Journal of Civil Engineering and Urban Planning (2023)
Clausius Scientific Press, Canada

DOI: 10.23977/jceup.2023.050807
ISSN 2616-3969 Vol. 5 Num. 8

Extension AHP-Based Assessment of Safety Risk Levels in Subway Deep Excavation Construction

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Keywords: Pit stability, extenics, analytic hierarchy process, safety risk levels

Abstract: Excavation projects in foundation pits are greatly influenced by geological conditions and surrounding environments. The construction process is complex, and apart from the stability of the pits themselves, there are also numerous risk factors. Failure to assess and prevent potential risks in foundation pits can result in severe consequences if accidents occur. This paper presents a method that combines the Analytic Hierarchy Process (AHP) with the theory of extenics to evaluate the safety risk levels in excavation construction of foundation pits. By establishing an extenics model and conducting relevance calculations, the safety risk levels in excavation construction of foundation pits are determined. Furthermore, based on actual engineering cases, the feasibility of the proposed model is demonstrated by comparing the results with the actual situations. The method presented in this paper effectively evaluates the magnitude of safety risks in excavation construction of foundation pits, thereby achieving the goal of guiding practical engineering projects.

1. Introduction

The 21st century is the century of underground space development and utilization [1], and foundation pit engineering plays a significant role in construction projects. Due to the large influence of geological conditions and surrounding environments, foundation pit construction is complex and involves numerous risk factors. Failure to assess and prevent risks associated with foundation pits can result in severe consequences if accidents occur. The stability of foundation pits is a crucial factor in determining their safety. Existing regulations and manuals [2] often use the calculation of the safety factor Fs to determine their stability. Methods for calculating the overall stability safety factor include the Swedish arc sliding method, simplified Bishop method, and force equilibrium method, among others. Methods for calculating anti-heave stability safety factors primarily include the limit equilibrium method, limit analysis method, and conventional displacement finite element method. By comparing Fs with safety index indicators, it can be determined whether a foundation pit will experience instability. Many scholars have conducted in-depth research in this area. Hou Xiaoliang et al. used an improved first-order second-moment method to calculate the reliability index of soft soil foundation pit heave resistance, considering the uncertainty of soil parameters and improving the traditional safety factor [3]. Jiang Hongwei et al. analyzed the stability safety factors of deep foundation pits under anisotropic conditions [4]. Zhang Wei calculated the safety factors of foundation pits under different reduction coefficients using the finite element strength reduction method to determine the stability of different working conditions [5]. He Yingdao established an empirical formula for safety factors considering seepage effects [6]. In addition, there have been significant advancements in risk assessment methods for foundation pits. Li Zhaoyang et al. established a three-level risk assessment index system to classify the risk levels of foundation pits in a subway station in Ningbo [7]. Hu Nielei proposed a multi-parameter safety assessment method, established a quantitative relationship between detection data and various mechanical indicators, and assessed construction risks of foundation pits [8]. Zhou Wen proposed a fuzzy evaluation method for assessing foundation pit engineering in soft soil areas with uncertainties [9]. It can be seen that the calculation of safety factors and existing assessment methods only provide preliminary evaluations before foundation pit construction. However, there are many uncertain factors during the construction process, and these calculation models and assessment systems cannot reflect or predict them.

This paper proposes a risk assessment method that combines the Analytic Hierarchy Process (AHP) with the theory of extenics. It evaluates the safety risk levels of foundation pit excavation construction under different working conditions using monitoring data and compares the results based on actual engineering cases.

2. Establishment of an Extenics Evaluation Model

Extenics is a new evaluation method [10] that can transform various evaluation indicators into a compatible problem. By establishing a matter-element model, it derives practical conclusions and provides effective reference recommendations. The application of extenics theory enables the evaluation of research objects based on feasibility and optimization, by selecting important parameter indicators according to the actual situation, without limitations on the factors and indicators chosen.

2.1 Determination of Classical Domains and Ontological Domains

Define the risk level domain Z of the object under evaluation:

$$Z = (z_1, z_2, z_3 \cdots z_n)$$

Considering various factors in the actual situation, select the feature set C of the object's risk:

$$C = (c_1, c_2, c_3 \cdots c_n)$$

Assume that the risk assessment is conducted for a certain object N. There are n characteristic factors that influence the risk level of this object. The risk situation of the object can be described using an n-dimensional matter-element:

$$R = (N, C, V) = \begin{Bmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{Bmatrix} \tag{1}$$

Where: N——Object under evaluation;

C——Characteristics of factors influencing the object's risk;

V——Quantitative values corresponding to the risk factor characteristics.

The classical domain matter-element of the object under evaluation is obtained as follows:

$$R_{ot} = (N_{ot}, C, x_{oti}) = \begin{Bmatrix} N_{ot} & c_1 & x_{ot1} \\ & c_2 & x_{ot2} \\ & \vdots & \vdots \\ & c_n & x_{otn} \end{Bmatrix} = \begin{Bmatrix} N_{ot} & c_1 & (a_{ot1}, b_{ot1}) \\ & c_2 & (a_{ot2}, b_{ot2}) \\ & \vdots & \vdots \\ & c_n & (a_{otn}, b_{otn}) \end{Bmatrix} \tag{2}$$

Where: N_{ot}——Object under evaluation is divided into t levels;
x_{oti}——Range of values determined by characteristic factor c.
The ontological domain is represented as:

$$R_p = (N_p, C, X_p) = \begin{Bmatrix} N_p & c_1 & x_{p1} \\ & c_2 & x_{p2} \\ & \vdots & \vdots \\ & c_n & x_{pn} \end{Bmatrix} = \begin{Bmatrix} N_p & c_1 & (a_{p1}, b_{p1}) \\ & c_2 & (a_{p2}, b_{p2}) \\ & \vdots & \vdots \\ & c_n & (a_{pn}, b_{pn}) \end{Bmatrix} \tag{3}$$

Where: N_p——Individual of risk level;
X_p——Range of values of characteristic factor c corresponding to the risk level.

2.2 Determination of Matter-Elements for Evaluation

Based on the collected data and information, the actual values corresponding to each characteristic factor of the object under evaluation can be obtained, as follows:

$$R = (N, C, x_n) = \begin{Bmatrix} N & c_1 & x_1 \\ & c_2 & x_2 \\ & \vdots & \vdots \\ & c_n & x_n \end{Bmatrix} \tag{4}$$

Where: x_n——Corresponding quantitative value for the characteristic factor, obtained from actual data.

2.3 Determination of Interrelationships among Risk Levels

The interrelationship between the i-th characteristic factor of the object under evaluation and the risk level z is calculated as follows:

$$k_t(x_i) = \begin{cases} \dfrac{-\rho(x_i, x_{oti})}{|x_{oti}|} & \text{if} \quad \rho(x_i, x_{pi}) - \rho(x_i, x_{oti}) = 0 \\ \dfrac{\rho(x_i, x_{oti})}{\rho(x_i, x_{pi}) - \rho(x_i, x_{oti})} & \text{if} \quad \rho(x_i, x_{pi}) - \rho(x_i, x_{oti}) \neq 0 \end{cases} \tag{5}$$

Where:

$$\rho(x_i, x_{oti}) = \left| x_i - \frac{1}{2}(a_{0ti} + b_{oti}) \right| - \frac{1}{2}(b_{oti} - a_{oti}) \tag{6}$$

$$\rho(x_i, x_{pi}) = \left| x_i - \frac{1}{2}(a_{pi} + b_{pi}) \right| - \frac{1}{2}(b_{pi} - a_{pi}) \tag{7}$$

$$|x_{oti}| = |a_{oti} - b_{oti}| \tag{8}$$

Based on the definition of extenics distance, $\rho(x_i,x_{oti})$ represents the distance from the actual value of characteristic factor c to the classical domain, $\rho(x_i,x_{pi})$ represents the distance from the actual value of characteristic factor c to the ontological domain, and $|x_{oti}|$ represents the magnitude of the classical domain interval $x_{oti}=(a_{oti},b_{oti})$.

2.4 Determination of Weight Coefficients

The Analytic Hierarchy Process (AHP) [11] is widely used to determine the weights of evaluation factors. In this paper, the AHP method is employed to determine the weight coefficients of each evaluation indicator. The specific steps are as follows:

(1) Determination of Risk Assessment Indicators

For a single-level risk assessment object, a specific risk incident is usually selected for classification. The required risk assessment indicators are obtained through consultation of relevant standards and literature.

(2) Construction of Judgment Matrix

The evaluation indicators determined in the previous step are used to construct a judgment matrix, and pairwise comparisons are performed to assign scores. Generally, a scale method using values from 1 to 9 and their reciprocals is employed to derive the judgment matrix S.

(3) Determination of Weight Factors

There are more than 20 methods for calculating weight coefficients based on the judgment matrix, such as linear programming and geometric mean. In this paper, the method of calculating the maximum eigenvalue λ_{max} and the corresponding eigenvector after normalization is adopted to obtain the weight vector W of the object's characteristic factors.

(4) Consistency Test

The consistency test refers to determining the acceptable range of inconsistency in the judgment matrix S. When performing a consistency test for hierarchical single sorting, the consistency index CI and the average random index RI need to be calculated. Specifically, $CI=\frac{\lambda_{\max}-n}{n-1}$. When CI=0, the matrix is perfectly consistent; the larger the value of CI, the poorer the consistency of the matrix. To measure the magnitude of CI, the average random consistency index RI is introduced, and the value of RI can be obtained from Table 1. When the consistency ratio $CR=CI/RI<0.1$, it indicates that the consistency of the judgment matrix S meets the requirements and passes the consistency test. The normalized eigenvector can then be used as the weight vector. Otherwise, it is necessary to reconstruct the judgment matrix and calculate new weight coefficients.

Table 1: RI Value Table

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

2.5 Determination of Risk Level

Based on the correlation formula (5)~(8), the correlation degree $k_t(x_{ij})$ of a certain risk factor of the object to be evaluated with respect to level z can be calculated. Combined with the weight coefficients w_i obtained from the Analytic Hierarchy Process, the correlation degree $k_t(x_{ij})$ of the object with respect to level z can be obtained.

$$K_t(N)=\sum w_i k_t(x_i) \tag{9}$$

The final level of the object to be evaluated is determined by taking the maximum correlation degree value $K_t(N)$ corresponding to a level.

3. Establishment of Excavation Construction Safety Risk Assessment Model for Foundation Pit

3.1 Selection of Evaluation Indicators

There are many factors that affect the safety of excavation construction for foundation pits. When establishing an evaluation model, the geological environment, design parameters, and monitoring parameters are chosen as primary indicators. The factors influencing the safety of excavation construction for foundation pits are shown in Figure 1.

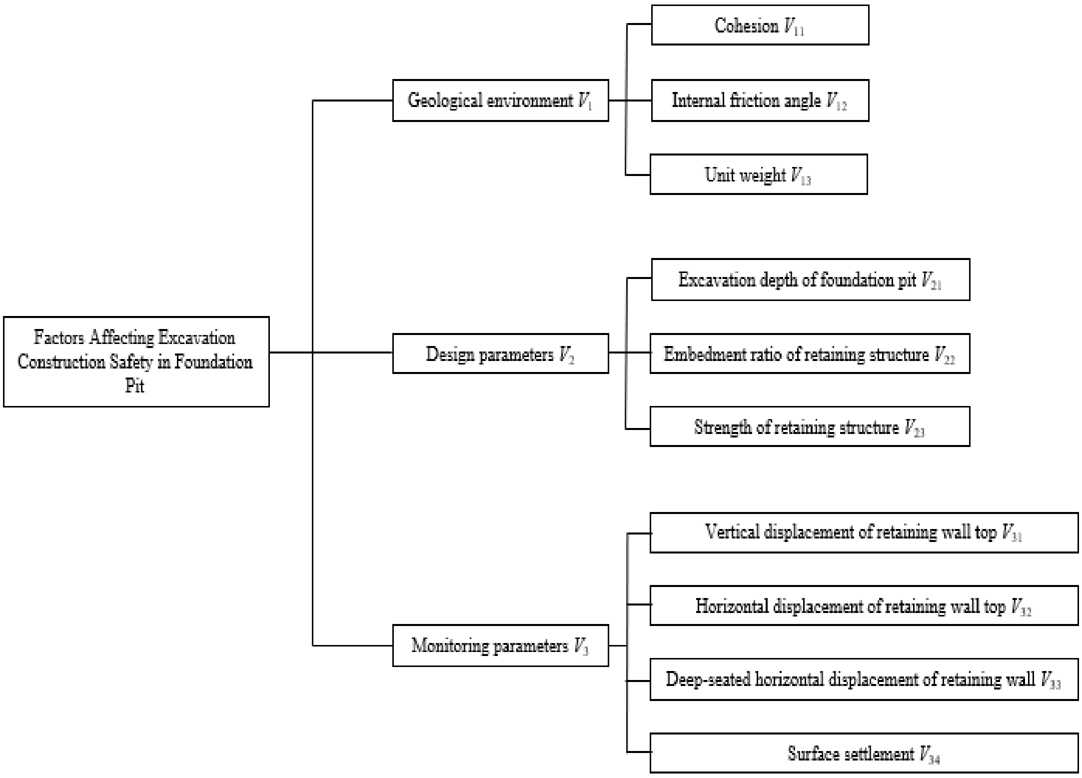

Figure 1: Factors Affecting Excavation Construction Safety in Foundation Pit

3.2 Determination of Risk Level Domain

Using the single-factor method, the safety risk of excavation construction in the foundation pit is classified into five levels: high (t=1), relatively high (t=2), moderate (t=3), relatively low (t=4), and low (t=5).

$$Z = (z_1, z_2, z_3, z_4, z_5) = (\text{high, relatively high, moderate,relatively low,low})$$

In general, when excavating in soil layers with low unit weight, high cohesion, and large internal friction angle, the stability of the foundation pit is stronger. However, as the excavation depth of the foundation pit increases, the safety of the excavation construction gradually decreases. Increasing the embedment ratio and strength of the retaining structure can effectively improve the stability of the foundation pit [12]. In terms of monitoring data, if the values remain below the warning threshold, the foundation pit is considered safe. However, if the values reach the warning threshold, the foundation pit may be unstable [13,14]. Based on these considerations, a risk classification for excavation construction in the foundation pit can be determined based on individual factors, as shown in Table 2.

Table 2: Risk Classification for Excavation Construction in the Foundation Pit based on Individual Factors

Factors \ Risk Level		t=1	t=2	t=3	t=4	t=5
V_1	V_{11}	0~5	5~15	15~25	25~40	40~60
	V_{12}	0~8	8~16	16~24	24~32	32~40
	V_{13}	30~40	20~30	10~20	5~10	0~5
V_2	V_{21}	30~40	20~30	10~20	5~10	0~5
	V_{22}	0~0.3	0.3~0.6	0.6~1.2	1.2~2.0	2.0~3.0
	V_{23}	0~15	15~30	30~45	45~55	55~60
V_3	V_{31}	25~35	15~25	10~15	5~10	0~5
	V_{32}	30~40	20~30	15~20	10~15	0~10
	V_{33}	40~50	30~40	20~30	10~20	0~10
	V_{34}	20~30	15~20	10~15	5~10	0~5

3.3 Classic Domains and Subdomains for Each Risk Level

1) Classic Domain Elements

After quantitative processing, the classical domain elements for the stability level of anti-uplifting in the foundation pit can be obtained based on Equation (2). Here, c_1~c_{10} represent the cohesion of the soil, internal friction angle of the soil, unit weight of the soil, excavation depth of the foundation pit, embedment ratio of the retaining structure, strength of the retaining structure, vertical displacement of the retaining wall top, horizontal displacement of the retaining wall top, deep-seated horizontal displacement of the retaining wall, and surface settlement, respectively.

$$R_{01}=\begin{bmatrix} N_{01} & c_1 & <0,0.08> \\ & c_2 & <0,0.2> \\ & c_3 & <0,0.25> \\ & c_4 & <0,0.25> \\ & c_5 & <0,0.1> \\ & c_6 & <0,0.25> \\ & c_7 & <0,0.286> \\ & c_8 & <0,0.25> \\ & c_9 & <0,0.2> \\ & c_{10} & <0,0.33> \end{bmatrix} R_{02}=\begin{bmatrix} N_{02} & c_1 & <0.08,0.25> \\ & c_2 & <0.2,0.4> \\ & c_3 & <0.25,0.5> \\ & c_4 & <0.25,0.5> \\ & c_5 & <0.1,0.2> \\ & c_6 & <0.25,0.5> \\ & c_7 & <0.286,0.571> \\ & c_8 & <0.25,0.5> \\ & c_9 & <0.2,0.4> \\ & c_{10} & <0.33,0.5> \end{bmatrix} R_{03}=\begin{bmatrix} N_{03} & c_1 & <0.25,0.42> \\ & c_2 & <0.4,0.6> \\ & c_3 & <0.5,0.75> \\ & c_4 & <0.5,0.75> \\ & c_5 & <0.2,0.4> \\ & c_6 & <0.5,0.75> \\ & c_7 & <0.571,0.714> \\ & c_8 & <0.5,0.625> \\ & c_9 & <0.4,0.6> \\ & c_{10} & <0.5,0.667> \end{bmatrix}$$

$$R_{04}=\begin{bmatrix} N_{04} & c_1 & <0.42,0.67> \\ & c_2 & <0.6,0.8> \\ & c_3 & <0.75,0.875> \\ & c_4 & <0.75,0.875> \\ & c_5 & <0.4,0.67> \\ & c_6 & <0.75,0.92> \\ & c_7 & <0.714,0.857> \\ & c_8 & <0.625,0.75> \\ & c_9 & <0.6,0.8> \\ & c_{10} & <0.667,0.833> \end{bmatrix} R_{05}=\begin{bmatrix} N_{05} & c_1 & <0.67,1> \\ & c_2 & <0.8,1> \\ & c_3 & <0.875,1> \\ & c_4 & <0.875,1> \\ & c_5 & <0.67,1> \\ & c_6 & <0.92,1> \\ & c_7 & <0.857,1> \\ & c_8 & <0.75,1> \\ & c_9 & <0.8,1> \\ & c_{10} & <0.833,1> \end{bmatrix}$$

2) Subdomain Elements obtained from Equation (3).

$$R_p = \begin{bmatrix} N_p & c_1 & <0,1> \\ & c_2 & <0,1> \\ & c_3 & <0,1> \\ & c_4 & <0,1> \\ & c_5 & <0,1> \\ & c_6 & <0,1> \\ & c_7 & <0,1> \\ & c_8 & <0,1> \\ & c_9 & <0,1> \\ & c_{10} & <0,1> \end{bmatrix}$$

3.4 Determination of Weight Coefficients for Evaluation Indicators using Analytic Hierarchy Process

1) Weight coefficients of the primary indicators

The two-by-two comparison matrix S for the relative importance of evaluation indicators:

$$S = \begin{bmatrix} 1 & 1/3 & 1/5 \\ 3 & 1 & 1/2 \\ 5 & 2 & 1 \end{bmatrix}$$

The maximum eigenvalue of the judgment matrix S can be calculated as λ_{max}=3.0037. By normalizing the corresponding eigenvector, the weight set W for evaluation indicators is obtained as W={0.1095, 0.3090, 0.5816}.

Given the consistency index $CI = \frac{\lambda_{max} - n}{n-1} = \frac{3.0037-3}{2} = 0.0018$, the random consistency ratio is $CR = \frac{CI}{RI} = \frac{0.0018}{0.58} = 0.0032 < 0.1$, that is the result consistency is satisfied. Therefore, the weight set W can be determined as the weights for the respective evaluation factors.

2) Weight coefficients for the secondary indicators

(a) Geological Environment:

The two-by-two comparison matrix S_1 for the relative importance of evaluation indicators:

$$S_1 = \begin{bmatrix} 1 & 1/2 & 3 \\ 2 & 1 & 4 \\ 1/3 & 1/4 & 1 \end{bmatrix}$$

The maximum eigenvalue of the judgment matrix S_1 can be calculated as λ_{max}=3.0183. By normalizing the corresponding eigenvector, the weight set W1 for evaluation indicators is obtained as W_1={0.3196,0.5584,0.1220}.

Given the consistency index $CI = \frac{\lambda_{max} - n}{n-1} = \frac{3.0183-3}{2} = 0.0091$, the random consistency ratio is $CR = \frac{CI}{RI} = \frac{0.0091}{0.58} = 0.0158 < 0.1$, indicating that the result satisfies the consistency requirement. Therefore, the weight set W_1 can be determined as the weights for the respective evaluation factors.

(b) Design Parameters:

The two-by-two comparison matrix S_2 for the relative importance of evaluation indicators:

$$S_2 = \begin{bmatrix} 1 & 1/2 & 2 \\ 2 & 1 & 2 \\ 1/2 & 1/2 & 1 \end{bmatrix}$$

The maximum eigenvalue of the judgment matrix S_2 can be calculated as λ_{max}=3.0536. By normalizing the corresponding eigenvector, the weight set W_2 for evaluation indicators is obtained as W_2={0.3108,0.4934,0.1958}.

Given the consistency index $CI = \frac{\lambda_{\max} - n}{n-1} = \frac{3.0536-3}{2} = 0.0268$, the random consistency ratio is $CR = \frac{CI}{RI} = \frac{0.0268}{0.58} = 0.0462 < 0.1$, indicating that the result satisfies the consistency requirement. Therefore, the weight set *W2* can be determined as the weights for the respective evaluation factors.

(c)Monitoring Parameters

The two-by-two comparison matrix *S3* for the relative importance of evaluation indicators:

$$S_3 = \begin{bmatrix} 1 & 2 & 2 & 1/2 \\ 1/2 & 2 & 1 & 1/2 \\ 1/2 & 2 & 1 & 1/2 \\ 2 & 2 & 2 & 1 \end{bmatrix}$$

The maximum eigenvalue of the judgment matrix *S2* can be calculated asλ_{max}=4.1213. By normalizing the corresponding eigenvector, the weight set $W_3$for evaluation indicators is obtained as W_3={0.2661,0.1381,0.1953,0.3905}.

Given the consistency index $CI = \frac{\lambda_{\max} - n}{n-1} = \frac{4.1213-4}{3} = 0.0404$, the random consistency ratio is $CR = \frac{CI}{RI} = \frac{0.0404}{0.90} = 0.0449 < 0.1$, indicating that the result satisfies the consistency requirement. Therefore, the weight set *W* can be determined as the weights for the respective evaluation factors.

Finally, the weight for each influencing factor can be obtained. The results are summarized in Table 3.

Table 3: Weight Coefficients for Evaluation Indicators

Primary Indicators	Weight	Secondary Indicators	Weight	Final Weight
Geological Environment	0.1095	Soil Cohesion	0.3196	0.0350
		Soil Internal Friction Angle	0.5584	0.0611
		Soil Unit Weight	0.1220	0.0134
Design Parameters	0.3090	Excavation Depth of the Foundation Pit	0.3108	0.0960
		Embedment Ratio of the Retaining Structure	0.4934	0.1525
		Strength of the Retaining Structure	0.1958	0.0605
Monitoring Parameters	0.5816	Vertical Displacement of the Retaining Wall Top	0.2661	0.1548
		Horizontal Displacement of the Retaining Wall Top	0.1381	0.0803
		Deep-seated Horizontal Displacement of the Retaining Wall	0.1953	0.1136
		Surface Settlement	0.3905	0.2271

4. Engineering Application

4.1 Project Overview

The excavation of a subway station foundation pit is carried out using the open-cut method. The construction of the retaining structure is done first, followed by dewatering and excavation of the soil from the ground to the design elevation. Waterproofing and main structural measures are then constructed from bottom to top, and finally, backfilling is performed. The standard section of the station pit adopts vertical three-lane support, with the first lane being reinforced concrete cross-shaped support placed on the crown beam. The second and third lanes are steel supports welded to embedded steel plates in the ground. At the end of the station, there are four vertical inclined supports, with the first lane being reinforced concrete support and the second, third, and fourth lanes being steel supports welded to embedded steel plates in the ground.

The overall depth of the excavation is 14.1 meters, and the width is 19.7 meters. The retaining structure consists of a ground-connected wall with an elastic modulus of 3.25×10^7 kN/m^2. The depth of embedment is 24 meters, and the embedment ratio is 0.7. Mechanized excavation is mainly used, and manual cleaning is carried out after reaching the base to minimize disturbance to the original condition of the site. The excavation process is divided into six construction conditions, as shown in Table 4.

Table 4: Construction Conditions

Number	Description
1	Excavation to the bottom of the first reinforced concrete support, excavation height of 1.5m; construction of pile cap, first concrete support, and connecting beams.
2	Excavation of the second layer of soil, excavation height of 2.2m.
3	Excavation from the third layer of soil to the bottom of the second steel support at a depth of 0.5m, excavation height of 2.2m; installation of the second steel support for the standard section.
4	Excavation of the fourth layer of soil, excavation height of 2.7m; installation of the third steel support for the end shaft, excavation until 0.5m below the steel support.
5	Excavation of the fifth layer of soil, excavation until 0.5m below the bottom of the third steel support for the standard section; excavation until 0.3m below the fourth steel support for the end shaft, excavation height of 2.7m.
6	Excavation from the sixth layer of soil to 0.3m above the bottom of the pit, excavation height of 2.8m; initial slot excavation in the middle and then retrograde excavation for the remaining portion of the soil; manual cleaning of the 0.3m thick soil at the base.

Table 5: Soil Parameters of Excavation Layers (Partial)

Soil Layer	Unit Weight$\gamma(kN/m^3)$	Cohesion $c(kPa)$	Friction Angle $\varphi(^o)$	Thickness(m)
Fill Sand	18.0	0	15	2.3
Fine Silty Sand	18.3	1	23	8.6
(Clayey) Silty Sand	18.5	4	24	10.0
Silty Clay	17.3	12	15	10.9

The station's main structure site is located in the open coastal plain of the southern bank of the Minjiang Estuary, with developed groundwater. The overlying artificial fill (Q_4^{ml}), the Quaternary Longxi Formation (Q_4^{mc}, Q_4^{m}), the Upper Pleistocene Dongshan Formation (Q_3^{m}), and the Late Yanshan Granite (γ_5^3) are the geological layers. Based on the results of geological survey, the layer distribution from top to bottom (only listing the soil layers involved in excavation) includes fill sand, fine silty sand, (clayey) silty sand, and silty clay. The specific parameter values of these soil layers are shown in Table 5.

4.2 Monitoring Overview

Horizontal observation points are arranged every 15 meters along the top of the continuous underground wall surrounding the excavation, used for monitoring the vertical and horizontal displacements of the retaining wall. Inclinometers are embedded inside the diaphragm wall for monitoring deep-seated horizontal displacements of the retaining wall. Surface settlement observation points are installed in the first row at a distance of 1 meter from the retaining structure, with spacing of 4.0 meters between the first to fourth rows and a spacing of 6 meters between the fourth and fifth rows. At each completion of the construction phases, which serve as nodes, the absolute maximum values of the monitoring data for each parameter are recorded, as shown in Table 6.

Table 6: Monitoring Data Table

Construction Phase	Vertical Displacement of Retaining Wall Top/mm	Horizontal Displacement of Retaining Wall Top/mm	Horizontal Displacement of Deep-Seated Retaining Wall/mm	Surface Settlement/mm
1	4.23	3.1	5.27	3.19
2	7.46	7.4	13.50	6.82
3	16.30	11.6	16.30	7.88
4	7.78	7.8	21.90	42.43
5	7.26	5.2	33.92	48.17
6	8.68	13.4	44.89	51.10

4.3 Risk Assessment

Due to the involvement of different soil layers during excavation, the soil parameters are taken as the weighted average values. The evaluation elements for the six construction phases can be obtained as follows:

$$R_1=\begin{Bmatrix} N & c_1 & 0 \\ & c_2 & 15 \\ & c_3 & 18.0 \\ & c_4 & 1.5 \\ & c_5 & 0.7 \\ & c_6 & 32.5 \\ & c_7 & 4.23 \\ & c_8 & 3.1 \\ & c_9 & 5.27 \\ & c_{10} & 3.19 \end{Bmatrix} \quad R_2=\begin{Bmatrix} N & c_1 & 0.64 \\ & c_2 & 20.1 \\ & c_3 & 18.2 \\ & c_4 & 3.7 \\ & c_5 & 0.7 \\ & c_6 & 32.5 \\ & c_7 & 7.46 \\ & c_8 & 7.4 \\ & c_9 & 13.5 \\ & c_{10} & 6.82 \end{Bmatrix} \quad R_3=\begin{Bmatrix} N & c_1 & 1 \\ & c_2 & 23 \\ & c_3 & 18.3 \\ & c_4 & 5.9 \\ & c_5 & 0.7 \\ & c_6 & 32.5 \\ & c_7 & 16.3 \\ & c_8 & 11.6 \\ & c_9 & 16.3 \\ & c_{10} & 7.88 \end{Bmatrix}$$

$$R_4 = \left\{ \begin{array}{ccc} N & c_1 & 1 \\ & c_2 & 23 \\ & c_3 & 18.3 \\ & c_4 & 8.6 \\ & c_5 & 0.7 \\ & c_6 & 32.5 \\ & c_7 & 7.78 \\ & c_8 & 7.8 \\ & c_9 & 21.9 \\ & c_{10} & 42.43 \end{array} \right\} \quad R_5 = \left\{ \begin{array}{ccc} N & c_1 & 1.44 \\ & c_2 & 23.1 \\ & c_3 & 18.3 \\ & c_4 & 11.3 \\ & c_5 & 0.7 \\ & c_6 & 32.5 \\ & c_7 & 7.26 \\ & c_8 & 5.2 \\ & c_9 & 33.92 \\ & c_{10} & 48.17 \end{array} \right\} \quad R_6 = \left\{ \begin{array}{ccc} N & c_1 & 4 \\ & c_2 & 23 \\ & c_3 & 18.5 \\ & c_4 & 14.1 \\ & c_5 & 0.7 \\ & c_6 & 32.5 \\ & c_7 & 8.68 \\ & c_8 & 13.4 \\ & c_9 & 44.89 \\ & c_{10} & 51.10 \end{array} \right\}$$

Using the correlation calculation formulas (5) to (8), the relevance degree of safety risk levels during the completion of each construction phase is calculated, as shown in Table 7.

Table 7: Calculation Results of Relevance Degree for Risk Levels during Completion of Each Construction Phase

No.	$K_1(N)$	$K_2(N)$	$K_3(N)$	$K_4(N)$	$K_5(N)$	Rating
1	-0.6853	-0.5931	-0.4736	-0.4273	0.0141	z_5
2	-0.5812	-0.4591	-0.2154	0.0217	-0.2532	z_4
3	-0.4911	-0.3119	-0.1251	0.0145	-0.3658	z_4
4	-0.3915	-0.5068	-0.2792	-0.2816	-0.5061	z_3
5	-0.3698	-0.4315	-0.3189	-0.3812	-0.5148	z_3
6	-0.2477	-0.4515	-0.2820	-0.3957	-0.6112	z_1

According to the table, after the completion of excavation for the first layer of soil, the safety risk rating for the excavation construction of the foundation pit is z_5 (low risk). After the completion of excavation for the second and third layers of soil, the safety risk rating for the excavation construction of the foundation pit is z_4 (moderate risk). After the completion of excavation for the fourth and fifth layers of soil, the safety risk rating for the excavation construction of the foundation pit is z_4 (medium risk). After the completion of excavation for the sixth layer of soil, the safety risk rating for the excavation construction of the foundation pit is z_1 (high risk). Based on the assessment results, a graph of the safety risk rating for the excavation construction of the foundation pit can be created, as shown in Figure 2. As the excavation depth increases, the risk of excavation construction of the foundation pit becomes greater, which is consistent with the actual situation. From the monitoring data, it can be observed that the maximum ground settlement increased to 42.43mm after the completion of excavation for the fourth layer of soil, which is approximately 5 times the maximum ground settlement after the excavation of the third layer. This directly leads to an increased risk in subsequent excavation of the foundation pit.

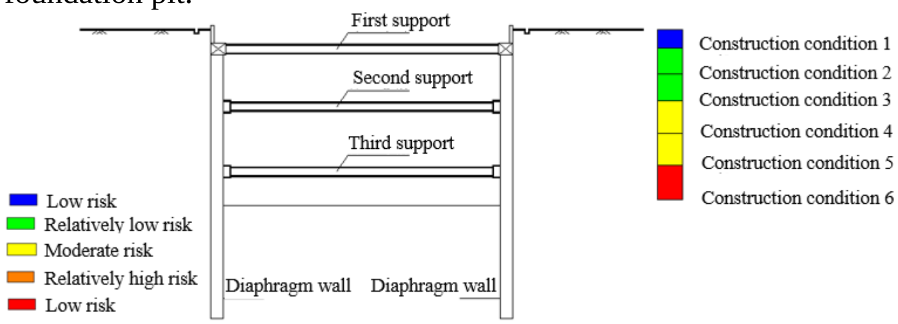

Figure 2: Safety Risk Level Diagram for Excavation Construction

Based on the analysis of monitoring alerts, the classification criteria for monitoring alert levels for this excavation project are shown in Table 8. The specific alert values are referenced from the monitoring regulations and can be found in Table 9. It can be observed that starting from Construction Condition 4, there were alerts indicating a moderate risk level in the excavation. This suggests that although alerts were triggered, the stability of the excavation still meets the construction requirements, ensuring the safe progress of the excavation work. However, in order to ensure the safety of subsequent construction, it is still necessary to implement risk management measures to reduce the risks associated with excavation construction and develop relevant contingency plans for risk mitigation.

Table 8: Classification Criteria for Monitoring Alert Levels

Monitoring Alert Leve	Monitoring Alert Leve
Yellow Alert	Deformation monitoring reaches 85% or more of the control target value
Orange Alert	Deformation monitoring reaches the control target value
Red Alert	Deformation monitoring exceeds the control target value

Table 9: Monitoring Alert Values for Excavation

Monitoring Item	Yellow Alert Value /mm	Orange Alert Value/mm	Red Alert Value/mm
Vertical Displacement of Retaining Wall Top	20	25	40
Horizontal Displacement of Retaining Wall Top	20	25	40
Horizontal Displacement of Deep Retaining Wall	45	50	75
Surface Settlement	35	40	60

5. Conclusion and Outlook

In this paper, a risk assessment model for excavation instability was established based on the Analytic Hierarchy Process-Extenics theory. The selection of assessment factors is not limited in terms of types and quantity, making it applicable to a wide range of scenarios. Additionally, the model is capable of considering various characteristic factors that influence risk levels comprehensively, resulting in a high level of credibility.

The validation of the assessment model was conducted based on a subway station excavation project, and the results align with the actual engineering conditions. This demonstrates the feasibility of the model and its ability to guide practical engineering projects. When applied in real projects, the model can be synchronized with updated monitoring data to reflect the excavation risk in real-time, thus enhancing timeliness and providing assessment results that align with the current project conditions.

References

[1] Qian Q. H. (1998) Prospects for the Development and Utilization of Underground Space in the 21st Century. In: Proceedings of the 8th Annual Conference of the China Civil Engineering Society. China Civil Engineering Society: 8.

[2] Liu J. H, Hou X. Y. (1997) Handbook of Excavation Engineering. Beijing: China Architecture & Building Press.

[3] Hou Xiaoliang, Tan Xiaohui. (2016) Application of Improved Second Moment Method in Reliability Evaluation of Anti-Uplift Stability of Excavation. Journal of Wuhan University (Engineering Edition), 49 (05): 791-795.

[4] Jiang H. W, Zhao X. H, Zhang B. L. (1997) Analysis of Anti-Uplift Stability of Deep Excavations in Anisotropic Soft

Soil. Chinese Journal of Geotechnical Engineering, (01): 3-9.
[5] Zhang W. (2019) Stability Analysis of Excavation Based on Finite Element Strength Reduction Method. Heilongjiang Water Resources Science and Technology, 47 (12): 141-143.
[6] He Y. D. (2020) Deformation Characteristics and Stability Study of Excavation Considering Seepage Effects. Journal of Water Resources and Architectural Engineering, 18 (01): 28-31+50.
[7] Li Z. Y, Ye C, Shen Y. S. (2014) Risk Assessment of Subway Excavation Based on Fuzzy Comprehensive Evaluation. Journal of Underground Space and Engineering, 10 (01): 220-226.
[8] Hu N. L. (2015) Research on Deep Excavation Support and Construction Risk Assessment. East China University of Technology.
[9] Zhou W. (2011) Risk Assessment of Excavation Engineering in Soft Soil Areas Based on Fuzzy Evaluation Method. Huaqiao University.
[10] Cai W. (1994) Physical Element Model and Its Application. Beijing: Science and Technology Literature Publishing House.
[11] Zhao H. C. (1986) Analytic Hierarchy Process: A Simple New Decision-Making Method. Beijing: Science Press.
[12] Su Q. H. (2019) Study on Stability Coefficient of Super Deep Excavation. Sichuan Building Materials, 45 (01): 79-80.
[13] Zhou Y. (2019) Analysis of Monitoring on the Stability of Super Deep Excavation of Bridge Abutment. Value Engineering, 38 (30): 175-178.
[14] Zhu J. C. (2019) Monitoring and Stability Analysis of Pump House Excavation in Sanmen Nuclear Power Phase II Project. Journal of Underground Space and Engineering, 15 (S1): 385-390.