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Safety Analysis of Work-at-height Protective Devices based on AHP-2 Level Fuzzy Comprehensive Evaluation Method

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Abstract

Among the many engineering accidents, fall from height accidents are the most frequent and have a high fatality rate. When working at height, workers will choose the appropriate protective equipment for protection against emergencies. There are many different types of aerial protective devices on the market, each with its own advantages and disadvantages. In this paper, the safety of a variety of aerial protective devices is the subject of a comprehensive and systematic evaluation by establishing a mathematical model of AHP-2 level fuzzy comprehensive evaluation. The result is a general presentation of the current aerial protection options and a guiding role for the development and optimization of future aerial protection devices.

Keywords

AHP-2 Level Fuzzy Comprehensive Evaluation; Aerial Protective Devices; Assess Safety.

1. Introduction

In building construction, engineering and sporadic operations, fall from height accidents are the most likely to cause casualties and one of the most frequent types of accidents. Therefore, we should avoid the possibility of falling from height from many aspects.

According to DEMATAEL and ISM methods, we can establish a hierarchical structure for the factors influencing fall from height. The final study concludes: The degree of construction safety management system improvement and the degree of safety training and education are the main motives for the occurrence of fall from height accidents. [1]However, even if all subjective influences are eliminated, there are still risk influences such as sudden environmental changes.

In practice, workers often need the protection of multiple safety guards. Traditional protective devices are diverse. Safety belts, self-locking devices are common protective devices. In order to deal with the occurrence of unexpected accidents, we should make innovative improvements and more reasonable matching of traditional protective devices. The most optimal way is to maximize the advantages of each protective device. Therefore, it is particularly important to classify and evaluate the safety of various protective devices.

Hierarchical analysis (AHP) is a model for solving multi-factor problems by comparing the relative importance of two factors [2], and is often applied in areas such as in resource allocation and production decisions [3]. Although the method plays a role in systematic analysis of decision making, it is more subjective. And the fuzzy comprehensive evaluation method integrates the judgment of multiple evaluation subjects, which can weaken the shortcomings of hierarchical analysis method. Therefore, the AHP-fuzzy comprehensive evaluation method combined with both methods can not only systematically consider the influencing factors of the evaluated object, but also reduce the influence of subjective judgment on the evaluation and decision-making process.

Therefore, this paper adopts the AHP-second-level fuzzy comprehensive evaluation method to select several evaluation indicators and conduct a comprehensive safety assessment of various aerial protection devices. According to the results, the advantages and disadvantages of various traditional protective devices are analyzed in different categories. This can provide theoretical guidance for reducing the occurrence of fall from height accidents as well as construction safety management and safety training education, thus providing a model basis for fall protection at height.

2. Protective Device Classification and Evaluation Index Selection

Every year, there is some degree of injury or death during work at heights such as construction or scrubbing. In order to prevent injuries from falls from height, workers usually take protective measures that are appropriate to the environment. Through research on e-commerce platforms and literature search [4], protective devices can be divided into five main categories. In specific scenarios, personnel may take a single protective measure, or may be used in combination. Protective devices are classified as Table 1.

Table 1. Classification of aerial protective devices

Strap type protection	Safety belt, safety helmet, protective gloves, airbag, etc
Hanging point protection	Safety rope (mostly used with self-locking device)
Self-locking protection	Climbing self-locking device, speed difference automatic control device, horizontal sliding safety device, etc.
Full body covering protection	Protective clothing
Fence protection	Edge protection fence, high-altitude protection fence, etc

A wide variety of protective devices have their own advantages and disadvantages and are suitable for different scenarios. To assess the excellent effectiveness of the device protection, relevant evaluation indicators need to be selected. Here, a multi-perspective conversion approach is adopted to optimally select the evaluation indicators from different perspectives. The determination of effective and reasonable evaluation indicators guarantees the reliability of the evaluation system establishment.

Simplicity($\boldsymbol{C_1}$): Overly cumbersome guards take up a lot of the worker's working time. If the work environment is not very demanding for the protective device, the heavy protection seems unnecessary. Therefore, whether the device is easy to wear and saves working time is one of the evaluation criteria.

Lightness($\boldsymbol{C_2}$): During the work process, clothing obstruction and accidental touching of conductors may lead to fall from height accidents. Overly heavy guards can also affect the efficiency and fatigue level of the worker. Therefore, assessing the safety of the device requires consideration of whether the protective device is lightweight.

Comfort($\boldsymbol{C_3}$): The comfort of the protective device should also be included as one of the evaluation criteria. Environmental factors such as temperature, wind, and humidity all affect the progress of workers. Ensuring that personnel are comfortably clothed will improve construction accuracy.

Economic practicability($\boldsymbol{C_4}$): Protective devices should meet the criteria of good value for money for basic commodities. Therefore, it is particularly necessary to include cost effectiveness as an evaluation criterion.

Improvement space($\boldsymbol{C_5}$): The degree of expectation and outlook for each type of protective device from the perspective of the construction worker affects the further performance and improvement of the protective device. The continuous improvement of protective devices is more conducive to improving construction safety.

Protective hazard (C_6): Some protective devices can cause secondary injuries when used improperly. Assessing the risk factor of improper use of protective devices should also be included as one of the criteria.

Protection effectiveness(C_7): The proportion of the protection device that can reduce the injury caused by falling from height reflects whether the protection device is effective.

Protection timeliness (C_8) : When there are unexpected factors, the moment when the protection device plays a protective effect affects the degree of injury of falling personnel. Timeliness plays a fairly important role in the assessment.

Protection firmness (C_9): If the protection device is taken as fixed protection, it is worth considering the impact of sudden environmental changes and other effects on the suspension of the point.

The above-mentioned multiple assessment indexes will be reasonably classified in order to facilitate the construction of a comprehensive assessment system for security analysis. The final result of security assessment is the target layer. The guideline layer can be basically divided into three categories: operational effect, market effect, and protection effect. The nine indicators are located in the indicator layer and are subordinate to the guideline layer. The specific as network diagram as shown in Figure 1.

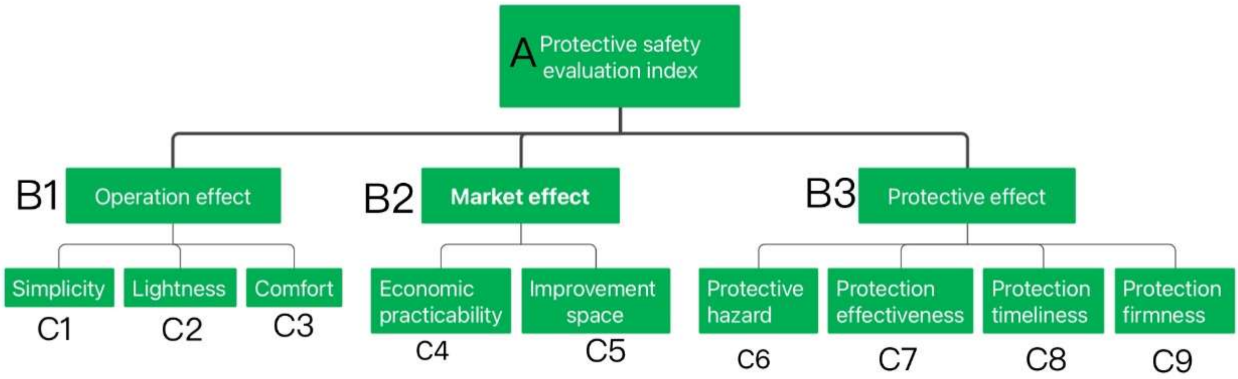

Figure 1. Assessment indicator layer construction

3. AHP-2 Level Fuzzy Comprehensive Evaluation Method System Establishment

We need to determine the evaluation results of the target layer based on the multilevel indicators of the overhead protection devices. In the application of mathematical models, the AHP-two-level fuzzy comprehensive evaluation method is more applicable to the assessment of the safety of protective devices in this paper.

3.1. Establishment of Hierarchical Analysis Method

AHP is a hierarchical analysis method, which combines qualitative and quantitative analysis to systematically and hierarchically classify decision targets, with the characteristics of simple and flexible application and clear results. It is widely used in the comprehensive evaluation of various fields.

Construct the comparison matrix [5]:

Constructing a comparison matrix is mainly done by comparing the effect of factors at the same level on the relevant factors at the previous level. That is, we need to compare two factors of the same level. The comparison is scored using the relative scale standard metric. At the same time, we need to pay attention to avoid the comparison of factors with different nature and avoid the influence of human factors.

In the AHP model, the scoring of factor comparisons is expressed in the form of a matrix. 1 to 9 indicate the relative importance of the indicators, from equally important to extremely important, respectively.

$$a_{ij} > 0, a_{ji} = \frac{1}{a_{ij}}, a_{ii} = 1(i, j = 1, 2, \cdots, \text{n})$$

Where, a_{ij} represents the scale of the metric. The final comparison matrix is formed $A = (a_{ij})_{n*n}$. The comparison matrix also becomes the judgment matrix, which can be inferred as a positive mutual inverse matrix.

Consistency test:

Since the results obtained by comparing each evaluation index with each other may be inconsistent, it is necessary to conduct consistency test on the matrix. The consistency of the judgment matrix can be calculated from the consistency index CI, which is defined as:

$$\text{CI}=\frac{\lambda_{\max} - n}{n-1}$$

Where, n denotes the judgment matrix order and $\lambda_{\max}$ denotes the maximum eigenvalue of the judgment matrix. Meanwhile, based on the CI value and the consistency index RI, the consistency ratio CR can be found as follows:

$$CR = \frac{CI}{RI}$$

If the calculated consistency ratio CR < 0.1, the judgment matrix can be considered to satisfy the consistency requirement. That is, the weights determined by the influencing factors are reasonable. Otherwise, the Pandan matrix needs to be reconstructed and judged again until the consistency requirement is met.

Calculate the combined weights:

Let the judgment matrix $A = (a_{ij})_{n*n}$, whose weight vector $w = (w_1, w_2, \cdots, w_n)^T$ can be determined by the following characteristic equation:

$$Aw = \lambda_{\max} w \qquad s.t. \sum_{i=1}^{n} w_i = 1$$

Where w_i is the weight of the ith indicator relative to that criterion.

Finally, the combined weight of indicators and the indicator layer weight are calculated, and the combined weight of each indicator is obtained according to its product.

3.2. Establishment of Fuzzy Comprehensive Evaluation Method

The problem of evaluating the safety of aerial protection devices requires a fuzzy variable weight algorithm in addition to combining the already constructed AHP hierarchical recursive architecture. That is, we need to quantify the physical quantities and the degree of safety of each influencing factor.

Determine the set of factors and the evaluation language [5]:

The set of n factors (indicators of the third level in AHP) that affect the evaluation results is established. It is $U=\{u_1,u_2,\cdots,u_n\}$. The combined full time of each indicator in the set of factors can be calculated according to the AHP model.

Establish the evaluation set consisting of evaluation indices. The evaluation set represents a collection of different fuzzy ratings (least safe, less safe, critical, safer, safest, and many other levels).

Construction of evaluation matrix and affiliation function:

The fuzzy subset of the ith indicator within the factor set U is denoted as: $R_i=\{r_{i1},r_{i2},\cdots,r_{im}\}$. Where is the affiliation degree of the ith indicator in the kth evaluation level. It is used to indicate the degree of affiliation of each element to the fuzzy set, between 0 and 1. The larger the affiliation value is, the greater the degree of the element belonging to this set.

According to the characteristics of the influencing factors and evaluation criteria, we can use the weighted average type fuzzy synthetic operator $M(\bullet,+)$ to construct the fuzzy evaluation matrix R, which can be expressed as:

$$R=\begin{bmatrix} R_1 \\ \vdots \\ R_n \end{bmatrix}=\begin{pmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{pmatrix}$$

Fuzzy integrated evaluation vector construction:

Denote the final evaluation result fuzzy integrated assessment vector B as:

$$B=AOR=(b_1,b_2,\cdots,b_m)$$

Where A is the weight vector, R is the fuzzy evaluation matrix, and b_j denotes the weight of the jth evaluation in the evaluation set V. Eventually, we can determine its optimal evaluation level according to the large subordination criterion. Ultimately, the AHP-second level fuzzy comprehensive evaluation method model can be summarized as shown in Figure 2:

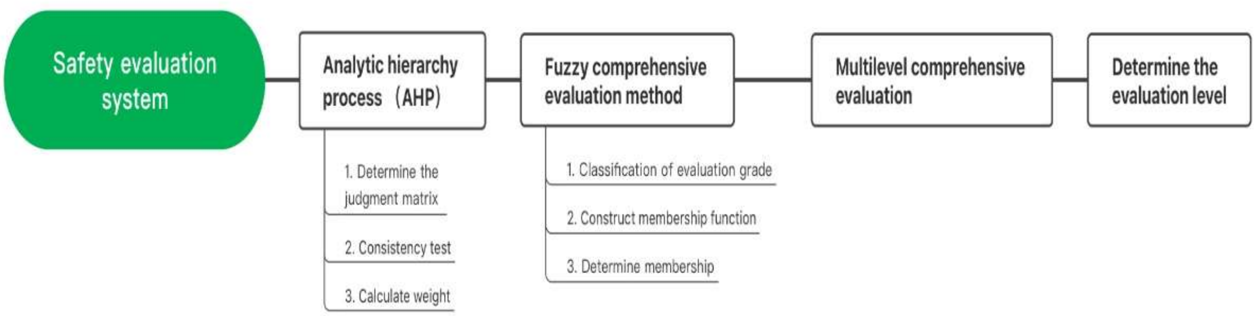

Figure 2. Evaluation model building ideas

4. Practical Simulations and Applications

Oral interviews and questionnaires were conducted for a two-by-two comparison of each safety indicator with aerial staff. The final results examined the relative importance of each assessment index at B and C levels. Finally we can get a relatively reasonable A-B judgment matrix with three B-C judgment matrices. The list of each level is shown in the following table 2, and the others are the same.

Table 2. A-B Judgment Array and B-C Judgment Array

A	B_1	B_2	B_3	B_1	C_1	C_2	C_3
B_1	1	1/3	1/2	C_1	1	2	1/3
B_2	3	1	2	C_2	1/2	1	1/3
B_3	2	1/2	1	C_3	3	3	1

For the A-B judgment matrix, the average value of each row of the matrix is obtained. Afterwards, normalization is performed to obtain the weight of B on A.

$$\overline{w} = [0.163 \cdot 0.540 \cdot 0.297]^T$$

The maximum eigenvalues of the matrix are:

$$\lambda_{max} = 3.009$$

According to the definition of CR in AHP, the CR values of this judgment matrix can be tested for consistency.

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n-1} = 0.005 \qquad CR = \frac{CI}{RI} = \frac{0.005}{0.580} = 0.009$$

The CR value of A-B judgment matrix is less than 0.1, then it passes the consistency test. Similarly, we can find the weights of indicators at all levels in turn. Finally, we can get the comprehensive weights of all indicators in the comprehensive evaluation system of the safety of high-altitude protection devices.

$$w = [w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_8, w_9]$$
$$w = [0.041, 0.026, 0.097, 0.432, 0.108, 0.031, 0.080, 0.106, 0.080]$$

In the first-level fuzzy comprehensive evaluation, (here, backstrap protection is used as an example), we need to construct the fuzzy history matrix and weight matrix of the lowest level contained in the criterion level (B). The calculation is as follows.

$$B_1 = W_1 * R_1 = [0.249, 0.157, 0.594] * \begin{pmatrix} 0.9 & 0.1 & 0 \\ 0.5 & 0.5 & 0 \\ 0.2 & 0.6 & 0.2 \end{pmatrix} = [0.4214, 0.4598, 0.1188]$$

Similarly, we can obtain B_2, B_3, and then obtain the second level evaluation matrix R and the fuzzy comprehensive evaluation matrix A.

$$R = [B_1, B_2, B_3]^T \quad A = W * R$$

Finally, the affiliation degree of protective measures is multiplied by the evaluation level score (5, 3, 1) to obtain the comprehensive evaluation score of safety assessment. The final results are shown in the following table 3.

Table 3. Comprehensive assessment score results

Harness protection	2.6221	Suspension point protection	6.1756
Self-locking device	5.8635	Full body covering protection	4.3872
Fence protection	3.5324	Self-locking device + strap protection	6.3241

5. Conclusion and Analysis

Through the modeling approach of AHP-2 level fuzzy comprehensive evaluation method, we finally arrived at the comprehensive score of each protective device. The scores correspond to the corresponding integrated advantages and disadvantages such as safety and practicality.

In fuzzy evaluation: relatively more advantageous safety guards are suspension guards, self-locking device guards, etc. They are more widely applied in use. In addition, in practice, operators also tend to use protective gear in an integrated manner. The results can also be seen by the results, the integrated use has the highest rating.

In the hierarchical analysis (AHP): we calculated the degree of consideration of the weight occupied by each indicator on the selection of protective gear. One of the major influences is the economic applicability, whose combined indicators account for about 40% or more. It is not difficult to think that for the operator, the cost effectiveness is very critical. Spending too much money or spending a long time for unnecessary protection is not desirable. The remaining indicators, which account for about 10%, are room for improvement, timeliness of protection, solidity of protection, and comfort. Such results show that the operators still have expectations and prospects for the protection devices, and hope that they will continue to progress and develop. At the same time, the safety of the protection is also the most important factor to be considered in addition to cost effectiveness, playing a decisive role.

$$w = [w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_8, w_9]$$
$$w = [0.041, 0.026, 0.097, 0.432, 0.108, 0.031, 0.080, 0.106, 0.080]$$

The assessment results reflect to some extent the current status of the high-altitude safety guards. Although the results still have some limitations, they also serve as a guide for the development related to high-altitude guards.

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