Safety Evaluation of Hydraulic Steel Gate Based on TOPSIS Model

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Abstract: The paper aims to evaluate the safety of spillway’s steel gates in Xiaoling Reservoir. The weight of each evaluation index was obtained by analytic hierarchy process. Based on the detected data, TOPSIS model was used to evaluate the safety of main components for each gate. And then the comprehensive safety evaluation for spillway’s gates was carried out on this basis. The results were as follows. The coating of supporting arm was thin for gate 1. The coating of main beam and supporting arm was thin for gate 2. The coating of supporting arm was thin and the corrosion was serious for gate 3. The order of the three gates safety was gate 2 > gate 1 > gate 3. The results can reveal the safety situation of the gates and provide a reference for engineering maintenance.

1. Introduction

Hydraulic steel gate is an indispensable part of hydraulic complex, which has a great influence on the safe operation of hydraulic structures. Within the service period of hydraulic structures, the steel gates may have some potential safety hazards such as corrosion due to the influence of environmental factors, for instance, wetting, sunshine and wind waves. If they are not properly handled, the components may fail and cause engineering accidents further. Therefore, it is necessary to carry out safety inspection and safety evaluation at regular intervals on hydraulic steel gates for the safety of hydraulic complex.

At present, the methods for safety evaluation of gates mainly include comprehensive evaluation and reliability method [1]. Li J.B [2], Jia W.B [3] and Zhang Y.C [4] used fuzzy comprehensive evaluation method to evaluate the safety of gates; Jiang R [5] evaluated the safety of hydraulic steel gates by the ideal point method; Yang Z.Z [1] introduced the concept of safety degree and established a method to evaluate the safety of gate. The purpose of the above methods is to determine the safety level for the gates, however the study on the weaknesses of the main components for the gate is rarely made. Thus, this paper will apply analytic hierarchy process (AHP) to get the weight of each evaluation index, afterwards, the TOPSIS model will be used to evaluate the safety of the gate. Firstly, the principle of evaluation model is introduced. Secondly, according to the detected data, the main components of each gate are evaluated and the weakness of each component is analyzed. Finally, the comprehensive safety evaluation for gates is conducted.
2. Materials and Method

2.1. AHP weight
Analytic Hierarchy Process (AHP) is a kind of qualitative and quantitative multi-criteria decision analysis method which was put forward by American operations researcher Professor T.L. Saaty in early 1970s. We can use the following steps to calculate the weight.

I Establishing the judgment matrix
In this paper, based on Saaty scale combined with expert estimation, \( n \times n \) judgment matrix \( K = (k_{ij})_{n \times n} \) can be obtained. \( k_{ij} \) in the judgment matrix indicates the importance of factor \( i \) compared with factor \( j \). The AHP judgment matrix has the following properties in equation (1) where, \( i, j = 1, 2, 3, \ldots, n \).

\[
10, 1, k_{ij} \geq k_{ji} \quad (1)
\]

II Calculating the weight
According to the judgment matrix, the feature vector corresponding to the maximum feature root could be obtained by equation (2). Then the weight of each evaluation index can be calculated by normalizing the feature vector.

\[
PW = \lambda_{\text{max}} W \quad (2)
\]

III Consistency checking
In order to check whether the weight distribution is reasonable, consistency test should be carried out by equation (3).

\[
CR = CI / RI \quad CI = (\lambda_{\text{max}} - n) / (n - 1)
\]

where \( CR \) is the consistency index; When \( CR < 0.1 \), the inconsistency of the judgment matrix is considered within the allowable range, otherwise, the matrix needs to be redefined to meet the consistency requirements; \( CI \) is the random consistency ratio of judgment matrix; \( RI \) is the average consistency index, and which values of the low-order matrix can be referred to Table 1; \( n \) is the order of judgment matrix.

| Order number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RI value    | 0.00| 0.00| 0.58| 0.90| 1.12| 1.24| 1.32| 1.41| 1.45|

2.2. TOPSIS model
TOPSIS model is used to evaluate the safety of gates in this study. The calculation steps are as follows:

I Constructing a normalized decision matrix
The TOPSIS model begins with creating a decision matrix and normalize it \(^{[6]}\). Since TOPSIS method uses distance scale to measure the sample gap, it is necessary to carry out homogenization treatment on the index. Equation (4) is used to convert the cost-type (the smaller the better) index to the revenue-type (the bigger the better) index where \( M \) is the maximum value of index \( X \).

\[
x' = \frac{1}{M} x \quad (x > 0) \quad \text{or} \quad x' = M - x
\]

The decision matrix can be creating as \( A = (a_{ij})_{m \times n} \), where \( a_{ij} \) is the value of the \( j^{th} \) index in the \( i^{th} \) scheme; \( m \) respects the number of schemes and \( n \) respects the number of indexes.

Afterwards, the decision matrix needs to be normalized by equation (5).

\[
z_{ij} = \frac{a_{ij}}{\sqrt{\sum_{j=1}^{n} a_{ij}^2}} \quad (5)
\]

II Calculating the idea solution
The positive idea solution (PIS) and the negative idea solution (NIS) can be calculated using the equation (6) and (7).
\[ Z^+ = \left( \max \{z_{m1}, z_{m2}, \ldots, z_{mn} \}, \max \{z_{1m}, z_{2m}, \ldots, z_{1n} \}, \ldots, \max \{z_{nm}, z_{2m}, \ldots, z_{nm} \} \right) \]  
\[ Z^- = \left( \min \{z_{m1}, z_{m2}, \ldots, z_{mn} \}, \min \{z_{1m}, z_{2m}, \ldots, z_{1n} \}, \ldots, \min \{z_{nm}, z_{2m}, \ldots, z_{nm} \} \right) \]  

III Computing the idea solution distance

The distance of each index compared to the PIS and the NIS can be computed by equation (8).

\[ D^+ = \sqrt{\sum_{j=1}^{n} w_j (Z_{j}^+ - z_j)^2} \]  
\[ D^- = \sqrt{\sum_{j=1}^{n} w_j (Z_{j}^- - z_j)^2} \]  

where \( w_j \) is the weight of the \( j^{th} \) index.

IV Calculating the closeness degree of each index to the PIS

\[ C_i = \frac{D^+}{D^+ + D^-} \]  

where \( C_i \) respects the degree of closeness and \( 0 \leq C_i \leq 1 \). The closer \( C_i \) is to 1, the better the index is.

V The evaluation results are obtained according to the value of \( C_i \).

2.3. Engineering Application

2.3.1. Engineering situation

Xiaoling Reservoir, located in Xiaoling Village, Fengchuan Town, Tonglu County, Zhejiang Province, is a medium-sized reservoir which is mainly used for irrigation, combined with flood control and power generation. The project include barrage, spillway, new and old water conveyance tunnels, flood discharge channel, power plant and booster station. The spillway is located in the right side of the dam and consists of sluice chamber, discharge chute and deflecting flow. In addition, the spillway has five emerged radial steel gates with 8.0m wide and 5.0m high, which are the research objects of this paper. For clear description, the five gates are numbered 1, 2, 3, 4 and 5 from the left bank to the right bank.

2.3.2. Detecting data

According to “Technical code for safety inspection of hydraulic steel gate and hoist machinery”, and considering the symmetry of the gate opening, gate 1, gate 2 and gate 3 are selected for detected. Testing contents include gate corrosion, coating thickness, thickness of main metal component, material strength, etc. The detecting data is listed in table 2. Regarding the corrosion status of the gate, a weld inspection ruler was used to measure the corrosion depth of each component, and the maximum corrosion depth was listed in the table 2. The coating thickness, thickness of main metal component and material strength were respectively tested by digital coating thickness gauge, ultrasonic thickness gauge and Leech hardness tester, and the mean values of detecting data were listed in Table 2.

| Gate number | Component     | Maximum corrosion depth (mm) | Coating thickness (μm) | Thickness of metal component (mm) | Materials strength (MPa) |
|-------------|---------------|-----------------------------|------------------------|----------------------------------|--------------------------|
| Gate 1      | Faceplate     | 0.20                        | 481                    | 9.66                             | 455                      |
|             | Main beam     | 0.05                        | 437                    | 10.30                            | 398                      |
|             | Longitudinal beam | 0                | 386                    | 9.76                             | 429                      |
|             | Supporting arm | 0.15                       | 269                    | 10.05                            | 470                      |
| Gate 2      | Face plate    | 0.10                        | 415                    | 9.68                             | 472                      |
|             | Face plate    | 0.15                        | 312                    | 10.25                            | 393                      |
|             | Main beam     | 0                          | 321                    | 9.72                             | 401                      |
|             | Longitudinal beam | 0.15              | 284                    | 9.99                             | 469                      |
| Gate 3      | Faceplate     | 1.45                        | 466                    | 9.70                             | 471                      |
|             | Main beam     | 0.50                        | 442                    | 9.44                             | 393                      |
|             | Longitudinal beam | 0                | 339                    | 9.28                             | 396                      |
|             | Supporting arm | 0.45                       | 271                    | 10.86                            | 448                      |
2.3.3. Safety evaluation

I Safety evaluation of gates’ main components

This section aims to evaluate the safety of the main components of each gate. Takes gate 1 as an example to explain the evaluation process.

(i) Analytic hierarchy process for weight

By means of expert estimation, an n*n judgment matrix is obtained as shown in Table 3.

| Evaluating indicator | Maximum corrosion depth | Coating thickness | Thickness of metal component | Materials strength |
|----------------------|-------------------------|------------------|-----------------------------|-------------------|
| Max corrosion depth  | 1                       | 3                | 1                           | 1/2               |
| Coating thickness    | 1/3                     | 1                | 1/3                         | 1/5               |
| Thickness of metal component | 1                 | 3                | 1                           | 1/3               |
| Materials strength   | 2                       | 5                | 3                           | 1                 |

According to the equation (2) and equation (3), the consistency index \( CR \) of the matrix is 0.013 and the weight of each index is 0.2285, 0.0803, 0.2081 and 0.4831.

(ii) Evaluation by TOPSIS model

Among the four indexes, the corrosion depth is a cost-type index, which should be converted to revenue-type by equation (4) where \( M = 4 \) mm. The decision matrix is constructed by the data after homogenization. Then the normalized matrix \( Z \) is calculated by Equation (5). For each index, the idea solution distance and the closeness degree \( C_i \) are calculated by equation (6)-(9).

The same process are used to evaluate the safety of gate 2 and 3. The results will show in Table 4.

(iii) The radar chart

In order to analysis the weakness of the components easier, for each gate, the radar chart is drawn as Figure 1 according to table 4.

II Comprehensive safety evaluation for gates

Taking the closeness degree of the main components of the gates in table 4 as the input data, the weight of each component determined by analytic hierarchy process are 0.5681, 0.2410, 0.0576 and 0.1333. Then the comprehensive safety conditions of three gates is evaluated by TOPSIS model. The results are listed in the table 5.

3. Results and discussion

| Gate number | Component | Max depth of corrosion | Coating thickness | Thickness of metal component | Materials strength | PIS D* | NIS D | \( C_i \) | Rank |
|-------------|-----------|------------------------|-------------------|-------------------------------|-------------------|--------|-------|----------|------|
| Gate 1      | C1        | 0.4871                 | 0.5730            | 0.4793                        | 0.4766            | 0.0766 | 0.095 | 0.553    | 3    |
|             | C2        | 0.5063                 | 0.5766            | 0.5359                        | 0.4881            | 0.0575 | 0.107 | 0.651    | 1    |
|             | C3        | 0.5127                 | 0.4932            | 0.4843                        | 0.5405            | 0.0573 | 0.106 | 0.649    | 2    |
|             | C4        | 0.4935                 | 0.3097            | 0.4986                        | 0.4923            | 0.1072 | 0.067 | 0.383    | 4    |
| Gate 2      | C1        | 0.4999                 | 0.6164            | 0.4883                        | 0.5421            | 0.0488 | 0.124 | 0.718    | 1    |
|             | C2        | 0.4935                 | 0.4634            | 0.5170                        | 0.4514            | 0.0926 | 0.076 | 0.451    | 4-   |
|             | C3        | 0.5128                 | 0.4768            | 0.4903                        | 0.4606            | 0.0853 | 0.084 | 0.495    | 3    |
|             | C4        | 0.4935                 | 0.4218            | 0.5039                        | 0.5387            | 0.0731 | 0.092 | 0.556    | 2    |
| Gate 3      | C1        | 0.3706                 | 0.6012            | 0.4929                        | 0.5498            | 0.1043 | 0.108 | 0.508    | 4    |
|             | C2        | 0.5086                 | 0.5702            | 0.4797                        | 0.4588            | 0.0804 | 0.100 | 0.552    | 1    |
|             | C3        | 0.5813                 | 0.4373            | 0.4716                        | 0.4623            | 0.0873 | 0.107 | 0.551    | 2    |
|             | C4        | 0.5159                 | 0.3496            | 0.5519                        | 0.5230            | 0.0839 | 0.094 | 0.527    | 3    |

Note: In the table, C1 represents faceplate, C2 is main beam, C3 is longitudinal beam, C4 is supporting arm.
Table 5 Results of comprehensive safety evaluation for gates

| Gate number | Faceplate | Main beam | Longitudinal beam | Supporting arm | C_i | Rank |
|-------------|-----------|-----------|-------------------|---------------|-----|------|
| Gate 1      | 0.5273    | 0.6332    | 0.6519            | 0.4073        | 0.4415 | 2    |
| Gate 2      | 0.6826    | 0.4580    | 0.4972            | 0.5779        | 0.6520 | 1    |
| Gate 3      | 0.4650    | 0.5456    | 0.5694            | 0.5417        | 0.2826 | 3    |

Figure 1. Radar chart of the three gates

According to the evaluation results shown in Table 4 and the radar chart shown in Figure 1, we can see that:

The values of metal components thickness and material strength have little difference between the three gates. The values of metal components thickness are both much greater than 6. The gate is made of Q235 steel, and all the detected values of material strength are within the strength range. However, the values of corrosion depth and coating thickness have greater difference between components of gates.

For gate 1, the order of the four main components safety is longitudinal beam > main beam > faceplate > supporting arm. The supporting arm and longitudinal beam have thinner coating, especially the thickness value of the supporting arm is only 260μm. This fail to meet the requirements in ‘Specifications for anticorrosion of hydraulic steel structure’. Therefore, the management department should pay more attention to the safety hazards such as corrosion caused by thin coating thickness in the later period.

For gate 2, the safety degree of the four main components is faceplate > supporting arm > longitudinal beam > main beam. The main beam and supporting arm have thinner coating and the coating thickness is respectively 312μm and 284μm. According to the anticorrosion specification, the coating thickness of supporting arm cannot meet the requirements. Due to the abundant rainfall in the project site, the components are in a humid environment after rain and it is necessary to pay attention to the further damage of the coating caused by dry-wet alternation.

For gate 3, the safety degree of the four main components is in the order of longitudinal beam > main beam > supporting arm > faceplate. It can be seen from the radar chart that the supporting arm has thinner coating and the value listed in table 2 is 271μm. It cannot meet the requirements of anticorrosion specification. The faceplate ranks the last mainly because of the serious corrosion. The detecting data
show that the maximum corrosion depth is 1.45mm. In addition to the large corrosion depth, there are more corrosion parts and larger corrosion area on the faceplate. So special attention should be paid to the corrosion problems for gate 3 to avoid the components weakening caused by corrosion.

The safety ranking of the three gates listed in table 5 is gate 2 > gate 1 > gate 3, which is consistent with the field investigation. Since gate 3 is the middle gate of the spillway, which will be first opened in the flood discharge. Compared to other gates, gate 3 opens and closes more and has a longer working time. Therefore, the water leakage and faceplate corrosion of the gate 3 are relatively serious, and it ought to be maintained regularly.

4. Conclusions
In this study, the analytic hierarchy process is used to determine the weight and the TOPSIS model is used to evaluate the gates’ safety. The TOPSIS model can give the relative safety degree of the evaluation objects. Also, the weakness of the evaluation objects can be visually seen by the aid of radar chart. The evaluate results can provide the direct guidance for engineering maintenance. However, TOPSIS model cannot determine the safety level of the gate, which is its defect.

All the data used in this research is obtained from the field test. However, considering there are many factors that affect the safety of the gate, and many factors are not easy to quantify, or the quantitative results are subjective. Therefore, only four indicators with objective values are used in this evaluation. For the further research how to completely consider the factors affecting gate safety and how to carry out reasonable quantification are still the directions.

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