

## Research Article

# Safety Evaluation Method of Antifloating Anchor System Based on Comprehensive Weighting Method and Gray-Fuzzy Theory

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The risk factors in the safety evaluation of antifloating anchor system of underground structure have the characteristics of complexity, grey, and fuzziness. Based on the Delphi method, analytic hierarchy process (AHP), and entropy weight method, this paper establishes a three-level evaluation index system based on four main risk factors and calculates the subjective and objective comprehensive weights of the index according to the comprehensive weighting method. It not only takes into account the valuable experience of the expert group but also reflects the objective impact of the subjective score on the system. On the basis of the above research, the grey-fuzzy safety evaluation method of antifloating anchor system is established by using the grey theory and the relevant theory of fuzzy mathematics. The reliability of the method is verified by an example, which has certain theoretical significance and application value.

## 1. Introduction

In recent years, the development and utilization of modern urban underground space resources has become one of the important trends of geotechnical engineering development in the 21st century [1, 2]. As a large amount of groundwater can be stored in pores and fractures of the rock and soil medium, in the case of extreme rainstorm climate and regional recovery of groundwater, it will lead to the increase of the buoyancy of the basement water of the underground structure. When a certain limit is reached, the local or overall buoyancy disaster of the structure will be caused [3, 4].

Antifloating measures of underground structures can be divided into temporary measures during construction (water insulation, precipitation, and drainage) and permanent measures during use (increasing self-weight, antiuplift piles, and antifloating anchors). Among them, antifloating anchor technology has been widely used in antifloating engineering because of its advantages of simple construction and low cost [5]. However, in recent years, the failure cases of the antifloating anchor system of underground structures are common, resulting in a large number of property losses

[6–8]. Therefore, the basic research on the safety analysis and evaluation methods of the antifloating anchor system has important theoretical significance and application value for adopting more scientific and reasonable preventive measures and promoting the safe operation of underground structures.

At present, the safety evaluation of antifloating anchor system in underground engineering mainly relies on expert experience and the analogy method based on engineering examples. However, in recent years, researchers in other fields have proposed a variety of safety evaluation methods, such as analytic hierarchy process, fuzzy comprehensive evaluation, and grey clustering theory [9–12]. But these methods also have some shortcomings: (1) The evaluation index system is not comprehensive enough, and the established index system lacks representativeness and comparability. (2) The weight of evaluation index cannot avoid the influence of subjectivity of expert rating and error of quantitative calculation in qualitative analysis. (3) The evaluation method is single, and each method has its advantages, disadvantages, and scope of application, which cannot ensure the high accuracy of the evaluation results.

Antifloating anchor system is a complex system composed of natural environment (such as antifloating anchor, foundation floor, and rock-soil body) and cultural environment (such as construction level and safety management). Its safety evaluation is a multilevel and multiattribute problem with qualitative and quantitative indexes. Due to the insufficiency of data collection and incompleteness of information, the evaluation information of each influencing factor has a certain grey level. Due to the overlap of evaluation index, it has a certain complex. Because the boundaries of evaluation criteria are not clear enough, the evaluation index are also ambiguous. Therefore, the safety evaluation of antifloating anchor system should consider the influence of the complexity, fuzziness, and grey of evaluation indexes at the same time.

This paper establishes a three-level index system for safety evaluation of antifloating anchor system and determines the index weight based on the Delphi method, analytic hierarchy process (AHP), and entropy weight method. It not only takes into account the valuable experience of expert groups but also reflects the objective impact of subjective score on the system. On the basis of the above research, based on the characteristics of risk analysis of antifloating anchor system itself, the grey-fuzzy evaluation model is used for comprehensive evaluation and analysis of safety. The method proposed in this paper combines the advantages of various decision-making theories, which makes the safety evaluation results more reasonable and scientific, and has certain theoretical significance and application value.

## 2. Preliminaries

*2.1. Analytic Hierarchy Process (AHP).* Analytic hierarchy process (AHP) is a multicriteria evaluation and analysis method, which is suitable for solving the decision-making problems of complex systems. According to the intrinsic logic relationship of complex system, the system is decomposed into several indexes and hierarchical structure is established. Then, the relative importance of each index is obtained by comparing two indexes under the same dominant index, and then the judgment matrix is established. By calculating the eigenvector of the judgment matrix, the weight of each index is determined, and the judgment matrix is established. The establishment of judgment matrix varies from decision-maker to decision-maker, which cannot overcome subjective arbitrariness. It belongs to the subjective weighting method [13, 14].

The key problem of calculating index weight by using the AHP method is to determine a reasonable scale value of relative importance between two indexes. In order to avoid the excessive error caused by the subjective preference of a single decision-maker, it is appropriate to use the Delphi method to determine the index scale value. This method can deeply mine the subjective experience and professional knowledge of the expert group and has certain objectivity. The specific method is to design the questionnaire first and use the 1–9 scale method to express the importance of each index. After several rounds of inquiry, several experts were asked for

their opinions, and finally the scale value was determined. The 1–9 scale method and its explanation are shown in Table 1.

In this paper, the AHP method is used to calculate the weight value of the evaluation index. The calculation steps are as follows.

*2.1.1. Construction of a Judgment Matrix.* Let there be  $n$  second-level evaluation indexes under a certain first-level index. This paper employs several experts according to the Delphi method to grade the relative importance of all secondary-level indexes under the first-level index. After several rounds of inquiry, a unified opinion is formed. Then the judgment matrix  $A$  constructed is as follows:

$$A = (a_{ij})_{n \times n} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}_{n \times n}, \quad (1)$$

where  $a_{ij}$  ( $i, j = 1, 2, \dots, n$ ) is expressed as the relative importance of two comparisons among the index on the same level, and it satisfies the following properties:  $a_{ii} = a_{jj} = 1$  and  $a_{ji} = 1/a_{ij}$ .

*2.1.2. Determination of Index Weight.* After the establishment of the judgment matrix, the weight of the index should be calculated according to the judgment matrix and arranged in order, i.e., hierarchical single ranking.

In this paper, the eigenvector method is used to calculate the weight of each index layer. Firstly, the maximum eigenvalue  $\lambda_{\max}$  of the judgment matrix is obtained, and then the corresponding eigenvector  $w$  is obtained as follows:

$$Aw = \lambda_{\max} w, \quad (2)$$

where the component  $w_i$  ( $i = 1, 2, \dots, n$ ) of  $w$  is the weight value of the second-level index relative to the first-level index.  $w_i$  satisfies the following relationships:  $0 < w_i < 1$  and  $\sum_{i=1}^n w_i = 1$ .

*2.1.3. Consistency Test.* Usually, because of the complexity of the evaluation problem and the subjective preferences of experts, the logical consistency of judgment thinking cannot be guaranteed. Therefore, in order to ensure that the evaluation results are basically reasonable, it is necessary to test the consistency of the judgment matrix. The calculation steps are as follows:

- (a) Calculation of the maximum eigenvalue  $\lambda_{\max}$  of the judgment matrix:

$$\lambda_{\max} = \sum_{i=1}^n \frac{(Aw)_i}{nw_i}. \quad (3)$$

- (b) Calculation of consistency index C.I.:

$$C.I. = \frac{\lambda_{\max} - n}{n - 1}. \quad (4)$$

TABLE 1: The 1–9 scale method and its explanation [15].

Scale	The importance of $A_i$ compared with $A_j$
1	Equally important
3	Slightly important
5	More important
7	Very important
9	Absolutely important

The values between the two importance levels are 2, 4, 6, and 8 scales.

(c) Calculation of consistency ratio C.R.:

$$\text{C.R.} = \frac{\text{C.I.}}{\text{R.I.}}, \quad (5)$$

where the average random consistency index R.I. is shown in Table 2. When the consistency ratio  $\text{C.R.} < 0.1$ , the consistency of the judgment matrix can be considered to satisfy the consistency requirement. When the consistency ratio  $\text{C.R.} > 0.1$ , the consistency of the judgment matrix is unacceptable. It is necessary to compare the index at this level and revise the scale value of the index until the requirements are met.

**2.2. Entropy Weight Method (EWM).** The entropy weight method (EWM) is a method to determine the weight by calculating the information entropy value according to the difference degree of objective information quantity of each index. It belongs to the objective weight method and has absolute objectivity. However, it ignores the practical significance of the index itself to the evaluation target and cannot reflect the valuable information such as the subjective experience of the decision-maker. Information entropy is a measure of the degree of disorder in a system. The greater the difference of data on an index, the greater the entropy value, indicating that the smaller the effective information provided by the index, the smaller the weight of the index; the smaller the difference of data, the smaller the entropy value, the larger the effective information provided, and the larger the weight [16, 17].

In this paper, the basic steps of determining index weight by using the method of entropy weight are as follows:

- (a) The determination of original evaluation matrix: Let there be  $n$  second-level evaluation indexes under a certain first-level index. This paper employs  $m$  experts to participate in the evaluation according to the Delphi method. These experts do not need to form a unified opinion. Let each expert score the second-level index according to the importance of the index in the range of 1–9. Then, the original evaluation matrix is formed as follows:

$$A = (a_{ij})_{n \times m} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nm} \end{bmatrix}_{n \times m}, \quad (6)$$

where  $a_{ij}$  ( $i = 1, 2, \dots, n$ ;  $j = 1, 2, \dots, m$ ) is the value of importance given by the  $j$ th expert for the  $i$ th index.

**2.2.1. Calculation of the Entropy Value of Evaluation Index according to the Definition of Entropy:**

- (a) Define the entropy value of the  $i$ th index:

$$H_i = -\frac{1}{\ln m} \sum_{j=1}^m p_{ij} \cdot \ln p_{ij}, \quad (7)$$

where  $p_{ij}$  ( $i = 1, 2, \dots, n$ ;  $j = 1, 2, \dots, m$ ) is the proportion of the evaluation value of the  $j$ th expert for the  $i$ th index in index  $i$ , that is,

$$p_{ij} = \frac{a_{ij}}{\sum_{j=1}^m a_{ij}}. \quad (8)$$

It is assumed that when  $p_{ij} = 0$ ,  $p_{ij} \ln p_{ij} = 0$ .

- (b) Calculate the entropy weight of the evaluation index by using the entropy value:

$$\omega_i = \frac{1 - H_i}{\sum_{i=1}^n (1 - H_i)}. \quad (9)$$

Finally, the weight vector set of the evaluation index based on the entropy weight method is obtained as follows:

$$\omega = (\omega_1, \omega_2, \omega_3, \dots, \omega_n). \quad (10)$$

**2.3. Grey-Fuzzy Evaluation Method.** Grey system theory focuses on the problem of “clear extension and unclear connotation,” while fuzzy mathematics focuses on the problem of “unclear extension and clear connotation.” In view of the complexity, grey, and fuzziness of the risk factors affecting the safety of the antifloating anchor system, this paper combines the two methods and establishes a grey-fuzzy evaluation model. The detailed calculation steps are as follows.

**2.3.1. Establishment of Fuzzy Grading Criteria for Evaluation Index.** In safety evaluation, some indexes are difficult to quantify, so the risk degree evaluation of quantitative and qualitative indexes can be expressed by fuzzy language [18]. Let the risk-level fuzzy set be  $V = (V_1, V_2, \dots, V_s)$ , and the risk-level  $V$  is divided into five grades in this paper, i.e., very high, high, medium, low, and very low. Several experts were hired to grade the evaluation index according to the Delphi method, and the above five criteria correspond to the values (9, 7, 5, 3, and 1), respectively. When the index level is between two adjacent levels, the corresponding values are 8, 6, 4, and 2.

**2.3.2. Determination of Evaluation Sample Matrix.** Assuming that there are  $n$  second-level evaluation indexes under a certain first-level index,  $m$  experts are invited to

TABLE 2: The average random consistency index R.I. [15].

$n$	3	4	5	6	7	8	9	10	11	12	13	14	15
R.I.	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54	1.56	1.58	1.59

participate in the evaluation. Let each expert score all  $n$  second-level indexes according to the risk-level fuzzy set, and the scoring range is between 1 and 9. The magnitude of the score indicates the degree of risk. The sample matrix of fuzzy evaluation is composed of all experts' scores of all evaluation indexes:

$$D = [d_{ij}]_{n \times m} = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1m} \\ d_{21} & d_{22} & \cdots & d_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nm} \end{bmatrix}_{n \times m}. \quad (11)$$

### 2.3.3. Determination of Fuzzy Grey Class for Evaluation.

To determine the evaluation grey class, the grade number, grey number, and whitening weight function of the evaluation grey class should be determined [19, 20]. The grade number of the evaluation grey class should be determined by qualitative analysis based on the fuzzy grade standard. According to the above grade standard, the evaluation grey class can be divided into five grades. The grey class number is  $k$ , i.e.,  $k = 1, 2, 3, 4, 5$ , which corresponds to very high, high, medium, low, and very low, respectively. The corresponding grey number and whitening weight function are expressed as follows:

- (a) The first grey class is "very high" ( $k = 1$ ): the number of grey is  $\otimes \in [0, 5, 10]$ , and the whitening weight function is

$$f_1(d_{ij}) = \begin{cases} \frac{d_{ij}}{5}, & d_{ij} \in [0, 5), \\ 1, & d_{ij} \in [5, 10), \\ 0, & d_{ij} \notin [0, 10). \end{cases} \quad (12)$$

- (b) The second grey class is "high" ( $k = 2$ ): the number of grey is  $\otimes \in [0, 4, 8]$ , and the whitening weight function is

$$f_2(d_{ij}) = \begin{cases} \frac{d_{ij}}{4}, & d_{ij} \in [0, 4), \\ \frac{2 - d_{ij}}{4}, & d_{ij} \in [4, 8), \\ 0, & d_{ij} \notin [0, 8). \end{cases} \quad (13)$$

- (c) The third grey class is "medium" ( $k = 3$ ): the number of grey is  $\otimes \in [0, 3, 6]$ , and the whitening weight function is

$$f_3(d_{ij}) = \begin{cases} \frac{d_{ij}}{3}, & d_{ij} \in [0, 3), \\ \frac{2 - d_{ij}}{3}, & d_{ij} \in [3, 6), \\ 0, & d_{ij} \notin [0, 6). \end{cases} \quad (14)$$

- (d) The fourth grey class is "low" ( $k = 4$ ): the number of grey is  $\otimes \in [0, 2, 4]$ , and the whitening weight function is

$$f_4(d_{ij}) = \begin{cases} \frac{d_{ij}}{2}, & d_{ij} \in [0, 2), \\ \frac{2 - d_{ij}}{2}, & d_{ij} \in [2, 4), \\ 0, & d_{ij} \notin [0, 4). \end{cases} \quad (15)$$

- (e) The fifth grey class is "very low" ( $k = 5$ ): the number of grey is  $\otimes \in [0, 1, 2]$ , and the whitening weight function is

$$f_5(d_{ij}) = \begin{cases} 1, & d_{ij} \in [0, 1), \\ 2 - d_{ij}, & d_{ij} \in [1, 2), \\ 0, & d_{ij} \notin [0, 2). \end{cases} \quad (16)$$

### 2.3.4. Calculation of Grey Evaluation Coefficient.

Calculating the grey evaluation coefficient is to whiten the scoring system in the evaluation sample. Let  $C_{ik}$  be the grey evaluation coefficient belonging to  $k$  ( $k = 1, 2, \dots, p$ )th fuzzy grey class of the  $i$ th second-level evaluation index under a certain first-level index. By substituting the evaluation sample matrix  $D$  under a certain first-level index into the whitening weight function  $f_k(d_{ij})$ , the grey evaluation coefficient can be obtained as follows:

$$C_{ik} = \sum_{j=1}^m f_k(d_{ij}). \quad (17)$$

For a certain first-level index, the total grey evaluation coefficient of the  $i$ th second-level index which is evaluated belongs to each evaluation grey class  $C_i$ :

$$C_i = \sum_{k=1}^p C_{ik}. \quad (18)$$

According to  $C_{ik}$  and  $C_i$ , it can be calculated that the evaluation weight  $r_{ik}$  of the  $i$ th second-level evaluation index belonging to the  $k$ th grey class is

$$r_{ik} = \frac{C_{ik}}{C_i} \quad (19)$$

Thus, the grey-fuzzy evaluation weight vector of the  $i$ th second-level evaluation index under a certain first-level index can be determined as

$$r_i = (r_{i1}, r_{i2}, \dots, r_{ip}). \quad (20)$$

After synthesizing the evaluation weight vectors of all  $n$  second-level indexes, the grey-fuzzy evaluation weight matrix of a certain first-level index is obtained as

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1p} \\ r_{21} & r_{22} & \cdots & r_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{np} \end{bmatrix}_{n \times p}. \quad (21)$$

**2.3.5. Fuzzy Comprehensive Evaluation.** Firstly, if there are  $N$  first-level indexes in the evaluation index system, the set of first-level indexes is  $A = (A_1, A_2, \dots, A_N)$ , and the weight vector set of the first indexes is  $W = (W_1, W_2, \dots, W_N)$ . If there are  $n$  sets of second-level index under a certain first-level index, then the set of second-level indexes is  $A_i = (A_{i1}, A_{i2}, \dots, A_{in})$ , and the weight vector of the second-level index is  $W_i = (W_{i1}, W_{i2}, \dots, W_{in})$ .

*(1) Fuzzy Comprehensive Evaluation of the First-Level Index.* According to the weight vector of second-level index  $W_i = (W_{i1}, W_{i2}, \dots, W_{in})$ , the grey-fuzzy evaluation weight matrix  $R$  can be used to obtain the fuzzy comprehensive evaluation vector  $B_i$  of the first-level index by the following operations:

$$B_i = W_i \cdot R, \quad (22)$$

where  $B_i = (B_{i1}, B_{i2}, \dots, B_{im})$ .

*(2) Fuzzy Comprehensive Evaluation of General Objectives.* After synthesizing the fuzzy comprehensive evaluation vectors of all the primary indexes, the fuzzy comprehensive evaluation matrix  $B$  of the index system is obtained. According to the weight vector of the first-level index  $W = (W_1, W_2, \dots, W_N)$ , the result of the fuzzy comprehensive evaluation of the overall objective of evaluation is as follows:

$$B = W \cdot B_i, \quad (23)$$

where  $B = (B_1, B_2, \dots, B_N)$ .

According to the risk-level fuzzy set  $V = (V_1, V_2, \dots, V_S)$ , the total score  $Z$  of safety evaluation of the antifloating anchor system can be obtained:

$$Z = B \cdot V^T. \quad (24)$$

According to the above results, the risk level of the antifloating anchor system can be judged.

### 3. The Proposed Model

**3.1. Construction of Evaluation Index System.** There are many risk factors considered in the safety evaluation of the antifloating anchor system, and these factors are interrelated, which leads to the complexity of its evaluation index system. Following the principles of scientificity, comprehensiveness, and importance, this paper takes the four main risk factors (geological environment safety, design scheme safety, construction quality safety, and safety management safety) existing in the antifloating anchor system as criteria, uses the idea of analytic hierarchy process to decompose the risk factors into some specific evaluation indexes, and establishes the evaluation index system of three-level hierarchical structure for the safety of the antifloating anchor system as shown in Figure 1. The first layer is the target layer, i.e., the overall objective is to evaluate the safety of the antifloating anchor system; the second layer is the first-level index layer of the criterion layer, i.e., the four main risk factors affecting the safety; the third level is the second-level index layer of the criterion layer, i.e., the further interpretation and specific evaluation criteria of the upper level are dominated by the respective first-level index, which are subdivided into 14 evaluation indexes.

**3.2. Determination of Index Weight by Subjective and Objective Comprehensive Weighting Method.** The weighting method adopted in this paper combines the advantages of subjective and objective weighting methods. It considers not only the valuable experience of decision-makers but also the information contained in the data itself, avoids the deviation between them, and makes the weight distribution more scientific and reasonable.

In this paper, analytic hierarchy process and entropy weight method are used to determine the weight of each index. Assuming that there are  $n$  second-level indexes under a certain first-level index, the set of index weights determined by the AHP method and entropy weight method is  $w = (w_1, w_2, w_3, \dots, w_n)$  and  $\omega = (\omega_1, \omega_2, \omega_3, \dots, \omega_n)$ , and then the set of comprehensive weight vectors of index is

$$W = (W_1, \dots, W_i, \dots, W_n), \quad (25)$$

$$W_i = \alpha w_i + (1 - \alpha) \omega_i, \quad (26)$$

where  $\alpha$  is a coefficient and satisfies  $0 \leq \alpha \leq 1$ .

The comprehensive weight varies with the change of  $\alpha$ . When  $\alpha = 0$  or  $\alpha = 1$ , the weights determined by the entropy weight method and the AHP method correspond to each other. The value of  $\alpha$  should be determined according to the actual situation. In this paper, according to the principle of combination of subjective and objective,  $\alpha = 0.5$  is selected.

**3.3. Computation of Flow of Evaluation Method.** The safety evaluation method of the antifloating anchor system proposed in this paper is mainly based on AHP and entropy weight methods to calculate the subjective and objective comprehensive weight of the evaluation index. On this basis,

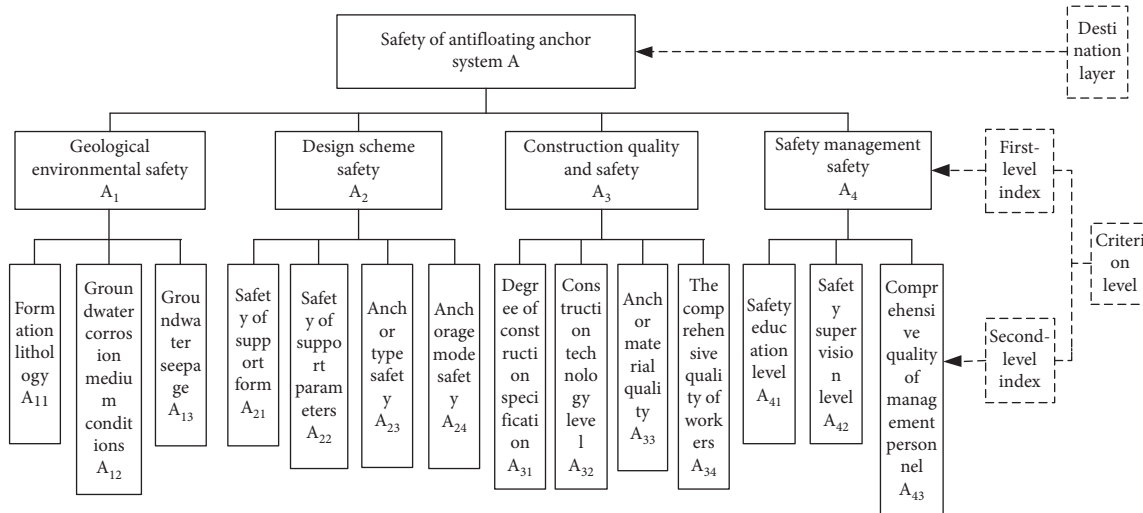


FIGURE 1: Safety evaluation index system of the antifloating anchor system.

the grey-fuzzy evaluation method is used to carry out comprehensive evaluation and analysis of safety. The specific steps are as follows.

*Step 1.* The safety evaluation index system of the antifloating anchor system is determined by the Delphi method. Firstly, several experts in relevant fields are hired, and their opinions on which indexes should be adopted for safety evaluation of the antifloating anchor system are sought. After that, the statistical results are sorted out, summarized, and counted and then anonymously fed back to the experts for further comments. After that, the results of the inquiry will be recentralized and feedback will be given until a stable opinion is obtained. Through this method, the safety evaluation index system of the antifloating anchor system is established.

*Step 2.* The AHP method and entropy weight method are used to calculate the subjective and objective comprehensive weights of the evaluation index. Firstly, the Delphi method is used to establish two important degree comparison judgment matrices of evaluation indexes of the antifloating anchor system based on the 1–9 scale method. Subjective weight values of each index are calculated according to the AHP method, and consistency test is carried out. Then, according to the Delphi method, each expert scored each index in the range of 1–9 according to the importance of the index, established the evaluation matrix of each index, and used the entropy weight method to calculate the objective weight value of each index. Finally, according to the comprehensive weighting method, the subjective and objective comprehensive weights of evaluation indexes are calculated.

*Step 3.* Comprehensive evaluation is carried out by using grey-fuzzy theory. Firstly, the Delphi method is used to score the risk level of each evaluation index according to the risk-level fuzzy set, and the sample matrix of the fuzzy evaluation is established. Then, the

grey theory method is used to determine the evaluation fuzzy grey class, calculate the grey evaluation coefficient, and establish the grey-fuzzy evaluation weight matrix. Finally, the final score of the antifloating anchor system risk level is calculated by combining the grey-fuzzy evaluation weight matrix and the weight values of each index, and the risk level is determined.

## 4. Illustrative Example

Taking the antifloating anchor bolt project in atrium area of a commercial square in Yinchuan, China as an example, this paper evaluates the safety of the antifloating anchor bolt system based on the established evaluation index system and grey-fuzzy evaluation method. The building area of the atrium is 260,000 square meters, five floors above ground, 28 floors above tower, and two floors below ground. It is mainly used as auxiliary rooms such as garage and equipment room. The bearing stratum of the basement floor is fine sand, and the characteristic value of bearing capacity is 340 kPa. The antifloating waterproofing level is  $-1.8$  m, the top level of the waterproofing board is  $-10.9$  m, and the thickness of the waterproofing board is 400 mm. Because of the high groundwater level, in order to meet the requirements of antifloating, an antifloating anchor rod is designed to resist water buoyancy. The total water buoyancy is 105355 kN, the weight of the waterproofing board in atrium area is 11090 kN, and the weight of superstructure is 40691 kN. The design value of single anchor is 320 kN. According to the load of column, 9 to 11 anchor are arranged in each span, and 220 anchors are actually arranged. Groundwater has microcorrosiveness to steel bar under long-term immersion condition.

### 4.1. Determination of the Weight of Safety Evaluation Index

*4.1.1. Determination of Index Weight by AHP Method.* According to the principle of the Delphi method, five experts from universities, design, construction, and supervision

industries have been consulted for many times, and finally a unified opinion has been formed. Then, the weight of each index has been calculated by the AHP method. Now, taking the “geological environment safety,” “design scheme safety,” “construction quality safety,” and “safety management safety” in the first index layer as examples, the weight has been calculated. The calculation steps are as follows:

- (a) According to the 1–9 scale method, relative importance degrees of four evaluation indexes in the first-level index are compared, and the judgment matrix is constructed as shown in Table 3.
- (b) According to formula (2), the maximum eigenvalue  $\lambda_{\max}$  and its eigenvector  $W$  are obtained. In this paper, the maximum eigenvalue  $\lambda_{\max} = 4.0975$  of the judgment matrix  $A$  is calculated and the set of eigenvector weights of the first-level index is  $W = 0.1296, 0.4959, 0.2887, 0.0858$ .
- (c) The consistency test is conducted. Firstly, according to the order  $n = 4$  of the judgment matrix, the consistency index C.I. is determined,  $C.I. = (\lambda_{\max} - n/n - 1) = 0.03251$ . Table 3 shows that  $R.I. = 0.89$ ,  $C.R. = (C.I./R.I.) = 0.03653 < 0.1$ , it satisfies consistency, and the weights determined by the judgment matrix are acceptable.

According to the above method, the weights of each evaluation index relative to each index in the secondary-level index can be determined. The weights and consistency test results are shown in Tables 4–7.

The weight value of the second-level index under the first-level index of “geological environmental safety” relative to the target layer  $A$  is as follows:

$$(0.5359, 0.1638, 0.2973)T \times 0.1296 = (0.06945, 0.02122, 0.03853). \tag{27}$$

The weights of the second-level index under the first-level index of “design scheme safety” relative to the target-level  $A$  are as follows:

$$(0.1466, 0.5557, 0.2358, 0.0619)T \times 0.4959 = (0.0727, 0.2756, 0.1169, 0.0307). \tag{28}$$

The weight value of the second-level index under the first-level index of “construction quality safety” relative to the target layer  $A$  is

$$(0.5056, 0.0868, 0.2642, 0.1434)T \times 0.2887 = (0.1460, 0.02392, 0.03088, 0.0414). \tag{29}$$

The weights of the second-level index under the first-level index of “safety management and safety” relative to the target-level  $A$  are as follows:

$$(0.3092, 0.5813, 0.1096)T \times 0.0858 = (0.0265, 0.0499, 0.0094). \tag{30}$$

TABLE 3: The judgment matrix  $A$  of the first-level index.

$A$	$A_1$	$A_2$	$A_3$	$A_4$
$A_1$	1	1/4	1/3	2
$A_2$	4	1	2	5
$A_3$	3	1/2	1	3
$A_4$	1/2	1/5	1/3	1

TABLE 4: The judgment matrix, weight value, and consistency test result of the second-level index subordinate to the first-level index of “geological environment safety.”

$A$	$A_{11}$	$A_{12}$	$A_{13}$	Subjective weight	$\lambda_{\max}$	C.R.
$A_{11}$	1	3	2	0.5389		
$A_{12}$	1/3	1	1/2	0.1638	3.0147	0.0142 < 0.1
$A_{13}$	1/2	2	1	0.2973		

TABLE 5: The judgment matrix, weight value, and consistency test result of the second-level index subordinate to the first-level index of “design scheme safety.”

$A$	$A_{21}$	$A_{22}$	$A_{23}$	$A_{24}$	Subjective weight	$\lambda_{\max}$	C.R.
$A_{21}$	1	1/4	1/2	3	0.1466		
$A_{22}$	4	1	3	7	0.5557	4.1072	0.0402 < 0.1
$A_{23}$	2	1/3	1	4	0.2358		
$A_{24}$	1/3	1/7	1/4	1	0.0619		

TABLE 6: The judgment matrix, weight value, and consistency test result of the second-level index subordinate to first-level index of “construction quality safety.”

$A$	$A_{31}$	$A_{32}$	$A_{33}$	$A_{34}$	Subjective weight	$\lambda_{\max}$	C.R.
$A_{31}$	1	5	2	4	0.5056		
$A_{32}$	1/5	1	1/3	1/2	0.0868	4.0379	0.014 < 0.1
$A_{33}$	1/2	3	1	2	0.2642		
$A_{34}$	1/4	2	1/2	1	0.1434		

TABLE 7: The judgment matrix, weight value, and consistency test result of the second-level index subordinate to the first-level index of “safety management and safety.”

$A$	$A_{41}$	$A_{42}$	$A_{43}$	Subjective weight	$\lambda_{\max}$	C.R.
$A_{41}$	1	1/2	3	0.3092		
$A_{42}$	2	1	5	0.5813	3.0063	0.0061 < 0.1
$A_{43}$	1/3	1/5	1	0.1096		

4.1.2. *Determination of Index Weight by Entropy Weight Method.* Now take each index in the first level as an example, and the weight is calculated by the method of entropy weight, and the calculation steps are as follows:

- (a) According to the principle of the Delphi method and after consulting five experts, the original evaluation matrix is shown in Table 8.
- (b) According to formula (8), the proportion matrix of five experts’ scores to the four first-level indexes is calculated as follows:

TABLE 8: The expert marking table  $A$  of the first-level index.

$A$	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
$A_1$	7	6	5	6	6
$A_2$	9	8	7	9	7
$A_3$	8	7	8	8	6
$A_4$	6	5	5	5	6

$$P_{ij} = \begin{bmatrix} 0.2333 & 0.2 & 0.1667 & 0.2 & 0.2 \\ 0.2225 & 0.2 & 0.175 & 0.225 & 0.175 \\ 0.2162 & 0.1892 & 0.2162 & 0.2162 & 0.1622 \\ 0.2222 & 0.1852 & 0.1852 & 0.1852 & 0.2222 \end{bmatrix}. \quad (31)$$

According to formula (7), the entropy value  $H_i = (0.9965, 0.9961, 0.9962, 0.9975)$  of four first-level indexes was calculated.

According to formula (9), the set of four first-level index weight vectors based on the entropy weight method is  $\omega = (0.2541, 0.2853, 0.2753, 0.1853)$ . The index weight determined by the entropy weight method is approximately the same as that determined by the AHP method, and the judgment difference of the fourth first-level index of "safety management safety" is the smallest.

According to the above method, the objective weights of the secondary-level index can be determined. The scoring tables, entropy values, and objective weights of the secondary-level index are shown in Tables 9–12.

The objective weights of the second-level index under the first-level index of "geological environment safety" are as follows:

$$(0.3056, 0.4592, 0.2351)T \times 0.2514 = (0.07683, 0.1154, 0.0591). \quad (32)$$

The weights of the second-level index under the first-level index of "design scheme safety" relative to the target-level  $A$  are as follows:

$$(0.2585, 0.3042, 0.2730, 0.1644)T \times 0.2853 = (0.0738, 0.0868, 0.0779, 0.0469). \quad (33)$$

The weight value of the second-level index under the first-level index of "construction quality safety" relative to the target layer  $A$  is

$$(0.3339, 0.2441, 0.2733, 0.1487)T \times 0.2753 = (0.0919, 0.0672, 0.0752, 0.0409). \quad (34)$$

The weights of the second-level index under the first-level index of "safety management and safety" relative to the target-level  $A$  are as follows:

$$(0.3515, 0.4025, 0.2460)T \times 0.1853 = (0.0651, 0.0746, 0.0456). \quad (35)$$

**4.1.3. Determination of Index Weight by Comprehensive Weighting Method.** In this paper, if  $\alpha = 0.5$ , the subjective and objective comprehensive weights of each index can be calculated by formula (26) as  $W = 0.1919, 0.3906, 0.282, 0.1356$ .

Repeat the above steps to obtain the comprehensive weights of the second-level index, as shown in Table 13.

## 4.2. Calculation and Analysis of Grey-Fuzzy Evaluation Method

### 4.2.1. Establishment of Fuzzy Evaluation Sample Matrix.

According to the Delphi principle, five experts were hired to grade the risk degree of each index by using five-level risk grade fuzzy sets. In this paper, the grey-fuzzy evaluation is carried out by taking the secondary-level indexes under the first-level index of "geological environment safety" as an example. The sample matrix of the fuzzy evaluation is shown in Table 14.

### 4.2.2. Calculation of Weight Coefficient of Grey Evaluation.

Taking the secondary-level index of "formation lithology  $A_{11}$ " as an example, the evaluation coefficients belonging to the  $k$ th evaluation ash class are calculated.

When  $k = 1$ ,  $C_{ik}$  is calculated by formula (17),  $C_{11} = f_1(6) + f_1(5) + f_1(5) + f_1(4) + f_1(6) = 4.8$ .

Similarly, when  $k = 2$ ,  $C_{12} = 3.5$ ; when  $k = 3$ ,  $C_{13} = 1.33$ ; when  $k = 4$ ,  $C_{14} = 0$ ; and when  $k = 5$ ,  $C_{15} = 0$ .

Therefore, according to formula (18), calculating the total grey evaluation coefficient  $C_1 = C_{11} + C_{12} + C_{13} + C_{14} + C_{15} = 9.63$  of the first second-level evaluation index of "stratigraphic lithology  $A_{11}$ " belongs to each evaluation grey class. The grey-fuzzy evaluation weight vector of the index can be determined by formula (19) as  $r_1 = (0.4984, 0.3634, 0.1381, 0, 0)$ .

Similarly, the weight vectors of the other second-level evaluation indexes can be calculated, and the grey-fuzzy evaluation weight matrix of the first-level index of "geological environment safety" can be established according to all the evaluation weight vectors:

$$R = \begin{bmatrix} 0.4984 & 0.3634 & 0.1381 & 0 & 0 \\ 0.3199 & 0.3157 & 0.2803 & 0.0842 & 0 \\ 0.7692 & 0.2308 & 0 & 0 & 0 \end{bmatrix}. \quad (36)$$

Repeat the above steps to obtain the grey-fuzzy evaluation weight matrix of the remaining first-level index. The sample matrix of the first-level evaluation index of "design scheme safety" is shown in Table 15, and the grey-fuzzy evaluation weight matrix is as follows:

$$R = \begin{bmatrix} 0.8333 & 0.1667 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0.6122 & 0.3061 & 0.0816 & 0 & 0 \\ 0.7692 & 0.2308 & 0 & 0 & 0 \end{bmatrix}. \quad (37)$$



TABLE 9: The scoring table, entropy value, and objective weight result of the second-level index subordinate to the first-level index of “geological environment safety.”

A	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Entropy	Objective weight
A <sub>11</sub>	7	7	8	6	8	0.9966	0.3056
A <sub>12</sub>	5	6	7	5	6	0.9949	0.4592
A <sub>13</sub>	9	8	9	7	8	0.9974	0.2351

TABLE 10: The scoring table, entropy value, and objective weight result of the second-level index subordinate to the first-level index of “design scheme safety.”

A	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Entropy	Objective weight
A <sub>21</sub>	6	5	6	6	5	0.9976	0.2585
A <sub>22</sub>	9	8	7	7	8	0.9972	0.3042
A <sub>23</sub>	7	7	6	8	7	0.9975	0.2730
A <sub>24</sub>	6	6	5	6	6	0.9985	0.1644

TABLE 11: The scoring table, entropy value, and objective weight result of the second-level index subordinate to the first-level index of “construction quality safety.”

A	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Entropy	Objective weight
A <sub>31</sub>	9	6	8	7	6	0.9920	0.3339
A <sub>32</sub>	3	3	4	4	4	0.9941	0.2441
A <sub>33</sub>	5	4	6	5	6	0.9934	0.2733
A <sub>34</sub>	4	5	4	5	5	0.9964	0.1487

TABLE 12: The scoring table, entropy value, and objective weight result of the second-level index subordinate to the first-level index of “safety management safety.”

A	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Entropy	Objective weight
A <sub>41</sub>	7	5	6	5	6	0.9949	0.3515
A <sub>42</sub>	9	7	8	6	7	0.9941	0.4025
A <sub>43</sub>	5	4	5	5	4	0.9964	0.2460

TABLE 13: The comprehensive weight of each second-level index.

Second-level index	Subjective weight	Subjective weight	Comprehensive weight
A <sub>11</sub>	0.06945	0.07683	0.07314
A <sub>12</sub>	0.02122	0.1154	0.06831
A <sub>13</sub>	0.03853	0.0591	0.048815
A <sub>21</sub>	0.0727	0.0738	0.07325
A <sub>22</sub>	0.2756	0.0868	0.1812
A <sub>23</sub>	0.1169	0.0779	0.0974
A <sub>24</sub>	0.0307	0.0469	0.0388
A <sub>31</sub>	0.146	0.0919	0.11895
A <sub>32</sub>	0.02392	0.0672	0.04556
A <sub>33</sub>	0.03088	0.0752	0.05304
A <sub>34</sub>	0.0414	0.0409	0.04115
A <sub>41</sub>	0.0265	0.0651	0.0458
A <sub>42</sub>	0.0499	0.0746	0.06225
A <sub>43</sub>	0.0094	0.0456	0.0275

TABLE 14: The expert scoring table for risk level of second-level index under the first-level index of “geological environment safety.”

D	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
A <sub>11</sub>	6	5	5	4	6
A <sub>12</sub>	3	4	4	3	5
A <sub>13</sub>	7	7	6	6	8

TABLE 15: The expert scoring table for risk level of the secondary-level index under first-level index of “design scheme safety.”

$D$	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
$A_{21}$	7	8	7	6	8
$A_{22}$	8	9	9	8	9
$A_{23}$	5	7	5	7	6
$A_{24}$	6	7	7	7	7

TABLE 16: The expert scoring table for risk level of secondary-level index under first-level index of “construction quality safety.”

$D$	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
$A_{31}$	5	6	4	6	6
$A_{32}$	8	7	7	9	8
$A_{33}$	7	7	6	8	7
$A_{34}$	6	7	5	7	6

TABLE 17: The expert scoring table for risk level of the secondary-level index under the first-level index of “safety management safety.”

$D$	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
$A_{41}$	8	7	7	6	8
$A_{42}$	6	5	6	4	7
$A_{43}$	4	4	3	3	5

The sample matrix of the first-level evaluation index of “construction quality safety” is shown in Table 16, and the weight matrix of the grey-fuzzy evaluation is as follows:

$$R = \begin{bmatrix} 0.5304 & 0.3591 & 0.1105 & 0 & 0 \\ 0.9091 & 0.0909 & 0 & 0 & 0 \\ 0.8 & 0.2 & 0 & 0 & 0 \\ 0.6596 & 0.2968 & 0.0435 & 0 & 0 \end{bmatrix}. \quad (38)$$

The sample matrix of the first-level evaluation index of “safety management safety” is shown in Table 17, and the weight matrix of the grey-fuzzy evaluation is as follows:

$$R = \begin{bmatrix} 0.8333 & 0.1667 & 0 & 0 & 0 \\ 0.5455 & 0.3409 & 0.1136 & 0 & 0 \\ 0.2987 & 0.3341 & 0.2885 & 0.0786 & 0 \end{bmatrix}. \quad (39)$$

#### 4.2.3. Multilevel Fuzzy Comprehensive Evaluation

(1) *Fuzzy Comprehensive Evaluation of the First-Level Index.* According to formula (22), the risk level of all first-level indexes can be evaluated. The results of the fuzzy comprehensive evaluation of the risk level of the first-level indicator “geological environment safety” are as follows:

$$B_1 = W_1 \cdot R = [0.07314 \ 0.06831 \ 0.048815] \cdot \begin{bmatrix} 0.4984 & 0.3634 & 0.1381 & 0 & 0 \\ 0.3199 & 0.3157 & 0.2803 & 0.0842 & 0 \\ 0.7692 & 0.2308 & 0 & 0 & 0 \end{bmatrix} = [0.0959 \ 0.0594 \ 0.0292 \ 0.0058 \ 0]. \quad (40)$$

The results of the fuzzy comprehensive evaluation of the risk level of the first-level index of “design scheme safety” are as follows:

$$B_2 = W_2 \cdot R = [0.07325 \ 0.1812 \ 0.0974 \ 0.0388] \cdot \begin{bmatrix} 0.8333 & 0.1667 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0.6122 & 0.3061 & 0.0816 & 0 & 0 \\ 0.7692 & 0.2308 & 0 & 0 & 0 \end{bmatrix} = [0.3317 \ 0.0510 \ 0.0079 \ 0 \ 0]. \quad (41)$$

The results of the fuzzy comprehensive evaluation of the risk level of the first-level index of “construction quality safety” are as follows:

$$B_3 = W_3 \cdot R = [0.11895 \ 0.04556 \ 0.05304 \ 0.04115] \cdot \begin{bmatrix} 0.5304 & 0.3591 & 0.1105 & 0 & 0 \\ 0.9091 & 0.0909 & 0 & 0 & 0 \\ 0.8 & 0.2 & 0 & 0 & 0 \\ 0.6596 & 0.2968 & 0.0435 & 0 & 0 \end{bmatrix} = [0.1741 \ 0.0697 \ 0.0149 \ 0 \ 0]. \quad (42)$$

The results of the fuzzy comprehensive evaluation of the risk level of the first-level index of “safety management and safety” are as follows:

$$B_4 = W_4 \cdot R = [0.0458 \ 0.06225 \ 0.0275] \cdot \begin{bmatrix} 0.8333 & 0.1667 & 0 & 0 & 0 \\ 0.5455 & 0.3409 & 0.1136 & 0 & 0 \\ 0.2987 & 0.3341 & 0.2885 & 0.0786 & 0 \end{bmatrix} = [0.0803 \ 0.0380 \ 0.0150 \ 0.0022 \ 0]. \quad (43)$$

(2) *Fuzzy Comprehensive Evaluation of General Objectives.* According to the abovementioned first-level fuzzy comprehensive evaluation, the following evaluation matrix is obtained:

$$B = B_i = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix} = \begin{bmatrix} 0.0959 & 0.0594 & 0.0292 & 0.0058 & 0 \\ 0.3317 & 0.0510 & 0.0079 & 0 & 0 \\ 0.1741 & 0.0697 & 0.0149 & 0 & 0 \\ 0.0803 & 0.0380 & 0.0150 & 0.0022 & 0 \end{bmatrix}. \quad (44)$$

The risk objective  $A$  is evaluated comprehensively, and the results are as follows:

$$A = W \cdot B = [0.1919 \quad 0.3906 \quad 0.282 \quad 0.1356] \cdot \begin{bmatrix} 0.0959 & 0.0594 & 0.0292 & 0.0058 & 0 \\ 0.3317 & 0.0510 & 0.0079 & 0 & 0 \\ 0.1741 & 0.0697 & 0.0149 & 0 & 0 \\ 0.0803 & 0.0380 & 0.0150 & 0.0022 & 0 \end{bmatrix} = [0.2080 \quad 0.0561 \quad 0.0149 \quad 0.0014 \quad 0]. \quad (45)$$

According to the above series of calculation results, it can be concluded that the fuzzy evaluation matrix of antifloating anchor system is  $B = (0.2080, 0.0561, 0.0149, 0.0014, 0)$  and then the evaluation vector is  $V = (9, 7, 5, 3, 1)^T$  by using the method of scoring each evaluation grade.

The results of the comprehensive evaluation are as follows:

$$Z = A \cdot V^T = [0.2080 \quad 0.0561 \quad 0.0149 \quad 0.0014 \quad 0] \cdot [9 \quad 7 \quad 5 \quad 3 \quad 1]^T = 2.3392. \quad (46)$$

The calculated results show that the risk level of the antifloating anchor system is lower and safer, which is consistent with the actual situation. Follow-up work should adopt targeted measures to different risk factors, so as to achieve targeted, focused.

## 5. Conclusion

Antifloating anchor system is a complex system composed of natural environment and human environment. Its safety evaluation is a multilevel and multiattribute problem with qualitative and quantitative indexes. There are many risk factors involved. These factors have the characteristics of complexity, grey, and fuzziness. This paper combines safety system engineering with decision-making theory and puts forward a safety evaluation method of the antifloating anchor system based on grey-fuzzy theory.

- (1) Based on the four main risk factors faced by the antifloating anchor system, a three-level evaluation index system is established according to the idea of the AHP method. The comprehensive weighting method, which combines the Delphi method, AHP method, and entropy method, is used to determine

the weight of the index, and the subjectivity of the previous methods is corrected.

- (2) On the basis of the above weight research, a grey-fuzzy evaluation method for the safety of the antifloating anchor system is established, which solves the problem of insufficient and uncertain information acquisition in this kind of complex system. The reliability of the model is verified by the project example.
- (3) In the follow-up research and application, we should further increase the number of research experts, expand the evaluation index system scientifically and reasonably, and combine it with computer technology to establish an expert system to increase its applicability.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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