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Integrating Combination Weighting of Game Theory and Fuzzy Comprehensive Evaluation for Selecting Deep Foundation Pit Support Scheme

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Abstract: Deep foundation pit support systems are important for reducing construction risks, to ensure the effectiveness and safety of support engineering, so the selection of a suitable support program is the inevitable requirement for the smooth construction of a foundation pit project. In order to improve the rationality of the support scheme, the analytic hierarchy process and the improved Entropy method are comprehensively used to determine the subjective and objective weights of the indexes, and the comprehensive weights are corrected based on the idea of game theory. Subsequently, fuzzy comprehensive evaluation is used for scheme selection, thereby constructing a model for optimizing deep foundation pit support schemes. The model is applied to a municipal pipe gallery project in Area A and the optimal support scheme is determined to be the soil nail wall and supporting piles and anchor ropes. The safety of the support scheme and the effectiveness of the selection model are verified through simulation and construction monitoring. Practice has proved the applicability and superiority of the model in dealing with construction projects characterized by ambiguity and insufficient data. In addition, the advantages and disadvantages of the mainstream evaluation methods of the current deep foundation pit support selection, applicable situations, and the influence mechanism of the geological environment are discussed in this paper, which helps to establish a more comprehensive framework for the selection of the support schemes.

Keywords: deep foundation pit engineering; decision making; deep foundation pit support schemes; combination weighting of game theory; improved entropy method; analytic hierarchy process (AHP)

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1. Introduction

Deep foundation pit engineering is a project closely related to high-rise buildings and complex underground projects in cities [1], which is highly comprehensive and complex, and attributed to high-risk engineering [2]. In the process of construction, it may cause deformation of the nearby soil and then damage the surrounding buildings and facilities, so a foundation pit support system is needed to protect the surrounding public facilities [3]. By selecting the appropriate support systems, such as retaining walls, bracing, and supporting structures, engineers can provide the adequate support to prevent the risk of structural damage or collapse during the construction and life of the structure. As a temporary supporting and strengthening structure, the main purpose of a foundation pit support system is to prevent the foundation pit from deformation and collapse under the action of earth pressure [4]. With the expansion of urban construction and the development and utilization of underground space, foundation pit engineering is also developing in the direction of larger areas and deeper depths, which puts forward higher requirements for the supporting effect of foundation pits [5]. An inappropriate foundation pit support system may lead to problems such as delays in the construction period, cost overrun, quality, safety, and so on [6]. Therefore, choosing a reasonable, safe, and economical support scheme is not only an important link to ensure the normal progress of the foundation pit project, but is also the foundation to ensuring the smooth completion of the construction project [7]. Deep foundation pit projects face multiple challenges in the selection of support systems, including different soil conditions, neighboring facilities, impacts on the environment, engineering limitations and spatial constraints, construction time pressure, technical feasibility, and economic viability.

Construction personnel and designers at home and abroad usually rely on previous experience and construction guidelines to select foundation pit support engineering schemes. However, in the context of increasingly complex urban renewal, relying on experience alone may not be able to fully address the multiple challenges faced in option selection [3]. In order to solve this problem, there is an urgent need to adopt scientific decision-making methods and comprehensively consider the key factors that may affect decision making, so as to provide an objective theoretical basis for scheme selection [8,9]. The multi-criteria decision-making (MCDM) method is widely used in different research fields and it can provide a logical framework, comprehensive evaluation, and comparison of various schemes, so that decision makers can choose more comprehensively and objectively [10]. Temiz and Calis [11] used AHP and the preference ordering organization method (PROMETHEE) to consider the fixed and quantitative indexes, rank the alternative schemes, and select the appropriate excavator for a construction site; Shahpari et al. [12] used Decision-making Trial and Evaluation Laboratory (DEMATEL) to determine the influence degree of each criterion, and then determine the index weight by the Analytic hierarchy process (AHP). Finally, the TOPSIS method was used to comprehensively evaluate the productivity level of residential construction. Branimir and Ana [13] applied te PROMETHEE II and AHP decision-making methods in a quarry and selected the best design model according to 22 different evaluation indexes. Palanikkumar et al. [14] applied the MCDM method of fuzzy logic to the selection of underground metal mining methods to determine the optimal mining methods. Weimin et al. [15] constructed a variable weight Fuzzy-AHP model to evaluate the safety of expansive soil slopes. Jin et al. [16] quantitatively analyzed the shadow response degree of factors related to the shear capacity of FRP-reinforced concrete deep flexural members by using the grey correlation method, and revealed the influence law of various factors on the shear capacity. At present, the general decision-making theory of engineering project schemes is relatively mature, but research on the decision making for foundation pit support schemes is relatively scarce, and foundation pit support involves the coupling of many complex factors, such as geology, soil, structure, construction, and so on. Its decision-making problem is more complex and special. Issa et al. [9] combined the fuzzy analytic hierarchy process with the TOPSIS method, and determined the optimal scheme of the project on the basis of considering the fuzziness of the evaluation index of the foundation pit scheme. Zhou Han and Cao Ping [17] established a hierarchical structure through the analytic hierarchy process, determined the index weight, then determined the relative superior degree matrix through expert investigation and theoretical analysis, established a fuzzy comprehensive evaluation model, and quantitatively evaluated the advantages and disadvantages of the alternative support scheme. Jing Wenqi et al. [18] determined the objective weight of the index through the CRITIC method and then used the TOPSIS-AISM clamping model to sort the spatial distances between the foundation pit support scheme and the ideal scheme, so as to determine the optimal support scheme. In the above studies, a single-decision method was used to determine the weight of evaluation index; however, the hybrid optimization decision method has a better efficiency and accuracy than the single-decision method [19,20]. In addition, in the safety and stability verification of the subsequent proposed scheme, key steps, such as scheme simulation calculation and construction monitoring, have not been carried out, which cannot fully prove the effectiveness and reliability of the foundation pit support scheme optimization model.

Deep foundation pit support structures play a crucial role in ensuring the safety of construction projects, especially in complex environments, such as comprehensive pipeline corridors, high-rise buildings, and other projects. The success of such projects depends largely on the effectiveness of the support scheme, so it becomes crucial to comprehensively assess the effectiveness and feasibility of the deep foundation pit support scheme, and the evaluation of the effectiveness of the support scheme is affected by both subjective and objective factors. In view of this, this paper comprehensively considers the influence of subjective and objective factors, uses the improved entropy value method and AHP method to determine the objective weights and subjective weights of the evaluation indexes, corrects the degree of contribution of subjective and objective weights to the comprehensive weights based on the game theory combination of weights, combines the fuzzy comprehensive evaluation theory to evaluate the merits of the program, and constructs a set of scientific and reasonable evaluation models of the deep foundation pit support program in order to support the decision makers of the construction project to select the most suitable deep foundation pit support program. The scientific validity and feasibility of the scheme selection model are substantiated through a detailed examination of a comprehensive pipeline corridor pit project, utilizing both simulation data and construction monitoring information.

2. Constructing the Decision Model for Deep Foundation Pit Support Scheme

2.1. Determination of Subjective Weight by Analytic Hierarchy Process (AHP)

The selection of the deep foundation pit support scheme is a complex decision-making problem containing multifaceted influencing factors, and the decision-making process involves multiple indicators such as the safety factor, technical level, and cost, etc. AHP is a method for multi-criteria analysis and decision making, which decomposes the complex decision-making problem into multiple indicators layer by layer and then establishes a judgment matrix of the relative importance degree to calculate the weight of each indicator [21], so it has been widely used in the evaluation of foundation pit support schemes, and the following are the steps used to calculate the weight:

Step 1: Construct the judgment matrix of each index through the experience of decision makers $X = (x_{ij})_{m\times m}$.

where x_{ij} represents the comparison result of the importance degree between element i and j, using a scale of 1–9 and $x_{ij} = \frac{1}{x_{ji}}$.

Step 2: Compute the nth root of the product of the elements of each row and normalize the vector to obtain the weights w_i and $W_1 = (w_1, w_2, \ldots, w_m)$.

$$\overline{w_i} = \sqrt[m]{\prod_{j=1}^{m} x_{ij}}, i = 1, 2, \ldots, m \tag{1}$$

$$w_i = \frac{\overline{w_i}}{\sum\limits_{i=1}^{m} \overline{w_i}} \tag{2}$$

where W_i is the subjective weight vector and $w_1, w_2, \ldots, w_m$ is the subjective weight of each index obtained by AHP.

Step 3: Calculate the maximum eigenvalue max coefficient of each index, and carry out a consistency test to ensure the accuracy and reliability of the data by using Equations (3)–(5). When the random consistency ratio CR < 0.10, it shows that the reliability of the judgment matrix is high, and the value of random consistency index is shown in Table 1.

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

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

$$CR = \frac{CI}{CR} \tag{5}$$

Table 1. Randomized consistency index (RI).

Matrix Order	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

2.2. Improved Entropy Method for Determining Objective Weights

The basic idea of the entropy method is to use the concept of information entropy to measure the amount of information of the index and its contribution to decision making, and to reflect the importance of the index through objective data, thus effectively weakening the influence of subjective factors [22,23]. However, because the evaluation index of the deep foundation pit support scheme is fuzzy and cannot be completely quantified, the traditional entropy method is used. There may be the problem of there being no way to obtain qualitative index data directly. In view of this, the algorithm is improved. For the evaluation index which cannot directly obtain the quantitative data, the set-value statistics method [24] is used to determine its state value, which is obtained by mapping qualitative indicators to quantitative data through Equation (6).

Step 1: Determine the initial matrix, in which the quantitative index can be obtained directly according to the actual project. For the qualitative index, the scoring interval is given by inviting a number of experts to take the percentile system as the scoring standard, and then the Formula (6) is used to determine its state value.

Assuming that there are q experts, the score range given by the k expert to the j evaluation index of the scheme is $\left[b_{1ij}^{k}, b_{2ij}^{k}\right] (k = 1, 2, \ldots, q)$. Then, the state value of the jth evaluation index in the ith scheme are calculated using Equation (6):

$$b_{ij} = \frac{\sum\limits_{k=1}^{q} \left[\left(b_{2ij}^{k}\right)^2 - \left(b_{1ij}^{k}\right)^2 \right]}{2 \sum\limits_{k=1}^{q} \left(b_{2ij}^{k} - b_{1ij}^{k}\right)} \tag{6}$$

Step 2: Dimensionless processing of the data. If there are m sample objects in the evaluation, and each sample has n evaluation indicators, the initial matrix is expressed as $X = (x_{ij})_{m \times m}$. Normalize the initial matrix as $A_{ij} = (a_{ij})_{m \times n}$. Because different indicators have different dimensions, it is necessary to standardize the data ysing Formula (7) to eliminate the dimension of benefit-oriented indicators.

$$a_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{7}$$

For cost-oriented indicators, let:

$$a_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \tag{8}$$

Step 3: Calculate the weighting of the *j*th evaluation indicator in the *i*th scheme.

$$P_{ij} = \frac{a_{ij}}{\sum\limits_{i=1}^{m} a_{ij}}, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{9}$$

Step 4: Calculate the information entropy e_j. The greater the value of the information entropy, the higher the uncertainty of the data, the more the amount of information, and the smaller the weight of the index.

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m}(P_{ij}\ln P_{ij}), i = 1,2,\ldots,m; j = 1,2,\ldots,n \quad (10)$$

Step 5: Calculate the coefficient of variation and objective weight of each index using Equations (11) and (12) to find the coefficient of variation and objective weight of each index, so obtain the objective weight vector $W_2 = (w_1, w_2, \ldots, w_n)$

$$g_j = 1 - e_j, j = 1,2,\ldots,n \quad (11)$$

$$w_j = \frac{g_j}{\sum\limits_{j=1}^{n} g_j}, j = 1,2,\ldots,n \quad (12)$$

2.3. Modifying the Comprehensive Weight Based on Combination Weighting of Game Theory

When using the analytic hierarchy process to determine the subjective weight, the consistency test can verify whether the expert judgment logic is consistent, but cannot eliminate the deviation caused by personal understanding; the entropy method obtains the objective weight of the index based on objective data, but the calculation results are extremely sensitive to extreme data, which may cause the calculation results to be contrary to reality. Therefore, the subjective weight obtained by the AHP method is combined with the objective weight obtained by the entropy method, and then the comprehensive weight of each index is calculated to overcome the limitations of using these two methods alone and ensure the accuracy of the decision-making results.

A reasonable allocation of the proportion of the weights obtained by different methods in the composite weights to ensure the scientific and reasonable nature of the composite weights is crucial to the calculation of the composite weights. Some scholars [25,26] have calculated the comprehensive weight by multiplicative addition, linear weighting, and average distribution, but they have not taken into account the mutual influence of different factors and the different influence range of the basic weight on the comprehensive weight. Therefore, this may produce a magnifying effect of the basic weight, which leads to a lack of reliability and accuracy of the evaluation results.

Drawing on the basic ideas of game theory, the subjective weights derived from AHP and the objective weights derived from the improved entropy method are used as the two game subjects in the non-cooperative game, and the deviation between the integrated weights and the subjective weights and objective weights is minimized by Equation (13) to correct the integrated weights, so as to make the results of the integrated weights more scientific and reliable. The specific calculation process is as follows [27]:

Step 1: Minimize the deviation between the comprehensive weight and the basic weights.

$$Min\left\|w - W_i^T\right\|, i = 1,2,\ldots,m \quad (13)$$

where the composite weight is calculated by $w = \sum\limits_{k=1}^{m} \alpha_k W_k^T$ and m is expressed as the number of base weights.

Then, Equation (13) is transformed into a system of linear equations equivalent to it by using the property of matrix differential.

$$\sum_{k=1}^{m} \alpha_k W_k W_k^T = W_i W_i^T, i = 1,2,\ldots,m \quad (14)$$

Step 2: By solving the linear equation group, obtaining the linear combination distribution coefficient $(\alpha_1, \alpha_2, \ldots, \alpha_m)$, and using Equation (15) to normalize it, the optimal linear combination coefficient can be obtained.

Step 3: Calculate the comprehensive weights of the indicators through Equation (15).

$$w^* = \sum_{k=1}^{m} \alpha_k^* W_k^T, k = 1, 2, \ldots, m \tag{15}$$

2.4. Scheme Optimization Based on Fuzzy Comprehensive Evaluation

Fuzzy comprehensive evaluation is an effective method for dealing with uncertainty in engineering decision-making problems. The application of fuzzy comprehensive evaluation in deep foundation pit engineering can effectively deal with the uncertainty problem by incorporating imprecise information and expert opinions, comprehensively considering multiple criteria such as safety, cost, and environmental impact, etc., and providing a flexible framework for program selection, so that the decision maker can objectively compare the satisfaction of the alternative programs and realize a quantitative analysis. Specifically, through expert discussion to determine the mapping relationship from indicator set $U = \{u_1, u_2, \ldots, u_n\}$ to evaluation set $V = \{v_1, v_2, \ldots, v_n\}$, so as to construct the affiliation matrix, transform the decision-making problem into a quantitative mathematical problem, and then use the weighted fuzzy algorithm to process the weighting information of each indicator to calculate the final evaluation results. The specific steps are as follows [28].

Step 1: Establish a quantitative evaluation set to express the pros and cons of each index, as shown in Table 2.

Table 2. Evaluation set.

Evaluation Grade	Very Poor	Poor	Ordinary	Good	Very Good
Point value (C)	1	2	3	4	5

Step 2: Evaluate the index through the experts and construct the membership matrix according to the evaluation results, which is expressed as:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}$$

where m is the number of experts and n is the number of assessment levels.

Step 3: Construct the fuzzy judgment matrix by Equation (16).

$$D = w^* R = (d_1, d_2, \ldots, d_n) \tag{16}$$

where w^* is the comprehensive weight of each index.

Step 4: Calculate the scheme evaluation value using Formula (17).

$$P = DC^T \tag{17}$$

3. Case Study and Model Application

3.1. General Situation of Project

The excavation depth of a municipal pipe corridor project in area is 14.6 m below the natural ground, and the construction period of the project is 9 months. There is a school under the construction site near the west side of the foundation pit and a main national highway running through the construction area on the north side. Therefore, the traffic cannot be interrupted during the construction period, and ground settlement around the foundation pit is highly required. In addition, there are two 120 kV high-voltage transmission lines over the construction area, which cannot be removed during the construction period, and the environment of the construction area is more complex, so it is necessary to comprehensively consider various factors to formulate the construction plan to ensure the safety and smooth progress of the construction. The soil layer involved in the excavation process of the foundation pit is mainly composed of miscellaneous fill, loess silt, silty clay, fine sand, medium coarse sand, and silt. The physical properties of each soil layer are shown in Table 3.

Table 3. Physical parameters of each soil layer.

Serial Number	Soil	Soil Thickness (m)	Bulk Density (kN/m^3)	Internal Friction Angle (°)	Adhesion (kPa)
1	Miscellaneous fillings	2.6	16.5	15.9	13.1
2	Loess	2.3	18.2	25.1	6.8
3	Powdery Clay	1.7	18.8	23.4	8.8
4	Fine sand	2.2	18.5	25	7
5	Medium coarse sand	1.3	18.9	25	30
6	Silt	4.5	16.1	5.6	5.2

According to the characteristics, geological conditions, and site characteristics of the foundation pit, three kinds of foundation pit support schemes are preliminarily determined, Scheme I: Soil nailing wall + supporting pile + steel support, Scheme II: soil nailing wall + supporting pile + anchor cable, and Scheme III: soil nailing wall + steel sheet pile.

3.2. Construction of Evaluation Index System

The deep foundation pit support scheme is a multi-level and multi-criteria complex decision-making problem, and its advantages and disadvantages are affected by many factors, so the construction of the evaluation index system of the deep foundation pit support scheme is the basis for scheme optimization. Combined with the actual characteristics of the project and on the basis of a large number of research papers [1,4,5,7], based on the principles of economy, safety, reliability, and science, starting from the four dimensions of technical index, economic index, environmental index, and safety index, the evaluation index system of the deep foundation pit support scheme is constructed, as shown in Figure 1. Among the secondary indexes, the construction period, foundation pit support cost, foundation pit support displacement, risk management cost, and support stability safety coefficient can be obtained directly according to the construction situation; the noise generated by the support project is expressed by the average daily noise decibel value during the construction period; and the air pollution caused by construction, the reliability of construction technology, the difficulty of construction, and the maturity of design theory are all qualitative indexes.

3.3. Determination of Deep Foundation Pit Support Scheme

A brainstorming session should be conducted in which the group, consisting of the construction manager, project manager, safety manager, and an experienced construction worker, discuss and arrive at a judgment matrix of the relative importance of each indicator. From Formulas (1) and (2), the subjective weight vector of the index is determined to be W_1 = (0.633, 0.106, 0.261, 0.667, 0.375, 0.25, 0.142, 0.525, 0.334), then the consistency test is carried out, and the CR < 0.1 is obtainted through the calculation of (3) to (5), so the consistency and credibility of the subjective weight are higher. According to the scoring range of each index of the three schemes by four experts, the set value of the qualitative index is calculated by Formula (6), as shown in Table 4, and the evaluation index parameters of each support scheme are shown in Table 5. Through Formulas (7)–(12), it is determined that the objective weight of each evaluation index is W_2 = (0.097, 0.094, 0.0101, 0.09, 0.151, 0.081, 0.081, 0.083, 0.134, 0.091, 0.0797). The subjective and objective weights are substituted into Equations (13) and (14) to find $\alpha_1^* = 0.822, \alpha_2^* = 0.177$. By using Formula (15), the comprehensive weight is w^* = (0.537, 0.104, 0.2364, 0.301, 0.631, 0.221, 0.141, 0.448, 0.284).

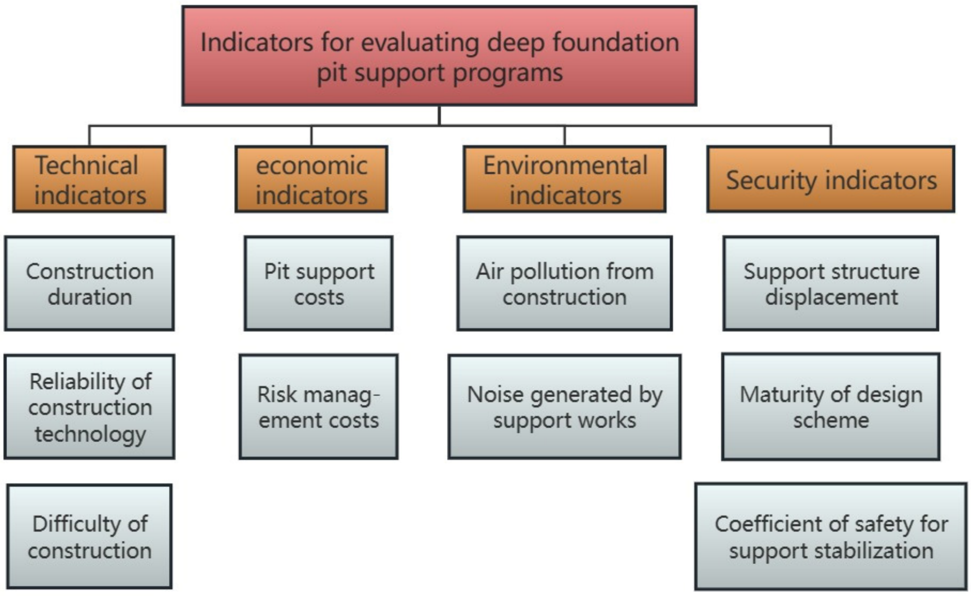

Figure 1. Evaluation index system of deep foundation pit support scheme.

Table 4. Qualitative indicator value.

Indicators	Scheme	Experts				Value	Unitization
		1	2	3	4		
Reliability of construction technology	I	[70, 80]	[70, 90]	[90, 100]	[70, 80]	81	0.81
	II	[70, 80]	[80, 90]	[90, 100]	[80, 90]	85	0.85
	III	[80, 90]	[80, 90]	[90, 100]	[90, 100]	90	0.9
Degree of construction difficulty	I	[80, 90]	[70, 90]	[70, 90]	[70, 80]	80.0	0.8
	II	[70, 80]	[70, 80]	[70, 80]	[60, 70]	72.5	0.725
	III	[60, 80]	[60, 80]	[50, 60]	[70, 80]	68.3	0.683
Air pollution from construction	I	[70, 80]	[80, 90]	[70, 80]	[80, 100]	85	0.85
	II	[80, 90]	[80, 90]	[80, 90]	[90, 100]	87	0.87
	III	[60, 70]	[70, 80]	[70, 80]	[70, 90]	81	0.81
Maturity of design scheme	I	[70, 80]	[70, 80]	[70, 80]	[60, 70]	72.5	0.725
	II	[80, 90]	[80, 90]	[90, 100]	[90, 100]	90	0.9
	III	[70, 80]	[70, 90]	[90, 100]	[70, 80]	81	0.81

Table 5. Evaluation indicator data for each support scheme.

Indicators	Guidelines	Scheme I	Scheme II	Scheme III
Technical indicators	Construction duration	70	55	45
	Reliability of construction technology	0.81	0.85	0.90
	Difficulty of construction	0.80	0.725	0.683
Economic indicators	Pit support costs	303.7	263.2	223.5
	Risk management costs	12.4	13.6	23.6
Environmental indicators	Noise generated by the support works	85	80	65
	Air pollution caused by construction	0.85	0.87	0.81
Safety indicators	Displacement of pit support	27	32	57
	Maturity of design scheme	0.725	0.90	0.81
	Coefficient of safety of support stabilization	1.95	1.90	1.68

Ten experts in related fields are invited to quantitatively evaluate the advantages and disadvantages of the evaluation indexes of each support scheme, and the evaluation results of Scheme I are shown in Table 6. The ratio of the frequency of occurrence of the evaluation grade to the total number of experts is taken as the affiliation degree of the index, so as to construct the affiliation degree matrix, and the affiliation degree matrix of Scheme I is:

$$R = \begin{bmatrix} 0.2 & 0.4 & 0.3 & 0.1 & 0 \\ 0.3 & 0.2 & 0.2 & 0.2 & 0.1 \\ 0.3 & 0.3 & 0.3 & 0.1 & 0 \\ 0.4 & 0.3 & 0.2 & 0.1 & 0 \\ 0.2 & 0.3 & 0.3 & 0.1 & 0.1 \\ 0.3 & 0.2 & 0.3 & 0.2 & 0 \\ 0.2 & 0.4 & 0.2 & 0.1 & 0.1 \\ 0 & 0.1 & 0.3 & 0.3 & 0.3 \\ 0.3 & 0.2 & 0.2 & 0.2 & 0 \\ 0 & 0 & 0.3 & 0.5 & 0.2 \end{bmatrix}$$

Table 6. Evaluation results of indicators for Scheme I.

Indicators	Evaluation Results				
	Very Poor	Poor	Average	Good	Very Good
Construction duration U_1	2	4	3	1	0
Reliability of construction technology U_2	3	2	2	2	1
Difficulty of construction U_3	3	3	3	1	0
Pit support costs U_4	4	3	2	1	0
Risk management costs U_5	2	3	3	1	1
Noise generated by support works U_6	3	2	3	2	0
Air pollution caused by construction U_7	2	4	2	1	1
Displacement of pit support U_8	0	1	3	3	3
Maturity of design scheme U_9	3	2	2	2	0
Coefficient of safety of support stabilization U_{10}	0	0	3	5	2

Combined with the comprehensive weight obtained by the combination weighting of game theory, the fuzzy judgment vector of the scheme is determined as $D = w^*R = (0.233, 0.233, 0.175, 0.243, 0.117)$, and the fuzzy comprehensive appraisal value of pit support Scheme I is calculated by Equation (17) as $P_1 = 2.776$. Similarly, the comprehensive appraisal value of Scheme II is calculated as $P_2 = 3.164$, $P_3 = 2.531$. The comprehensive appraisal value of the schemes: $P_2 > P_3 > P_1$, therefore, it is determined that Scheme II: soil nail wall + supporting piles + anchor cable is the optimal support scheme.

The excavation depth of the foundation pit is deep, and the setting of a soil nailing wall in the upper part can significantly improve the overall stability of the foundation pit and limit the displacement of the soil; according to the analysis of the characteristics and properties of the soil layer, the soil quality of the foundation pit is relatively soft, but in the face of a soft soil layer such as silty clay, the setting of an anchor cable can effectively resist the lateral thrust of the soil and effectively prevent the collapse of the foundation pit slope. In addition, there are schools, national trunk roads, and high-voltage transmission lines near the construction area, and the construction environment is complex. The construction area of the combined square plan of the soil nailing wall, supporting pile, and anchor cable is relatively small, and the construction process has less interference on the surrounding environment. Therefore, the results of the optimization model of the foundation pit support scheme based on the combination weighting of game theory and fuzzy comprehensive evaluation are consistent with the actual engineering situation, which shows that the model is feasible and effective in real engineering.

3.4. Verification of the Proposed Foundation Pit Support Scheme

Referring to the research idea of reference [29], this paper uses the combination of simulation calculation and construction monitoring to verify the safety, applicability, and reliability of the proposed deep foundation pit support scheme. The specific simulation calculation and construction monitoring results are as follows.

3.4.1. Simulation Calculation of the Proposed Scheme

The excavation depth of the upper part of the foundation pit is 5.4 m, the soil nailing is set to 4 rows, the length of the soil nailing is 6 m, and the slope inclination angle is assumed to be 45°. The Fellenius method of slices is used to calculate the overall stability of the upper part of the foundation pit. The pull-out load of each soil nail is within the standard value of 76–107 kN, the pull-out safety factor of soil nail is more than 6, and the maximum influence range of the foundation pit excavation is 6.949 m, so the upper part can be supported by a soil nailing wall. The supporting pile + anchor cable supporting structure is adopted in the lower part.

In the supporting model, the top height of the supporting pile is 5.4 m, the embedded depth is 13.5 m, the pile diameter is 0.8 m, the pile body material is reinforced concrete, and the concrete strength is C30. There are four rows of anchor cables, with horizontal spacings of 2.6 m, vertical spacings of 2 m, an incident angle of 15°, and an anchor cable length of 22 m. The lower part of the pit support pile and anchor cable structure is shown in Figure 2. ZH-1 to ZH-6 are foundation pit supporting piles. The supporting pile at ZH-6 is selected for simulation calculation, and the result is shown in Figure 3. When the foundation pit is excavated to 7.9 m and the first anchor cable is erected, the maximum earth pressure on the supporting pile is 433.41 kN, the maximum displacement is 1.18 mm, the maximum bending moment is 67.16 kN/m, and the maximum shear is 77.67 kN. After excavation to 9.9 m and the erection of the second anchor cable, the maximum soil pressure force is 438.68 kN, the maximum displacement is 2.51 mm, the maximum bending moment is 117.64 kN/m, and the maximum shear is 106.88 kN. After excavation to 11.9 m and the erection of the third anchor cable, the maximum earth pressure on the supporting pile is 444.36 kN, the maximum displacement is 6.29 mm, the maximum bending moment is 264.12 kN/m, and the maximum shear is 205.68 kN; after excavation to 13.9 m and the erection of the fourth anchor cable, the maximum earth pressure is 461.89 kN, the maximum displacement 15.9 mm, the maximum bending moment is 449.75 kN/m, and the maximum shear increases to 338.98 kN. From the above data, it can be seen that, with an increase in the depth of the foundation pit, the dead weight and lateral pressure of the soil increase, and the earth pressure on the supporting pile also increases, which leads to an increase in the displacement, bending moment, and shear of the supporting pile. It is further calculated that the radius of the sliding surface of the foundation pit is 24.26 m, and the safety factor of the overall stability of the foundation pit is 1.61, which is greater than the 1.30 required by the code, so the supporting pile and anchor cable structure can be used in the lower support.

3.4.2. Monitoring Data Analysis of the Proposed Scheme

(1) An analysis of horizontal displacement monitoring data of the supporting pile + anchor cable structure at the location of monitoring points on the construction site and the construction monitoring data at ZH-6 are shown in Figure 4. In the initial stage of the foundation pit excavation, the stress form of the supporting pile is in the cantilever state, so the horizontal displacement of the upper part of the pile is larger, while the lower part of the pile is embedded in the soil, so the displacement of the pile tends to be 0. With the excavation of foundation pit and the construction of an anchor cable, the horizontal displacement of the pile increases, the maximum displacement appears after the fourth anchor cable is erected, the maximum displacement is 16.3 mm, the maximum deformation of foundation pit supporting structure is less than the standard value 20 mm specified in the code, and the construction result is in accordance with the safety code.

In addition, comparing the maximum displacement value of 16.3 mm in the monitoring data with the maximum displacement value of 15.9 mm calculated by simulation, the relative error is 2.46%, indicating that the monitoring results are consistent with the scheme simulation calculation, which further verifies the theoretical and practical feasibility of the proposed scheme.

(2) An analysis of the surface settlement monitoring data around the foundation pit settlement monitoring points are set up at distances of 2 m and 8 m from the edge of each side of the foundation pit, the monitoring points are JC-1 to JC-12, and JC5 (2 m from the edge of the pit) and JC-6 (8 m from the edge of the pit) are randomly selected to analyze the monitoring data from excavation to backfilling. According to the settlement monitoring results at JC-5 and JC-6, with an increase in excavation depth, the settlement gradually increases, among which, the settlement at JC-5 is the largest and the final settlement at the observation point of 11.2 mm JC-5 is 6.2 mm. The settlement change rate of the two monitoring points gradually decreases, and finally tends to be stable, and both are within the safe range of foundation pit settlement.

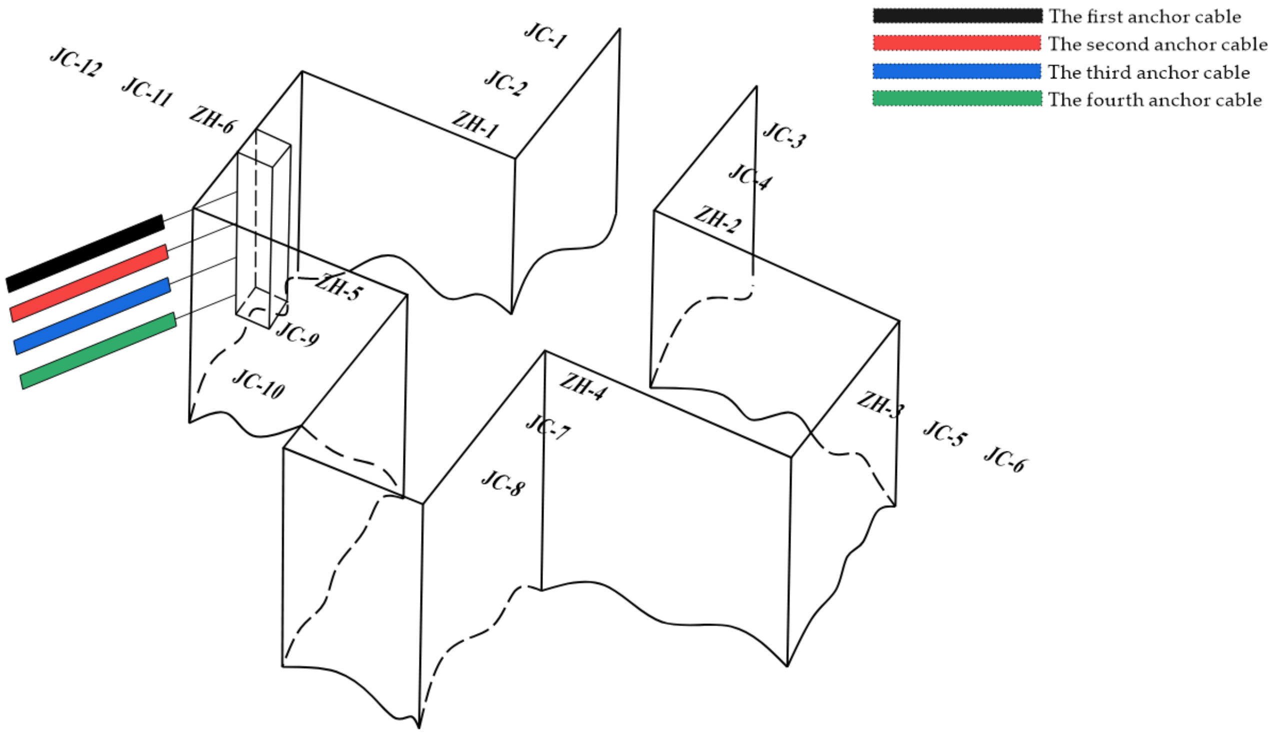

Figure 2. Three-dimensional drawing of partial support pilea and anchor cable structure under the pit.

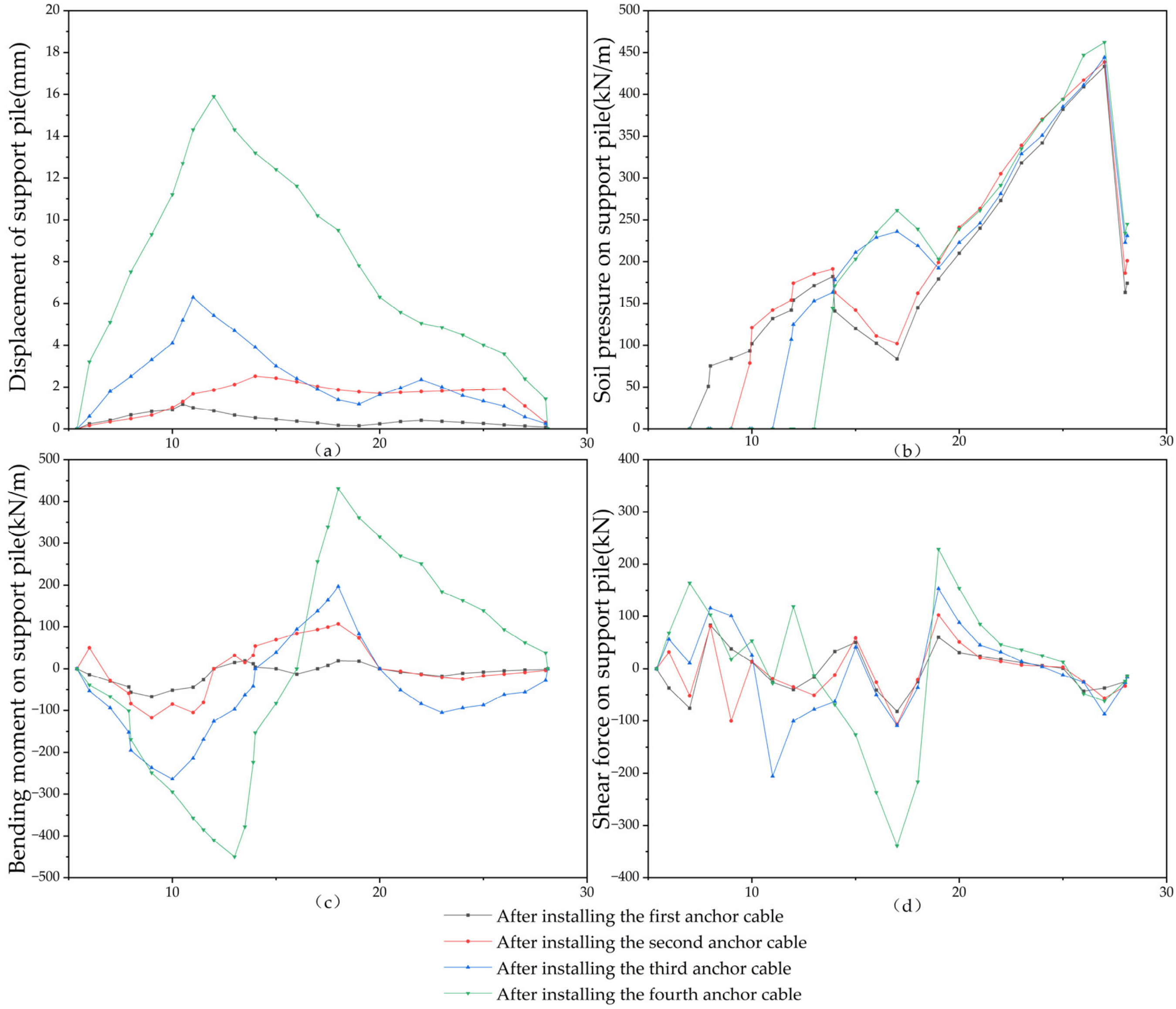

Figure 3. Simulation results. (**a**) Displacement of supporting piles at different burial depths under different working conditions; (**b**) soil pressure on supporting piles at different burial depths under different working conditions. (**c**) bending moments of supporting piles at different burial depths for different working conditions; and (**d**) shear of supporting piles at different burial depths for different working conditions.

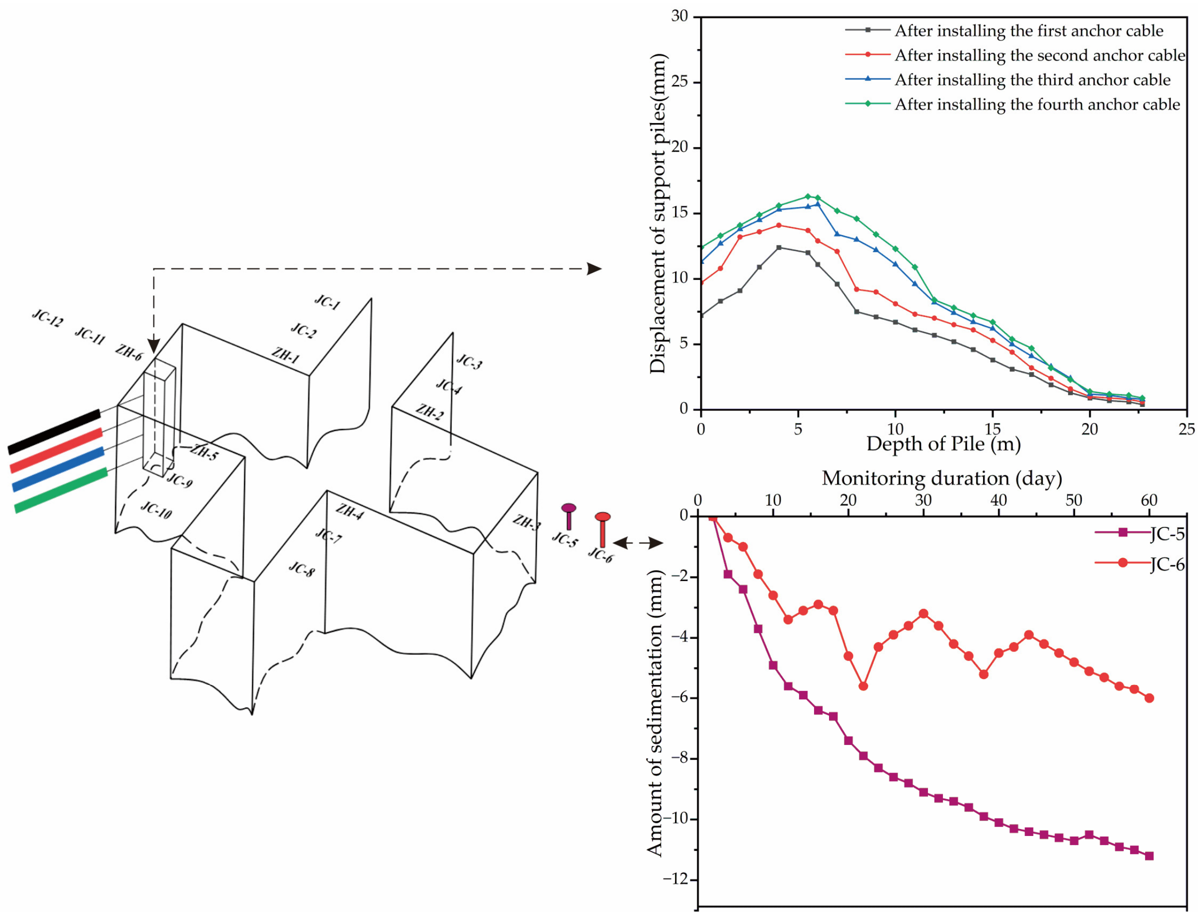

Figure 4. Pit monitoring results.

4. Discussion

The selection of a foundation pit support scheme is a complex decision-making process which is affected by many factors. Although a scheme selection framework which can be directly referenced and suitable for all situations has not been established, the appropriate multi-criteria decision-making method can provide strong support for the optimization of the foundation pit support scheme. Different optimization methods of foundation pit support schemes have unique characteristics and applicable conditions, so when selecting support schemes, it is necessary to consider the project characteristics, technical level, and other factors, and use appropriate decision-making methods to ensure the feasibility and applicability of the proposed scheme. Through a large number of literature studies, this paper systematically combs the mainstream optimization methods of foundation pit support schemes and summarizes their advantages and disadvantages and application, as detailed in Table 7. At present, the mainstream evaluation methods, such as the Analytic hierarchy process, Entropy method, TOPSIS, Fuzzy BP Neural Network, and so on, have certain conditions and applicability when they are used. When the evaluation index is not clear, the project data are limited, or the expert experience is insufficient, this will affect the accuracy of the evaluation results. The optimization model of the foundation pit support scheme constructed in this paper can overcome these conditions. A comparison of the calculation results of different methods is shown in Figure 5. By using the combination weighting of game theory to optimize the linear combination of subjective and objective weights, a more scientific comprehensive weight is obtained, which reduces the dependence on data, weakens the influence of subjective factors, and improves the accuracy of decision making. The fuzzy comprehensive evaluation method is used to evaluate the advantages and disadvantages of the scheme, and then determine the optimal support scheme, which can better deal with fuzzy and uncertain decision-making problems.

Table 7. Mainstream methods.

Methods	Advantages and Disadvantages	Application	Typical Literature
AHP and fuzzy comprehensive evaluation	Advantages: relatively simple and easy to use, able to consider the hierarchical relationship between multiple factors Disadvantages: relies on the experience of experts, strong subjective factors, there may be the problem that the program selection results do not match the actual project.	It is suitable for simple works, low risk factor, and experienced experts.	[15,17,30]
Entropy method	Advantages: the concept of information entropy is taken into account, which is conducive to the comprehensive consideration of the uncertainty and inconsistency of various factors Disadvantages: high data requirements, needs a large amount of data support, in some cases may be affected by data distribution.	It is suitable for projects with more adequate data where uncertainty and information entropy need to be taken into account.	[25,31–33]
TOPSIS	Advantages: Can make up for the shortcomings of the respective methods to a certain extent, and improve the comprehensiveness and objectivity of decision making. Disadvantages: TOPSIS also has some limitations when dealing with uncertainty, high data volume requirements.	It is suitable for relatively simple and well-structured decision problems, especially when there are relatively sufficient data to provide more credible results for decision making.	[5,18,34]
Prospect theory and best–worst method	Advantages: considering the optimal and worst scenarios comprehensively, it helps to reduce the uncertainty of decision making. Disadvantages: need to clarify the optimal and worst scenario, higher requirements for the acquisition and accuracy of information, the calculation process is more complex.	Applicable to decision-making problems that require consideration of different scenarios.	[4,35]
Fuzzy neural network	Advantages: able to deal with nonlinear relationships, applicable to the evaluation of complex systems, able to adaptively adjust the model parameters. Disadvantages: high data requirements, needs a large amount of training data, model structure is more complex, poor interpretability.	Suitable for evaluation and prediction of complex support works and projects with adequate data.	[36–38]

In addition, because the supporting structure is completely placed in the geological environment, the geological environment is also an important constraint for the selection of the foundation pit support scheme: on the one hand, the supporting structure depends on the geological environment, and the geological environment has a direct influence on the selection of the supporting scheme. On the other hand, a variety of underground geological resources occur in the geological environment, so there is an indirect influence path between the geological environment and the choice of foundation pit support plan, with groundwater, geothermal energy, and underground space as the medium, as shown in Figure 6. According to the influence path of the geological environment on the support scheme of the foundation pit, the factors affecting the selection of the support scheme are analyzed and generalized, in order to provide help for the establishment of a framework for the selection of support schemes for deep foundation pits.

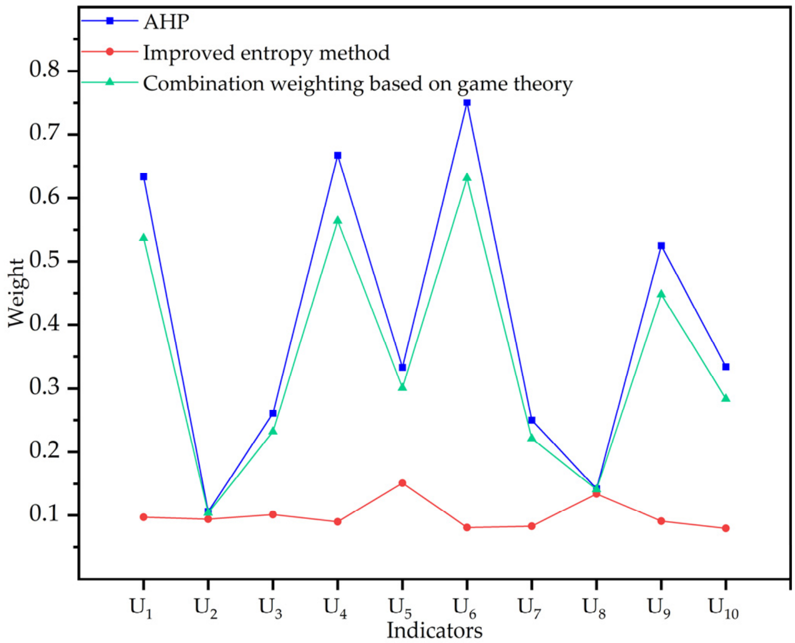

Figure 5. Comparison of the calculation results of different methods.

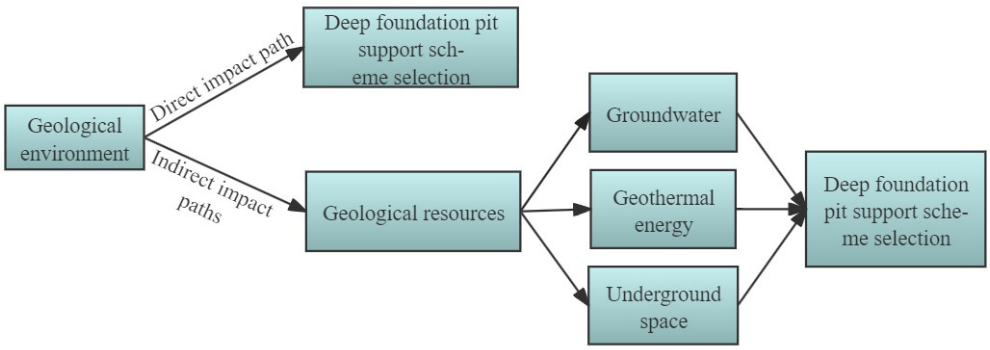

Figure 6. The influence mechanism of geological environment on deep foundation pit support scheme.

1. Direct influence mechanism

The direct influence of the geological environment on the selection of a foundation pit support scheme is mainly reflected in: (1) different soil types in geological environments having different requirements for foundation pit support schemes. For example, silt is prone to liquefaction under the condition of a high groundwater level, which leads to a poor stability and low safety factor of a foundation pit. In the view of silt, which has a poor water stability and high capillarity, support methods such as mixing piles, bored piles, and soil nailing walls can be adopted. On the other hand, sandy soil has a lower shear strength, so it requires a higher stability of foundation pit support, and the supporting methods suitable for sandy soil include excavation retaining walls, foundation pit supporting piles, and so on; sandy soil is easy to collapse and lose under a higher groundwater level, so it is suitable to adopt rigid supporting structures with strong impermeability, such as mixing pile walls, bored pile supports, and so on. (2) If the foundation pit is in the seismic zone or undergoes an active fault, the longitudinal and transverse seismic forces should be considered when selecting the foundation pit supporting structure to ensure that the supporting structure can effectively resist vibration when an earthquake occurs. Structures with a strong seismic capacity, such as seismic bracing walls, bracing beams, rubber bearings, or seismic isolation, should be considered.

2. Indirect influence mechanism

The indirect influence of the geological environment on the selection of a foundation pit support scheme is mainly realized by groundwater, geothermal energy, and underground space.

The effects of groundwater on the supporting structure of foundation pits include: (1) Some groundwater may contain special ions such as chloride ions and sulfate ions, which have a corrosive effect on the supporting structure, so when choosing the supporting scheme of a foundation pit, corrosion-resistant supporting structures such as stainless steel and glass steel should be used. (2) If the groundwater level below the foundation pit is high, it may lead to soil liquefaction and loss, and then affect the stability of the supporting structure. Impervious walls and mixing piles should be considered when selecting supporting structures, in order to control the groundwater level and prevent water infiltration.

The main effects of geothermal energy on foundation pit supporting structures are as follows: (1) Geothermal energy will increase the soil temperature and accelerate the soil creep rate, resulting in an uneven volume change of soil, leading to the deformation and stress concentration of the supporting structure. Finally, it has an impact on its stability and safety. (2) The supporting structure may produce the phenomena of thermal expansion and cold shrinkage due to the increase in the temperature of the surrounding soil, resulting in the deformation of the supporting structure, then affecting the friction between the supporting structure and the soil. Therefore, for areas rich in geothermal energy resources, structural materials with a good thermal expansion and cold shrinkage adaptability should be selected to reduce the uneven expansion and contraction caused by temperature changes.

The influence of underground space on the selection of a foundation pit support scheme is mainly reflected by: (1) Because underground space resources are limited, adjacent underground pipelines and underground structures will affect the selection of the foundation pit support scheme. While protecting the surrounding built underground engineering, more stable supporting structures should be selected to reduce the impact on the surrounding underground structures, such as spray deep geotechnical supports, mixing pile supports, deep foundation pit wall column supports, and other support methods. To sum up, when determining the foundation pit support scheme, we should not only choose the appropriate optimization method according to the situation of the project, but also pay attention to the influence of the geological environment of the research area on the supporting structure. Therefore, in the construction preparation stage, a geological survey should be used to determine the geological resources and soil properties within the scope of the foundation pit excavation, so as to ensure the effectiveness and safety of the support scheme. A follow-up study can proceed from these two sides to construct a set of selection frames, which can determine the foundation pit support scheme according to the technical level, characteristics, geological environment, and other factors of the project.

5. Conclusions

The selection of the appropriate pit support solutions is important for the duration, quality, and stability of construction projects, including deep foundation pit projects. Suitable support solutions help to improve construction efficiency, and by selecting support technologies that are suitable for the requirements of a particular project, the construction time can be shortened to meet the requirements of the project's compact schedule and improve the overall efficiency of the project. Considering the impact on the surrounding environment during the selection of the support scheme and adopting the appropriate support structure can help to minimize the negative impact on the surrounding ecosystem and existing buildings, and promote the development of the construction project in a sustainable direction. Therefore, this study proposes an option preference model to provide support for decision makers to deal with the issue of option decision making in construction projects. The applicability and superiority of the model constructed in this paper are explored through literature combing and method comparison. Meanwhile, the influence mechanism of the geological environment on the deep foundation pit support scheme is analyzed. The main research results are as follows.

1. The subjective and objective weights of the evaluation indexes of the deep foundation pit support scheme are calculated by using the AHP and improved entropy method, respectively, which overcomes the limitations caused by the single method and takes into account the situation that the index data cannot be obtained directly. Then, the comprehensive weight of each index is determined based on the combination weighting of game theory. Compared with the traditional method for obtaining the weight of the scheme evaluation index, the method used in this paper is more objective and scientific in determining the index weight. Finally, the fuzzy comprehensive evaluation method is used to evaluate the scheme. Uncertain decision-making problems such as foundation pit support scheme optimization are effectively dealt with, and a deep foundation pit scheme optimization model is constructed to provide decision support for similar projects.
2. The optimization model of deep foundation pit support schemes constructed in this paper is applied to an actual project, and it is determined that the optimal scheme of a city administration corridor project in area A is soil nailing wall + supporting pile + anchor cable. The deformation trend of the supporting pile under different working conditions is simulated, and the calculation results show that the pull-out safety factors of soil nails in the upper part of the foundation pit are all above 6 and the displacement of the supporting pile after installing anchor cables in the lower part meets the design requirements. The coefficient of safety of the supporting structure is 1.61, which is greater than the 1.3 required in the construction safety code, proving the theoretical feasibility and safety of the proposed scheme. Further analysis combined with the actual construction monitoring data shows that the relative error between the actual displacement of the supporting pile and the simulation results is 2.46%, the surface settlement is within the safe range, and the overall supporting structure has a good stability. The accuracy and rationality of the optimization model of the supporting scheme are fully verified.
3. By summarizing the advantages, disadvantages, and applicability of the current mainstream optimization methods for deep foundation pit support schemes and comparing the optimization model constructed in this paper, this reflects the applicability and superiority of the model in dealing with insufficient project data, facing fuzzy problems, limited expert experience, and so on. The indirect and direct influence mechanisms of the geological environment on the selection of deep foundation pit support schemes are identified and generalized, and then the influence factors and action path of the selection of support scheme are analyzed. Through the study of geological conditions, the support scheme suitable for the geological environment can be better selected, so as to improve the stability and safety of the project. At the same time, research ideas are provided to establish a framework for the selection of support schemes that can be directly referred to.

Overall, the deep foundation pit support scheme selection model proposed in this study combines multiple methods, making the scheme evaluation more objective and scientific, thus improving the science and reliability of engineering decision making. The scheme selection model constructed in this paper can be flexibly applied to the decision making of similar construction projects.

In the future work, it is recommended that scholars consider the geological environment and engineering conditions comprehensively to formulate the selection criteria of foundation pit support programs for direct reference by on-site construction personnel and relevant researchers. At the same time, it can also be combined with modern engineering simulation modeling technology to select deep foundation pit support schemes more scientifically in actual construction, so as to improve the safety of construction projects.

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References

1. Zhang, Y.; Rong, S.; Li, H. Research on risk analysis method of super-large deep foundation pit based on dynamic monitoring and fault tree analysis. *J. Saf. Sci. Technol.* **2023**, *19*, 89–95.
2. Gong, X. Some major problems in the development of foundation pit engineering. *Chin. J. Geotech. Eng.* **2006**, *28*, 1321–1324.
3. Liu, B.; Xu, W.; Reddy, K.R. *Effects of Demolishing the Deep Excavation Support System Used for Tall Building Construction on Adjacent Metro Line; Modeling and Field Comparison*; IFCEE: Dallas, TX, USA, 2015; pp. 1107–1121.
4. Sun, B.; Zhang, S.; Yang, J. Optimal decision model for the sup-porting scheme of the deep foundation pit based on the prospect theory and BWM. *J. Saf. Environ. Eng.* **2021**, *21*, 70–77.
5. Zheng, S.; Li, S. Improved TOPSIS decision method for optimizing mixed indexes supporting schemes for foundation pit. *J. Saf. Sci. China* **2014**, *24*, 98–103.
6. Tu, B.; Zheng, J.; Ye, S.; Shen, M. Study on excavation response of deep foundation pit supported by SMW piles combined with internal support in soft soil area. *Water* **2023**, *15*, 3430. [CrossRef]
7. He, Y.; Qin, W.; Wang, Y. Optimization of supporting schemes for deep foundation pit based on combined weight and grey Euclid theory. *J. Saf. Sci. Technol.* **2016**, *12*, 94–97.
8. Hefny, A.M.; Sorour, T.M.; Ezzat, M.E. *Prediction of the Field Response of Soil-Support Systems in Deep Excavations*; Geo-China: Beijing, China, 2016; pp. 141–151.
9. Issa, U.; Saeed, F.; Miky, Y.; Alqurashi, M.; Osman, E. Hybrid AHP-fuzzy TOPSIS approach for selecting deep excavation support system. *Buildings* **2022**, *12*, 295. [CrossRef]
10. Salimian, S.; Mousavi, S.M.; Tupenaite, L.; Antucheviciene, J. An Integrated Multi-Criteria Decision Model to Select Sustainable Construction Projects under Intuitionistic Fuzzy Conditions. *Buildings* **2023**, *13*, 848. [CrossRef]
11. Temiz, I.; Calis, G. Selection of Construction Equipment by using Multi-criteria Decision Making Methods. *Procedia Eng.* **2017**, *196*, 286–293. [CrossRef]
12. Shahpari, M.; Saradj, M.F.; Pishvaee, S.M.; Piri, S. Assessing the productivity of prefabricated and in-situ construction systems using hybrid multi-criteria decision making method. *J. Build. Eng.* **2020**, *27*, 100979. [CrossRef]
13. Branimir, F.; Ana, H. Multi-Criteria Analysis for the Selection of the Optimal Mining Design Solution—A Case Study on Quarry "Tambura". *Energies* **2021**, *14*, 3200.
14. Palanikkumar, D.; Upreti, K.; Venkatraman, S.; Suganthi, J.R.; Kannan, S.; Srinivasan, S. Fuzzy Logic for Underground Mining Method Selection. *Intell. Autom. Soft Comput.* **2022**, *32*, 1843–1854. [CrossRef]
15. Ye, W.; Gao, C.; Liu, Z.; Wang, Q.; Su, W. A Fuzzy-AHP-based variable weight safety evaluation model for expansive soil slope. *Nat. Hazards* **2023**, *119*, 559–581. [CrossRef]
16. Jin, L.; Song, B.; Du, X. A modified method for calculating the shear capacity of RC deep flexural members. *J. Build. Struct.* **2023**, *44*, 170–182.
17. Zhou, H.; Cao, P. A fuzzy AHP approach to select supporting schemes for city foundation pit in soft soil. *J. Cent. South Univ. (Nat. Sci. Ed.)* **2012**, *43*, 3582–3588.
18. Jing, W.; Song, S.; Li, Y.; Luo, X. Application of TOPSIS-AISM Interpretation Model in Support Scheme Optimization for Foundation Pit. *J. Saf. Environ. Eng.* **2023**, *30*, 76–83.
19. Wu, Z. Research on the Intelligent Optimization Design Method of Deep Foundation Pit Support. Master's Thesis, Hunan University, Changsha, China, 2005.
20. Wei, D. Risk Assessment for Subway Construction Based on Fault Tree Analysis and Analytical Hierarchy Process: A Case Study of Destabilization of Pit Supporting Structure of Tunnel Shaft. *Saf. Environ. Eng.* **2018**, *25*, 100–104.
21. Jiang, Q.; Zhong, S.; Zhu, W. Research on comprehensive risk assessment of forest fire in Beijing-Tianjin-Hebei region. *J. Saf. Sci. China* **2020**, *30*, 119–125.

22. Huang, Y.K.; Xu, S.; Jiang, M.; Li, W. Evaluation for the channel waters navigation safety based on the synthetic weighing of the game theory. *J. Saf. Environ.* **2021**, *21*, 2430–2437.
23. Liu, Z.; Liu, Y.; Xie, R. Identification and fusion of abnormal results in accident reconstruction based on entropy method. *China Saf. Sci. J.* **2023**, *33*, 96–104.
24. Luo, X. Fuzzy Synthetic Evaluation Based on Set-Valued Statistics and Its Application. *Math. Pract. Theory* **2005**, *35*, 42–45.
25. Ma, Y.; Shi, T.; Zhang, W.; Hao, Y.; Huang, J.; Lin, Y. Comprehensive policy evaluation of NEV development in China, Japan, the United States, and Germany based on the AHP-EW model. *J. Clean. Prod.* **2018**, *214*, 389–402. [CrossRef]
26. Wang, G.; Shang, B.; Liu, X.; Li, T.; Qian, C. Study on causes of poisoning and asphyxiation in roadway opening by AHP-entropy weight method. *China Saf. Sci. J.* **2021**, *31*, 187–192.
27. Wei, D.Y.; Du, C.F.; Lin, Y.F.; Chang, B.; Wang, Y. Thermal Environment Assessment of Deep Mine Based on Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation. *Case Stud. Therm. Eng.* **2020**, *19*, 100618. [CrossRef]
28. Wu, X.L.; Hu, F. Analysis of Ecological Carrying Capacity Using A Fuzzy Comprehensive Evaluation method. *Ecol. Indic.* **2020**, *113*, 106243. [CrossRef]
29. Cao, H.; Liu, J. Combinatorial Calculation Model of Active Earth Pressure under Non-limit State and Its Engineering Application. *J. Basic Sci. Eng.* **2019**, *27*, 590–601.
30. Yang, G.; Chen, R. Application of analytic hierarchy process in optimization of deep foundation pit support scheme. *J. Shaanxi Univ. Technol. (Nat. Sci. Ed.)* **2018**, *34*, 28–34.
31. Wei, D.; Li, Y.; Zhang, Y. An Interval Evidential Reasoning-based Approach for Selecting Supporting Scheme for Deep Foundation Pit. *J. Highw. Transp. Res. Dev.* **2023**, *40*, 127–134.
32. Jiang, Y.; Deng, Z.; Wang, D. Research on Supporting Scheme Optimization for Deep Foundation Pit Based on Set Pair Analysis. *Chin. J. Undergr. Space Eng.* **2016**, *12*, 131–137.
33. Zhang, A.; Li, Y.; Zhang, Y. Research on entropy weight-ideal point decision model in foundation pit support scheme selection. *Yangtze River* **2014**, *45* (Suppl. S2), 213–216.
34. Yuan, W. Application of Improved TOPSIS Model to the Comprehensive Evaluation of Foundation Pit Support Scheme. *J. Chang. River Sci. Res. Inst.* **2014**, *31*, 82–86.
35. Wang, M.; Zhao, K.; Zhu, Q.; Jiang, H.; Jin, J. Decision-making model of supporting schemes of foundation pit based on cumulative prospect theory and connection number. *Rock Soil Mech.* **2016**, *37* (Suppl. S2), 622–628.
36. Gao, W.; Zhang, Z.; Zhu, J. Optimization of Supporting Plan of Deep Excavation Based on Fuzzy Back Propagation Neural Network. *J. Saf. Sci. China* **2006**, *16*, 4–8+1.
37. He, Y.; Li, C. Optimization of supporting plan for deep foundation pit based on principal component analysis and BP neural network. *Sichuan Build. Sci.* **2015**, *41*, 32–35+39.
38. Zhang, H.; He, Y. A Study of Optimum Seeking Decision for Bracing Schemes of Deep Foundation Pit based on Artificial Neural Network. *Constr. Des. Eng.* **2004**, *5*, 69–71.