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Safety Risk Assessment of Deep Foundation Pit Excavation Adjacent to Existing Railway Stations

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Abstract: *The construction of three-dimensional underground transportation systems has made the expansion of existing lines increasingly common. However, there has been limited practical engineering research on new stations closely adjoining existing ones. Such projects are characterized by their uniqueness, complexity, and high risk. Establishing a risk assessment system for construction close to existing structures can aid in risk control for similar projects. This paper, based on the actual project at Wudaokou Station on Beijing Metro Line 13, evaluates the risks during the excavation stage of a foundation pit close to existing structures. It thoroughly analyzes the factors affecting the safety of foundation pit excavation construction adjacent to existing structures. Based on this analysis, a risk assessment system for foundation pit excavation construction close to existing structures is established. The Analytic Hierarchy Process (AHP) is used to determine the weights of the risk factors at different levels. Furthermore, based on fuzzy mathematics theory, a risk assessment model for foundation pit excavation construction close to existing structures is constructed. The model calculates and scores each factor, concluding that the accident possibility level for foundation pit excavation construction close to existing structures is Level 3, indicating a high-risk project. The assessment results are reliable, consistent with practical engineering, and can serve as a reference for similar projects.*

Keywords: *Deep foundation pit excavation, risk assessment, Analytic Hierarchy Process (AHP), Fuzzy comprehensive evaluation method*

1. Introduction

In recent years, rail transportation has begun to develop in a three-dimensional manner, including subway projects. This has led to the establishment of the concept of underground three-dimensional interchange in the design philosophy of tunnels and underground works, resulting in an increasing number of existing line expansion projects[1-3]. Many scholars have conducted research on the construction of new tunnels or stations adjacent to existing tunnels, covering aspects such as settlement control, deformation control, and construction techniques[4-6]. Currently, research on risk assessment for stations closely adjacent to existing ones mainly includes: Wang Gang[7]'s work on the Dalian Subway Line 2's south section crossing under the Harbin-Dalian Passenger Dedicated Line station area. To enhance the scientific and practical application of safety risk assessments, he combined risk assessment with rock mechanics analysis, following the "initial risk assessment - numerical simulation - detailed risk assessment" process, thereby improving the feasibility of engineering plans. The construction process of the project under the south station of the Red Line of the Boston I-93 Interstate Highway in the United States was monitored 24 hours a day, ensuring the normal operation of the existing station and its facilities[8]. This demonstrates that conducting safety risk assessments for subway projects is feasible and effective.

In projects closely adjoining existing main structures, there has been limited actual engineering and research on the expansion of stations closely adjoining existing ones. These projects are characterized by their high construction difficulty and risk, requiring the assurance of both the operation of existing stations and the normal construction of new stations. Therefore, the study of a safety risk assessment system for the expansion of subway stations closely adjacent to existing operational subway stations is urgent. This paper relies on the actual engineering project of the expansion of Wudaokou Station on Beijing Metro Line 13, closely adjoining an existing subway station, to assess the safety risk of foundation pit excavation adjacent to existing structures.

The main deep foundation pit is divided into two parts, with interlayer area and no interlayer area. The depth of the foundation pit in the non-interlayer area is about 6m, which is far away from the existing station. The excavation of the foundation pit has little effect on the existing station. The depth of the foundation pit in the interlayer area is about 10 m, and the nearest distance from the existing station is about 3.4 m. The deformation of the retaining structure of the foundation pit excavation has a great influence on the existing structure of the station.

2. Introduction to Safety Risk Assessment Methods

Currently, common risk analysis methods for deep foundation pit engineering include Fault Tree Analysis, Fuzzy Comprehensive Evaluation, AHP, Risk Matrix, and others[9]. This paper, based on actual engineering projects, employs fuzzy-analytic hierarchy process theory to assess the risks associated with foundation pit excavation adjacent to existing structures.

2.1 Establishment of the Evaluation Index System

The objective layer is defined as the safety risk of foundation pit excavation adjacent to existing structures; the criterion layer consists of a set of factors $B = \{B_1, B_2, \ldots, B_i\}$, where the ith subset of factors within the first layer is denoted as B_i. The subset of factors within the third layer is denoted as $B_i = \{C_{i1}, C_{i2}, \ldots, C_{ij}\}$. Where C_{ij} is the first layer of the ith sub-set of the jth factor set.

2.2 Calculation of Index Weights Based on AHP

AHP, introduced in the 1970s by American operations researcher T-L-Saaty, is a decision-making method based on AHP. It decomposes various factors in a problem into multiple levels and objectives, such as goals, objectives, and schemes. This method is comprehensive, easy to operate, widely applicable, and effective in solving complex issues. The AHP method involves pairwise comparisons among evaluation indices to determine the relative importance of each factor at one level to those at another level, thereby establishing the hierarchy of factors. The specific steps are as follows:

(1) Establishment of the Hierarchical Structure Model

First, analyze the evaluation indices and classify each factor into different levels to delineate the relationships among them.

(2) Construction of Pairwise Comparison Judgment Matrices

Starting with the first layer factors, conduct pairwise comparisons for indices under the same upper layer factor to assess their importance. This process creates pairwise judgment matrices down to the lowest layer indices. The importance of the factors is compared, and pairwise judgment matrices are constructed using a 1-9 scale and its reciprocals as scale values, as shown in Table 1. Finally, through the method of optimal transfer matrices and weighted vector method, the specific weights of the indices in the evaluation system are determined.

Table 1: Description of Judgment Scale

Scale	Meaning
1	Indicate both elements have the same importance.
3	Indicate the former element is slightly more important than the latter.
5	Indicate the former element is clearly more important than the latter.
7	Indicate the former element is strongly more important than the latter.
9	Indicate the former element is extremely more important than the latter.
2, 4, 6, 8	Indicate an intermediate value between the above adjacent judgments.

(3) Solving for the Weight Vector of the Pairwise Comparison Matrix

The solution for the weight vector of the pairwise comparison matrix involves calculating the eigenvector and the largest eigenvalue of the judgment matrix to determine the weights between indices. The specific steps are as follows:

1) Calculate the nth root of the product of each row's values in the judgment matrix.

$$M_i = \left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}, i = 1,2,\ldots,n \tag{1}$$

2) Normalize the magnitude M

$$w_i = M_i / \sum_{j=1}^{n} M_j, i = 1,2,\dots,n \tag{2}$$

Calculate according to Formula 2 to obtain the eigenvector $W = (w_1, w_2, \dots, w_n)^T$.

3) Calculate the largest eigenroot of the judgment matrix

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(Aw)_i}{w_i} \tag{3}$$

Where the Aw vector's ith element is indicated as $(Aw)_i$

4) Consistency Check of the Judgment Matrix

During the process of generating a judgment matrix, due to the variability of assessment targets and the inaccuracy of assessment results, estimates can only be made intuitively. This makes it difficult to ensure the good consistency of the judgment matrix.

By combining the calculation process of weights and judging the changes in eigenvalues, a consistency test can be completed. Introduce the formula: $CI = \frac{\lambda_{max} - n}{n-1}$, and also introduce the Average Random Consistency Index (RI) value and the Random Consistency Ratio (CR), where $CR = \frac{CI}{RI}$, to effectively measure whether different order judgment matrices meet the consistency test. When the Consistency Index (CI) of the judgment matrix compared to the Average Random Consistency Index (RI) of the same order $CR = \frac{CI}{RI} < 0.1$ is considered to have satisfactory consistency. Otherwise, the judgment matrix needs to be adjusted to achieve satisfactory consistency. For matrices of different orders, the RI values are shown in Table 2 below:

Table 2: Consistency Index Values Table

1	2	3	4	5	6	7	8	9	10
0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

2.3 Multi-level Fuzzy Comprehensive Evaluation

The basic idea of multi-level fuzzy comprehensive evaluation is to first conduct a comprehensive evaluation based on the factors at the lowest level, then evaluate based on the factors at the next higher level, and so on, step by step, until the highest level of evaluation result is obtained. The main steps are to first establish the factor set of the evaluation object:

$$U = \{u_1, u_2, \dots, u_n\} \tag{4}$$

Then establish the evaluation set:

$$V = \{v_1, v_2, \dots, v_n\} \tag{5}$$

Next, establish the weight set:

$$\underline{A} = (a_1, a_2, \dots a_n) \tag{6}$$

Where $\sum_{j=1}^{n} a_j = 1$

Following that, establish a single-factor evaluation matrix:

$$\underline{R} = \begin{bmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix} \tag{7}$$

Ultimately, obtain the fuzzy evaluation of the object being judged:

$$\underline{B} = \underline{A} * \underline{R} \tag{8}$$

The risk assessment of foundation pit excavation adjacent to existing structures starts from the impact factors at the lowest level, then a comprehensive evaluation is conducted layer by layer, until a risk rating for the foundation pit excavation adjacent to existing structures is derived.

3. Risk Assessment of Foundation Pit Excavation Adjacent to Existing Structures Based on Fuzzy-Analytic Hierarchy Process

3.1 Determining the Risk Assessment Index System

Starting from the perspective of construction safety, based on principles of integrity, systematics, science, hierarchy, representation, simplicity, operability, and wide applicability, and combining domestic and international safety risk assessments of foundation pit excavation projects, effective risk identification was conducted for special circumstances adjacent to existing structures, and a complete risk assessment index system for foundation pit excavation adjacent to existing structures was established as shown in Table 3.

Table 3: Risk Assessment Index System for Foundation Pit Excavation Adjacent to Existing Structures

Objective Layer	Criterion Layer	Index Layer
Risk of Foundation Pit Excavation Adjacent to Existing Structures	Surrounding Environment	Platform Pile Foundation
		Underground Utilities
		Overpass
		High-rise Buildings
	Engineering Geology	Rock Mass Classification
		Adverse Geological Conditions
		Groundwater
		Surface Water
	Construction Management	Construction Personnel Management
		Emergency Plan
		Machinery Operation
		Monitoring Measurement
	Construction Scheme	Excavation Method
		Support Method
		Internal Support Design
		Retention Structure Design

3.2 Calculation of Index Weights Using AHP

(1) Calculation of Criterion Layer Weights

The criterion layer's judgment matrix is constructed using the AHP as shown in Table 4.

Table 4: Criterion Layer Judgment Matrix

	Surrounding Environment	Engineering Geology	Construction Management	Construction Scheme
Surrounding Environment	1	2	4	1/2
Engineering Geology	1/2	1	2	1/4
Construction Management	1/4	1/2	1	1/8
Construction Scheme	2	4	8	1

Calculating the nth root of the product of the values in each row of the judgment matrix obtains $M=\begin{bmatrix}1.4141\\0.7071\\0.3536\\2.8284\end{bmatrix}$, and after normalization, the eigenvector $W=\begin{bmatrix}0.267\\0.133\\0.067\\0.533\end{bmatrix}$ is obtained.

Substituting into the formula for the largest eigenvalue gives $\lambda_{\max}$=4.00003. CI=$\frac{4.00003-4}{4-1}=0.00001$. Since the judgment matrix is of the fourth order with RI=0.9, then CR=$\frac{CI}{RI}=\frac{0.00001}{0.9}$=0.000011. Because CR<0.1, it passes the consistency test, and the weight vectors Q are respectively 0.267, 0.133, 0.067, 0.533.

(2) Calculation of Index Layer Weights

The judgment matrices for the index layer are constructed using the AHP as shown in Tables 5 to 8.

Table 5: Surrounding Environment Judgment Matrix

	Platform Pile Foundation	Underground Utilities	Overpass	High-rise Buildings
Platform Pile Foundation	1	3	9/2	9
Underground Utilities	1/3	1	3/2	3
Overpass	2/9	2/3	1	2
High-rise Buildings	1/9	1/3	1/2	1

Calculating the nth root of the product of the values in each row of the judgment matrix obtains $M = \begin{bmatrix} 3.32 \\ 1.1067 \\ 0.7378 \\ 0.3689 \end{bmatrix}$, and after normalization, the eigenvector $W = \begin{bmatrix} 0.6 \\ 0.2 \\ 0.133 \\ 0.067 \end{bmatrix}$ is obtained.

Substituting into the formula for the largest eigenvalue gives $\lambda_{\max}$=4. CI=$\frac{4-4}{4-1} = 0$. Since the judgment matrix is of the fourth order with RI=0.9, then CR=$\frac{CI}{RI} = \frac{0}{0.9}$=0. Because CR<0.1, it passes the consistency test, and the weight vectors Q are respectively 0.6, 0.2, 0.133, 0.067.

Table 6: Engineering Geological Conditions Judgment Matrix

	Rock Mass Classification	Adverse Geological Conditions	Groundwater	Surface Water
Rock Mass Classification	1	5	5/4	5/2
Adverse Geological Conditions	1/5	1	1/4	1/2
Groundwater	4/5	4	1	2
Surface Water	2/5	2	1/2	1

Calculating the nth root of the product of the values in each row of the judgment matrix obtains $M = \begin{bmatrix} 1.9882 \\ 0.3976 \\ 1.5905 \\ 0.7953 \end{bmatrix}$, and after normalization, the eigenvector $W = \begin{bmatrix} 0.417 \\ 0.083 \\ 0.333 \\ 0.167 \end{bmatrix}$ is obtained.

Substituting into the formula for the largest eigenvalue gives $\lambda_{\max}$=4.00002. CI=$\frac{4.00002-4}{4-1} = 0.000007$. Since the judgment matrix is of the fourth order with RI=0.9, then CR=$\frac{CI}{RI} = \frac{0.000007}{0.9}$=0.000008. Because CR<0.1, it passes the consistency test, and the weight vectors Q are respectively 0.417, 0.083, 0.333, 0.167.

Table 7: Construction Management Judgment Matrix

	Construction Personnel Management	Emergency Plan	Machinery Operation	Monitoring Measurement
Construction Personnel Management	1	1/2	1/3	1/5
Emergency Plan	2	1	2/3	2/5
Machinery Operation	3	3/2	1	1/2
Monitoring Measurement	5	5/2	2	1

Calculating the nth root of the product of the values in each row of the judgment matrix obtains $M = \begin{bmatrix} 0.4273 \\ 0.8546 \\ 1.2247 \\ 2.2361 \end{bmatrix}$, and after normalization, the eigenvector $W = \begin{bmatrix} 0.09 \\ 0.18 \\ 0.258 \\ 0.471 \end{bmatrix}$ is obtained.

Substituting into the formula for the largest eigenvalue gives $\lambda_{\max}$=4.004. CI=$\frac{4.004-4}{4-1} = 0.0013$. Since the judgment matrix is of the fourth order with RI=0.9, then CR=$\frac{CI}{RI} = \frac{0.0013}{0.9}$=0.0014. Because CR<0.1, it passes the consistency test, and the weight vectors Q are respectively 0.09, 0.18, 0.258, 0.471.

Table 8: Construction Scheme Judgment Matrix

	Excavation Method	Support Method	Internal Support Design	Retention Structure Design
Excavation Method	1	1/3	1/6	1/5
Support Method	3	1	1/2	3/5
Internal Support Design	6	2	1	6/5
Retention Structure Design	5	5/3	5/6	1

Calculating the nth root of the product of the values in each row of the judgment matrix obtains $M = \begin{bmatrix} 0.3247 \\ 0.974 \\ 1.948 \\ 1.6233 \end{bmatrix}$, and after normalization, the eigenvector $W = \begin{bmatrix} 0.067 \\ 0.2 \\ 0.4 \\ 0.333 \end{bmatrix}$ is obtained.

Substituting into the formula for the largest eigenvalue gives $\lambda_{\max}$=4. CI=$\frac{4-4}{4-1} = 0$. Since the judgment matrix is of the fourth order with RI=0.9, then CR=$\frac{CI}{RI} = \frac{0}{0.9}$=0. Because CR<0.1, it passes the consistency test, and the weight vectors Q are respectively 0.067, 0.2, 0.4, 0.333.

Based on the calculations of the weights for the criterion layer and index layer, the research evaluation weight table 9 for the risk assessment of foundation pit excavation adjacent to existing structures is obtained.

Table 9: Summary of Construction Risk Impact Factor Weights for Foundation Pit Excavation Adjacent to Existing Structures

Objective Layer	Criterion Layer	Index Weights	Index Layer	Index Weights
Risk of Foundation Pit Excavation Adjacent to Existing Structures	Surrounding Environment	0.267	Platform Pile Foundation	0.6
			Underground Utilities	0.2
			Overpass	0.133
			High-rise Buildings	0.067
	Engineering Geology	0.133	Rock Mass Classification	0.417
			Adverse Geological Conditions	0.083
			Groundwater	0.333
			Surface Water	0.167
	Construction Management	0.067	Construction Personnel Management	0.09
			Emergency Plan	0.18
			Machinery Operation	0.258
Risk of Foundation Pit Excavation Adjacent to Existing Structures	Construction Management	0.067	Monitoring Measurement	0.471
	Construction Scheme	0.533	Excavation Method	0.067
			Support Method	0.2
			Internal Support Design	0.4
			Retention Structure Design	0.333

It can be concluded that the platform pile foundation has the greatest impact on the construction of foundation pits adjacent to existing structures, necessitating focused supervision and control in this area.

3.3 Fuzzy Comprehensive Evaluation of Risk Level

(1) Establishment of Evaluation Set

The construction risk of foundation pit excavation adjacent to existing structures is divided into three levels, The evaluation set is $V = \{3,2,1\}$: high risk (3), medium risk (2), and low risk (1), as shown in Table 10.

Table 10: Accident Possibility Level Standards

Probability Range	Level Description	Level
>0.3	High Risk	3
0.003~0.3	Medium Risk	2
<0.003	Low Risk	1

(2) Establishment of Evaluation Factor Membership Matrix

Considering the on-site construction conditions and the safety risk assessment system for foundation pit excavation adjacent to existing structures, a single-factor evaluation is established, and a fuzzy relation matrix R from U to V is created. Through expert surveys and reviews, the membership vector $r_{ij} = \{r_{ij1}, r_{ij2}, \dots, r_{ijm}\}$ for a single factor is derived, where r_{ijm} represents the estimated probability of a certain level of accident possibility occurring for a given evaluation factor. Thus, the membership matrix Rij is composed of single-factor membership vectors as follows:

$$R_{11} = \begin{bmatrix} 0.4 & 0.4 & 0.2 \\ 0.3 & 0.5 & 0.2 \\ 0.2 & 0.5 & 0.3 \\ 0.1 & 0.4 & 0.4 \end{bmatrix} \quad R_{12} = \begin{bmatrix} 0.2 & 0.3 & 0.5 \\ 0 & 0 & 1 \\ 0.5 & 0.4 & 0.1 \\ 0.2 & 0.5 & 0.3 \end{bmatrix}$$

$$R_{13} = \begin{bmatrix} 0 & 0 & 1 \\ 0.1 & 0.2 & 0.7 \\ 0.3 & 0.5 & 0.2 \\ 0.4 & 0.4 & 0.2 \end{bmatrix} \quad R_{14} = \begin{bmatrix} 0.4 & 0.4 & 0.2 \\ 0.4 & 0.4 & 0.2 \\ 0.3 & 0.6 & 0.1 \\ 0.2 & 0.2 & 0.6 \end{bmatrix}$$

(3) Multi-level Fuzzy Comprehensive Evaluation

1) First-level Fuzzy Evaluation

The first-level fuzzy evaluation involves comprehensive judgment based on each factor within a category. The specific formula is $B_{ij} = A_{ij} \times R_{ij}$, where A_{ij} represents the weight of each factor at the third level, and R_{ij} is the corresponding single-factor evaluation matrix. The result of the first-level fuzzy evaluation is as follows:

$B_{11} = (0.2733\ \ 0.4333\ \ 0.2334)$ $\quad B_{12} = (0.2833\ \ 0.3418\ \ 0.3749)$

$B_{13} = (0.2838\ \ 0.3534\ \ 0.3618)$ $\quad B_{14} = (0.2934\ \ 0.4134\ \ 0.2932)$

2) Second-level Fuzzy Evaluation

The second-level fuzzy comprehensive evaluation further considers the comprehensive impact between categories based on the first-level evaluation. The single-factor evaluation matrix of the second-level fuzzy comprehensive evaluation is composed of the results from the first-level fuzzy comprehensive judgment, where $R_1 = \begin{bmatrix} B_{11} \\ B_{12} \\ B_{13} \\ B_{14} \end{bmatrix}$, A_i represents the weight of each factor at the second level. The specific formula is $B_i = A_i \times R_i$ to obtain the second-level fuzzy evaluation results as follows:

$$B_i = A_i \times R_i = (0.267\ \ 0.133\ \ 0.067\ \ 0.533) \times \begin{bmatrix} 0.2733 & 0.4333 & 0.2334 \\ 0.2833 & 0.3418 & 0.3749 \\ 0.2838 & 0.3534 & 0.3618 \\ 0.2934 & 0.4134 & 0.2932 \end{bmatrix}$$

$$B_I = (0.286\ \ 0.405\ \ 0.293)$$

(4) Judgment Result Analysis

The judgment function uses a Type I function, with the final result being 1×0.286+0.1×0.405+0.01×0.293=0.329. According to the Accident Possibility Level Standards, the construction risk probability for this foundation pit project is classified as level 3, high risk, which matches the actual project's safety rating of level 1 for sidewall safety. This confirms the necessity of subsequent optimization of foundation pit support parameters.

4. Conclusion

This paper utilizes a combination of the AHP and Fuzzy Comprehensive Evaluation to conduct a comprehensive evaluation of the major safety factors in foundation pit excavation projects adjacent to existing structures, with the following conclusions:

(1) Starting from the main factors such as the surrounding environment of the pit, engineering geology, the construction scheme for pit excavation, and construction management, risk identification for the factors affecting the risk of foundation pit excavation adjacent to existing structures was carried out, establishing a complete and reasonable safety risk assessment index system.

(2) By calculating the weights of various indices for foundation pit excavation adjacent to existing structures using the AHP, it was found that the existing platform pile foundations have the most significant impact on the construction of foundation pits adjacent to existing structures, necessitating focused supervision and control in this area.

(3) Taking into account the actual project situation and the risk evaluation index system, a safety risk assessment model for foundation pit excavation adjacent to existing structures was constructed using Fuzzy Comprehensive Evaluation. It was concluded that the actual construction safety risk level of the Wudaokou Station on Beijing Metro Line 13 is level 3, classified as "high risk", which corresponds with the on-site conditions.

References

[1] HONG Kairong. State-of-art and Prospect of Tunnels and Underground Works in China[J]. Tunnel Construction, 2015, 35(2): 95-107.

[2] HONG Kairong. Development and Prospects of Tunnels and Underground Works in China in Recent Two Years[J]. Tunnel Construction, 2017, 37(2): 123-134.

[3] YOU Xinhua, HE Guangyao, WANG Qiangxun, et al. Current Status and Development Trend of Urban Underground Space in China[J]. Tunnel Construction, 2019, 39(2): 173-188.

[4] MENG Lingzhi. Study on settlement control system of the large section tunnel with closely adjacent down-traversing the existing tunnel[J]. Building Structure, 2018, 48(S1): 772-777.

[5] WANG Jianchen, LIU Yunliang, ZHANG Dingli, et al. Study of Deformation Control and Deformation Law of Existing Tunnel with Parallel Running Underneath Subway Station[J]. Journal of the China Railway Society 2017, 39(11): 131-137.

[6] YU Jun. Study on Construction Scheme Optimization of Shallow-buried Tunnel undercrossing Existing Metro Station with Zero-clearance[J]. Tunnel Construction, 2013, 33(1): 22-26.

[7] WANG Gang, LI Junsong, ZHANG Xinggang. Study on Safety Risk Management of Metro Tunnel with Hidden-digging Method Under-passing Existing Railway Station[J]. Railway Standard Design, 2014(9): 93-98.

[8] CHANG S, MOON S. A case study on instrumentation of a large tunnel crossing under the existing subway structure[C]. Proceedings of the KGS 2000 Spring Conference, 2000. 56-59.

[9] Li Shuguang, Ren Shaoqiang, Wang Hongkun, et al. Deformation Law and Safety Risk Assessment of Deep Foundation Pit Construction of Subway Station[J]. Highway, 2022, 67(01): 355-362.