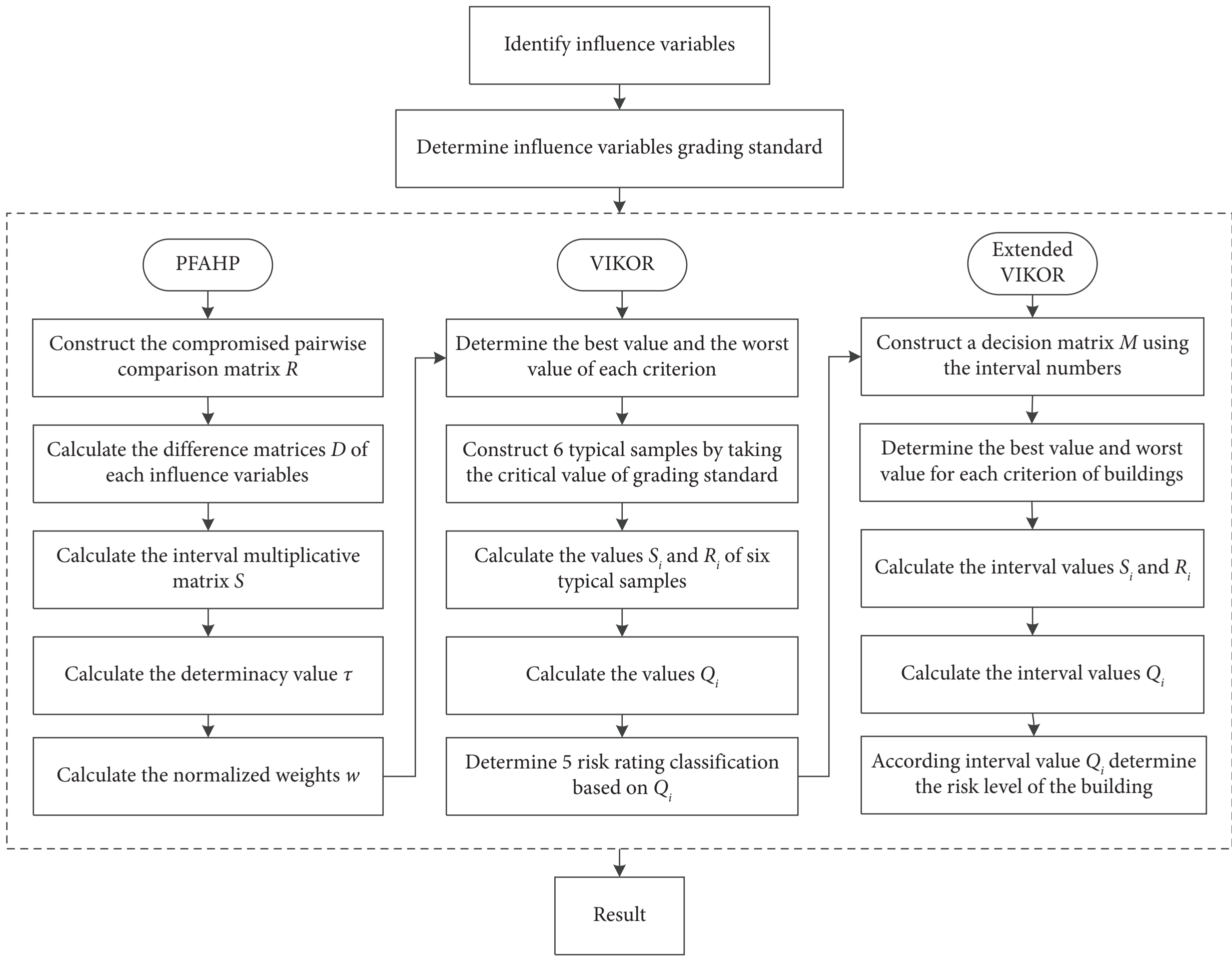


Figure 1: Flowchart of risk assessment of adjacent buildings in shield tunneling environments.

and 8.735 m, respectively. The outer and inner diameters of the segmental lining are 6 and 5.4 m, respectively. The ring width is 1.5 m.

Based on geological information and integrate with the expert judgments, values of 19 evaluation factors were obtained for those five adjacent buildings, as presented in Table 3. In this paper, the $3^{\#}$ building was taken as an example to show the procedure of the new method based on PFAHP and extended VIKOR.

4.2. Risk Analysis

4.2.1. Weighting Calculation Using PFAHP. An expert group of ten members participated in the risk assessment process. Restricted to space, the main criteria is an example to show the process of PFAHP. First, the pairwise comparison matrix $R = (r_{ik})_{m\times m}$ is constructed based on the experts' opinions given in Table 4. The experts' opinions are obtained using the scale from Table 1. The difference matrix $D = (d_{ik})_{m\times m}$ between the lower and upper values of the membership and nonmembership functions using equations (4) and (5) are shown in Table 5. Then, the interval multiplicative matrix $S = (s_{ik})_{m\times m}$ is presented in Table 6 using equations (6) and (7). Subsequently, the determinacy value $\tau = (\tau_{ik})_{m\times m}$ shown in Table 7 is calculated using equation (8). The matrix of unnormalized weights $T = (t_{ik})_{m\times m}$ given in Table 8 is calculated using equation (9). Finally, the normalized weights w_i are presented in Table 9 using equation (10).

Since how to obtain the weights is already explained in the main criteria, the other influence variables' calculation steps are omitted. The normalized weight of each influence variable is presented in Table 10.

4.2.2. Determining Risk Rating Classification Based on VIKOR. After identifying the influence variable's weights, the VIKOR method is applied for determining risk rating classification. According to the risk level classification of influence variables, six typical samples were selected from the best to worst values of variables. Then, the matrix R was formed.

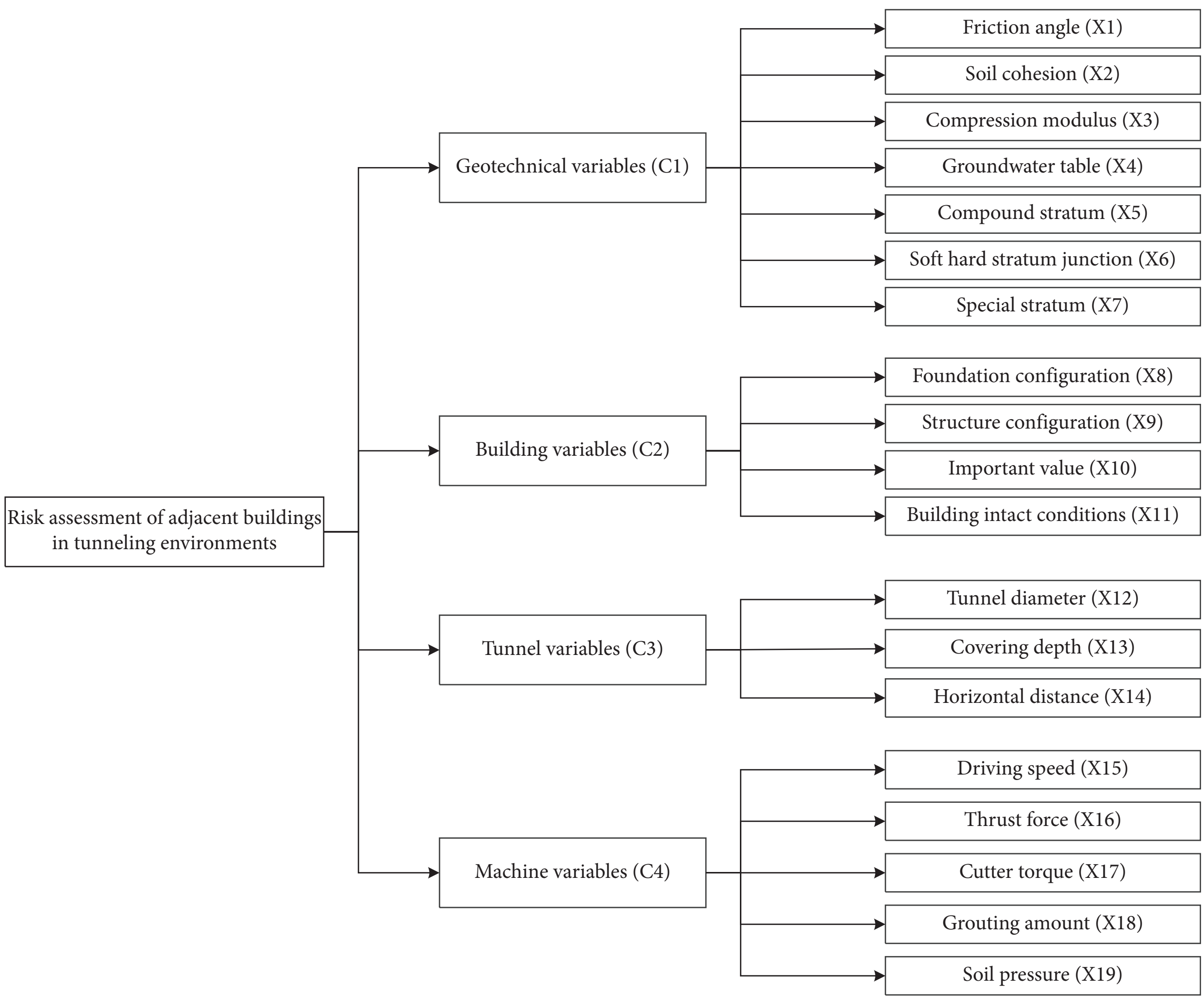


Figure 2: Risk assessment system for adjacent buildings in shield tunneling environments.

Table 2: Risk level of influence variables.

Main criteria	Factors	Influence variables	Risk level				
			I	II	III	IV	V
Geotechnical variables (C1)	X1	Friction angle (°)	[25, 45]	[15, 25)	[10, 15)	[5, 10)	[0, 5)
	X2	Soil cohesion (kPa)	[20, 25]	[15, 20)	[10, 15)	[5, 10)	[0, 5)
	X3	Compression modulus (MPa)	[40, 60]	[20, 40)	[10, 20)	[5, 10)	[0, 5)
	X4	Groundwater table (m)	[30, 50]	[20, 30)	[10, 20)	[5, 10)	[0, 5)
	X5	Compound stratum (score)	[80, 100]	[60, 80)	[40, 60)	[20, 40)	[0, 20)
	X6	Soft hard rock interface (score)	[80, 100]	[60, 80)	[40, 60)	[20, 40)	[0, 20)
	X7	Special geology (score)	[80, 100]	[60, 80)	[40, 60)	[20, 40)	[0, 20)
Building related variables (C2)	X8	Foundation configuration (score)	[80, 100]	[60, 80)	[40, 60)	[20, 40)	[0, 20)
	X9	Structure configuration (score)	[80, 100]	[60, 80)	[40, 60)	[20, 40)	[0, 20)
	X10	Significance value (score)	[0, 20)	[20, 40)	[40, 60)	[60, 80)	[80, 100]
	X11	Building intact conditions (score)	[80, 100]	[60, 80)	[40, 60)	[20, 40)	[0, 20)
Tunnel related variables (C3)	X12	Tunnel diameter (m)	[0, 5)	[5, 8)	[8, 12)	[12, 16)	[16, 20]
	X13	Covering depth (m)	[30, 40]	[20, 30)	[15, 20)	[10, 15)	[0, 10)
	X14	Horizontal distance (m)	[30, 40]	[20, 30)	[10, 20)	[5, 10)	[0, 5)
Machine related variables (C4)	X15	Driving speed (mm/min)	[0, 15)	[15, 30)	[30, 45)	[45, 60)	[60, 75]
	X16	Thrust force (10^3 kN)	[0, 10)	[10, 15)	[15, 20)	[20, 25)	[25, 35]
	X17	Cutter torque (10^3 kN·m)	[0, 1)	[1, 2)	[2, 3)	[3, 4)	[4, 5]
	X18	Grouting amount (m^3)	[0, 7)	[7, 10)	[10, 12)	[12, 15)	[15, 25]
	X19	Soil pressure (bar)	[0, 0.9)	[0.9, 1.8)	[1.8, 2.7)	[2.7, 3.6)	[3.6, 4.5]

Note. Compound stratum means several geology strata existed at the same position. Soft hard rock interface means soft rock strata interface with hard rock strata. Special geology is mainly swelling layer and karst cave. Significance value means the higher the value, the higher the score, the greater the loss in the event of harm, so the higher the risk level.

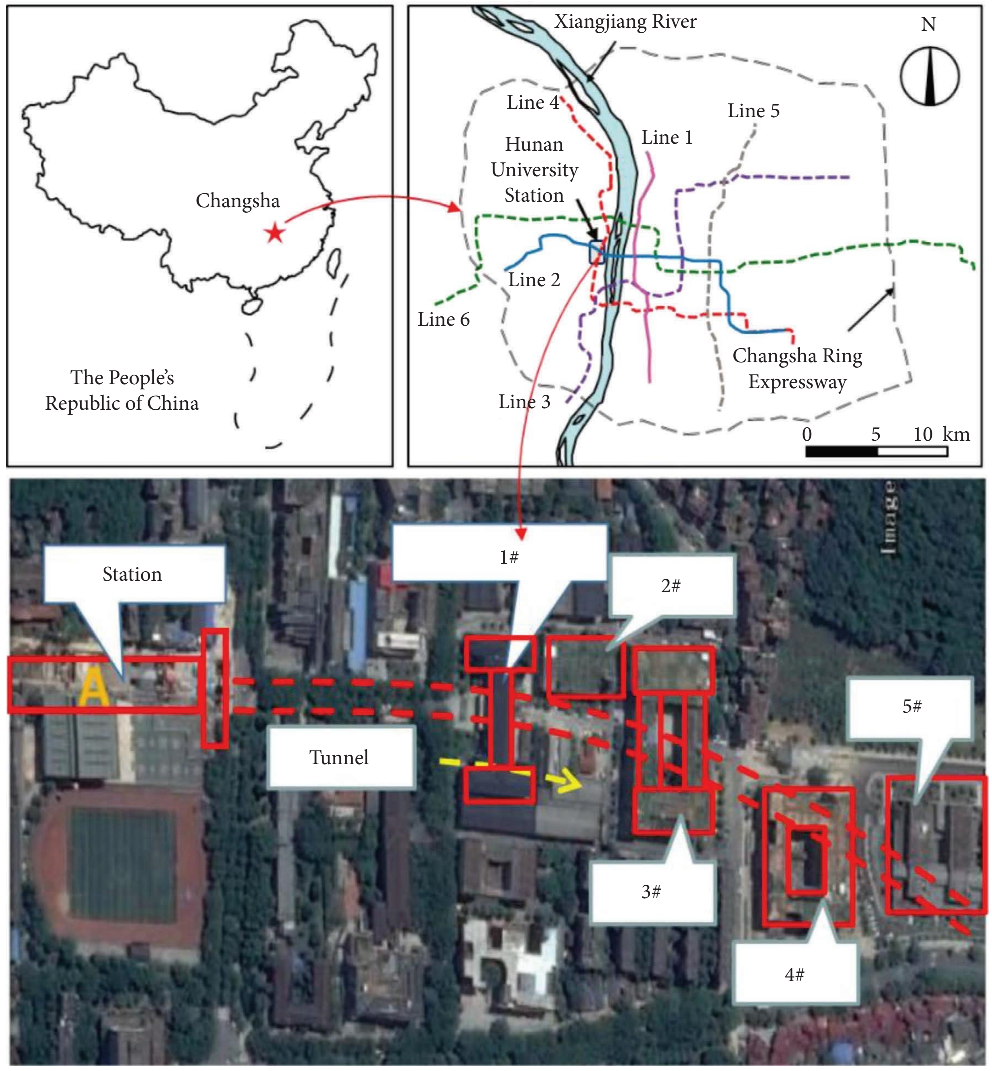
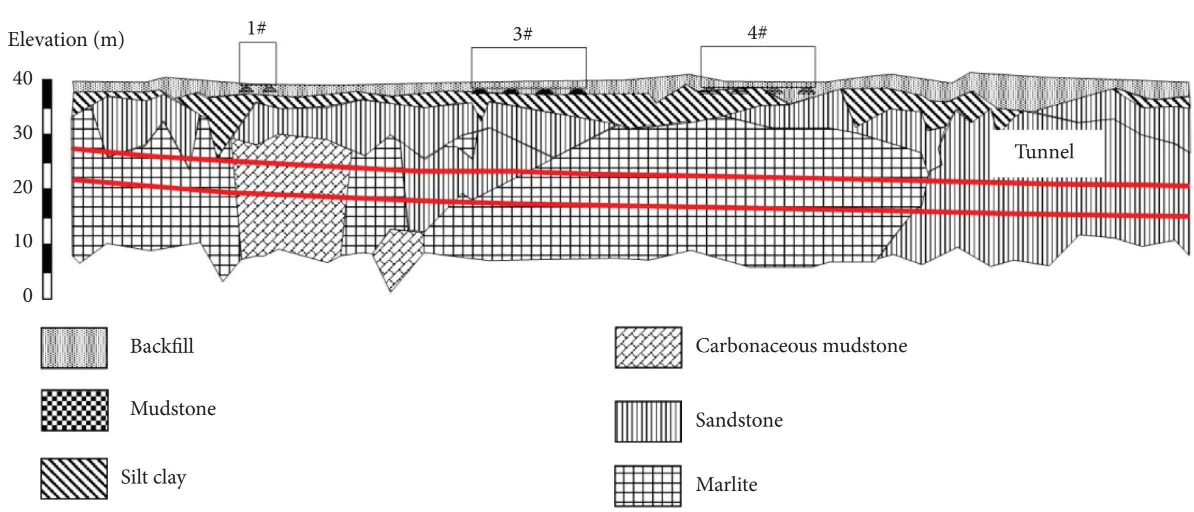
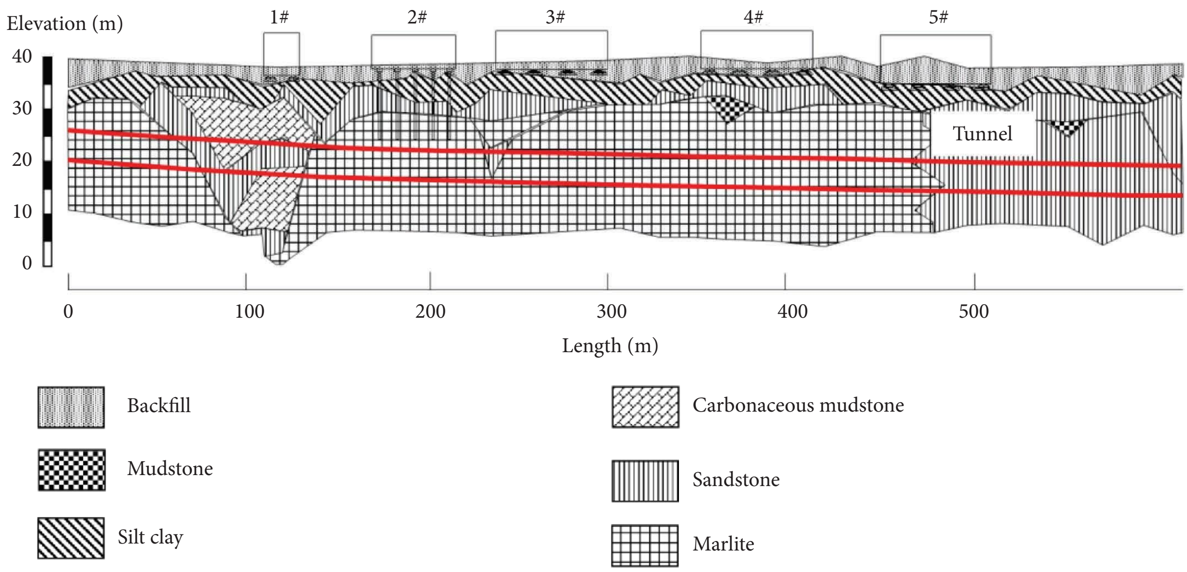


Figure 3: Distribution of Changsha metro lines and location of buildings [47].



(a)

Figure 4: Continued.



(b)

Figure 4: Geological profile of five buildings: (a) right line; (b) left line.

Table 3: Values of 19 evaluation factors for 5 adjacent buildings.

Factors	Buildings				
	1#	2#	3#	4#	5#
Friction angle (°)	[16.5, 17.5]	[16.5, 17.5]	[16.5, 17.5]	[20, 30]	[16.5, 17.5]
Soil cohesion (kPa)	[5, 10]	[5, 10]	[5, 10]	[10, 20]	[5, 10]
Compression modulus (MPa)	[5, 11]	[5, 11]	[5, 11]	[20, 50]	[5, 11]
Groundwater table (m)	[14, 15]	[14, 15]	[7, 16]	[18, 20]	[18, 20]
Compound stratum (score)	[40, 50]	[40, 50]	[60, 70]	[60, 70]	[40, 50]
Soft hard rock interface (score)	[25, 45]	[40, 50]	[50, 60]	[50, 60]	[30, 45]
Special geology (score)	[55, 65]	[60, 70]	[70, 80]	[20, 30]	[60, 70]
Foundation configuration (score)	[45, 55]	[90, 100]	[60, 70]	[30, 40]	[70, 80]
Structure configuration (score)	[20, 40]	[60, 80]	[60, 80]	[60, 80]	[60, 80]
Significance value (score)	[80, 90]	[60, 70]	[60, 80]	[80, 90]	[60, 80]
Building intact conditions (score)	[55, 65]	[80, 90]	[80, 90]	[80, 90]	[80, 90]
Tunnel diameter (m)	[6, 6]	[6, 6]	[6, 6]	[6, 6]	[6, 6]
Covering depth (m)	[16, 16.5]	[17.5, 19]	[19, 20]	[20, 21]	[20, 21]
Horizontal distance (m)	[0, 0]	[35, 35]	[7, 7]	[15, 15]	[25, 25]
Driving speed (mm/min)	[45, 60]	[5, 45]	[8, 51]	[10, 55]	[25, 60]
Thrust force (10^3 kN)	[8, 14]	[9, 14]	[8, 15]	[9, 15]	[8, 15]
Cutter torque (10^3 kN·m)	[1, 2]	[2, 4.7]	[2.1, 4.5]	[2, 4.3]	[1.6, 4.2]
Grouting amount (m^3)	[6, 7]	[6, 8.7]	[6, 11.4]	[6, 10.7]	[5.5, 7]
Soil pressure (bar)	[1.6, 2.6]	[0.4, 1.6]	[0.3, 1.5]	[0.1, 1.4]	[0.5, 1.6]

Table 4: Compromised pairwise comparison matrix of the main criteria.

Main criteria	Geotechnical variables	Building related variables	Tunnel related variables	Machine related variables
Geotechnical variables	(0.1965, 0.1965, 0.1965, 0.1965)	(0.5, 0.6125, 0.3875, 0.5)	(0.525, 0.6375, 0.3625, 0.475)	(0.5, 0.6125, 0.3875, 0.5)
Building related variables	(0.3875, 0.5, 0.5, 0.6125)	(0.1965, 0.1965, 0.1965, 0.1965)	(0.3875, 0.5, 0.5, 0.6125)	(0.3875, 0.5125, 0.4875, 0.6125)
Tunnel related variables	(0.3625, 0.475, 0.525, 0.6375)	(0.5, 0.6125, 0.3875, 0.5)	(0.1965, 0.1965, 0.1965, 0.1965)	(0.45, 0.5625, 0.4375, 0.55)
Machine related variables	(0.3875, 0.5, 0.5, 0.6125)	(0.4875, 0.6125, 0.3875, 0.5125)	(0.4375, 0.55, 0.45, 0.5625)	(0.1965, 0.1965, 0.1965, 0.1965)

Table 5: The difference matrix of the main criteria.

Main criteria	Geotechnical variables	Building related variables	Tunnel related variables	Machine related variables
Geotechnical variables	(0, 0)	(0, 0.225)	(0.05, 0.275)	(0, 0.225)
Building related variables	(−0.225, 0)	(0, 0)	(−0.225, 0)	(−0.225, 0.025)
Tunnel related variables	(−0.275, −0.05)	(0, 0.225)	(0, 0)	(−0.1, 0.125)
Machine related variables	(−0.225, 0)	(−0.025, 0.225)	(−0.125, 0.1)	(0, 0)

Table 6: The interval multiplicative matrix of the main criteria.

Main criteria	Geotechnical variables	Building related variables	Tunnel related variables	Machine related variables
Geotechnical variables	(1, 1)	(1, 2.1752)	(1.1885, 2.5852)	(1, 2.1752)
Building related variables	(0.4597, 1)	(1, 1)	(0.4597, 1)	(0.4597, 1.0902)
Tunnel related variables	(0.3868, 0.8414)	(1, 2.1752)	(1, 1)	(0.7079, 1.5399)
Machine related variables	(0.4597, 1)	(0.9173, 2.1752)	(0.6494, 1.4125)	(1, 1)

Table 7: The determinacy value of the main criteria.

Main criteria	Geotechnical variables	Building related variables	Tunnel related variables	Machine related variables
Geotechnical variables	1	0.775	0.775	0.775
Building related variables	0.775	1	0.775	0.75
Tunnel related variables	0.775	0.775	1	0.775
Machine related variables	0.775	0.75	0.775	1

Table 8: The weight matrix of the main criteria.

Main criteria	Geotechnical variables	Building related variables	Tunnel related variables	Machine related variables
Geotechnical variables	1	1.23	1.462	1.23
Building related variables	0.566	1	0.566	0.581
Tunnel related variables	0.476	1.23	1	0.871
Machine related variables	0.566	1.16	0.799	1

Table 9: The normalized weights of the main criteria.

Main criteria	Weight
Geotechnical variables	0.334
Building related variables	0.184
Tunnel related variables	0.243
Machine related variables	0.239

Table 10: The normalized weights of each influence variables.

Factors	Weight
Friction angle (°)	0.035
Soil cohesion (kPa)	0.022
Compression modulus (MPa)	0.038
Groundwater table (m)	0.055
Compound stratum (score)	0.042
Soft hard rock interface (score)	0.068
Special geology (score)	0.073
Foundation configuration (score)	0.031
Structure configuration (score)	0.045
Significance value (score)	0.069
Building intact conditions (score)	0.040
Tunnel diameter (m)	0.064
Covering depth (m)	0.094
Horizontal distance (m)	0.085
Driving speed (mm/min)	0.037
Thrust force (10^3 kN)	0.022
Cutter torque (10^3 kN·m)	0.027
Grouting amount (m^3)	0.082
Soil pressure (bar)	0.071

$$R = \begin{bmatrix} 45 & 25 & 60 & 50 & 100 & 100 & 100 & 100 & 100 & 0 & 100 & 0 & 40 & 40 & 0 & 0 & 0 & 0 & 0 \\ 25 & 20 & 40 & 30 & 80 & 80 & 80 & 80 & 80 & 20 & 80 & 5 & 30 & 30 & 15 & 10 & 1 & 7 & 0.9 \\ 15 & 15 & 20 & 20 & 60 & 60 & 60 & 60 & 60 & 40 & 60 & 8 & 20 & 20 & 30 & 15 & 2 & 10 & 1.8 \\ 10 & 10 & 10 & 10 & 40 & 40 & 40 & 40 & 40 & 60 & 40 & 12 & 15 & 10 & 45 & 20 & 3 & 12 & 2.7 \\ 5 & 5 & 5 & 5 & 20 & 20 & 20 & 20 & 20 & 80 & 20 & 16 & 10 & 5 & 60 & 25 & 4 & 15 & 3.6 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 100 & 0 & 20 & 0 & 0 & 75 & 35 & 5 & 25 & 4.5 \end{bmatrix}. \quad (25)$$

The normalized data using equations (11)–(12) are given in matrix V.

$$V = \begin{bmatrix} 0.822 & 0.674 & 0.793 & 0.798 & 0.674 & 0.674 & 0.674 & 0.674 & 0.674 & 0.000 & 0.674 & 0.000 & 0.704 & 0.727 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.456 & 0.539 & 0.529 & 0.479 & 0.539 & 0.539 & 0.539 & 0.539 & 0.539 & 0.135 & 0.539 & 0.168 & 0.528 & 0.545 & 0.135 & 0.197 & 0.135 & 0.207 & 0.135 \\ 0.274 & 0.405 & 0.264 & 0.319 & 0.405 & 0.405 & 0.405 & 0.405 & 0.405 & 0.270 & 0.405 & 0.268 & 0.352 & 0.364 & 0.270 & 0.296 & 0.270 & 0.296 & 0.270 \\ 0.183 & 0.270 & 0.132 & 0.160 & 0.270 & 0.270 & 0.270 & 0.270 & 0.270 & 0.405 & 0.270 & 0.402 & 0.264 & 0.182 & 0.405 & 0.394 & 0.405 & 0.355 & 0.405 \\ 0.091 & 0.135 & 0.066 & 0.080 & 0.135 & 0.135 & 0.135 & 0.135 & 0.135 & 0.539 & 0.135 & 0.537 & 0.176 & 0.091 & 0.539 & 0.493 & 0.539 & 0.444 & 0.539 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.674 & 0.000 & 0.671 & 0.000 & 0.000 & 0.674 & 0.690 & 0.674 & 0.739 & 0.674 \end{bmatrix}. \quad (26)$$

The best value f_j^* and the worst value f_j^- for all influence variables are shown in Table 11.

The R_i and S_i values of each sample are calculated in Table 12.

The value Q_i with $v = 0.5$ is calculated by using equation (15). Then, the risk level classification is presented in Table 13 based on the value Q_i.

4.2.3. Determine Building Risk Level Using Extended VIKOR. The $3^{\#}$ building was taken as an example to illustrate the reliability of the extended VIKOR method with interval numbers. Table 3 shows the values of 19 evaluation factors that were obtained for the 3# building. The decision matrix M with the interval numbers is constructed using equation (16).

$$M = [[16.5, 17.5]\,[5, 10] \cdots\cdots [6, 11.4]\,[0.3, 1.5]]. \quad (27)$$

The best value f_j^* and the worst value f_j^- for buildings are presented in Table 14 using equations (17)–(18).

Table 15 shows the values $[S_i^L, S_i^U]$ and $[R_i^L, R_i^U]$ by using equations (19)–(22).

The values $[Q_i^L, Q_i^U]$ with $v = 0.5$ calculated by using equations (23) and (24) are 0.576 and 0.648, respectively. In accordance with the risk level classification (Table 13), the $3^{\#}$ building's risk level is III, which is medium risk situation.

The same risk assessment procedures are also applied to $1^{\#}$, $2^{\#}$, $4^{\#}$, and $5^{\#}$ buildings. The overall values $[Q_i^L, Q_i^U]$ and risk level classification are shown in Figure 5. The $1^{\#}$ building's risk level is IV, which means in a high risk situation. The $1^{\#}$ and $5^{\#}$ buildings are both in the situation between II to III risk level and the $3^{\#}$ and $4^{\#}$ buildings are both in the medium risk level.

5. Discussion

The accuracy of the results calculated by the model is verified by the actual situation of the damage degree of 1–$5^{\#}$ buildings during the shield tunneling process. Among them, no significant settlement occurred in buildings 2–$5^{\#}$ during the shield tunneling process, and there were no obvious cracks in the building walls. For building $^{\#}1$, the maximum settlement of the building was 9.2 mm when the right line passed through building $^{\#}1$, and at this time the appearance of the building did not show any cracks or plaster peeling off. When the left line went down through building $^{\#}1$, the alternating interface of fully weathered sandstone and medium weathered sandstone in the stratum caused the shield machine to stop for more than 32 hours, at which time large settlement occurred in the stratum. When the left line crossed the building, the maximum settlement of the building was nearly 37 mm. The building wall showed significant cracks with lengths of 0.6~7.6 m and widths of 0.5~5.0 mm. According to the damage assessment based on damage phenomena, the building is in the "minor damage" to "moderate damage" category. In summary, the accuracy and effectiveness of the constructed new approach in the risk assessment of shield underpass existing buildings are verified by comparing the obtained evaluation results with the actual situation on-site. At the same time, this study contributes to future construction studies, as this work provides a new method for similar engineering risk assessment.

To reduce the impact of shield construction on existing buildings, measures need to be taken to control the risk as much as possible. In the design stage, the tunnel should be placed in the deep soil and the soil layer with good mechanical properties. Keep the tunnel as far away from the

Table 11: The best value and worst value of each influence variables.

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19
f_j^*	0.822	0.674	0.793	0.798	0.674	0.674	0.674	0.674	0.674	0.000	0.674	0.000	0.704	0.727	0.000	0.000	0.000	0.000	0.000
f_j^-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.674	0.000	0.671	0.000	0.000	0.674	0.690	0.674	0.739	0.674

Table 12: The R_i and S_i values of six typical samples.

	S_i	R_i
Sample 1	0.000	0.000
Sample 2	0.245	0.023
Sample 3	0.449	0.047
Sample 4	0.631	0.064
Sample 5	0.796	0.074
Sample 6	1.000	0.094

Table 13: The risk level classification.

Risk level	Q_i
I	$0 \leq Q \leq 0.248$
II	$0.248 \leq Q \leq 0.475$
III	$0.475 \leq Q \leq 0.656$
IV	$0.656 \leq Q \leq 0.796$
V	$0.796 \leq Q \leq 1$

Table 14: The best value and worst value for buildings.

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19
f_j^*	45	25	60	50	100	100	100	100	100	0	100	0	40	40	0	0	0	0	0
f_j^-	0	0	0	0	0	0	0	0	0	100	0	20	0	0	75	35	5	25	4.5

Table 15: The R_i and S_i values for buildings.

Factor	S_i^L	S_i^U	R_i^L	R_i^U
Value	0.402	0.547	0.070	0.070

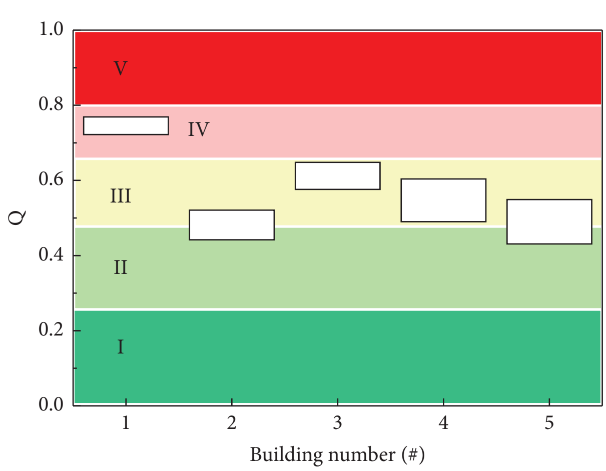


Figure 5: The buildings risk level.

buildings as possible in the horizontal direction. In the construction process, the relevant parameters of the shield tunneling machine should be well controlled, and the tunneling should not be completed too quickly and too aggressively. Make all relevant factors as close as possible to the level of risk level I in Table 2.

There are also some limitations to the method. Despite plenty of influence variables that have been considered, there are still many factors that have not been taken into account. The weightings and ratings of the criteria and variables by the experts could have been subjective and their personal opinions and perspectives might have been influenced by their expertise and knowledge. Therefore, the subjectivity and the personal prejudice of the experts of the study might have affected the results. To generalize the risk assessment to building adjacent tunneling, further investigations and studies should be conducted.

6. Conclusion

To assess adjacent buildings' potential risk, a novel risk assessment method with detailed step-by-step procedures has been proposed. It merges the PFAHP method, VIKOR method, and extended VIKOR method with interval numbers to support the construction safety risk perception. A case study was presented to analyze the buildings' safety performance adjacent to the Changsha Metro Line 4 construction in China. The results demonstrated the feasibility of the proposed method and its application potential. The following conclusions can be drawn:

(1) Based on engineering practice and expert estimates regarding tunnel-soil-building interaction, a risk assessment system for adjacent buildings in shield tunneling environments was proposed, including four types of variables: geotechnical variables, building-related variables, tunnel related variables, and machine-related variables. These influence variables can be assessed within five different risk levels, namely, "I (safe), II (low risk), III (medium risk), IV (high risk), and V (extreme risk)," with the building health condition and the environmental condition.

(2) This approach provides a more powerful tool for knowledge representation and reasoning under vagueness and uncertainty compared to traditional risk assessment method. Experts can feel free while assigning variables weightings when lacking sufficient pieces of information. Using the PFAHP method can easily change expert linguistical opinion to fuzzy sets, as well as maintain accuracy. Compared to traditional risk level classification, in this article, the risk level is unevenly classified by using VIKOR method, which is more accurate and reasonable.

(3) For the first time, the extended VIKOR method with interval number was introduced in risk assessment to determine specific building risk levels. Due to the complexity of the geological condition and tunneling condition, using interval values instead of crisp values can be reliable, which also guarantees that the interval numbers reflect the actual knowledge of domain experts.

(4) The proposed approach was used to evaluate the risk assessment of several buildings adjacent to tunnel construction of Metro Line 4 of Changsha. The accuracy and effectiveness of the constructed new approach were verified by comparing the obtained evaluation results with the actual situation on-site. The evaluation case verified that the new approach is highly operational when applied to evaluate the risk assessment of several buildings adjacent to tunnel construction.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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