Study on the Foundation Selection Method for Overhead Transmission Lines

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Abstract. The foundation is an important part of the overhead transmission line, to improve the science and accuracy of the line foundation selection program, comprehensively consider the technical, economic, and environmental factors, based on the hierarchical analysis method to construct a three-level evaluation index system for foundation selection, determine the evaluation criteria for the selection of the foundation, and carry out a comprehensive evaluation of the 220kV-YG module of the universal design of the foundation of the transmission line to verify the proposed applicability and feasibility of the method. The case results show that: among the foundation schemes of 220kV-YG module of universal design of transmission line foundation, the one that performs better in terms of technical performance and economic performance is dug hole pile foundation, and the one that performs better in terms of environmental performance is rock anchor foundation; the dug hole pile foundation is the optimal foundation among the 4 types of foundations.

Keywords: transmission line foundation; foundation selection; fuzzy hierarchy analysis; index evaluation system

1 Introduction

Overhead transmission line distance is long, across a wide area, along the line terrain changes, foundation engineering nature is complex, tower position is point distribution, foundation selection, design, and construction need to consider the influence of many factors. Overhead transmission line foundation is subjected to complex loading characteristics, and resistance to elevation and overturning stability is usually the control condition of transmission line foundation design, which is a significant difference between the foundation of overhead transmission lines and the foundation design of other industries, such as construction, transportation, and so on. The foundation is an important part of the overhead transmission line; its cost, duration, and labor consumption in the whole project account for a large proportion. According to statistics, foundation construction accounts for about half of the entire duration, transportation accounts for about 60% of the entire project, and cost accounts for about 15% to 35% of the entire project

Y. Xu et al. (eds.), *Proceedings of the 2026 5th International Conference on Engineering Management and Information Science (EMIS 2026)*, Advances in Computer Science Research 130,
https://doi.org/10.2991/978-94-6239-652-4_2

[1]. Based on ensuring safety and reliability, selecting a technologically advanced, economically reasonable, mechanized construction and environmentally friendly foundation type is conducive to shortening the construction period, reducing investment, improving the quality of construction, and promoting the sustainable development of the power grid [2, 3]. Therefore, it is of important research value to carry out a comprehensive evaluation of the transmission line foundation, adapt to local conditions, reasonably select foundation type, reduce the cost of the foundation, and at the same time reduce the damage to the ecological environment, to achieve better economic and social benefits [4].

The selection of the comprehensive evaluation method of the foundation program will directly affect the correctness and reliability of the election results. At present, the commonly used comprehensive evaluation methods include data envelopment analysis [5], life cycle evaluation [6], gray correlation analysis [7], Delphi method [8], analytic hierarchy process (AHP) [9,10], fuzzy comprehensive evaluation (FCE) [11,12], and portfolio evaluation methods [13]. Among them, the Fuzzy Hierarchical Analysis (FAHP) evaluation model is a kind of evaluation method combining FCE and AHP [14,15], which plays the advantages of FCE and AHP, combining qualitative analysis with quantitative analysis, which can realize the quantitative evaluation of the indexes, reduce the drawbacks caused by subjective judgments and multi-factors, ambiguity and other problems during the evaluation process, and overcome the qualitative and semi-quantitative evaluation methods to overcome the shortcomings of qualitative and semi-quantitative evaluation methods and make the evaluation results more comprehensive and reliable [16]. In the field of power transmission and transformation engineering, the FAHP method has been applied to the safety evaluation of line foundations [17], the reliability evaluation of tower foundation-bearing capacity [18], and the assessment of power grid emergency response capacity [19].

This paper comprehensively analyzes the economic, technical, and environmental factors affecting the selection of transmission line foundations, and from the perspective of facilitating mechanized construction and environmental protection, it proposes a transmission line foundation scheme selection method based on the FAHP method, to provide a technical basis for accurate and scientific selection of transmission line foundations.

2 List of Transmission Line Basis Evaluations

China is a vast country with large differences in the geological environment, and the foundation types used in transmission line construction are also more diverse. Commonly used foundation types include: hollowed foundation, rock embedded foundation, rock anchor foundation, extended foundation, pile foundation, composite sinkhole foundation, assembled foundation, etc. [3]. To further promote the mechanized construction of transmission lines, implement the requirements of green construction, and standardize the foundation selection and design, the State Grid Corporation of China Ltd. organized the preparation of the transmission and substation engineering universal design 35~750kV Series Transmission line foundation booklet, in which the foundation type includes: rock anchor foundation, miniature pile foundation, helical anchor foundation, grouted pile foundation, dug hole pile foundation, hollowing out foundation 6 types of in-situ soil (rock) foundation. According to statistics, 90% of the projects currently under construction are located in mountainous areas, and more than 50% of the super/ultra-high voltage corridors under construction in southwestern mountainous areas are located in mountainous areas. Limited to space, this paper selects a 220kV-YG module applicable to hilly and mountainous terrain, no groundwater, cover layer thickness of 2~4m, non-extremely soft rock and non-extremely fractured rock terrain, and geological conditions, to carry out foundation program selection analysis. The main construction process and applicable scope of each type of foundation are shown in Table 1.

Table 1. 220kV-YG module base process and scope of application

Type of foundation	Main process flow	Engineering scope
Rock anchor foundation	Drilling and clearing of holes, grouting of anchor holes, and acceptance of anchor pullout resistance	Rock basic quality grade I~IV, and rock foundation of basic quality grade V except for very soft and very broken, and the thickness of the cover layer does not exceed 2.5m and the slope of the topography of the tower does not exceed 35° or the thickness of the cover layer does not exceed 4m and the slope of the topography of the tower does not exceed 30°; there is no groundwater.
Cast-in-place micropiles	Drilling and clearing of holes, reinforcement tying, and concrete pouring	Hilly, mountainous terrain; overburden thickness 2-4m, not extremely soft rock, not extremely fractured rock.
Bored pile foundation	Drilling rig positioning, straight hole drilling, pile hole excavation, retaining wall construction, and pile concrete pouring	All types of rock and soil formations in the absence of groundwater. In particular, in loose soil layers, it is not suitable to design bottom expansion, and support measures are required.
Digged foundation	Straight-hole drilling, hand-hollowing, rebar tying, and concrete pouring	Non-loose rock and soil formations in the absence of groundwater, including firm, hard-plastic, and plastic clayey soils, dense, medium-dense, and slightly dense chalk, sand, and gravelly soils, as well as loess, strongly weathered, and moderately weathered rock and soil formations.

3 Foundation Selection Based on Fuzzy Hierarchical Analysis

3.1 Evaluation Indicator System

Aiming at the technical characteristics of overhead transmission line project construction, according to the principle of hierarchical analysis method, from the perspective of facilitating mechanized construction and protecting the environment, the first-level indexes including 3 latitudes of technology, economy, and environment are constructed, and 5 second-level indexes are set up under the first-level indexes according to the evaluation demand, and the second-level indexes are subdivided into 13 third-level indexes, and the evaluation index system of the basic program is shown in Table 2.

Table 2. Evaluation index system of overhead transmission line foundation

Target level (V layer)	Guideline layer		Indicator layer
	First-level indexes (O layer)	Second-level indexes (P layer)	Third-level indexes (r layer)
Overhead transmission line foundation selection program	Technical performance(O_1)	Technological superiority(P_1)	Mechanical inputs per base(r_1)
			Manpower input per base(r_2)
			Amount of concrete used per base(r_3)
			Reinforcing steel used per base(r_4)
		Technical reliability(P_2)	The complexity of the construction process(r_5)
			Foundation quality stability(r_6)
		Technical suitability(P_3)	Engineering suitability(r_7)
			Scope of application of vertical force(r_8)
	Economic performance(O_2)	Economic cost(P_4)	Construction cost per base(r_9)
			Annual operation and maintenance costs(r_{10})
	Environmental performance(O_3)	Environmental benefit(P_5)	Water use abatement effect(r_{11})
			Abatement effect of soil disposal(r_{12})
			Carbon dioxide emission reduction effect(r_{13})

3.2 FAHP Evaluation Model

3.2.1 Calculation of Indicator Weights Based on AHP.

A two-by-two comparison of each factor at each level was made to assign a rating in terms of its level of importance, and this judgment was described using the AHP1-9 scaling method. The scale method for the judgment matrix elements is shown in Table 3 for the results of the comparison of the importance of the factors and elements to satisfy.

Table 3. AHP 1-9 Scale

Scale	Meanings
1	Equally important
3	Slightly important
5	Significantly important
7	Strongly important
9	Extremely important
2,4,6,8	The median of the above neighboring judgments
Reciprocal	*i* compared to *j* on a scale of 5, then *j* compared to *i* is 1/5.

Steps to calculate the weights of indicators at different levels using AHP: 1) According to the results of experts' assignment of the relative importance of each indicator in the evaluation index system of the basic program, the judgment matrix can be constructed; 2) By calculating the eigenvectors of the judgment matrix, the weights of each indicator on the previous level can be calculated respectively; 3) According to the consistency test based on the largest characteristic root of the judgment matrix, when the proportion of random consistency is less than 0.1, the judgment matrix passes the consistency test, the comprehensive weight of each evaluation index can be obtained by normalization.

3.2.2 Fuzzy Comprehensive Evaluation.

Through literature and expert research, the evaluation criteria for each indicator in the transmission line foundation scheme preference evaluation system are categorized into three rating levels: very good, good, and average (Table 4).

Table 4. Ranking criteria for evaluation indicators

Evaluation indicators	Evaluation criteria		
	Very good (5 points)	Better (3 points)	Fair (1 point)
Mechanical inputs per base(r_1)	More	Less	Rarely
Manpower input per base(r_2)	Rarely	Less	More
Amount of concrete used per base(r_3)	Rarely	Less	More
Reinforcing steel used per base(r_4)	Rarely	Less	More
The complexity of the construction process(r_5)	Low	Higher	High
Foundation quality stability(r_6)	Good	Fair	Poor
Engineering suitability(r_7)	Good applicability can be used in most projects	Moderate applicability, general engineering use	Poor applicability, difficult to use in general engineering
Scope of application of vertical force(r_8)	Larger	Large	small
Construction cost per base(r_9)	Low	Middle	High

Annual operation and maintenance costs(r_{10})	Low	Middle	High
Water use abatement effect(r_{11})	Water use abatement rate > 20%	Water use abatement rate 10%~20%	Water use abatement rate<10%
Abatement effect of soil disposal(r_{12})	Abandoned soil abatement rate > 20%	Abandoned soil abatement rate 10%~20%	Abandoned soil abatement rate<10%
Carbon dioxide emission reduction effect(r_{13})	Carbon dioxide abatement rate > 20%	Carbon dioxide abatement rate 10%~20%	Carbon dioxide abatement rate<10%

The weight matrix is constructed according to the scoring results of the experts on each evaluation index of the 4-type foundation, and the first, second, and third fuzzy comprehensive evaluation sets are calculated according to equations (1) to (3) to obtain the first, second and third fuzzy comprehensive evaluation sets by the calculation steps of the first-level, second-level and third-level fuzzy comprehensive evaluations, respectively; and then the three evaluation levels of the indexes of very good, good and general are assigned to be 5, 3 and 1 points respectively, and the comprehensive score of the evaluation results and technology of the 4-type foundation guideline level can be calculated according to the second-level and third-level fuzzy comprehensive evaluation sets respectively. Points, according to the second layer of fuzzy comprehensive evaluation and the third layer of fuzzy comprehensive evaluation set, can be calculated respectively to obtain the evaluation results of the 4-type basic criterion layer and the comprehensive score of the technology.

The first level of fuzzy evaluation set $\boldsymbol{B}_{Pi}$ is calculated as follows:

$$\boldsymbol{B}_{Pi} = \boldsymbol{W}_{Pi} \times \boldsymbol{R}_{Pi} \tag{1}$$

where $\boldsymbol{B}_{Pi}$ is the P layer fuzzy comprehensive evaluation set of the base selection; i is the serial number of the P layer indicator, $i = 1,2,\ldots,5$; $\boldsymbol{W}_{Pi}$ is the r weight matrix of the third-level indicator corresponding to the second-level indicator P_i of the base selection; $\boldsymbol{R}_{Pi}$ is the fuzzy evaluation matrix of the r layer indicator corresponding to the second-level indicator P_i of the base selection.

The second-level fuzzy evaluation set $\boldsymbol{B}_{Oj}$ is calculated as follows:

$$\boldsymbol{B}_{Oj} = \boldsymbol{W}_{Oj} \times \boldsymbol{R}_{Oj} \tag{2}$$

where $\boldsymbol{B}_{Oj}$ is the O-level fuzzy comprehensive evaluation set of the evaluation technique; j is the serial number of the O-level indicator, $j = 1,2,3$; $\boldsymbol{W}_{Oi}$ is the weight of the P-level indicator corresponding to the first-level indicator O_i; and $\boldsymbol{R}_{Oi}$ is the fuzzy evaluation matrix of the P-level indicator corresponding to the first-level indicator O_i.

The third-level fuzzy evaluation set $\boldsymbol{B}_V$ is calculated as follows:

$$\boldsymbol{B}_V = \boldsymbol{W}_V \times \boldsymbol{R}_V \tag{3}$$

In which, $\boldsymbol{B}_V$ is the V-layer fuzzy comprehensive evaluation set of the evaluation technique; $\boldsymbol{W}_V$ is the weight of the O-layer indicators; $\boldsymbol{R}_V$ is the fuzzy evaluation matrix of the O-layer indicators.

4 Evaluation Results and Analysis

4.1 Evaluation Weighting Results

According to the results of the experts' assignment of the relative importance of the evaluation indicators in the evaluation system of the foundation construction technology of the line project, the weights of the indicators at different layers can be calculated. The following is an example of the weight calculation process of the indicators in the *O*-level indicators. The first-level indicators O_1, O_2 and O_3 of the target layer is compared two by two to get the comparison matrix Table 5, and the weights of the first-level indicators can be obtained by using the eigenvalue method in Table 6.

Table 5. Comparison matrix for *O*-level indicators

a_{ij}	O_1	O_2	O_3
O_1	1	1/3	1/2
O_2	3	1	1
O_3	2	1	1

Table 6. First-level indicator weights

First-level indicator	O_1	O_2	O_3
Eigenvalue method weighting	0.2098	0.5499	0.2402

The consistency indicator $CI = (\lambda_{max} - n)/(n - 1) = (3.0183 - 3)/2 = 0.0091$ for the first level indicator, the consistency ratio $CR = CI/RI = 0.0176 < 0.1$, and the judgment matrix passes the consistency test and is acceptable. Among them, the average random consistency indicator is taken from Table 7.

Table 7. Mean Randomized Consistency Indicators RI

n	1	2	3	4	5	6	7	8	9	10	11	12	13
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54	1.56

Similarly, the comparison matrices of the indicators at different levels and the weights for meeting the consistency requirements (Tables 8 - 13), as well as the combined weights of the indicator levels to the target levels, can be obtained, as detailed in Table 14. As can be seen in Table 14, among the indicators of layer *P*, the economic performance indicators account for the largest weight, which indicates that the economic indicators are more important than the technical indicators and the environmental indicators in the construction of the line infrastructure. In the *r*-layer indicators, the cost per base has the largest weight, indicating that cost is the most important indicator in line infrastructure construction.

Table 8. Comparison matrix of secondary indicators for O_1

O_1	P_1	P_2	P_3
P_1	1	1/5	1/3
P_2	5	1	2
P_3	3	1/2	1
$CR = (\lambda_{\max} - n)/(n-1)/RI = 0.0036 < 0.1$			

Table 9. Comparison matrix of third-level indicators for C_1

C_1	D_1	D_2	D_3	D_4
D_1	1	2	3	5
D_2	1/2	1	2	3
D_3	1/3	1/2	1	2
D_4	1/5	1/3	1/2	1
$\mathrm{CR} = (\lambda_{\max} - n)/(n-1)/\mathrm{RI} = 0.0054 < 0.1$				

Table 10. Comparison matrix of third-level indicators for C_2

C_2	D_5	D_6
D_5	1	1/3
D_6	3	1
$CR = (\lambda_{\max} - n)/(n-1)/RI = 0 < 0.1$		

Table 11. Comparison matrix of third-level indicators for C_3

C_3	D_7	D_8
D_7	1	2
D_8	1/2	1
$CR = (\lambda_{\max} - n)/(n-1)/RI = 0 < 0.1$		

Table 12. Comparison matrix of third-level indicators for C_4

C_4	D_9	D_{10}
D_9	1	3
D_{10}	1/3	1
$CR = (\lambda_{\max} - n)/(n-1)/RI = 0 < 0.1$		

Table 13. Comparison matrix of third-level indicators for C_5

C_5	D_{11}	D_{12}	D_{13}
D_{11}	1	1/3	1
D_{12}	3	1	2
D_{13}	1	1/2	1
$CR = (\lambda_{\max} - n)/(n-1)/RI = 0.0176 < 0.1$			

Table 14. Indicator weights for line base evaluation

V layer	WeightsW_P	O layer	WeightsW_O	r layer	Weights W_r	Combined weights W
Technical performance	0.1692	Technological superiority	0.1095	Mechanical inputs per base	0.4829	0.0089
				Manpower input per base	0.2720	0.0050
				Amount of concrete used per base	0.1570	0.0029
				Reinforcing steel use per base	0.0882	0.0016
		Technical reliability	0.5816	Complexity of the construction process	0.25	0.0246
				Foundation quality stability	0.75	0.0738
		Technical suitability	0.3039	Engineering suitability	0.6667	0.0343
				Scope of application of vertical force	0.3333	0.0171
Economic performance	0.4434	Economic cost	1	Construction cost per base	0.75	0.3326
				Annual operation and maintenance costs	0.25	0.1109
Environmental performance	0.3874	Environmental benefit	1	Water use abatement effect	0.2098	0.0813
				Abatement effect of soil disposal	0.5499	0.2130
				Carbon dioxide emission reduction effect	0.2402	0.0931

4.2 Fuzzy Integrated Evaluation Results

Thirteen experts in the industry were invited to score the 4-type foundation according to the indicator evaluation Table 14. Questionnaires were returned, and percentages were used to count the experts' opinions, and the results are shown in Table 15.

Table 15. Statistical results of expert scoring for transmission line 220kV-YG basic module

Evaluation indicators	Rock anchor foundation			Cast-in-place micropiles			Bored pile foundation			Excavation of the foundation base		
	Very good	Good	Fair	Very good	Good	Fair	Very good	Good	Fair	Very good	Good	Fair
Mechanical inputs per base	0.5	0.25	0.25	0.125	0.375	0.5	0.5	0.125	0.375	0.25	0.375	0.375
Manpower input per base	0.25	0.625	0.125	0.25	0.5	0.25	0.375	0.625	0	0.375	0.125	0.5
Amount of concrete used per base	0.5	0.25	0.25	0.625	0.375	0	0.25	0.625	0.125	0.25	0.5	0.25
Reinforcing steel use per base	0.429	0.429	0.142	0.5	0.25	0.25	0.25	0.625	0.125	0.5	0.25	0.25
Complexity of the construction process	0.286	0.714	0	0.125	0.375	0.5	0.25	0.625	0.125	0.25	0.375	0.375
Foundation quality stability	0.25	0.375	0.375	0.5	0.25	0.25	0.5	0.375	0.125	0.25	0.5	0.25
Engineering suitability	0.125	0.25	0.625	0.5	0.25	0.25	0.625	0.25	0.125	0.5	0.25	0.25
Scope of application of vertical force	0.5	0.25	0.25	0.25	0.5	0.25	0.5	0.375	0.125	0.75	0.125	0.125
Construction cost per base	0.25	0.5	0.25	0.25	0.25	0.5	0.375	0.5	0.125	0.125	0.375	0.5
Annual operation and maintenance costs	0.5	0.25	0.25	0.75	0.25	0	0.5	0.375	0.125	0.5	0.375	0.125
Water use abatement effect	0.5	0.375	0.125	0.25	0.25	0.5	0.5	0.25	0.25	0.125	0.375	0.5
Abatement effect of soil disposal	0.75	0.125	0.125	0.25	0.25	0.5	0.625	0.25	0.125	0.25	0.5	0.25
Carbon dioxide emission reduction effect	0.625	0.25	0.125	0.125	0.5	0.375	0.5	0.25	0.25	0.25	0.5	0.25

4.2.1 Guideline Layer Evaluation Results.

Results of the second-level fuzzy comprehensive evaluation of the rock anchor foundations: Technical performance indicators:$\boldsymbol{B}_{O1} = \{0.2732, 0.3836, 0.3381\}$; Economic performance indicators: $\boldsymbol{B}_{O2} = \{0.3125,0.4375,0.2500\}$; Environmental performance indicators:$\boldsymbol{B}_{O3} = \{0.6675, 0.2075, 0.1250\}$.

Results of the second-level fuzzy comprehensive evaluation of the cast-in-place micropiles: Technical performance indicators:$\boldsymbol{B}_{O1} = \{0.3925, 0.3085, 0.2940\}$; Economic performance indicators: $\boldsymbol{B}_{O2} = \{0.3750, 0.2500, 0.3750\}$; Environmental performance indicators:$\boldsymbol{B}_{O3} = \{0.2200, 0.3100, 0.4699\}$.

Results of the second-level fuzzy comprehensive evaluation of the bored pile foundation: Technical performance indicators:$\boldsymbol{B}_{O1} = \{0.4760, 0.3851, 0.1339\}$; Economic performance indicators:$\boldsymbol{B}_{O2} = \{0.4063, 0.4688, 0.1250\}$; Environmental performance indicators:$\boldsymbol{B}_{O3} = \{0.5687, 0.2500, 0.1812\}$.

Results of the second-level fuzzy comprehensive evaluation of the excavation of the foundation base: Technical performance indicators:$\boldsymbol{B}_{O1} = \{0.3562, 0.3705, 0.2683\}$; Economic performance indicators:$\boldsymbol{B}_{O2} = \{0.2188, 0.3750, 0.4063\}$; Environmental performance indicators:$\boldsymbol{B}_{O3} = \{0.2238, 0.4737, 0.3024\}$.

Based on the results of the second-level fuzzy comprehensive evaluation, the scores of each type of foundation in terms of technical performance, economic performance, and environmental performance were calculated respectively, as shown in Fig. 1. As can be seen from the figure, in terms of technical performance and environmental performance, the bored pile foundation scores higher; in terms of environmental performance, the rock anchor foundation scores the highest.

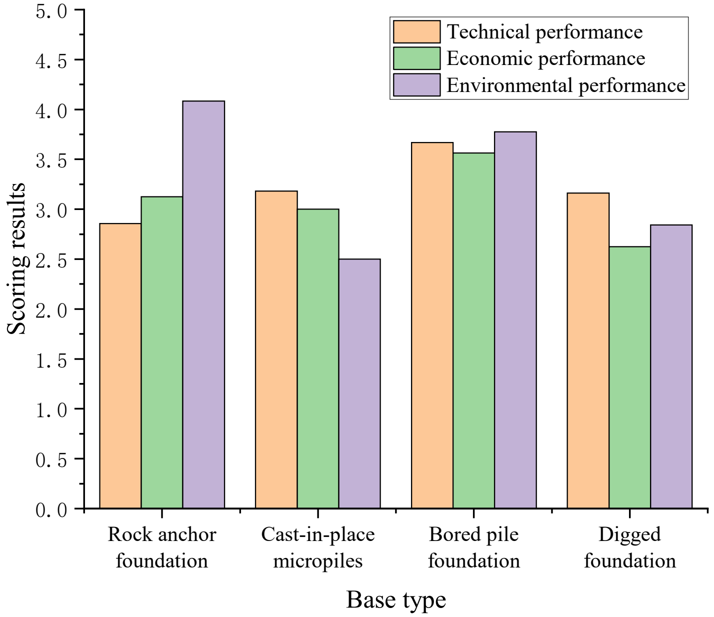

Fig. 1. Evaluation results of the 4-type base guideline layer

4.2.2 Comprehensive Evaluation Results.

The results of the three-level fuzzy comprehensive evaluation are as follows: rock anchor foundation for $\{0.4434, 0.3393, 0.2165\}$; cast-in-place mini-pile foundation for $\{0.3179, 0.2831, 0.3981\}$; bored pile foundation for $\{0.481, 0.3698, 0.1483\}$; and hollowed-out foundation for $\{0.2439, 0.4125, 0.3427\}$.

According to the results of the three-level fuzzy comprehensive evaluation, the rock anchor foundation is 3.45, the cast-in-place mini-pile foundation is 2.84, the dug pile foundation is 3.66, and the hollowed-out foundation is 2.80. Under the existing technical conditions, integrating economy and environment, among the four types of foundations selected, the bored pile foundation has the highest overall score and is recommended in priority, followed by the rock anchor foundation, which is recommended in second best, and the excavation of the foundation base has the lowest score.

5 Conclusions

1. There are many factors affecting the foundation selection, and the FAHP method can quantify the qualitative problems under the condition of multiple influencing factors, and process the foundation selection process, making the selection results more scientific and precise, and at the same time, it has strong operability.

2. A transmission line foundation evaluation index system containing three first-level evaluation indexes, five second-level evaluation indexes, and 13 third-level evaluation indexes for technical performance, economic performance, and environmental performance is constructed, and the weights of the evaluation indexes at different levels are calculated using the AHP method, and the three-level fuzzy comprehensive evaluation set of each technology is obtained through the FCE model, from which the comprehensive scores of each foundation are calculated.

3. The AHP-FCE model was used to carry out a comprehensive evaluation of the 4 types of foundations, and the dug pile foundation had the highest comprehensive score under the existing technological conditions, taking into account the economy and low-carbon nature.

Acknowledgments

The study is supported by the Science and Technology Project of State Grid Corporation of China (Nos. 5200-202355156A-1-1-ZN).

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