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Engineering Construction Safety Risk Evaluation based on Structural Equations and Fuzzy Integrated Evaluation Method

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Abstract There are many safety problems in construction projects during the construction stage, which seriously endanger people's life and property safety. In order to evaluate the engineering construction safety risk more precisely, the engineering construction safety risk evaluation index system is constructed from the perspective of five aspects: personnel, material and equipment, technology, management and environment. The structural equation model (SEM) is used to determine the path coefficients of each variable, calculate the index weights, and combine with the fuzzy comprehensive evaluation method to determine the engineering construction safety risk level. The results of the empirical study show that the construction safety risk level of the studied project is high and the evaluation results are consistent with the actual situation of the project. The proposed model can better determine the evaluation index weights and quantify the mutual influence between the indexes, which makes the evaluation results more accurate and reasonable, and provides a new effective method for construction safety risk evaluation of construction projects.

Keywords Construction safety; Risk evaluation; Structural equation; Fuzzy integrated evaluation

1. Introduction

The construction industry can visually reflect the level of national economic development at every historical stage. With the rapid development of the country's economic level, the total construction industry also follows, playing an important role in the national economic system. However, in recent years, many safety problems have emerged in the construction stage of building projects, which seriously endanger people's lives and property. If such risks are not identified and controlled in a timely manner, great economic losses and casualties will be incurred. Therefore, construction safety risk evaluation has become a key issue of concern and research in the construction field.

In order to improve the level of engineering construction safety risk management, the state has promulgated and implemented relevant regulations and policies, such as "Construction Quality Management Acceptance Standards for Energy-saving Construction Projects", etc. However, at this stage, there is no mature construction safety risk evaluation system, and not much research has been done in this area, and the frequency of engineering construction safety risk accidents has not been controlled, therefore, a practical engineering construction safety Risk evaluation system should be established as soon as possible. Compared with some European countries, China started the study of risk management a little later, and only at the end of the last century did China start to conduct systematic research on risk management [1]. Hu Zhenzhong [2] proposed to combine the respective advantages of 4D technology and BIM technology to establish a risk management model, which can control not only static risks, but also some dynamic risks; Zhang Dan [3] proposed a project risk evaluation method by combining fuzzy evaluation method and hierarchical analysis method for risk analysis against the problem of unclear boundaries between certain risk factors; Wang Mei [4] proposed that the purpose of engineering risk management is to identify, analyze and evaluate risks, etc., so as to predict engineering risks comprehensively and control them with reasonable means, and finally achieve the goal of maximizing the comprehensive benefits of engineering construction [5].

The above studies provide a variety of methods for building construction safety risk evaluation with certain effects, but they do not completely solve the problems of subjectivity and interactions between indicators in building construction safety risk evaluation. Considering that the structural equation model can better deal with the relationship between variables and the fuzzy comprehensive evaluation method has the advantage of strong objectivity and can better solve the uncertainties, this study constructs a construction safety risk evaluation model based on structural equation and fuzzy comprehensive evaluation method in an attempt to improve the effectiveness of the construction safety risk evaluation and provide a basis for the reasonable development of risk avoidance programs, while effectively reducing the probability of safety accidents.

2. Build the Model

The basic idea of model establishment is to construct an evaluation index system for the characteristics of safety risks of assembly building construction, use SEM to determine the path coefficients of each variable, calculate the index weights, and combine the fuzzy evaluation method to construct a safety risk evaluation model for assembly building construction in order to determine the safety risk evaluation level more effectively.

2.1 Evaluation index selection and fuzzy evaluation set

As the risk of construction safety involves many influencing factors and is uncertain, in order to make the evaluation index system constructed can fully and accurately respond to the risk information, it is necessary to screen numerous index factors. The number of selected indicators should neither be too many nor too few. Too many indicators will cause the evaluation system to be too complex and have more uncontrollable factors; too few indicators will lead to insufficient representativeness and cannot reflect the problem comprehensively.

The collection of all possible comments of each indicator is called evaluation set. The evaluation set is determined according to the possible results of safety risk evaluation in the construction phase of building projects, such as "low, medium, high", etc.

2.2 Indicator evaluation matrix

After the fuzzy evaluation set is determined, the fuzzy evaluation set is applied to quantify each risk evaluation index $X_i(i=1,2,\cdots,n)$, and the affiliation value of each secondary evaluation index is calculated, and then the fuzzy evaluation matrix is obtained as follows.

$$\boldsymbol{R}=\begin{bmatrix}(\boldsymbol{R}\mid X_1)\\(\boldsymbol{R}\mid X_2)\\\vdots\\(\boldsymbol{R}\mid X_n)\end{bmatrix}=\begin{bmatrix}r_{11}&r_{12}&\cdots&r_{1m}\\r_{21}&r_{22}&\cdots&r_{2m}\\\vdots&\vdots&&\vdots\\r_{n1}&r_{n2}&\cdots&r_{nm}\end{bmatrix}_{n\times m}$$

where: R is the fuzzy evaluation matrix; r_{ij} is the affiliation value of each index corresponding to the evaluation set.

2.3 Determination of evaluation index weights

SEM is a multivariate analysis method for verifying the correlation between one or more independent variables and one or more dependent variables [6], and is good at analyzing and dealing with measurement errors and structural relationships between potential variables.The joint set of equations of SEM is:

Measurement equation：

$$x=\Lambda_x\xi+\delta$$
$$y=\Lambda_y\eta+\varepsilon$$

Structural equations：

$$\eta = \psi\eta + \Gamma\xi + \zeta$$

where: x, y are observed variables; η, ξ are latent variables; Λ_x, Λ_y, Ψ, Γ are coefficient matrices; ε, δ, ζ are error terms.

According to the constructed evaluation index system, questionnaires were designed and distributed, and the obtained questionnaire data were tested for reliability and validity. After the reliability and validity tests are passed, the primary evaluation indexes are used as potential variables and the secondary evaluation indexes are used as observed variables, and the application software Amos 26.0 is used for SEM calculation to obtain the path coefficients of each evaluation index, which reflects the degree of influence of each evaluation index on the security risk. The weights of each primary evaluation index were calculated based on the path coefficient using the following equation [7]

$$W_{U_i} = \frac{\lambda_{U_i}}{\sum_{i=1}^{n} \lambda_{U_i}}$$

where: W_{Ui} is the weight coefficient of the *i*th level 1 evaluation index; λ_{Ui} is the path coefficient of the *i*th level 1 evaluation index; U_i is the *i*th level 1 evaluation index; *i* is the evaluation index serial number. Similarly, the weights of the second-level evaluation indexes can be calculated.

2.4 Fuzzy comprehensive evaluation

Multiply the weight vector ***W*** of the construction project risk evaluation index with the fuzzy evaluation matrix ***R*** of the first-level evaluation index to obtain the evaluation result vector ***B*** of the first-level evaluation index

$$\boldsymbol{B} = \boldsymbol{W} \times \boldsymbol{R} = (w_1, w_2, \ldots, w_n) \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \vdots & \\ r_{n1} & r_{n3} & \cdots & r_{nm} \end{bmatrix}_{n \times m} = (b_1, b_2, \cdots, b_n)$$

where: b_i is the degree of affiliation of the risk evaluation index to the rank fuzzy subset V_n. bi follows the principle of maximum affiliation evaluation, that is, if $b_i = \max(b_1, b_2, \cdots, b_n)$, then b_i is the risk rank corresponding to the evaluation index of the construction project.

3. Empirical Study

A certain building residential project H in Jinan, covering an area of 34318.84m2, with a total construction area of 114648.92m2, 34 floors above ground, 2 floors underground, and a building height of 96.84m. The main structure of the project adopts assembled monolithic frame structure and cast-in-place frame structure, with seismic class III, and the prefabricated components include interior and exterior wall panels, air conditioning panels, stairs, laminated panels, etc. The project The prefabricated assembly rate reached 62.86%. The established construction safety risk evaluation model based on structural equations and fuzzy integrated evaluation method was applied to project H for construction safety risk evaluation.

3.1 Evaluation of risk evaluation index levels

According to the above index selection principles, a search was conducted with the titles or keywords of "construction" and "construction safety risk", and the influencing factors mentioned in the literature were summarized after deleting the same literature and eliminating those that did not use clear research methods. Initially, an expert opinion consultation form on construction safety risk factors was established. Two rounds of consultation forms were distributed to experts through the Delphi method, and experts were asked to evaluate the indicators in terms of importance, familiarity and accessibility using a 5-point Likert scale (1~5 indicates an increasingly higher degree). For any imperfections in the consultation form, experts could offer their own comments and suggestions for revision. After the first round of expert consultation forms were recycled, the risk indicators with average scores lower than 3.00 were removed, and the consultation forms were refined according to the opinions proposed by experts, and then the second round of expert consultation forms were distributed and recycled, and the risk indicators with average scores lower than 3.50 were removed to obtain the final evaluation index system, as shown in Table 1.

A 5-point Likert scale was used to classify the construction safety risk evaluation results of Project H into 5 levels [8], i.e., the evaluation set V = low, low, medium, high, and high. Fifteen experts were invited to participate in the questionnaire survey, and 22 risk indicators were evaluated and scored according to the 5 levels, and the final risk level evaluation matrix of each indicator was obtained (Table 1)

Table 1: Risk level evaluation matrix for each indicator

Primary Rating Indicators	**Secondary Rating Indicators**	**Risk level evaluation matrix**				
		Low	**relatively low**	**Moderate**	**Relatively hige**	**High**
Personnel risk U1	Personnel safety awareness level U_{11}	3	3	3	4	2
	Violation of operation by personnel U_{12}	1	4	3	6	1
	Wearing of safety equipment for personnel U_{13}	2	4	4	5	0
	Physical and mental health of personnel U_{14}	2	3	3	5	2
	Personnel experience and technical level U_{15}	2	4	5	4	0
Material and equipment risk U2	Selection of equipment and machinery U_{21}	2	5	3	4	1
	Maintenance and repair of equipment U_{22}	2	3	2	6	2
	Production quality of prefabricated components U_{23}	1	4	4	5	1
	Unsafe condition of precast componentsU_{24}	2	3	4	6	0
	Stacking condition of construction materialsU_{25}	1	5	4	4	1
Technology risk U3	Accuracy of positioning of precast components pins and fittingsU_{31}	3	2	4	4	2
	Safety inspection technologyU_{32}	2	3	3	5	2
	Quality and safety technical delivery U_{33}	2	4	4	4	1
	Safety protection technologyU_{34}	1	5	4	4	1
Management risk U4	Status of multi-party coordination managementU_{41}	2	4	4	5	0
	Establishment and implementation of safety management systemU_{42}	1	5	3	6	0
	Management standards and supervision mechanismU_{43}	2	3	4	5	1
	Safety education and trainingU_{44}	3	3	3	6	0
Environmental risk U5	Working surface and light lighting situationU_{51}	2	5	3	4	1
	Protective measures for the edge hole U_{52}	1	4	3	6	1
	Dangerous sources around the construction site U_{53}	2	4	4	5	0
	Force majeure factorsU_{54}	1	5	4	4	1

2.2 Determine the fuzzy evaluation matrix of indicators

Taking the first-level evaluation index of personnel risk U1 in Table 1 as an example, calculate the affiliation degree of its second-level evaluation index.

$(\boldsymbol{R} \mid U_{11})=$ (0.200，0.200，0.200，0.267，0.1133)，$(\boldsymbol{R} \mid U_{12})=$(0.067，0.267，0.200，0.400，0.067)，$(\boldsymbol{R} \mid U_{13})=$(0.133，0.267，0.267，0.333，0.000)，$(\boldsymbol{R} \mid U_{14})=$(0.133，0.200，0.200，0.333，0.133)，$(\boldsymbol{R} \mid U_{15})=$(0.133，0.267，0.333，0.267，0.000)。

Therefore, the fuzzy evaluation matrix $\boldsymbol{R}_{U1}$ for personnel risk U_1 is:

$$\boldsymbol{R}_{U_1}=\begin{bmatrix} 0.200 & 0.200 & 0.200 & 0.267 & 0.133 \\ 0.067 & 0.267 & 0.200 & 0.400 & 0.067 \\ 0.133 & 0.267 & 0.267 & 0.333 & 0.000 \\ 0.133 & 0.200 & 0.200 & 0.333 & 0.133 \\ 0.133 & 0.267 & 0.333 & 0.267 & 0.000 \end{bmatrix}。$$

Similarly, the fuzzy evaluation matrix of other first-level evaluation indicators can be obtained, in order:

$$\boldsymbol{R}_{U_2}=\begin{bmatrix} 0.133 & 0.333 & 0.200 & 0.267 & 0.067 \\ 0.133 & 0.200 & 0.133 & 0.400 & 0.133 \\ 0.067 & 0.267 & 0.267 & 0.333 & 0.067 \\ 0.133 & 0.200 & 0.267 & 0.400 & 0.000 \\ 0.067 & 0.333 & 0.267 & 0.267 & 0.067 \end{bmatrix},$$

$$\boldsymbol{R}_{U_3}=\begin{bmatrix} 0.200 & 0.133 & 0.267 & 0.267 & 0.133 \\ 0.133 & 0.200 & 0.200 & 0.333 & 0.133 \\ 0.133 & 0.267 & 0.267 & 0.267 & 0.067 \\ 0.067 & 0.333 & 0.267 & 0.267 & 0.067 \end{bmatrix},$$

$$\boldsymbol{R}_{U_4}=\begin{bmatrix} 0.133 & 0.267 & 0.267 & 0.333 & 0.000 \\ 0.067 & 0.333 & 0.200 & 0.400 & 0.000 \\ 0.133 & 0.200 & 0.267 & 0.333 & 0.067 \\ 0.200 & 0.200 & 0.200 & 0.400 & 0.000 \end{bmatrix},$$

$$\boldsymbol{R}_{U_5}=\begin{bmatrix} 0.133 & 0.333 & 0.200 & 0.267 & 0.067 \\ 0.067 & 0.267 & 0.200 & 0.400 & 0.067 \\ 0.133 & 0.267 & 0.267 & 0.333 & 0.000 \\ 0.067 & 0.333 & 0.267 & 0.267 & 0.067 \end{bmatrix}。$$

2.3 Determination of index weights

The questionnaire design and survey were conducted according to the risk evaluation indexes in Table 1. 330 questionnaires were distributed, 324 were returned, 22 invalid questionnaires were excluded, and the effective rate was 93.2%. In order to ensure the validity of the data, SPSS 26.0 software was used to test the reliability and validity of the questionnaire data. The test results showed that Cronbach's α value was 0.900, the KMO value was 0.916, and Bartlett's test value was 0.000, which was less than 0.001. Therefore, the data reliability and validity were good and suitable to be used for research analysis.

The software Amos 26.0 was used to test the fit of the data for the above risk factors. The seven indicators shown in Table 2 were selected for model fit assessment based on existing studies.

Table 2: Fitting assessment indexes

Fitting assessment indicators	Indicator name	Acceptable range
χ^2/df	Cardinality Ratio of Freedom	(1.000~3.000) Excellent fit
I_{GF}	Suitability index	>0.800 good fit >0.900Fit excellent
I_{AGF}	Adjusted fitness index	>0.800 good fit >0.900 good fit
R_{MSEA}	Mean square and square root of asymptotic residuals	<0.050 good fit <0.080 good fit <0.100 fair fit
I_{CF}	Comparative fitness index	>0.900 good fit
I_{TL}	Non-regularized fitness index	>0.900 good fit
I_{IF}	Value-added fitness index	>0.900 excellent fit

The first-order validated factor analysis model of safety risk of assembly building construction was obtained after the software Amos 26.0 operation, as shown in Figure 1. Analysis of the output of the model shows that: the residuals e_i(i=1,2,3,…,22) of each observed variable are positive, and the path coefficients of 22 indicators are between 0.51 and 0.72, and all are within the range of 0.50-0.95. $\chi^2/df = 1.313 < 3.000$, $I_{GF} = 0.923 > 0.900$, $I_{AGF} = 0.902 > 0.900$, $I_{CF} = 0.965 > 0.900$, $I_{TL} = 0.959 > 0.900$, $I_{IF} = 0.965 > 0.900$, $R_{MSEA} = 0.034 < 0.050$, with good fitness of each indicator. Therefore, the first-order model has a good fit. The correlation coefficients between the first-order evaluation indicators were mostly concentrated between 0.6 and 0.7, and all indicators reached the significant level of 0.05, which indicated that there might be higher-order common influencing factors between them. Therefore, a second-order validated factor analysis model needs to be constructed for further analysis, and the second-order model is shown in Figure 2.

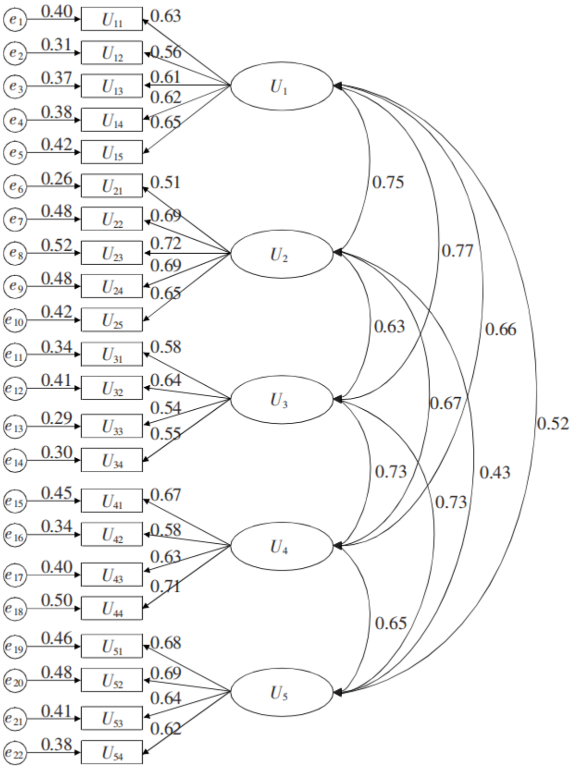

Figure 1: First-order validated factor analysis model

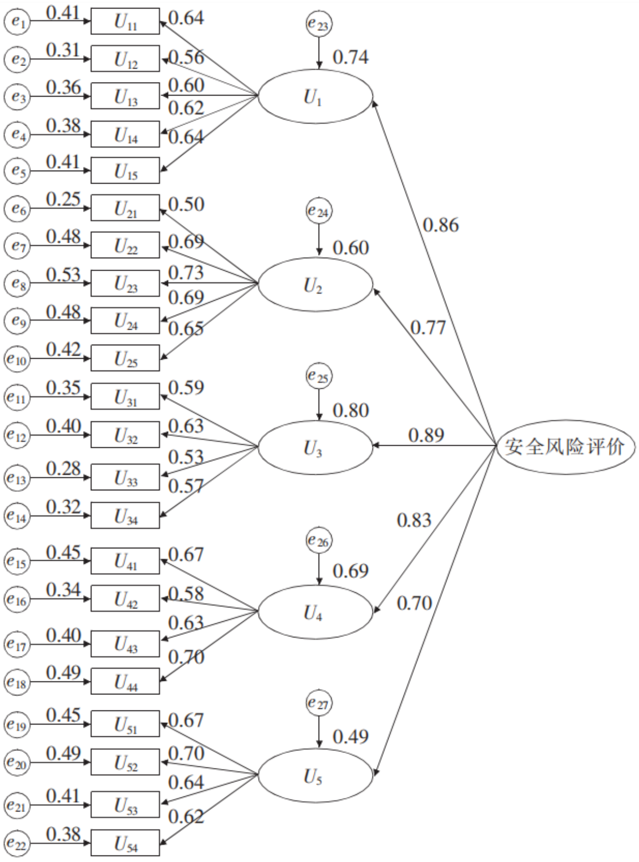

Figure 2: Second-order validated factor analysis model

Fitting the second-order model constructed in Figure 2 and analyzing the output shows that the residuals e_i（$i=1, 2, 3, \ldots, 27$） of each observed and latent variable are positive, and the path coefficients of each variable range from 0.50 to 0.89 and are all within the range of 0.50 to 0.95. $\chi^2/df=1.409<3.000$, $I_{GF}=0.914>0.900$, $I_{CF}=0.953>0.900$, $I_{TL}=0.946>0.900$, $I_{IF}=0.953>0.900$, $R_{MSEA}=0.038<0.050$, and although $I_{AGF}=0.894$, which is slightly less than 0.900, it is still within an acceptable range of greater than 0.800. Therefore, the second-order model generally fits well and is suitable for the research analysis. According to the path coefficients between the risk indicators in Figure 2, the weights of the indicators at each level can be obtained by applying the formula, which is shown in Table 3.

Table 3: Indicator weights

Primary Evaluation Indicators	**The weighting of primary evaluation indicators**	**The Weighting of Secondary Rating Indicators**				
		Sub-risks1	**Sub-risks2**	**Sub-risks3**	**Sub-risks4**	**Sub-risks5**
Personnel risk U_1	0.212	0.209	0.183	0.196	0.203	0.209
Material and equipment risk U_2	0.19	0.153	0.212	0.224	0.212	0.199
Technology risk U_3	0.22	0.254	0.272	0.228	0.246	—
Management risk U_4	0.205	0.26	0.225	0.244	0.271	—
Environmental risk U_5	0.173	0.255	0.266	0.243	0.236	—

3.4 Fuzzy comprehensive evaluation

Taking the personnel risk evaluation indexes in Table 3 as an example, the weight factors of the five secondary evaluation indexes form a weight vector $\boldsymbol{W}_{\mathrm{U1}}$, i.e. $\boldsymbol{W}_{\mathrm{U1}}=(0.209,\ 0.183,0.196,0.203,0.209)$. The combined evaluation of personnel risk indicators is calculated as $\boldsymbol{B}_1=\boldsymbol{W}_{\mathrm{U1}}\boldsymbol{R}_{\mathrm{U1}} = (0.135, 0.239, 0.241, 0.318, 0.067)$. Similarly, the comprehensive evaluation results of other risk indicators are obtained as:

$$\boldsymbol{B}_2=\boldsymbol{W}_{\mathrm{U2}}\boldsymbol{R}_{\mathrm{U2}}=[0.105\ \ 0.262\ \ 0.228\ \ 0.338\ \ 0.067],$$

$$\boldsymbol{B}_3=\boldsymbol{W}_{\mathrm{U3}}\boldsymbol{R}_{\mathrm{U3}}=[0.134\ \ 0.231\ \ 0.249\ \ 0.285\ \ 0.102],$$

$$\boldsymbol{B}_4=\boldsymbol{W}_{\mathrm{U4}}\boldsymbol{R}_{\mathrm{U4}}=[0.136\ \ 0.247\ \ 0.234\ \ 0.366\ \ 0.016],$$

$$\boldsymbol{B}_5=\boldsymbol{W}_{\mathrm{U5}}\boldsymbol{R}_{\mathrm{U5}}=[0.100\ \ 0.299\ \ 0.232\ \ 0.318\ \ 0.051]。$$

The fuzzy weight vector $\boldsymbol{W} = (0.212,0.190,0.220,0.205,0.173)$ of the first-level evaluation index, then the fuzzy comprehensive evaluation result of the first-level evaluation index is:

$$\boldsymbol{B}^*=\boldsymbol{W}\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix}=[0.123\ \ 0.254\ \ 0.237\ \ 0.324\ \ 0.061]。$$

The evaluation results show that: the proportion of the rated low risk level is 12.3%, the proportion of the lower risk level is 25.4%, the proportion of the medium risk level is 23.7%, the proportion of the higher risk level is 32.4%, and the proportion of the high risk level is 6.1%. According to the principle of maximum affiliation, the construction safety risk evaluation level of this construction project is higher. The comparison with the practical results of construction safety risk management of Project H shows that the results are consistent with the actual situation of the project.

3.5 Analysis of results and recommendations

The final safety risk level of Project H is higher. As can be seen from the weights of the primary evaluation indexes in Table 3, the influence of technical and personnel factors on safety risk is more prominent, among which the accuracy of safety inspection technology and positioning of prefabricated components assembling has a greater impact on technical risk. Therefore, it is necessary to increase the investment in technology research and development and innovation, focus on training professional personnel team, and increase the use of key technologies such as BIM. Personnel factors also have a greater impact on the safety risk, mainly due to the weak safety awareness and insufficient experience and technical level of operators. Therefore, it is necessary to strengthen the safety awareness of operators, to carry out professional skills training in all aspects of the construction phase, to improve the operational proficiency and technical level of operators, to eliminate operational errors to the greatest extent possible, and to ultimately achieve the goal of reducing the occurrence of safety accidents [9].

From the weights of the secondary evaluation indexes in Table 3, it can be seen that safety inspection techniques, the state of coordinated management of multiple parties, safety education and training, and protective measures for the adjacent cavities are important factors that affect the construction safety of the project. Therefore, the risks can be controlled from the following aspects.

(1) For the risk factor of "safety detection technology", senior experts and professional technicians can be invited to provide on-site guidance, and the operators of on-site installation should have strong professional quality and be able to skillfully point out the specific lifting points. In addition, fully use BIM and RFID technology to simulate and dynamically monitor the whole process of construction, and implement supervision measures in construction to correct the unreasonable phenomena in construction in time to reduce the occurrence of safety accidents.

(2) For the risk factor of "multi-party coordination and management", the construction unit should complete the establishment of organizational structure before entering the construction site, clarify the person in charge of each department and the corresponding responsibilities, and link the job responsibilities of each department with the economic index. Improve the information exchange technology and platform among all departments of the project, establish effective communication mechanism, and organize routine meetings to communicate and solve the problems in time.

(3) For the risk factor of "safety education and training", education and professional skills training should be carried out regularly, and experts should be invited to conduct pre-job training for operators, and the training results should be assessed, and after passing the assessment, an induction certificate should be issued, and operators should be licensed to work. Before the start of each construction work in advance of construction rehearsal, improve the comprehensive ability of operators, so as to reduce the occurrence of construction site safety accidents.

(4) "For the risk factor of "protective measures for the edge of the hole", take safety protective measures for the edge of the hole and conduct regular inspection. Adjust the lighting equipment around the construction site adjacent to the opening to ensure adequate lighting during nighttime construction. Ensure that the safety warning signs next to the adjacent openings are reasonably placed.

4 Risk response measures

On the basis of completing the evaluation of engineering construction safety risks, the corresponding risk countermeasures are proposed from the perspective of the developer, standing in the position of industry development.

(1) Build a mature structure system. Enterprises should increase investment in scientific research funds for building construction, actively seek cooperation with relevant scientific research institutes and colleges and universities, establish an innovation system of industry-university-research, and develop a structural system suitable for construction based on ensuring the quality and safety of building structures.

(2) Strengthen the quality supervision of prefabricated components. In order to ensure the quality of prefabricated building components meets the standards, on the one hand, prefabricated component manufacturers should conduct professional training for industrial workers, improve the professionalism of workers, and upgrade the component production line to control the quality of prefabricated components at the source to meet the design and construction standards; on the other hand, supervisory enterprises should cultivate and assign professional prefabricated component supervisors to prefabricated component factories.

(3) Improve on-site construction program. Construction projects have high requirements for the lifting technology of precast components on site, and the construction is difficult and needs to consider factors such as the route of on-site transportation vehicles and the storage location of components, so construction enterprises should comprehensively learn to master on-site construction technology and reasonably use BIM technology to reduce risks and improve construction and building efficiency.

(4) Reduce construction costs. The fading out of demographic dividend and the lack of youth labor in recent years have led to increasing construction costs. On the one hand, we can make up for the lack of quantity by cultivating industrial workers with high-quality talents; on the other hand, we can introduce advanced foreign equipment to change labor-intensive to technology-intensive, so that it can reduce the cost under the benefit of scale.

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