Application of fuzzy comprehensive evaluation of improved AHP in ship safety evaluation in plateau reservoir area

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Abstract: There are many factors that affect the safety of transport ships in the plateau reservoir area, which makes it difficult to allocate weights reasonably, and a large amount of single factor information is submerged. A fuzzy comprehensive evaluation model using improved AHP (AHP) is proposed, the advantages of the model are explained, and the method of constructing the model is introduced. The practicality of the model is verified through examples, and the results show that the model can scientifically and reasonably assess the safety risks of ships, and provide a reference for ship management companies and maritime safety bureaus to improve management methods.

1. Introduction
The construction of the Xunhua-Longwu Gorge Expressway crosses the Yellow River reservoir area on the plateau. The two banks of the reservoir area have steep cliffs, complex topography, and dangerous terrain. There is no ready-made road transportation construction machinery, materials and personnel in the reservoir area. The reservoir area is located in a national-level scenic spot, which means that environmental protection requirements are extremely high. Taking into account the needs of environmental protection and cost, the project construction party makes full use of the water transport conditions in the reservoir area and adopts ship transportation to avoid damage to the ecological environment of the reservoir area by the construction of access roads. However, the water environment of the plateau reservoir area is complex and the security risk is relatively high. Therefore, it is necessary to adopt appropriate safety assessment methods to evaluate the safety of transport ships in the reservoir area in real time in order to avoid risks.

At present, the safety assessment of transport ships mainly includes gray system method [1], probability theory method [2], neural network method [3-4], AHP [5], fuzzy comprehensive evaluation method [6], and analytic hierarchy-based fuzzy comprehensive evaluation method [7], etc., in which the last one combines the advantages of the previous two. However, when using the AHP to determine the weight of each factor, the subjectivity of the expert score greatly affects the consistency of the judgment matrix and the scientific nature of the weight vector. In order to overcome the above shortcomings, we optimize the AHP, and develop a fuzzy comprehensive evaluation method based on the improved AHP [8] to make the determined weight vector more objective and scientific.

2. Construct an improved fuzzy comprehensive evaluation model of AHP

2.1 Building a risk assessment index system
Combining the practice of transport ships in the plateau reservoir area, and referring to the theory of "man-machine-environment-management", the safety risk assessment index system for transport ships in the plateau reservoir area is constructed as shown in Table 1.
Table 1 Safety risk assessment index system for transport ships in the plateau reservoir area

| Overall index | First-level index (U_i) | Weight (w_i) | Second-level index (U_ij) | Weight (w_ij) | Third-level index (U_ijk) | Weight (w_ijk) |
|---------------|------------------------|-------------|--------------------------|--------------|--------------------------|---------------|
| Natural environment(U_i) | 0.40 | Weather(U_11) | 0.40 | | | |
| Safety risk assessment index system for transport ships in the plateau reservoir area | 0.15 | Channel patency(U_21) | 0.60 | | | |
| Navigation order(U_2) | | Ship order(U_22) | 0.40 | | | |
| Ship operating status(U_3) | 0.15 | Ship proximity(U_31) | 0.33 | | | |
| Ship loading(U_33) | | Personnel management(U_41) | 0.80 | | | |
| Management factor(U_4) | 0.30 | Ship management(U_42) | 0.20 | | | |

2.2 Determining factor set and evaluation set
According to Table 1, the factor set is determined to be composed of 4 first-level indicators, 10 second-level indicators and 24 third-level indicators. According to international conventions and considering the degree of impact of risk factors on ship safety, the evaluation set adopts five-level evaluation method, Z=[Safe(Z_1), Considerably safety (Z_2), Critical (Z_3), Pretty danger (Z_4), Danger (Z_5)].

2.3 Determining weights of indicators at each level
There are many methods to establish weights, such as fuzzy statistics, Delphi method, preference comparison method, AHP and so on. Among them, AHP is the most commonly used one. AHP is a decision-making method combining quantitative and qualitative analysis. In the process of analysis, complex problems can be decomposed into various factors that make up the problem. Then, the importance of each factor relative to the upper factors can be determined by two-to-two comparison method and the weight of each factor can be finally obtained. The steps for determining factor weights by AHP are as follows:

2.3.1 Establishing a comparative judgment matrix
Use ranking calculation and scale measurement to construct judgment matrix and judgment matrix.

\[
A = \begin{bmatrix}
    a_{ij} \\
    x_1 & x_2 & \Lambda & x_n \\
    x_1 & a_{11} & a_{12} & \Lambda & a_{1n} \\
    x_2 & a_{21} & a_{22} & \Lambda & a_{2n} \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    x_n & a_{n1} & a_{n2} & \Lambda & a_{nn}
\end{bmatrix}_{n \times n}
\]

(1)

\[
a_{ij} = \begin{bmatrix}
    a_{1j} \\
    x_1 & x_2 & \Lambda & x_n \\
    x_1 & a_{1j} \\
    x_2 & a_{2j} \\
    \vdots & \vdots & \ddots & \vdots \\
    x_n & a_{nj}
\end{bmatrix}_{n \times n}
\]

(2)
Where, $a_{ij}$ denotes that factor $i$ is more important than factor $j$, and $a_{ij}=1/a_{ji}$, $a_{ii}=1$, $(i, j=1,2,3...n)$. The meanings of scale measurements are shown in Table 2 below:

| Interpretation scale | Meaning                           |
|----------------------|----------------------------------|
| 1                    | Factor $i$ is as important as Factor $j$ |
| 3                    | Comparing factor $i$ and factor $j$, one is slightly more important |
| 5                    | Comparing factor $i$ and factor $j$, one is obviously more important |
| 7                    | Comparing factor $i$ and factor $j$, one is significantly more important |
| 9                    | Comparing factor $i$ and factor $j$, one is definitely more important |
| 2.4.6.8              | Between adjacent judgment scales |
| 1,1/2,...,1/9         | One is no more important than the other expressed in the reciprocal above |

2.3.2 Hierarchical single ranking and consistency test
Hierarchical single ranking is usually applied by the methods of "sum, product" and "square root". The calculation steps of square root method are concise as follows:

(1) Calculate the product $M_i$ of each line element of the judgment matrix

$$M_i = \prod_{j=1}^{n} a_{ij} (i, j = 1,2,3...n)$$  \hspace{1cm} (3)

(2) Calculate $M_i$’s n-power root $\bar{w}_i$

$$\bar{w}_i = \sqrt[n]{M_i}$$  \hspace{1cm} (4)

Vector $\bar{w}$ is obtained.

$$\bar{w} = \left[ \bar{w}_1 \quad \bar{w}_2 \quad \bar{w}_3 \quad ... \quad \bar{w}_n \right]^T$$  \hspace{1cm} (5)

(3) Normalize the vector $\bar{w}$, i.e.

$$\bar{w}_i = \frac{\bar{w}_i}{\sum_{j=1}^{n} \bar{w}_j}$$  \hspace{1cm} (6)

The following vector is obtained, which is the eigenvector.

$$w = \left[ w_1 \quad w_2 \quad ... \quad w_n \right]^T$$  \hspace{1cm} (7)

Generally, judgment matrices are not consistent and consistency checks are required when using them.

(4) Finding the maximum eigenvalue $\lambda_{\text{max}}$ of the judgment matrix

$$\lambda_{\text{max}} = \frac{1}{n} \sum_{i=1}^{n} (AW)_i$$  \hspace{1cm} (8)

Where, A is the judgement matrix, $\lambda_{\text{max}} \geq n$.

(5) Finding the consistency index $CI$ of the judgement matrix

$$CI = \frac{\lambda_{\text{max}} - n}{n-1}$$  \hspace{1cm} (9)
When $CI = 0$, the judgment matrix $A$ is a consistency matrix. The larger the $CI$ is, the more inconsistent the judgment matrix $A$ is. Therefore, $CI$ represents the average of the remaining characteristic roots.

**6. Consistency test of judgment matrix**

Comparing $CI$ with average RI (randomness index), i.e. $CR = CI/RI$, the judgment matrix has consistency index only when $CR$ is less than 0.1. Otherwise, it needs to be adjusted until the consistency requirement is met. In order to evaluate the results effectively, only the judgment matrix meets the consistency index.

| Order | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| RI    | 0.58| 0.89| 1.12| 1.26| 1.36| 1.41| 1.46| 1.49|

**2.3.3 Improved AHP**

Although scale measurements can turn stereotyping into quantitative analysis, to use vague terms such as "slightly important, obviously important, significantly important, extremely important", the rater can only assign points according to his own understanding and experience, which is more subjective. What’s more, there are differences in each person's understanding of these terms, affecting the consistency and weight of the judgment matrix and accuracy of vectors. The improved AHP changes $a_{ij}$ in the judgment matrix from the ratio of importance of two factors to the ratio of weight of two factors. The judgment matrix established by the improved AHP is:

$$A' = \begin{bmatrix} 1 & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & 1 & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & 1 \end{bmatrix}$$

(10)

Then, the eigenvalues of judgment matrix $A'$ are obtained by formula (3) to (9) in turn and the consistency of judgment matrix is checked. Practice has proved that the improved AHP method builds a better consistency of judgment matrix, and the weight vector obtained is more adaptive and accurate.

**2.3.4 Example**

According to the structural characteristics of risk assessment index system for transport ships in plateau reservoir area, the importance of the first four indexes (natural conditions, navigation order, navigation status and management factors) is compared by expert investigation method, and the index weights are obtained by AHP. The method is as follows:

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

(11)

$W = [W_1 \ W_2 \ W_3 \ W_4]^T = [0.408 \ 0.152 \ 0.149 \ 0.291]^T$ is obtained in turn from formula (3) to (9). $\lambda_{max} = 4.061$, $CI = 0.020$, $CR = 0.022 < 0.1$, which indicates that the judgment matrix passes the consistency test and meets the consistency requirements. Establish judgment matrix $A'$ with the improved AHP,
According to formula (3) to (9), $\lambda'_\text{max} = 4.056$, $\text{CI}' = 0.018$, $\text{Cr}' = 0.020 < \text{CR} = 0.022 < 0.1$, which proves that the judgment matrix established by the improved AHP has better consistency and the subsequent weight vector of each index is more accurate. According to the above method, the index weight vector of other layers can be obtained in turn, and the index weight of each level is shown in Table 1 above.

### 2.4 Membership subset of evaluation index

The lowest level evaluation index membership subset is obtained using expert survey method. The meteorological and traffic data and other relevant data affecting the safety of transport vessels in plateau reservoir area of one day were collected, and questionnaires were distributed to professors of maritime colleges, officials of maritime administration, experts of shipping enterprises, ship captains and chief engineers in the reservoir area. After sorting out, a subset table of the lowest level index membership of transport vessels in plateau reservoir area is obtained as shown in Table 4.

**Table 4 Membership subsets of the lowest level index of transport ships in plateau reservoir area**

| Second-level index ($U_i$) | Third-level index ($U_{im}$) | Data collection | Navigation safety membership ($R_{i,m}$) |
|---------------------------|-------------------------------|-----------------|----------------------------------------|
|                           |                               | Safe            | Considerably safe | Critical | Pretty danger | Danger |
| **Weather**               |                               |                 |                      |          |              |        |
| Wind                      | Under level 3                 | 0.42            | 0.45                 | 0.13     | 0            | 0      |
| Rain                      | Above 100mm                   | 0               | 0                    | 0.12     | 0.59         | 0.29   |
| State of visibility       | Medium                        | 0               | 0                    | 0.12     | 0.82         | 0.06   |
| Temperature               | Above 30℃                     | 0.13            | 0.11                 | 0.54     | 0.21         | 0.01   |
| **Geological disaster**   |                               |                 |                      |          |              |        |
| Landslide                 | Yes                           | 0.60            | 0.40                 | 0        | 0            | 0      |
| Debris flow               | Yes                           | 0.60            | 0.40                 | 0        | 0            | 0      |
| **Hydrology**             |                               |                 |                      |          |              |        |
| Flow                      | Above 1.0m/s                  | 0               | 0.12                 | 0.82     | 0.06         | 0      |
| Flow regime               | Complicated                   | 0               | 0.06                 | 0.53     | 0.41         | 0      |
| Variation of water level  | Large                         | 0.12            | 0.59                 | 0.29     | 0            | 0      |
| Channel width             | 150-200m                      | 0.30            | 0.40                 | 0.30     | 0            | 0      |
| **Channel patency**       |                               |                 |                      |          |              |        |
| Channel water depth       | Below 3m                      | 0               | 0                    | 0        | 0.40         | 0.60   |
| Obstruction               | Many                          | 0.30            | 0.40                 | 0.20     | 0.10         | 0      |
| **Ship order**            |                               |                 |                      |          |              |        |
| Hazardous Ship Ratio      | Above 20%                     | 0.10            | 0.20                 | 0.30     | 0.20         | 0.20   |
| Passenger ferry ratio     | 20-35%                        | 0.40            | 0.20                 | 0        | 0.30         | 0.10   |
| **Ship proximity**        |                               |                 |                      |          |              |        |
| Navigation Spacing        | Above 20m                     | 0.50            | 0.30                 | 0.20     | 0            | 0      |
| **Speed**                 |                               |                 |                      |          |              |        |
| Safe speed                | Above 50km/h                  | 0               | 0.20                 | 0.30     | 0.30         | 0.20   |
2.5 Fuzzy comprehensive evaluation

From the risk assessment index system of transport ships in the plateau reservoir area, there are many affecting factors. If the single-level fuzzy comprehensive evaluation model is adopted, it will be found that the weight is difficult to be reasonably allocated and a large number of single information factors are buried. Therefore, the multi-level fuzzy comprehensive evaluation model is used to evaluate the risk index of transport ships in the reservoir area. Since the risk assessment index system is a three-tier structure, it is necessary to adopt a three-level evaluation model. First, the evaluation starts from the third level index, and then transfers to the upper level to the final result.

2.5.1 First level fuzzy comprehensive evaluation
The third level index membership matrix is constructed, which is composed of the third level evaluation index membership subset

\[
R_y = \begin{bmatrix}
    r_{y11} & r_{y12} & r_{y13} & \cdots & r_{y1n} \\
    r_{y21} & r_{y22} & r_{y23} & \cdots & r_{y2n} \\
    r_{y31} & r_{y32} & r_{y33} & \cdots & r_{y3n} \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    r_{yn1} & r_{yn2} & r_{yn3} & \cdots & r_{ynn}
\end{bmatrix}
\]

(13)

Where, i is the first level index number, j is the second level index number, m is the third level index number, and n is the evaluation set level number. Using improved AHP to establish the third level index weight

\[
W_y = \begin{bmatrix} W_{y1} & W_{y2} & W_{y3} & \cdots & W_{ym} \end{bmatrix}
\]

(14)

The meaning of i, j and m numbers is the same as the above meaning, and the multiplication rule of matrix is used

\[
B_y = R_y \times W_y
\]

(15)

B_y is the first level fuzzy comprehensive evaluation result and the second level evaluation index membership.

2.5.2 Second level fuzzy comprehensive evaluation
The first level fuzzy comprehensive evaluation result is the foundation of the second level fuzzy comprehensive evaluation. Similarly, the improved AHP is used to determine the weight of the second level index, \[W_y = \begin{bmatrix} W_{y1} & W_{y2} & W_{y3} & \cdots & W_{yn} \end{bmatrix}\], and the matrix multiplication rule is used to obtain the
second level fuzzy comprehensive evaluation result, that is:

\[
B_i = \mathbf{W}_1 \times \begin{bmatrix}
B_{i1} \\
B_{i2} \\
\vdots \\
B_{ij}
\end{bmatrix}
\]

(16)

\[B_i\] is also the first level of index membership.

2.5.3 Third level fuzzy comprehensive evaluation

The third level fuzzy comprehensive evaluation is the final evaluation of the model. Similarly, the results of the second level fuzzy comprehensive evaluation should be used, and the weight of the first level index should be determined

\[
B = \mathbf{w} \times \begin{bmatrix}
B_1 \\
B_2 \\
\vdots \\
B_i
\end{bmatrix}
\]

(17)

Where, \(\mathbf{W} = \begin{bmatrix} \mathbf{W}_1 \end{bmatrix} \) is the weight of the first level index, \(B_i\) is the second level fuzzy comprehensive evaluation result, which is also the membership of the first level index, and \(B\) is the third level fuzzy comprehensive evaluation result, which is also the final evaluation of the model.

3. Application of the model

According to the third-level fuzzy comprehensive evaluation principle, combined with the index weight of each layer obtained by the improved AHP, as shown in Table 1, and combined with the third level index membership subset table, as shown in Table 4, the fuzzy comprehensive evaluation results of each second level index, the first level index fuzzy comprehensive evaluation result and the final evaluation result of the model are obtained, as shown in Table 5 below.

| Final evaluation results | Evaluation results of first-level index | Evaluation results of second-level index |
|-------------------------|----------------------------------------|-----------------------------------------|
| \((Z_1, Z_2, Z_3, Z_4, Z_5)\) | \((Z_1, Z_2, Z_3, Z_4, Z_5)\) | \((Z_1, Z_2, Z_3, Z_4, Z_5)\) |
| Natural environment | [0.19 0.28 0.16 0.32 0.05] | Weather condition |
| [0.25 0.25 0.23 0.22 0.05] | Geological disasters |
| [0.60 0.40 0 0 0] | Hydrological status |
| [0.19 0.28 0.16 0.32 0.05] | Channel patency |
| Natural environment | [0.21 0.22 0.17 0.20 0.20] | Ship order |
| [0.25 0.20 0.15 0.25 0.15] |
According to the principle of maximum membership, it can be seen that the maximum value of 0.32 in the final evaluation result corresponds to the “Danger” item of the evaluation set, indicating that under this condition, the ship in the reservoir area is in danger and needs to take measures such as anchoring or berthing nearby.

4. Conclusion

Taking the safety of transport ships in the plateau reservoir area as the research object, in view of the numerous factors that affect the safety of ships in the reservoir area and the difficulty to quantify and other issues, we first established a clear and reasonable structure of a three-tier indicator system, and then used the improved AHP to determine the weight of indicators at each level. Finally, a third-level fuzzy comprehensive evaluation model is used to obtain the final evaluation results. The improved AHP overcome the shortcomings of greater subjectivity and insufficient objectivity when determining the weights, and improves the scientificity and accuracy of the evaluation results. The third-level fuzzy comprehensive evaluation reasonably solves the problem that the weight is difficult to allocate reasonably and a large amount of single-factor information is buried. The verification results show that the improved fuzzy comprehensive evaluation method of AHP can well solve the complicated problem of ship safety risk assessment. If it is modified appropriately, it can be promoted to other engineering fields.

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