AHP_FCE-based high-rise building construction risk assessment

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Abstract: There are many uncertain factors in the construction of high-rise buildings. By identifying the risk factors existing in the construction of high-rise buildings, this paper establishes a comprehensive evaluation index system for construction risks of high-rise buildings; and the method of combining analytic hierarchy process and fuzzy comprehensive evaluation is adopted, and the respective advantages are used to establish a construction risk evaluation model: The analytic hierarchy process was used to calculate the weights of the indicators at all levels with the help of MALAB software. The fuzzy comprehensive evaluation method was used to construct the risk evaluation matrix, and the Zadeh operator was used to calculate the evaluation indicators at various levels. The risk factors in the construction process of high-rise buildings are evaluated at the second level and passed. An example verifies the practicability of the above method.

1. Introduction

As a pillar industry, the construction industry continues to promote the rapid development of the national economy. However, with the acceleration of China's urbanization process, land resources are becoming more and more tight, and high-rise buildings have emerged at the historic moment. The high-rise building has the characteristics of long construction period, many cross operations, complicated construction procedures, and many units involved, which makes it a great risk factor in the construction process. Therefore, how to reduce the casualty rate has become an important subject of concern in the construction industry, and assessing construction safety risks has also become an important step in risk management in the engineering field.

At present, most of the domestic and foreign researches focus on the research of construction risk management of subway tunnels, highways, railways, underground spaces, etc., and relatively few studies on the construction safety risks of high-rise buildings. Foreign research on engineering risk management started earlier. Einstein.H.H [1] first applied risk management to tunnel engineering, and analyzed the characteristics of tunnel engineering risk management and the concepts to be followed. Nieto-Morote A [2] etc. carried out an in-depth analysis of engineering project risk management in combination with examples of building repair projects. Rahimi Yaser [3] etc. proposed a hybrid method based on failure mode impact analysis (FMEA) to effectively identify, assess and control risks. The domestic research on risk management started relatively late, and it was not applied to engineering construction projects until the middle and late 20th century [4]. Huang Hongwei [5] etc. used expert survey method combined with AHP to identify and evaluate the main risks of key nodes of
Shanghai Metro Line 11; Sun Bo [6] etc. used AHP and FCE to evaluate the fire risk of bridges; Zhao Yanxi [7] etc. applied risk management to deep buried long rock tunnels in TBM construction; Zhou Hongbo [8] etc. conducted the most significant structural safety risks and large facility risks in the construction of super high-rise buildings Quantitative Study.

Fuzzy set theory is a mathematical theory founded by American scientist L.A. Zadeh in 1965 [9]. At present, risk analysis is widely used in banking, insurance and other financial industries, logistics industry, petrochemical industry, engineering and manufacturing industries [10]. Common risk analysis methods are: qualitative analysis methods (including expert scoring method, Delphi method, etc.), semi-quantitative analysis methods (including accident tree method, fault tree method, etc.), quantitative analysis methods (including FCE, Monte Carlo method, neural network method, AHP, etc.), comprehensive methods (including expert confidence index method, fuzzy analytic hierarchy process, fuzzy accident method, etc.) [6, 10-12].

This article combines engineering examples to first identify the safety risk factors that affect high-rise buildings construction and establish a two-level risk assessment index system; then the AHP is used to determine the weight of each indicator factor and the expert scoring method is used to determine the degree of membership of each factor index to the evaluation set; lastly, the FCE is used to analyze the level of security risks for high-rise buildings.

2. Evaluation System of Safety Risk Indicators for High-rise Building Construction

The essay has set up a two-level evaluation index system by in-depth study of the influencing factors of safety risks in the construction of tall buildings and combining the characteristics of high-rise construction. The following figure 1 shows the safety risk index evaluation system for the high-rise building construction stage [13-15].

Combining the above figure, we can see that there are 6 ① grades of evaluation indicators and 21 ② grades of evaluation indicators. Level ① is the main factor layer, including the deep foundation trench construction risk $U_1$, construction risk of main structure $U_2$, tower crane operation risk $U_3$, curtain wall construction risk $U_4$, organizational management risk $U_5$, and environmental risk $U_6$. Level ② is the index layer, which includes slope landslides, local collapse, surface cracks, object blows, and vehicle injuries, which are respectively expressed as $U_{11}, U_{12}, U_{13}, U_{14}, U_{15}$; defects in the quality of the poured concrete, instability of the formwork during pouring, inadequate protection of the "four mouths, five front edges", and deformation and collapse of the construction platform are expressed as $U_{21}, U_{22}, U_{23}, U_{24}$; mechanical injuries, tower crane overturns and broken wire ropes are expressed as $U_{31}, U_{32}, U_{33}$; the overall fall of the basket, the fall of people at high places, and the impact of objects are expressed as $U_{41}, U_{42}, U_{43}$; organizational ability, training, education and regular inspections are expressed as $U_{51}, U_{52}, U_{53}$; severe weather (high temperature, wind, fog, rain and snow), fire, and poisoning are expressed as $U_{61}, U_{62}, U_{63}$. 
3. Construction of AHP-FCE Model

FCE method is a very efficient multifactorial evaluation method for making comprehensive assessment of objects influenced by multiple factors. Its feature is that the results of assessment is not an absolute negative or positive, but represented by a fuzzy set [11].

3.1. Establish evaluation index set

The evaluation index set is a common set consisting of a variety of indicators that affect the evaluation object [16]. According to the two-level evaluation index system constructed above, the level ① evaluation index is represented by the set \( U = \{ U_1, U_2, ..., U_m \} \), and each element \( U_i \) represents corresponding influencing factor; the evaluation index of level ② is represented by the set \( U_i = \{ U_{i1}, U_{i2}, ..., U_{im} \} \), then each element represents a sub-factor under the level ① evaluation factor.

3.2. Establishing Evaluation Sets

The evaluation set is the aggregate of various evaluation sets that may be made on the evaluation object [16]. It is usually represented by an uppercase letter \( V \), that is, \( V = \{ V_1, V_2, ..., V_k \} \), and each element \( V_i (i = 1, 2, ..., k) \) represents a variety of probable overall judgment results. For example, when assessing the safety risk of high-rise construction, we use \( V = \{ \text{very high, high, medium, low, very low} \} \) to express the impact of five risk levels.
3.3. Determine the single factor assessment matrix
Single factor fuzzy assessment is to estimate an influencing factor respectively, and determine the membership degree of the assessment object to the elements of the assessment set[16]. The fuzzy index \( R_i \) of the evaluation set \( V \) by the evaluation index \( U_i \) can be expressed as
\[
R_i = \{ r_{i1}, r_{i2}, ..., r_{im} \} \quad (i = 1, 2, ..., n)
\]
This single factor assessment matrix composed of each fuzzy set as rows is expressed as
\[
R = \begin{bmatrix}
    r_{11} & r_{12} & ... & r_{1p} \\
    r_{21} & r_{22} & ... & r_{2p} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{m1} & r_{m2} & ... & r_{mp}
\end{bmatrix}
\]
(1)

In the formula, \( R \) represents a single factor evaluation matrix; \( r_{ij} \) represents the membership degree of the \( i \)-th element in this evaluation indicator set to the \( j \)-th element in this evaluation set.

3.4. First-level fuzzy comprehensive evaluation
First, the single factor fuzzy evaluation is performed on the second-level assessment index set, and the single-factor fuzzy assessment matrix \( B_i \) is obtained, which is expressed as
\[
B_i = W_i \circ R_i = [w_{i1}, w_{i2}, ..., w_{in}] \circ \begin{bmatrix}
    r_{11} & r_{12} & ... & r_{1p} \\
    r_{21} & r_{22} & ... & r_{2p} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{m1} & r_{m2} & ... & r_{mp}
\end{bmatrix} = [b_{i1}, b_{i2}, ..., b_{ip}]
\]
(2)

In the formula, \( B_i \) represents the first-level fuzzy comprehensive assessment matrix; \( w_i \) represents the weight set; and the weight \( w_{in} \) represents the importance of each factor affecting the parameter value. \( \circ \) is expressed as a fuzzy synthetic operator, that is, the main factor determining type \( M(\vee, \wedge) \), and is also called a Zadeh operator, that is \( b_j = \vee(a_i \wedge r_j) \) \((j = 1, 2, ..., n)\). In general, the weights should meet normality and non-negative conditions:
\[
\sum_{i=1}^{n} w_j = 1, w_j \geq 0, (i = 1, 2, ..., n)
\]
(3)

3.5. Two-level fuzzy comprehensive evaluation
Then the FCE is performed on that first-level evaluation indicator set. From the first-level fuzzy comprehensive assessment matrix \( B_i \), the second-level fuzzy membership matrix \( R \) can be acquired, which can be expressed as
\[
R = \begin{bmatrix}
    B_1 \\
    B_2 \\
    \vdots \\
    B_n
\end{bmatrix} = \begin{bmatrix}
    W_1 \circ R_1 \\
    W_2 \circ R_2 \\
    \vdots \\
    W_n \circ R_n
\end{bmatrix}
\]
(4)

Then by the first-level weight set \( W \), the result of the second-level fuzzy comprehensive assessment is
\[
B = W \circ R = [b_1, b_2, ..., b_n]
\]
(5)

3.6. Determining the weight of each risk factor by analytic hierarchy process
1) Construct the judgment matrix
The values of the elements of the judgment matrix reflect human comprehension of the relative significance of each and every element. Experts are usually asked to compare each factor in pairs, and
use the scale method of 1-9 and its inverse to get the judgment matrix \[ S = (u_{ij})_{n \times n} \]. The criteria for evaluating the relative importance between two factors and their assignments are accounted for in the following table [4].

| Scale \((b_{ij})\text{ assignment}\) | Meaning | 
|---------------------------------|--------|
| 1                               | i and j are equally important |
| 3                               | i factor is slightly more important than j factor |
| 5                               | i factor is significantly more important than j factor |
| 7                               | i factor is more important than j factor |
| 9                               | i factor is extremely important than j factor |
| \(1/3\)                         | i factor is mildly less crucial than j factor |
| \(1/5\)                         | i factor is obviously less significant than j factor |
| \(1/7\)                         | i factor is stronger than j factor |
| \(1/9\)                         | i factor is overly less crucial than j factor |

The middle numerical value of the above two adjacent judgments, such as "2", belongs to the same important and slightly important.

2) Calculate the judgment matrix

The maximum eigenvalues of the matrix \(\lambda_{max}\) of the this matrix and its relative eigenvector \(W\). This eigenvector is the weight vector of every risk factor. By normalizing the vector, the weight coefficient of each indicator is acquired. The calculation steps of the matrix's maximum eigenvalue are as follows [4]:

1) Determine the product of the elements of each row of this judgment matrix.

\[
M_i = \prod_{j=1}^{n} a_{ij}
\]  

(6)

2) Determine the nth square root of \(M_i\)

\[
W_j = \sqrt[n]{M_i}
\]  

(7)

3) Normalize the vector \(\bar{w} = [\bar{w}_1, \bar{w}_2, \ldots, \bar{w}_n]^T\).

\[
W_j = \frac{w_j}{\sum_{i=1}^{n} w_i}
\]  

(8)

Then \(w\) is the required feature vector, \(w = [w_1, w_2, \ldots, w_n]^T\).

Maximum eigenvalues of the matrix \(\lambda_{max} = \sum_{i=1}^{n} \frac{(Aw)_i}{nw_i}\). Where \((Aw)_i\) is the i-th element of vector \((Aw)\).

If this dimension of the judgment matrix \(S\) is too large to calculate, it can be solved by MATLAB [18].

3) Consistency check [17]

For the consistency check of this matrix, we need to calculate the consistency indicator \(CI = \frac{\lambda_{max} - n}{n - 1}\) and then compare with the average random consistency index \(RI\). If \(CR = \frac{CI}{RI} < 0.10\), it is considered that the ranking results of AHP have satisfactory consistency, in other words, the allocation of weight coefficients is rational; if not, the values of the elements of this assessment matrix must be revised and the values of the weight coefficients are redistributed. The following table provides an explanation.
4. Engineering case analysis

A high-rise building in Zhengzhou is mainly composed of a 23-story tower, a 5-story podium, and a 2-story underground garage. The building height is 99.3m and the podium is 31.55m. The total construction area is 95508.79 ㎡, of which the floor construction area is 62451.50 ㎡ and the building base area is 5010.49 ㎡. The foundation pit depth of this project is 8.4m ~ 8.9m. Engineering design level: Level 1; design life: 50 years; high-rise building category: first grade; fire resistance grade: first grade; waterproof grade: underground waterproof grade is second grade, roof waterproof grade is first grade, external wall waterproof grade is one grade; seismic crack resistance: 7 degrees; building structure selection: frame-shear wall structure, part of steel-concrete composite structure; foundation form: pile foundation raft foundation. Subgrade and foundation: According to site conditions and structural characteristics, a concrete pouring pile foundation is used. Exterior wall: glass curtain wall, aluminum plate curtain wall, stone curtain wall, aluminum canopy. Three tower cranes (one QTZ6012, one QTZ6513, and one QTZ5510) were arranged on site. The construction of this project takes a long time, and it has to undergo rainy and winter construction. The total construction period is 1198 calendar days.

The AHP-FCE model introduced above was used to estimate the construction risk of the tall building. The specific calculation steps and results are as follows:

4.1. Determining weights with AHP

Applying the AHP and MATLAB software to determine the weight of risk factors in the construction of high-rise buildings.

The weight of the first-level indicator factor set is W = [0.346 0.346 0.140 0.087 0.045 0.036].

The weights of the second-level indicator factor sets are:
- Risk of deep foundation pit W₁ = [0.439 0.294 0.158 0.065 0.044];
- Risk of main structure W₂ = [0.564 0.263 0.055 0.118];
- Risk of tower crane operation W₃ = [0.075 0.592 0.333];
- Curtain wall construction risk W₄ = [0.625 0.238 0.136];
- Technical management risk W₅ = [0.200 0.117 0.683];
- Environmental risk W₆ = [0.249 0.594 0.157].

4.2. Establish membership matrix

By consulting 10 experts, a fuzzy estimation of this type of risk index factors is performed, that is, we apply expert scoring method to score the severity and probability of occurrence of various risks to form a matrix of risk factors. And this specific secondary index membership matrix is as follows:

The evaluation matrix of risk factors for deep foundation pit construction is:

\[ R₁ = \begin{bmatrix}
0.1 & 0.3 & 0.4 & 0.1 & 0.1 \\
0.1 & 0.3 & 0.3 & 0.2 & 0.1 \\
0.2 & 0.2 & 0.3 & 0.1 & 0.2 \\
0.2 & 0.3 & 0.3 & 0.1 & 0.1 \\
0.2 & 0.2 & 0.2 & 0.1 & 0.3 
\end{bmatrix} \]

The evaluation matrix of the main structure construction risk factors is:
R = \begin{bmatrix}
0.3 & 0.3 & 0.2 & 0.1 & 0.1 \\
0.2 & 0.2 & 0.4 & 0.1 & 0.1 \\
0.1 & 0.3 & 0.3 & 0.2 & 0.1 \\
0.1 & 0.3 & 0.2 & 0.2 & 0.2
\end{bmatrix}

R_5 = \begin{bmatrix}
0.1 & 0.2 & 0.2 & 0.2 & 0.3 \\
0.2 & 0.3 & 0.3 & 0.1 & 0.1 \\
0.1 & 0.2 & 0.2 & 0.4 & 0.1
\end{bmatrix}

R_4 = \begin{bmatrix}
0.1 & 0.2 & 0.5 & 0.1 & 0.1 \\
0.1 & 0.3 & 0.4 & 0.1 & 0.1 \\
0.1 & 0.2 & 0.3 & 0.3 & 0.1
\end{bmatrix}

R_3 = \begin{bmatrix}
0.1 & 0.1 & 0.2 & 0.3 & 0.3 \\
0.0 & 0.1 & 0.2 & 0.3 & 0.4 \\
0.2 & 0.3 & 0.2 & 0.2 & 0.1
\end{bmatrix}

R_2 = \begin{bmatrix}
0.1 & 0.2 & 0.3 & 0.3 & 0.1 \\
0.1 & 0.2 & 0.4 & 0.2 & 0.1 \\
0.1 & 0.2 & 0.2 & 0.3 & 0.2
\end{bmatrix}

4.3. Fuzzy comprehensive assessment

According to the calculation of the weight set wi and membership matrix RI of the above two levels of indicators, the fuzzy calculation is carried out, and we can attain the first level assessment matrix.

B_1 = \begin{bmatrix}
0.158 & 0.300 & 0.400 & 0.200 & 0.158 \\
0.300 & 0.300 & 0.263 & 0.118 & 0.118 \\
0.200 & 0.300 & 0.300 & 0.333 & 0.100 \\
0.100 & 0.238 & 0.500 & 0.136 & 0.100 \\
0.200 & 0.300 & 0.200 & 0.200 & 0.200 \\
0.100 & 0.200 & 0.400 & 0.249 & 0.157
\end{bmatrix}

The above-mentioned first-level assessment matrix is combined into a second-level assessment matrix R. Next, this overall fuzzy assessment of the high-rise building construction risk factors is

B=W \circ R = \begin{bmatrix}
0.158 & 0.300 & 0.400 & 0.200 & 0.158 \\
0.300 & 0.300 & 0.263 & 0.118 & 0.118 \\
0.200 & 0.300 & 0.300 & 0.333 & 0.100 \\
0.100 & 0.238 & 0.500 & 0.136 & 0.100 \\
0.200 & 0.300 & 0.200 & 0.200 & 0.200 \\
0.100 & 0.200 & 0.400 & 0.249 & 0.157
\end{bmatrix}

According to the "Maximum Membership Principle", in the five-level risk impact assessment of "very high, high, medium, low, very low", the construction risk of this high-rise building belongs to the "medium" level.

5. Conclusion

In the article, the AHP and FEC method are applied to identify and analyze the safety risks of high-rise construction. Combined with engineering examples, the following conclusions can be drawn through research:
(1) First, this paper systematically analyzes the possible safety risks in the construction of high-rise buildings, and establishes a risk assessment indicator system for high-rise construction.

(2) Then, combining the advantages of the AHP and FEC method, the article proposes a calculation model for the second-level fuzzy comprehensive assessment of tall building construction risks, and the analytic hierarchy process is applied to determine the indicator factors at all levels. According to the expert scoring method to calculate the membership matrix of risk factors, a two-level fuzzy comprehensive assessment was performed, and the Zadeh fuzzy operator was used to calculate the index evaluation set at all levels to obtain the safety risk level of high-rise construction.

(3) Finally, combining with actual engineering cases and applying the above calculation model, the results show that the proposed theory and method can effectively analyze the prediction of safety risks in the construction of high-rise buildings.

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