Risk assessment research on the application of improved analytic hierarchy process in building foundation pit based on fault tree model

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Abstract: Foundation pit engineering plays an important role in infrastructure construction, but the collapse of support structure of the foundation pit often occurs. This paper takes the structural importance in the fault tree as the basis of the analytic hierarchy judgment matrix, pointing out that the construction process planning is the most important for the foundation pit engineering. The improved analytic hierarchy process (AHP) helps to reduce subjectivity, which is used to conduct the risk assessment of the collapse of the support structure of the foundation pit. In this way, this paper provides reference for the risk evaluation of the foundation pit engineering.

1. Research background
As an indispensable part of the construction process, the foundation pit engineering is high in technical requirements and huge in early-stage investment. Due to its characteristics, accidents related to it can cause serious casualties and property loss. Therefore, it is necessary to conduct risk prediction and prevention from the whole life cycle of exploration, design, and construction. Risk assessment of foundation pit engineering is still in its infancy in China, with the foundation pit risk assessment methods including the improved analytic hierarchy process AHP of grey correlation model [1], the theory of fuzzy set and improved evidence [2], fuzzy set and neural network [3] and so on.

This paper aims to find out the cause of the base pit accident using the fault tree model, and to obtain the total hierarchical ordering by calculating the importance of the basic event and taking it as the judgment factor of AHP to construct the judgment matrix. The method focuses on the combination of the fault tree and AHP to avoid human subjectivity in AHP application.

2. Model design
Firstly, this chapter introduces the concepts of fault tree and AHP. Then, based on the notification of the foundation pit accidents from the Ministry of Housing and Urban-Rural Development, the fault tree index system model is established to explore the basic causes, which are also used as the indicator layer of the AHP model.
2.1 Fault tree analysis method

The fault tree is common to see in the process of the identification and analysis of risk sources. It mainly conducts calculation after various basic events have passed through logic gate, so as to show the probability of occurrence of each basic event. The top of the fault tree is the possible resultant event, which is then analyzed in searching for the cause. The fault tree aims to explore the basic events that may lead to the top event using causal relationship.

There are two definitions of the minimum cut set in the fault tree method, namely, the analyst solving the logical model of each fault tree to generate a fault sequence, and a set of minimum basic events that leads to the top events. Specifically speaking, if any of the basic events in the cut set does not occur, the top event will never occur. The more the minimum cut set in the fault tree, the more likely the top event will occur, and the more dangerous the system will be.

Each basic event influences the top event to different degrees, which is called the structural importance. The structural importance analysis is a means to provide important information related to system security. The formula for calculating the structural importance is [4]:

\[
I_p(i) = \frac{1}{m} \sum_{j=1}^{k} \frac{1}{Z_j}
\]

where \( I_p(i) \) is the approximate discriminant of the importance of the i-th basic event; \( m \) is the number of minimum cut sets in the fault tree; \( Z_j \) is the number of basic events of the j-th minimum cut set containing the i-th basic event.

2.2. AHP

AHP was proposed by Professor Satie from the University of Pittsburgh in the mid-1970s. Composed of the target layer, the criteria layer, and the indicator layer, it is often used to handle complex problems related to decision-making and evaluation. It mainly analyzes the relationship between various factors of the indicator layer, and decomposes a system problem into several layer problems. The factors in the layer are compared with those in the former layer, so as to figure out the degree of influence.

① Establishment of a hierarchical model

First, it is necessary to stratify the problem and describe it based on logic and hierarchy. Then, make arrangements and establish the relationship according to the relationship of the target layer, the criteria layer, and the indicator layer.

(1) Target layer: a problem that may occur in the system or the final goal of the system;
(2) Criteria layer: the inevitable intermediate links for subdividing the content of the target layer;
(3) Indicator layer is subdivided into several factors by the criteria layer, such as specific policies, policies, issues, etc.

② Establishment of the judgment matrix and weight division

The idea of AHP is to decompose complex problems layer by layer, construct the hierarchical structure model by comparing the relationship between the quantifiable basic events, and build a quantitative matrix by comparing the factors of the same layer and the importance of each factor to the criteria layer. The quantitative matrix is usually determined using the 1~9 scale method, and it is called the judgment matrix.

\[
A = \begin{bmatrix}
a_{11} & \cdots & a_{1n} \\
\vdots & \ddots & \vdots \\
a_{n1} & \cdots & a_{nn}
\end{bmatrix}
\]

where \( a_{ij} \) is the comparison result between factors i and j in the same layer, or the importance of factor i compared to that of factor j; \( a_{ji} \) is the importance of factor j compared to that of factor i.

\[
a_{ij} = \frac{1}{a_{ji}}
\]

In order to obtain the influence of the lower factors on the upper ones, it is necessary to first verify the consistency of the judgment matrix. If the judgment matrix satisfies the consistency requirement,
its maximum eigenvalue and eigenvector can be obtained. Then the weight vector of the single hierarchical order, which represents the degree of influence of the lower factors on the upper ones, can be obtained through normalization. If the judgment matrix does not meet the consistency requirements, it needs to be adjusted until it does. After calculating the single hierarchical order, it is necessary to calculate the weight vector of the indicator layer relative to the target layer and the comprehensive weight of the indicator layer relative to the target layer, so as to further calculate the influence of the indicator layer on the target layer. The weight of each factor of AHP relative to the target layer is between 0 and 1. The closer the weight is to 1, the more important the factor is to the system goal, and vice versa.

2.3. Evaluation model construction

2.3.1. Construction of a fault tree model
Based on the analysis of the safety accident notifications on the official website of the Ministry of Housing and Urban-Rural Development, it can be seen that the probability of the collapse accident is the highest among all accidents in the foundation pit. The collapse accidents during construction mainly include the collapse of the earthwork, the instability of the retaining structure, and the collapse of surrounding buildings due to the uneven excavation and stacking of the soil. This paper focuses on the collapse of the support structure of the foundation pit during construction by constructing the fault tree with the of the collapse accidents of the support structure of the foundation pit during construction as the top event. The intermediate events are divided into design problems, construction problems, which are further divided into 13 basic events.

2.3.2. Establishment of AHP model
Take the basic events in the fault tree model as the factors of the indicator layer in AHP, and conduct clustering analysis on them, so as to determine each type of criteria layer. The target layer is also for the safety of the support structure of the foundation pit during construction. For the model of hierarchical analysis of structural importance [5], take the judgment factors in the indicator layer as the basic events in the fault tree, see Table 1.

| Goal layer | Criteria layer | Index layer |
|------------|----------------|-------------|
| Safety of foundation pit accident support structure during construction | Geographical factor | $x_2$ Flaw soil properties |
| | | $x_6$ Surrounding buildings |
| | | $x_7$ Underground pipeline |
Design factor

- $x_3$ Unexplored rock and soil conditions
- $x_4$ Improper model simplification
- $x_5$ Improper design load
- $x_6$ Calculation error

Management factor

- $x_8$ Improper construction process planning
- $x_9$ Not timely support
- $x_{10}$ Insufficient anchoring structure
- $x_{11}$ Failure to consider soil stress changes during construction
- $x_{12}$ Pouring inferior materials
- $x_{13}$ Improper drainage measures

① Structural importance of basic events
There are many basic events in the fault tree, representing the degree of influence of each basic event on the top event. This paper takes the structural importance as the judgment factor of each factor in AHP, and the judgment factor of the criteria layer is the sum of all judgment factors in each indicator layer.

② Construction of the judgment matrix of AHP
The judgment matrix of the indicator layer and the criteria layer can be obtained by comparing the judgment factors calculated based on the structural importance.

③ Total hierarchical ordering
The weight vectors of the indicator layer and the criteria layer are obtained using the judgment matrix. Then, the comprehensive weight of the indicator layer factor relative to the target layer can be determined. In this way, the total hierarchical ordering can be obtained.

3. Model calculation
First, it is necessary to calculate the structural importance of the basic events in the fault tree. The factors of the indicator layer of AHP are related to the basic events in the fault tree, so they can be used as the judgment factor of AHP. In this way, the judgment matrix of each level and the influence level of the indicator layer on the target layer can be obtained.

3.1. Calculation of fault tree model
This paper obtains 10 minimum cut sets for instability accidents related to the support structure of the foundation pit during construction using the fault tree method:

- $E_1 = \{x_1, x_2\}$
- $E_2 = \{x_3\}$
- $E_3 = \{x_4\}$
- $E_4 = \{x_5\}$
- $E_5 = \{x_6, x_7\}$
- $E_6 = \{x_8, x_{10}\}$
- $E_7 = \{x_9, x_{11}\}$
- $E_8 = \{x_9, x_{12}\}$
- $E_9 = \{x_8, x_{13}\}$
- $E_{10} = \{x_8, x_9\}$

The structural importance of each basic event can be obtained by using Formula (1), see Table 2.

| Basic event | Structural importance | Basic event | Structural importance | Basic event | Structural importance | Basic event | Structural importance |
|-------------|-----------------------|-------------|-----------------------|-------------|-----------------------|-------------|-----------------------|
| $l_1$       | 1/20                  | $l_2$       | 1/20                  | $l_9$       | 1/20                  | $l_{10}$    | 1/20                  |
| $l_3$       | 1/10                  | $l_6$       | 1/20                  | $l_9$       | 5/20                  | $l_{11}$    | 1/20                  |
| $l_4$       | 1/10                  | $l_7$       | 1/20                  | $l_{12}$    | 1/20                  | $l_{13}$    | 1/20                  |

Table 2 Structural importance of basic events
3.2. AHP model calculation

Based on the structural importance of the basic events, the judgment factors of the criteria layer are 3/20 7/20 1/2. The judgment matrixes of the criteria layer and the indicator layer are obtained by conducting pairwise comparison between the factors.

|    | Geographical factor | Design factor | Management factor |
|----|---------------------|---------------|-------------------|
| Geographical factor | 1                  | 3/7           | 3/10              |
| Design factor       | 7/3                | 1             | 7/10              |
| Management factor   | 1/10               | 1/10          | 1                 |

AHP calculation shows that the weight vector of the criteria layer $\omega=(0.15,0.35,0.5)^T$, and the judgment matrix passes the consistency test. Similarly, the judgment matrix of the indicator layer can be calculated, which can also pass the consistency test.

1. For the geographical factor $A_1$, the soil mass of the foundation pit is poor in performance, and the weight vector of the surrounding buildings and underground pipelines is $\omega_{21}=(0.333, 0.333, 0.333)^T$.

2. For the design factor $A_2$, the weight vector of unclear geotechnical conditions, improperly simplified model, and improper design load, and the calculation error is $\omega_{22}=(0.1429, 0.2857, 0.2857, 0.2857)^T$.

3. For the management factor $A_3$, the weight vector of improper construction process planning, delayed support, insufficiently embedded support structure, improper drainage measures, and delayed consideration of the soil stress change during construction, and the inferior material is $\omega_{23}=(0.5, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1)^T$.

The above results represent single hierarchical ordering, and the total ordering can be calculated based on AHP, as shown in Table 4.

| Indicator factor | Weight of the criteria and indicator layers | Hierarchical total ordering |
|------------------|-------------------------------------------|-----------------------------|
|                  | $A_1$ | $A_2$ | $A_3$ |                     |
| $X_2$            | 0.3333 |       |       | 0.049995           |
| $X_6$            | 0.3333 |       |       | 0.049995           |
| $X_7$            | 0.3333 |       |       | 0.049995           |
| $X_1$            | 0.1429 |       |       | 0.050015           |
| $X_3$            | 0.2857 |       |       | 0.099995           |
| $X_4$            | 0.2857 |       |       | 0.099995           |
| $X_5$            | 0.2857 |       |       | 0.099995           |
| $X_8$            | 0.5    |       |       | 0.25              |
| $X_9$            | 0.1    |       |       | 0.05              |
| $X_{10}$         | 0.1    |       |       | 0.05              |
| $X_{11}$         | 0.1    |       |       | 0.05              |
| $X_{12}$         | 0.1    |       |       | 0.05              |
Table 4 shows that the improper construction process planning has the greatest impact on the target layer, followed by the improperly simplified model, improper design load, and calculation errors, which are basically consistent with the actual situation. The construction process planning involves all aspects of design and construction, thus posing high requirements for construction management personnel. Therefore, the risk of improper construction process planning is the highest. As for the improper simplified model, improper design load, and the calculation error, they have a relatively high impact on the target layer, which is because the model simplification and the load value are directly related to the safety of the overall structure. Model selection concerns not only the calculation of structural material, but also the anti-seismic performance and crack width, and the stress of the model in finite element analysis. Therefore, the relevant departments must pay attention to the planning and design of the foundation pit in order to reduce the occurrence of accidents during construction. Only in this way can we effectively control the cause of the foundation pit accident and minimize the risk of the foundation pit.

4. Conclusion and recommendation
Fault tree and AHP are widely used in the risk-related areas. This paper combines the two to evaluate the risk of foundation pit accidents, find the basic events using the fault tree, and cluster them as the indicator layer in AHP. The focus is to take the structural importance in the fault tree as the judgment factor in AHP, and determine the influence degree of the factors in the indicator layer on the target layer based on pairwise comparison. In this way, the subjectivity in AHP can be avoided, and the reliability can be enhanced to a certain extent. This paper is hoped to provide reference for the future risk assessment of foundation pit accidents.

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