Research on Safety Risk Evaluation Model of Bridge Construction Based on Analytic Hierarchy Process

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Abstract. Bridges are the key to connecting the entire highway, directly affecting the economic and social benefits of the highway. In recent years, China’s highway bridges have faced such phenomena as frequent traffic accidents caused by heavy traffic, high vehicle loads, and fast speeds, and the severity of accidents has become worse. It is imperative to evaluate the safety of bridges. Bridge safety risk assessment is an important means to effectively prevent and reduce traffic accidents. Based on the in-depth analysis of the influencing factors of bridge construction safety, this paper determines the impact of bridge construction safety evaluation index system, on this basis, adopts the analytic hierarchy process (AHP), establishes a bridge construction safety risk evaluation model based on the AHP, proposes the impact the key factors of bridge construction safety, and provides a reference for improving the bridge construction safety in China.

1. Introduction

In recent years, with the rapid growth of China's transportation infrastructure construction, the proportion of bridges and mileage have increased significantly. As a controlling project in highway construction, bridges are difficult to construct, high in technology, and complex in construction techniques. Therefore, the risk of bridge construction is relatively high, and it has gradually become the biggest challenge for construction safety control. Bridge safety accidents occur frequently, causing huge economic losses and negative social impacts. Behind many bridge construction accidents, there are often insufficient risk management techniques and risk management research. Therefore, strengthening the research on risk assessment and management during the construction and operation of bridges, especially large bridges, has important economic and social benefits for improving the safety of bridges. [1]

2. The Bridge construction safety risk assessment index system

The risk of bridge construction is characterized by objectivity, universality, uncertainty, regularity, predictability, and variability. How to comprehensively reflect the safety factors in bridge construction, and how to correctly identify the main risks in bridge construction safety among the numerous factors affecting bridge safety, is the key to the safety risk control in bridge construction. Otherwise, it may lead to the failure of risk management, or even cause serious accidents. Some aspects condition evaluation system of safety evaluation index reflects the physical quantities, can be used with the
particular meaning of values to represent by the aspects of the evaluation system of security condition, a series of safety evaluation index of security evaluation index system, it can be real, real-time, a comprehensive reflection of all aspects of the evaluation system [2]. According to the actual situation of bridge construction and the evaluation index system of safety risk in major construction of large Bridges, the risk factors in bridge construction are determined to be composed of human factors, technical factors, material factors, environmental factors, management factors, etc. Each influencing factor is decomposed into several relatively independent evaluation indexes. The evaluation index system of bridge construction safety is shown in Fig.1.

![Fig. 1. Evaluation index system of bridge construction safety](image)

3. Risk evaluation model based on analytic hierarchy process

3.1. Analytic Hierarchy Process

The analytic hierarchy process is an American operations researcher, University of Pittsburgh professor Satie in the early 1970s, in the US Department of Defence research "power distribution based on the size of the contribution of each industrial sector to the national welfare" subject, applied the network System theory and multi-objective comprehensive evaluation method, a level weight decision analysis method proposed. It decomposes the elements that are always related to decision-making into goals, criteria, plans, and other levels. On this basis, a decision-making method of qualitative and quantitative analysis is carried out, and a complex multi-objective decision-making problem is regarded as a system, and the goal is decomposed into multiple levels. Targets or criteria are then decomposed into multiple levels of multiple indicators (or criteria, constraints), and the level single ranking (weight) and total ranking are calculated through the fuzzy quantification method of qualitative indicators, which can be used as the target (multi-index) and multi-plan optimization decision-making This method uses the existing very small amount of quantitative information or even non-quantitative information to mathematical the entire decision-making thinking method, in order to quantify these complex problems, obtain more intuitive results, and obtain satisfactory decision results.

The steps of the analytic hierarchy process (AHP) to determine the weight are as follows [4]:

1. Construction of judgment matrix. The target is represented by A, u_i, u_j (i, j = 1, 2, ..., n) represents factors. u_ij is the value of the relative importance of u_i to u_j. The A-U judgment matrix P is composed of u_ij.
3 Calculate the importance ranking. According to the judgment matrix, find the eigenvector \( \mathbf{w} \) corresponding to the largest eigenvalue \( \lambda_{\text{Max}} \). The equation is as follows:

\[
\mathbf{P} \mathbf{w} = \lambda_{\text{Max}} \mathbf{w}
\]

The required feature vector \( \mathbf{W} \) is normalized, that is, the importance of each evaluation factor is ranked, that is, the weight distribution.

(3) Consistency check. Whether the weight distribution obtained above is reasonable or not, the consistency test of the judgment matrix is also needed. The test uses the formula:

\[
\text{CR} = \frac{\text{CI}}{\text{RI}}
\]

In the formula, CR is the random consistency ratio of the judgment matrix; CI is the consistency index of the judgment matrix. It is given by:

\[
\text{CI} = \frac{\lambda_{\text{Max}} - n}{n-1}
\]

RI is the average random consistency index of the judgment matrix. RI values of judgment matrices of order 1 ~ 9 are shown in the following Table 1.

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
|RI| 0 | 0 | 0.52 | 0.89 | 1.12 | 1.26 | 1.36 | 1.41 | 1.46 |

When the judgment matrix \( \mathbf{P} \)'s CR<0.1 or \( \lambda_{\text{Max}} = n \), CI=0, \( \mathbf{P} \) is considered to have satisfactory consistency; otherwise, the elements in \( \mathbf{P} \) need to be adjusted to make it have satisfactory consistency.

3.2 Particle Swarm Optimization (PSO)

Due to the strong subjectivity of expert scoring in AHP, the scoring matrix often appears inconsistent or missing filling, so we can use a particle swarm optimization algorithm to modify the expert scoring matrix [5].

Particle Swarm Optimization (PSO) was proposed by Dr. Eberhart and Dr. Kennedy together in 1995. Its basic core is to make use of the information shared by the individuals in the group to move the whole group evolve from disorder to order in the problem-solving space, to obtain the optimal solution of the problem. PSO is initialized as a group of random particles (random solutions). Then we iterate to find the optimal solution. In each iteration, the particle updates itself by tracking two “extremes” (\( \mathbf{p}_{\text{best}} \), \( \mathbf{g}_{\text{best}} \)). After finding these two optimal values, the particle updates its velocity and position by following the formula.

\[
V_{i+1} = V_i + c_1 \times \text{rand}(0-1) \times (\mathbf{p}_{\text{best},i} - \mathbf{x}_i) + c_2 \times \text{rand}(0-1) \times (\mathbf{g}_{\text{best},i} - \mathbf{x}_i)
\]

\[
\mathbf{x}_{i+1} = \mathbf{x}_i + V_{i+1}
\]

Where \( i=1,2,\ldots, \mathbf{M} \), \( \mathbf{M} \) is the total number of particles in the population; \( V_i \) is the velocity of the particle; \( \mathbf{p}_{\text{best}} \) is the individual optimal value; \( \mathbf{g}_{\text{best}} \) is the global optimal value; \( \text{rand}(0-1) \) is a random number between (0, 1); \( \mathbf{x}_i \) is the current position of the particle. \( C_1 \) and \( C_2 \) are learning factors, usually \( C_1 = C_2 = 2 \). In each dimension, the particle has a maximum speed limit, \( V_{\text{max}} \); If the speed of one dimension exceeds the set \( V_{\text{max}} \), then the speed of that dimension is limited to \( V_{\text{max}} \).
3.3. Hierarchy total ranking test

The total sorting of the analytic hierarchy process is to obtain the combined weight of a certain layer of elements in the hierarchy for the overall target and their interaction with the upper elements. It needs to use the result of single sorting of all levels of the layer, and then calculate the combined weight of the elements of the layer. This process is called the total sorting of the hierarchy.

The step of total hierarchy sorting needs to be sorted layer by layer from top to bottom, and finally, the lowest element is calculated, that is, the relative weight of the priority of the decision-making plan [6].

The total rank order is based on the single rank order in the analytic hierarchy process (AHP). The process of level total sorting is roughly the same as the process of level single sorting.

\[
CR = \frac{\sum \text{wi} \text{Cl}_i + \sum \text{wi} \text{Cl}_i + \cdots + \sum \text{wi} \text{Cl}_m}{\sum \text{wi} \text{RI}_i + \sum \text{wi} \text{RI}_i + \cdots + \sum \text{wi} \text{RI}_m}
\]  

(7)

If the total ranking consistency CR<0.1, it means that the total ranking consistency test is passed. Otherwise, it is necessary to reconsider the model or reconstruct those judgment matrices with a larger consistency ratio CR.

3.4. Conclusion of group decision making

By calculating the geometric average of the corresponding position of the matrix modified by each expert, the group decision matrix is obtained, and the final group conclusion is calculated based on this group matrix.

4. Bridge risk assessment model based on analytic hierarchy process

Based on determining the bridge construction safety risk assessment index system, the analytic hierarchy process is adopted to analyze the questionnaire of five experts, and MshFrameMain software is used for model calculation. On this basis, the particle swarm optimization algorithm is used to solve the final group decision data. The group decision results are shown in Table 2~10.

4.1. Weight of Scheme layer at the bottom in group decision making

| Table 2. Bridge evaluation - the human factor U₁ |
|-----------------------------------------------|
| u₁₁ | u₁₂ | weight(wi) |
| u₁₁ | 1   | 0.7752     | 0.4367 |
| u₁₂ | 1.2899 | 1         | 0.5633 |

After correction the weight matrix is used for calculation, \( \lambda_{max}=2; \text{CR}=0; \text{CI}=0 \)

| Table 3. Bridge evaluation - technical reasons U₂ |
|-----------------------------------------------|
| u₂₁ | u₂₂ | u₂₃ | weight(wi) |
| u₂₁ | 1   | 2.357 | 1.8564 | 0.5107 |
| u₂₂ | 0.4243 | 1   | 0.9276 | 0.2288 |
| u₂₃ | 0.5387 | 1.0781 | 1   | 0.2605 |

After correction the weight matrix is used for calculation, \( \lambda_{max}=3.003; \text{CR}=0.0029; \text{CI}=0.0015 \)

| Tables 4. Bridge evaluation - material factors U₃ |
|-----------------------------------------------|
| u₃₁ | u₃₂ | u₃₃ | weight(wi) |
| u₃₁ | 1   | 4.2672 | 4.0544 | 0.6744 |
| u₃₂ | 0.2343 | 1   | 0.7835 | 0.1482 |
| u₃₃ | 0.2466 | 1.2764 | 1   | 0.1774 |

After correction the weight matrix is used for calculation, \( \lambda_{max}=3.0041; \text{CR}=0.004; \text{CI}=0.0021 \)
Table 5. Bridge evaluation - environmental factors $U_4$

|     | $u_{41}$ | $u_{42}$ | $u_{43}$ | weight(wi) |
|-----|---------|---------|---------|------------|
| $u_{41}$ | 1       | 1.4772  | 1.7036  | 0.4402     |
| $u_{42}$ | 0.6769  | 1       | 1.3788  | 0.3163     |
| $u_{43}$ | 0.587   | 0.7253  | 1       | 0.2435     |

After correction the weight matrix is used for calculation, $\lambda_{\text{max}}=3.0035$; CR=0.0034; CI=0.0018

Table 6. Bridge evaluation - management factors $U_5$

|     | $u_{51}$ | $u_{52}$ | weight(wi) |
|-----|---------|---------|------------|
| $u_{51}$ | 1       | 0.9029  | 0.4745     |
| $u_{52}$ | 1.1076  | 1       | 0.5255     |

After correction the weight matrix is used for calculation, $\lambda_{\text{max}}=2$; CR=0; CI=0

Table 7. Weight at the bottom (scheme layer) of group decision making

| The underlying element | Conclusion value (global weight) | At the same weight | The superior |
|------------------------|----------------------------------|--------------------|--------------|
| $u_{11}$               | 0.0947                           | 0.4367             | $U_1$        |
| $u_{12}$               | 0.1221                           | 0.5633             | $U_2$        |
| $u_{21}$               | 0.1452                           | 0.5107             | $U_3$        |
| $u_{22}$               | 0.065                            | 0.2288             | $U_4$        |
| $u_{23}$               | 0.074                            | 0.2605             | $U_5$        |
| $u_{31}$               | 0.1316                           | 0.6744             |              |
| $u_{32}$               | 0.0289                           | 0.1482             |              |
| $u_{33}$               | 0.0346                           | 0.1774             |              |
| $u_{41}$               | 0.0424                           | 0.4402             |              |
| $u_{42}$               | 0.0305                           | 0.3163             |              |
| $u_{43}$               | 0.0234                           | 0.2435             |              |
| $u_{51}$               | 0.0984                           | 0.4745             |              |
| $u_{52}$               | 0.109                            | 0.5255             |              |

4.2. Weight of Criterion layer in the middle in group decision making

Table 8. Bridge evaluation

|     | $U_1$ | $U_2$ | $U_3$ | $U_4$ | $U_5$ | Weight (wi) |
|-----|-------|-------|-------|-------|-------|-------------|
| $U_1$ | 1     | 0.9712| 0.813 | 2.5273| 0.9991| 0.2168      |
| $U_2$ | 1.0297| 1     | 2.0394| 2.8389| 1.295 | 0.2842      |
| $U_3$ | 1.23  | 0.4903| 1     | 1.9383| 1.0086| 0.1952      |
| $U_4$ | 0.3957| 0.3522| 0.5159| 1     | 0.4793| 0.0963      |
| $U_5$ | 1.0009| 0.7722| 0.9915| 2.0864| 1     | 0.2075      |

After correction the weight matrix is used for calculation, $\lambda_{\text{max}}=5.0599$; CR=0.0134; CI=0.015
Table 9. Group decision criteria layer weights

| node | Global weight | At the same weight |
|------|---------------|--------------------|
| U₁   | 0.2168        | 0.2168             |
| U₂   | 0.2842        | 0.2842             |
| U₃   | 0.1952        | 0.1952             |
| U₄   | 0.0963        | 0.0963             |
| U₅   | 0.2075        | 0.2075             |

4.3. Consistency of total sorting of group decision matrix

Table 10. Consistency of total ordering of matrices

| parent level | consistency |
|--------------|-------------|
| Bridge evaluation | 0.0033 |

It can be seen from Table 2~7., that the weight order of decision-making in the scheme layer is \( u_{42} < u_{32} < u_{43} < u_{33} < u_{13} < u_{23} < u_{14} < u_{53} < u_{52} < u_{21} < u_{31} < u_{12} < u_{11} \).

Insufficient engineering survey \( u_{21} \) is the most important factor associated with safety risks in bridge construction from the decisions made at the underlying level in this evaluation system. After this, unqualified building materials \( u_{31} \), inadequate protection \( u_{12} \), whose weight results are close to each other, these two are the main factors of bridge construction safety risk. At the bottom of the list is traffic is not interrupted during the complex construction period \( u_{43} \), and before that are mechanical and power failure \( u_{22} \), complex surrounding buildings, and underground pipelines \( u_{42} \), whose weighted result values are close to each other, is a relatively unimportant factor of bridge construction safety risk.

The weight order of the results obtained from Table 8~9. in the criterion layer is \( U₄ < U₃ < U₂ < U₁ \). Method \( U₂ \) is the most important factor leading to the safety risk of bridge construction under the criterion layer decision, followed by Man \( U₁ \), Management \( U₅ \), Material \( U₃ \), their weight coefficients are very close; At the bottom of the criteria layer is Environments \( U₄ \), the weight coefficient of which has a big difference compared with the factors of the same level.

Table 10 shows that the consistency test of the target layer \( CR=0.0033<0.1 \), which verifies that the decision consistency test is passed.

5. Conclusions
The risk in the bridge construction phase has gradually become the biggest challenge faced by construction safety control. Aiming at the safety risks that the bridge may face during the construction process, this paper divides the risk factors in the bridge construction process into human factors, technical factors, material factors, environmental factors, management factors, etc., and divides them into consideration for each influencing factor. It is decomposed into several relatively independent evaluation indexes, and the bridge safety evaluation system is established. On this basis, the AHP method is used to establish a bridge construction safety risk assessment model, which is modified with particle swarm optimization, and the accuracy of the model is verified. The results show that insufficient engineering survey is the main factor affecting bridge safety. This has important theoretical and practical significance for improving the safety of bridge construction in China.

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