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Risk Assessment of High-grade Highway Construction Based on Combined Weighting and Fuzzy Mathematics

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Abstract: High-grade highways are an important part of the modern comprehensive transportation system. However, due to frequent natural disasters, harsh meteorological conditions, and fragile geological environments, high-grade highway construction projects face significant risks, and how to specifically manage and control these construction risks to reduce them to a socially acceptable level has become a pressing technical issue. Therefore, this study combines the construction characteristics and risk features of high-grade highways, applies the Hall's three-dimensional structural theory to comprehensively identify potential risk factors from the dimensions of time, structure, and logic, and builds the logical dimension from four aspects: people, materials, environment, and management. To filter the main influencing factors, the Delphi method is adopted to construct a risk assessment indicator system, with the expert opinions fully taken into consideration. To address the subjectivity in the weight calculation process of risk assessment indicators, the Analytic Hierarchy Process (AHP) and Entropy Weight Method are used to calculate the subjective and objective weights, respectively. A combined weighting model is established based on game theory principles and is used to optimize the weights of the risk assessment indicators. In view of the fuzziness of risks during high-grade highway construction, fuzzy mathematics theory is introduced to construct the risk assessment model. In this study, this method is applied to the construction of the Elsiyah Highway to clarify the risk level of the project and propose targeted control measures. The results show that the risk level of the Elsiyah Highway project is relatively high. The risk level is conditionally acceptable, but measures must be taken to reduce the risks.

Keywords: High-grade highway; Combined weighting; Fuzzy mathematics; Risk identification; Construction risk assessment

1 Introduction

As the national socio-economic development continues, high-grade highways, as an important part of the national transportation infrastructure, play a crucial role in the economic development and political, economic, and cultural exchanges between regions [1]. However, compared to general high-grade highways, mountainous terrains are more complex, with variable geology and hydro-meteorological conditions that are significantly different from those in plain areas, and this leads to considerable difficulties in the construction of high-grade highways in mountainous areas [2], raising higher demands on structure [3], materials [4], and construction. Given the huge investments in engineering construction and the severe consequences of engineering accidents, effectively assessing and controlling the risks in the construction of high-grade highways has become an urgent technical issue.

Risk factor identification is the primary step in assessing the risks of high-grade highway construction in complex environments. Before carrying out risk assessment, summarizing, classifying, and organizing potential risk factors is beneficial in determining the main risk factors, thereby accurately assessing the risks. Li and Zou [5] classified the risks in high-grade highway construction into seven categories, including 25 risk factors, among which planning defects, low residual value of projects, lack of qualified bidders, design defects, and prolonged project approval time have the most significant impact. Esmaeili and Hallowell [6] established a decision support system that integrates safety risk data into project schedules, quantifying the relative safety risks of 25 highway construction tasks using the Delphi method and multiple controls to reduce cognitive biases. Zhang et al. [7] developed a framework using BIM technology, including an automatic safety rule-checking algorithm specifically for BIM, to identify risk sources in construction projects. Crawley [8] summarized guidelines for risk source identification, provided commonly used risk identification methods, and proposed the use of a three-dimensional HAZOP structured analysis to identify risk sources. Perry and Hayes [9] identified risk factors in highway engineering, categorizing them into risks for consulting firms, construction firms, and construction units. Sawacha et al. [10] and Kim et al. [11] conducted studies on risk factors at construction sites and the main accident factors in highway project safety management, respectively.

Additionally, to seek a scientifically reasonable method for safety risk assessment, experts in related fields have conducted extensive in-depth research. For example, Zayed et al. [12] focusing on highway project construction, started from the perspectives of companies and projects, identified risk areas that significantly impact project construction, and assessed their influence, developing an R model using the AHP for a scientific and accurate evaluation of influencing factors. Mousavi et al. [13] used non-parametric jackknife resampling techniques for ranking risks, comparing common risk grades with jackknife risk grades, and contrasting them with highway project risk data analysis for safety risk evaluation management. Hallowell et al. [14] evaluated and analyzed the interactions between basic risk impacts of 25 common U.S. highway construction projects, quantifying the impact of 600 types of risk interactions on potential risks using the Delphi method. Sharaf and Abdelwahab [15] identified and determined a list of risk factors for Egyptian highway projects, evaluating and ranking these factors using software developed in MATLAB, determining the most important risk factors, and evaluating the overall project risk level. EI-Sayegh [16] calculated the priority of each risk by multiplying the probability by the impact of each risk and calculated the Relative Importance Index (RII) of risk priorities, helping project managers assess risks before the start of a project and devise appropriate countermeasures. Ahmadi et al. [17] used fuzzy FMEA to assess and determine the priority of risks, and applied the fuzzy AHP method for quantification and combination, establishing countermeasures for risk events.

In summary, current domestic and international research in the field of high-grade highway construction risk control has achieved significant results, but there are still some shortcomings. In terms of risk factor identification, most studies are subjective in identifying angles and levels, and in determining factor selection rules, leading to incomplete or redundant risk factors. This often results in overlapping or missing indicators, failing to effectively consider the combined effects of various factors such as different stages of engineering construction and different types of structural constructions, making the established indicator system less systematic and scientific. The emergence of Hall's three-dimensional structure provides a unified methodological approach to planning, organizing, and managing large and complex systems, and has been widely recognized and applied in countries around the world [18]. The construction of the logical dimension is a challenging aspect of Hall's three-dimensional structure. To address this, the theory of system safety is introduced to determine the logic behind the occurrence of risk accidents. According to system safety theory, the logic of accident occurrence is that the second type of hazard source breaks the constraint of the first type of hazard source. The first type of hazard source, which is the energy required for an accident to occur, is normally constrained, but may be triggered by inducing factors (the second type of hazard source) to break the constraint and cause an accident. In terms of highway construction, it can be considered that the occurrence of accidents in construction management is influenced by a combination of material failure, human error, and environmental factors. Therefore, combining Hall's three-dimensional structure and system safety theory can more systematically and comprehensively identify various risk factors. In the assessment of highway construction risks, several research methodologies utilize overly simplistic approaches for determining the weights of indicators, relying solely on either subjective or objective methods. This one-dimensional approach can lead to distortions and reduced accuracy in the final risk assessment outcomes, especially when multiple factors are involved. Some research methods do not sufficiently consider the fuzziness and uncertainty present in the risk assessment process of highway construction, such as BIM technology [19], finite element method [20], and neural networks [21], which have high data requirements and are greatly affected by the choice of model and parameter settings, leading to significant calculation deviations. As the most widely used results in subjective and objective weighting methods, the AHP and entropy weight method each have their unique advantages. To retain the advantages of both methods, a combined weighting method is proposed to determine the weight of indicators. At the same time, to address the fuzziness or uncertainty in the evaluation process and the difficulty in quantifying qualitative indicators, this study introduces fuzzy mathematics theory to handle such issues.

Out of these concerns, to establish a more systematic and scientific indicator system and to more accurately assess the magnitude of risks, this study comprehensively uses Hall's three-dimensional structure theory, system safety theory, and the Delphi method for risk factor identification; combines the AHP, Entropy Weight Method

(EWM), and fuzzy comprehensive evaluation method; uses a combined weighting method that integrates subjective and objective aspects to determine the risk weight of evaluation indicators; and constructs an AHP-EWM-FUZZY safety risk evaluation model to determine the risk level of high-grade highways.

2 Materials and Methods

2.1 Project Overview

The middle section of the Cochabamba-Santa Cruz Highway, the "Elsiyah" two-way four-lane construction project, is located in the Chapare region of Cochabamba Province, Bolivia. It is a key part of the Number 4 Highway connecting the two major cities of Cochabamba and Santa Cruz. The highway is situated approximately between 100 and 128 kilometers from the central part of the Cochabamba to Santa Cruz Highway, starting from Saint Hasid Bridge and ending at Saint Esbiritu II Bridge, spanning a total length of 30.3 kilometers. This project is a typical mountain highway with steep terrain, winding descents, a starting elevation of 1850 meters above sea level, and an ending elevation of 450 meters, averaging a longitudinal slope of 5%. It includes two separate tunnels totaling 1700 meters, 29 bridges (totaling 3.4 km in length), 5.6 km of retaining wall structures, and 120 culverts, with a high proportion of bridges and tunnels. The road is designed with a total width of 20.6 meters, featuring a double-layer asphalt concrete surface.

2.2 High-Grade Highway Construction Risk Identification

Risk factor identification is the primary phase in assessing the risks of high-grade highway construction in complex environments. It is a process of systematically and comprehensively identifying various risk factors that may exist during the construction process using appropriate risk identification methods. Before undertaking risk assessment, it's beneficial to summarize, categorize, and organize potential risk factors to identify the main risks, merging or excluding minor risk factors, thereby establishing a scientifically accurate risk assessment indicator system.

2.2.1 Risk identification method

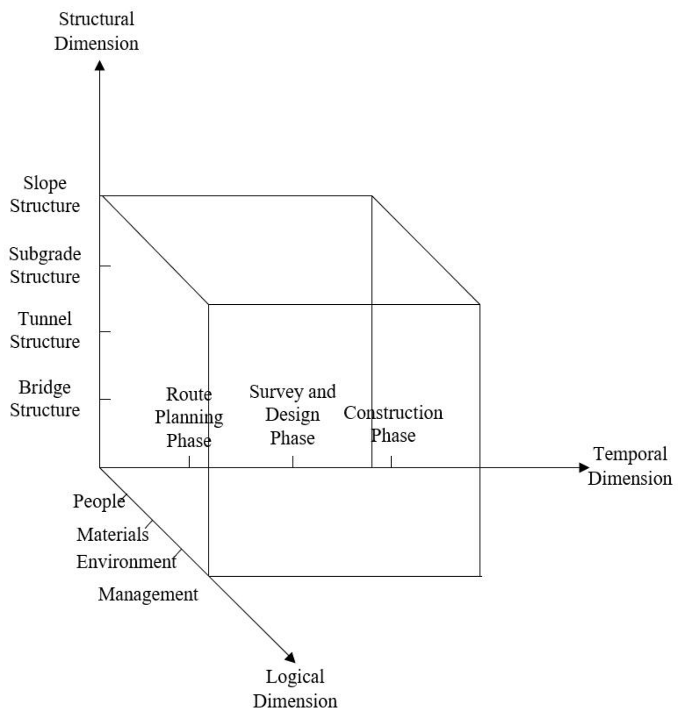

Figure 1. Hall's three-dimensional risk identification structure for high-grade highway construction in complex environments

Given the complex hydrogeological conditions and variable climate conditions of mountainous highway construction, there are many potential risk factors during the construction period, with complex relationships between various types of risk factors. To scientifically and comprehensively identify potential risks, the principles of scientific rigor, systematic approach, typicality, and operability [22] should be followed when selecting assessment indicators. Considering the complexity and diversity of risk factors, this study initially screens risk factors based on a combination of literature analysis and Hall's three-dimensional structural theory, followed by the optimization and integration of risk factors using the Delphi method to build a scientifically reasonable risk assessment indicator system.

Hall's three-dimensional structure theory [23], proposed by the American systems engineer A.D. Hall based on extensive engineering practice experience, is a risk identification method that has shown effective application in planning and managing large, complex system engineering projects. Hall's three-dimensional structure classifies engineering risks based on their different characteristics and carefully screens and judges various risk factors that may occur during construction from dimensions such as systemic, comprehensive, and dynamic aspects (commonly using temporal, knowledge, and logical dimensions), ultimately making the risk identification results reliable and widely applicable in practice.

Based on Hall's three-dimensional structure identification theory, this approach identifies and analyzes risk factors in high-grade highway construction in complex environments from perspectives like "temporal, logical, and structural" dimensions, considering different construction stages, various structural types of constructions, and different sources of risk. The identification structure is illustrated in Figure 1.

Temporal Dimension: Divides the risks of high-grade highway construction in complex environments based on different temporal dimensions of engineering construction [24]. Common engineering examples primarily include phases such as route planning, survey and design, and construction.

Structural Dimension: Divides the risks of high-grade highway construction in complex environments based on different structural dimensions in engineering construction. Common engineering examples mainly include bridges, tunnels, subgrades, slopes, etc. Each specific structural form has its own construction characteristics and potential risks.

Logical Dimension: Divides the risks of high-grade highway construction in complex environments based on different entities that might lead to risks in engineering construction. Combining system safety theory [25], the entities that could cause risks are divided into four aspects: people, materials, environment, and management.

2.2.2 Construction of risk assessment indicator system

The Delphi method is essentially a feedback-based anonymous inquiry method [26]. Its workflow mainly involves determining the experts, then contacting the experts through survey personnel. The experts do not communicate with each other and use anonymous methods for review and opinion sharing. After one round, the survey personnel organize, summarize, statistically analyze, and provide feedback on the results, then start a new round of research until a unified opinion is reached. The main advantages are its simplicity and intuitiveness, ease of operation, wide-ranging brainstorming, high accuracy, fully leveraging the expertise of each expert, expressing points of divergence, and not requiring the establishment of cumbersome mathematical models. It can also quantitatively estimate qualitative indicators in the absence of statistical data and original materials.

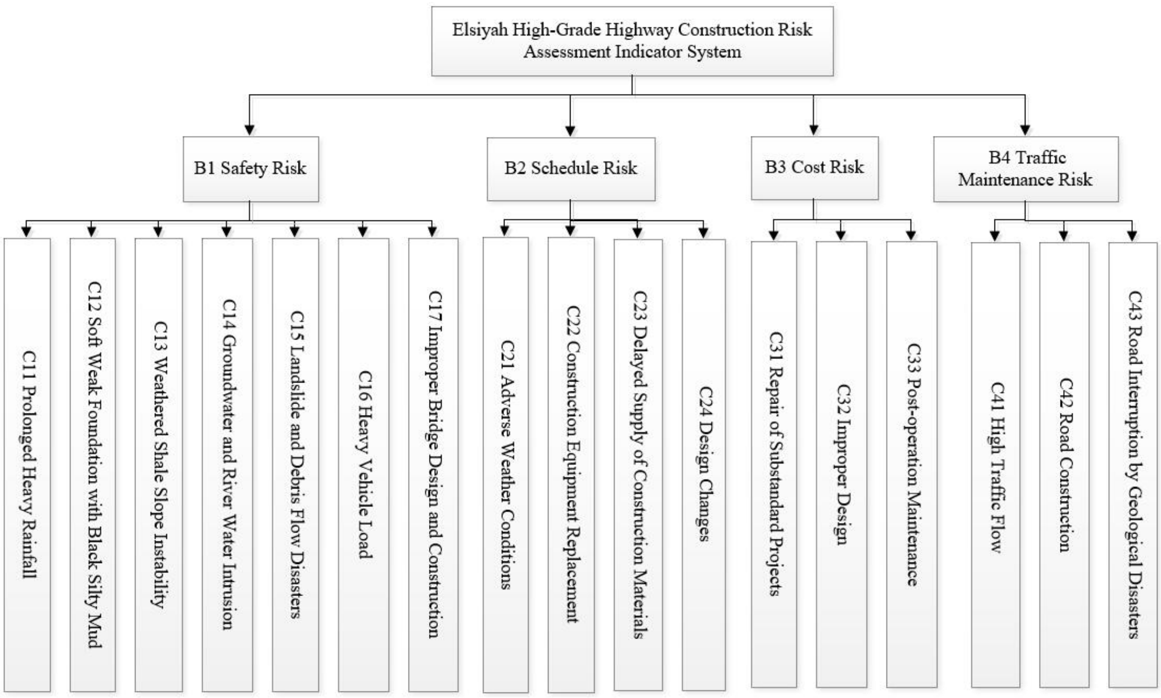

Figure 2. Elsiyah high-grade highway construction risk assessment indicator system

Based on the theories discussed earlier, through the summary and analysis of a large amount of relevant research and similar engineering examples, and combining the geological survey results of the Elsiyah Highway, local Bolivian policies, government and public risk preferences, 20 experienced experts familiar with the project were invited to use the Delphi method to screen indicators, constructing the risk assessment indicator system as shown in Figure 2.

2.3 High-Grade Highway Construction Risk Assessment

2.3.1 AHP-EWM combined weighting model based on game theory principles

Currently, there are many methods for determining indicator weights, which can generally be divided into subjective and objective weighting methods [27]. Subjective weighting methods determine weights based on expert subjective judgments, which are simple to operate but lack objectivity and require high expertise from evaluators. Objective weighting methods determine weights based on the relationships among original data, which have a solid mathematical theoretical basis but may not always align well with practical engineering situations.

To retain the advantages of both subjective and objective weighting methods and compensate for their deficiencies, and to address the issue of strong subjectivity in the calculation process of evaluation indicator weights, this study uses the AHP to calculate subjective weights and the EWM to calculate objective weights. Finally, a game theory-based combined weighting approach is adopted to process the results of both weights.

Principles and Steps of the AHP

The AHP is a hierarchical weighting decision analysis method [28]. This method views the research object as a system and makes decisions in a manner of decomposition, comparative judgment, and synthesis. It has become an important tool for system analysis, developed after mechanistic and statistical analyses, and its computational process and steps are shown in Figure 3.

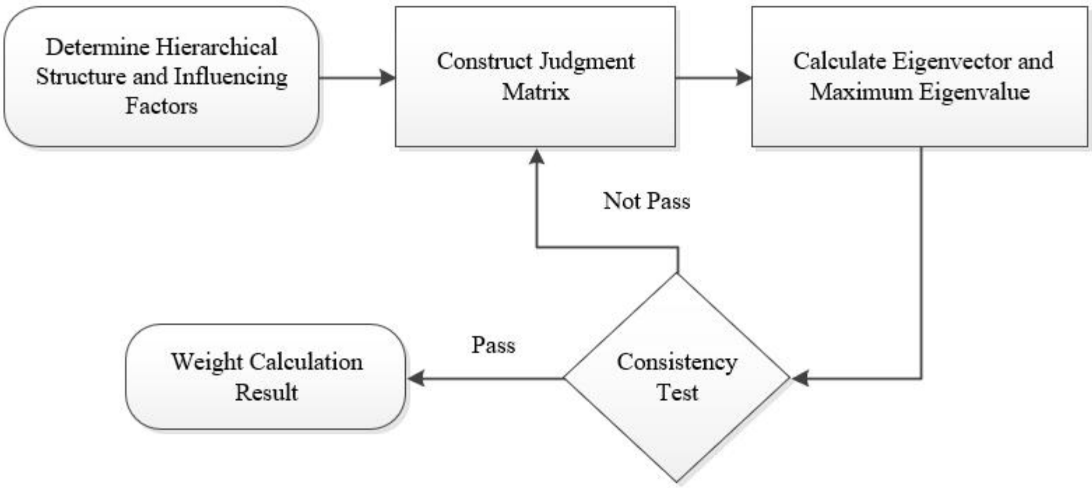

Figure 3. Flowchart of AHP

(1) Construct Judgment Matrix

Table 1. Evaluation scale of judgment matrix

Scale (a_{ij})	**Importance Level**
1	Elements i and j are equally important
3	Element i is slightly more important than element j
5	Element i is obviously more important than element j
7	Element i is strongly more important than element j
9	Element i is extremely more important than element j
$2, 4, 6, 8$	Middle values of importance levels for adjacent scales

Invite experts to score each risk factor in the risk assessment indicator system, constructing a judgment matrix for elements on the same level, facilitating pairwise comparisons. The specific form is shown in Eq. (1).

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} & \dots & a_{1j} \\ a_{21} & a_{22} & a_{23} & \dots & a_{2j} \\ a_{31} & a_{32} & a_{33} & \dots & a_{3j} \\ \dots & \dots & \dots & \dots & \dots \\ a_{i1} & a_{i2} & a_{i3} & \dots & a_{ij} \end{pmatrix} \tag{1}$$

where, a_{ij} represents the importance of the i-th factor relative to the j-th factor in the risk assessment indicator system, which can be assigned using a 1-9 scale [29], as shown in Table 1. When $i = j,\ a_{ij},\ a_{ji} = 1/a_{ij}$.

(2) Calculation of Subjective Weight

The purpose of constructing a judgment matrix is to determine the subjective weight value of the i-th element, W_{Hi}, through the calculation of the judgment matrix. The process of determining the relative weights of factors at each indicator level based on the established judgment matrix is as follows:

1) Determine the maximum eigenvalue λ_{max} of the judgment matrix;

2) Calculate the corresponding eigenvector based on the maximum eigenvalue;

3) Normalize the eigenvector, and the value of each element after normalization represents the relative weight W_{Hi} of its corresponding factor.

When constructing the judgment matrix, due to the complexity of risk factors in the evaluation indicator system, logical errors may occur during the assignment process. These errors are hard to avoid but should be limited within a certain range. Therefore, Eq. (2) can be used for consistency testing.

$$C \cdot R = \frac{\lambda_{\max} - n}{(n-1)RI} \tag{2}$$

where, RI, the Random Index, can be obtained from a lookup table. When $C \cdot R < 0.1$, it is considered that the consistency is acceptable, and the hierarchy single sorting is effective. Otherwise, if there is a significant deviation, re-evaluation is necessary. RI values are shown in Table 2.

Table 2. RI values

Matrix Order	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
RI	0.90	1.12	1.24	1.32	1.41	1.46	1.49	1.52	1.54	1.56

Principles and Steps of EWM

The EWM is an objective weighting method that determines the weights of indicators based on the entropy size of each indicator [30]. It calculates the entropy value of indicators to determine their dispersion and influence weight in the evaluation. As this method considers only the dispersion of data, it has a strict mathematical significance and regularity, avoiding subjectivity and fully reflecting the objective information of the indicators. However, its limitation lies in the tendency to overlook the experience of decision-makers. The process and steps of the EWM are shown in Figure 4.

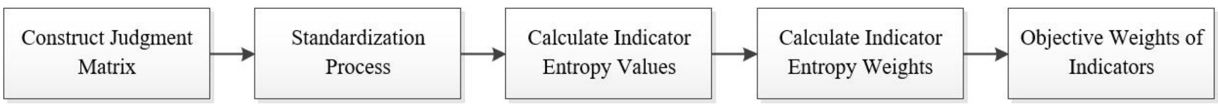

Figure 4. Flowchart of EWM

(1) Obtain the Original Evaluation Data Matrix

Invite n experts to score m evaluation indicators, obtaining a judgment matrix with an order of $m \times n$. The scoring scale can be defined on a 1-9 scale. The risk level of evaluation indicators is divided into five categories: low risk, relatively low risk, moderate risk, relatively high risk, and high risk, assigned with values of 1, 3, 5, 7, 9, respectively. If a risk level falls between two adjacent values, the number between the two values is used, which are 2, 4, 6, and 8, respectively. The judgment matrix X is shown in Eq. (3).

$$X = (X_{ij})_{m \times n} = \begin{pmatrix} x_{11} & x_{12} & x_{13} & \dots & x_{1n} \\ x_{21} & x_{22} & x_{23} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & x_{m3} & \dots & x_{mn} \end{pmatrix} \tag{3}$$

where, X_{ij} represents the score given by the j-th expert to the i-th indicator.

(2) Standardization of Matrix Data

After obtaining the original data, it is necessary to standardize the data. This step is divided into two forms. The processing for 'the larger, the better' type indicators is referred to as positive processing, as shown in Eq. (4):

$$p_{ij} = \frac{x_{ij} - \min_j(x_{ij})}{\max_j(x_{ij}) - \min_j(x_{ij})} \tag{4}$$

The processing for 'the smaller, the better' type indicators is referred to as negative processing, as shown in Eq. (5):

$$p_{ij} = \frac{\max_j(x_{ij}) - x_{ij}}{\max_j(x_{ij}) - \min_j(x_{ij})} \tag{5}$$

where, $\min_j(x_{ij})$ is the lowest score given by experts for the i-th indicator. $\max_j(x_{ij})$ is the highest score given by experts for the i-th indicator. p_{ij} is the standardized score for the i-th indicator given by the j-th expert, and $0 < p_{ij} < 1$. After standardization, a standardized judgment matrix is obtained.

(3) Calculate the Entropy Value of Indicators

$$e_i = -k \times \sum_{i=1}^{n} z_{ij} \times \ln z_{ij} \tag{6}$$

where, $0 < i < m$; e_i represents the entropy value of the i-th evaluation indicator, $k = \frac{1}{\ln n}$, $z_{ij} = \frac{p_{ij}}{\sum_{j=1}^{n} p_{ij}}$; and it is stipulated that, when $z_{ij} = 0$, $z_{ij} \times \ln z_{ij} = 0$.

(4) Calculate the Entropy Weight W_{Ei} (Objective Weight) of the i-th Indicator

$$W_{Ei} = \frac{1 - e_i}{m - \sum_{i=1}^{m} e_i} \tag{7}$$

where, W_{Ei} is the entropy weight of the i-th evaluation indicator, $0 < D_i < 1$, $\sum\limits_{i=1}^{m} D_i = 1$.

Combined Weighting Model Based on Game Theory Principles

Game theory-based combined weighting is an approach that considers the phenomenon of significant discrepancies between subjective and objective weights. It simulates a set of combined weights with the smallest deviation from both subjective and objective weights through an algorithm [31]. The use of this method to calculate combined weights can effectively compensate for the shortcomings of a single weighting method, making the weight values more consistent with actual situations and the evaluation results more scientific and reasonable.

The specific steps of the combined weighting based on game theory are as follows [32]:

(1) Construct the Basic Weight Vector Set

Assuming M subjective and objective weighting methods are used to assign weights to the evaluation indicators, M sets of combined weights are obtained. Based on these M sets of weights, construct the basic weight vector set, as shown in Eq. (8):

$$w_k = (w_{k1}, w_{k2}, ..., w_{kn}), k = 1, 2, ..., M \tag{8}$$

Then any linear combination of M different weight vectors is as shown in Eq. (9):

$$w = \sum_{k=1}^{m} a_k w_k^T, a_k > 0 \tag{9}$$

where, w represents a comprehensive weight value of the M sets of weights; a_k represents linear combination coefficients.

(2) Solve for the Optimal Combined Weight

When solving the optimal combined weight, it is necessary to calculate the most satisfactory weight vector w based on the concept of game theory. This process can be transformed into optimizing the linear combination coefficients a_k. The optimization goal is to minimize the deviation between w and each w_k, thus determining a set of optimal combined weights. The strategy model for this is shown in Eq. (10):

$$\min = \left\| \sum_{k=1}^{M} a_k w_k^T - w_i \right\|_2, i = 1, 2, ..., M \tag{10}$$

where, w_i represents the weight vector of indicators determined by the i-th method.

Based on the differential properties of matrices, the first-order derivative condition for optimization is as shown in Eq. (11):

$$\sum_{k=1}^{M} a_k w_{\mathrm{i}} w_k^T = w_i w_i^T \tag{11}$$

The corresponding system of linear equations is as shown in Eq. (12):

$$\begin{bmatrix} w_1 w_1^T & w_1 w_2^T & ... & w_1 w_M^T \\ w_2 w_1^T & w_2 w_2^T & ... & w_2 w_M^T \\ ... & ... & ... & ... \\ w_M w_1^T & w_M w_2^T & ... & w_M w_M^T \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ ... \\ a_M \end{bmatrix} = \begin{bmatrix} w_1 w_1^T \\ w_2 w_2^T \\ ... \\ w_M w_M^T \end{bmatrix} \tag{12}$$

According to the system of equations, $(a_1, a_2, ...a_M)$ can be calculated and then normalized to obtain $a_k^* = a_k / \sum a_k$. Substituting this into Eq. (9) gives the combined weight vector, as shown in Eq. (13):

$$w^* = \sum_{k=1}^{M} a^* w_k^T \tag{13}$$

2.3.2 Construction risk evaluation model based on fuzzy mathematics theory

Risk Evaluation Level Standard Division

Referring to the *Guidelines for Safety Risk Assessment of Highway Bridge and Tunnel Engineering (Trial) and Basic Norms for Safety Production Risk Identification, Assessment, and Control in Highway and Waterway Industries (Trial)* and other related materials, this study divides the risks of high-grade highway construction in complex environments into 5 levels. Additionally, value ranges are designated for each risk level. The corresponding risk evaluation standards and value ranges for each level vary. Different risk levels require different response strategies, and the formulation of these strategies should be in line with local actual conditions. For the Elsiyah Highway in Bolivia, after extensive communication and discussion with the local National Public Works Department, the formulated response strategies are as listed in Table 3.

Table 3. Risk level division and response strategies

Risk Value	Risk Level	Response Strategy
$(0 \sim 2]$	Low Risk	The risk level is acceptable, current measures are effective, and no additional technical or management preventive measures are needed.
$(2 \sim 4]$	Relatively Low Risk	The risk level is conditionally acceptable, and corresponding measures can be taken if conditions such as cost and schedule are met.
$(4 \sim 6]$	Moderate Risk	The risk level is conditionally acceptable, and the project has the necessity to implement further preventive measures to enhance safety.
$(6 \sim 8]$	Relatively High Risk	The risk level is conditionally acceptable, and measures to reduce risks must be implemented, with an emergency plan prepared.
$(8 \sim 10]$	High Risk	The risk level is unacceptable, and effective measures must be taken to reduce the risk level to relatively high risk or below; if the cost of control is too high, consider changing the plan or abandoning the project.

Construction of the Risk Evaluation Model

During the construction of high-grade highways in complex environments, the specific forms and severity of risks often remain uncertain and possess a certain degree of fuzziness. Additionally, most risks cannot be quantified based on actual data; instead, many risk indicators require domain experts to measure them based on their experience. However, due to different levels of expertise among experts, there is subjectivity in the process of acquiring project information, and differences exist in the quantification process.

The fuzzy comprehensive evaluation method is an evaluation methodology based on fuzzy mathematics. This method transforms qualitative evaluation into quantitative evaluation through the theory of membership degree, considering multiple factors affecting the subject comprehensively. It is characterized by clear results and strong systematicness, effectively addressing fuzzy and hard-to-quantify issues, and can quantitatively process factors with fuzzy boundaries and difficult quantification.

This study employs the fuzzy comprehensive evaluation method to construct a risk evaluation model, with the following steps:

(1) Determine the Fuzzy Comprehensive Evaluation Factor Set U

The fuzzy comprehensive evaluation factor set is a collection of various factors affecting the degree of risk. U={C11 Prolonged Heavy Rainfall, C12 Soft Weak Foundation with Black Silty Mud, C13 Weathered Shale Slope Instability, . . . , C43 Road Interruption by Geological Disasters}.

(2) Establish the Comprehensive Evaluation Comment Set V

The comment set is a collection of indicators measuring the merits and demerits of evaluation factors, with each level corresponding to a fuzzy subset. By using the comment set, the membership degree of each indicator can be calculated for comprehensive evaluation. V={Low Risk, Relatively Low Risk, Moderate Risk, Relatively High Risk, High Risk}.

(3) Establish the Fuzzy Judgment Matrix R

The fuzzy relation matrix R defines a fuzzy relation from the evaluation factor set U to the comment set V when conducting a comprehensive evaluation of each evaluation indicator in the factor set according to the evaluation set. This can be seen as a kind of fuzzy mapping or membership degree, as shown in Eq. (14):

$$R=\begin{pmatrix} r_{11} & r_{12} & r_{13} & \cdots & r_{15} \\ r_{21} & r_{22} & r_{23} & \cdots & r_{25} \\ r_{31} & r_{32} & r_{33} & \cdots & r_{35} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ r_{i1} & r_{i2} & r_{i3} & \cdots & r_{i5} \end{pmatrix} \tag{14}$$

where, r_{ij} represents the degree of membership of the i-th factor for the j-th evaluation level.

The definition of membership degree is as follows: For any element C_{ij} in the evaluation factor set U, there is a corresponding number, $r_{ij} \in [0, 1]$, known as the degree of membership of C_{ij} for the j-th level in the comment set V. The closer the membership degree is to 1, the higher the degree of r_{ij} belonging to the evaluation level j. When C_{ij} changes in U, r_{ij} becomes a membership degree function. In this study, the membership degree function is as shown in Eq. (15):

$$r_{ij} = d_{ij}/n \tag{15}$$

where, d_{ij} is the number of experts who evaluate the i-th indicator to be at the j-th level. n is the total number of experts participating in the evaluation of a certain indicator. That is, the more experts evaluate the i-th indicator as level j, the greater the degree of membership of the i-th indicator for the evaluation level j.

(4) Determine the Weight Vector W of Evaluation Indicators

The scientificity and rationality of the weights of evaluation indicators will directly affect the final result of risk evaluation. Using the weight coefficients obtained from Eq. (13), combined with the subjective weights W_H and objective weights W_E, and calculated using Eq. (9), the weight vector is as shown in Eq. (16):

$$W = \{W_1\ , W_2, W_3, W_4\} \tag{16}$$

$W_i = \alpha_1 \times W_{Hi} + \alpha_2 \times W_{Ei}$

(5) Calculate the Fuzzy Evaluation Vector B

Perform fuzzy synthesis calculations on the weight vector W and fuzzy relation matrix R determined earlier, obtaining the fuzzy evaluation vector B, as shown in Eq. (17):

$$B = W \times R \tag{17}$$

(6) Comprehensive Evaluation to Determine Risk Level

Based on the comment set V, construct the starting score value vector set $S = (1, 3, 5, 7, 9)$. According to the principle of maximum membership degree, calculate the comprehensive risk value F for the evaluation object. Based on the calculation results and in conjunction with the risk level division standards, determine the overall risk level, as shown in Eq. (18):

$$F = B \times S \tag{18}$$

3 Results

3.1 Calculation of Risk Evaluation Indicator Weights

Using the combined weight calculation model constructed earlier, after normalization, the values obtained are $\alpha_1 = 0.637$ and $\alpha_2 = 0.363$. The comprehensive weights of the risk evaluation indicators for the Elsiyah high-grade highway construction are calculated as shown in Table 4 (Figure 5).

Similarly, the weights of each indicator at the criterion level are shown in Figure 6.

Table 4. Comprehensive weights of risk evaluation indicators for Elsiyah high-grade highway construction

Criterion Layer Indicators	Subjective Weight W_H	Objective Weight W_E	Comprehensive Weight W
C11 Prolonged Heavy Rainfall	0.084	0.086	0.085
C12 Soft Weak Foundation with Black Silty Mud	0.158	0.042	0.116
C13 Weathered Shale Slope Instability	0.113	0.086	0.103
C14 Groundwater and River Water Intrusion	0.048	0.086	0.062
C15 Landslide and Debris Flow Disasters	0.027	0.147	0.071
C16 Heavy Vehicle Load	0.014	0.042	0.024
C17 Improper Bridge Design and Construction	0.022	0.042	0.029
C21 Adverse Weather Conditions	0.076	0.042	0.064
C22 Construction Equipment Replacement	0.026	0.041	0.031
C23 Delayed Supply of Construction Materials	0.015	0.042	0.025
C24 Design Changes	0.045	0.042	0.044
C31 Repair of Substandard Projects	0.037	0.086	0.055
C32 Improper Design	0.067	0.044	0.059
C33 Post-operation Maintenance	0.020	0.044	0.029
C41 High Traffic Flow	0.077	0.042	0.064
C42 Road Construction	0.122	0.039	0.092
C43 Road Interruption by Geological Disasters	0.048	0.044	0.047

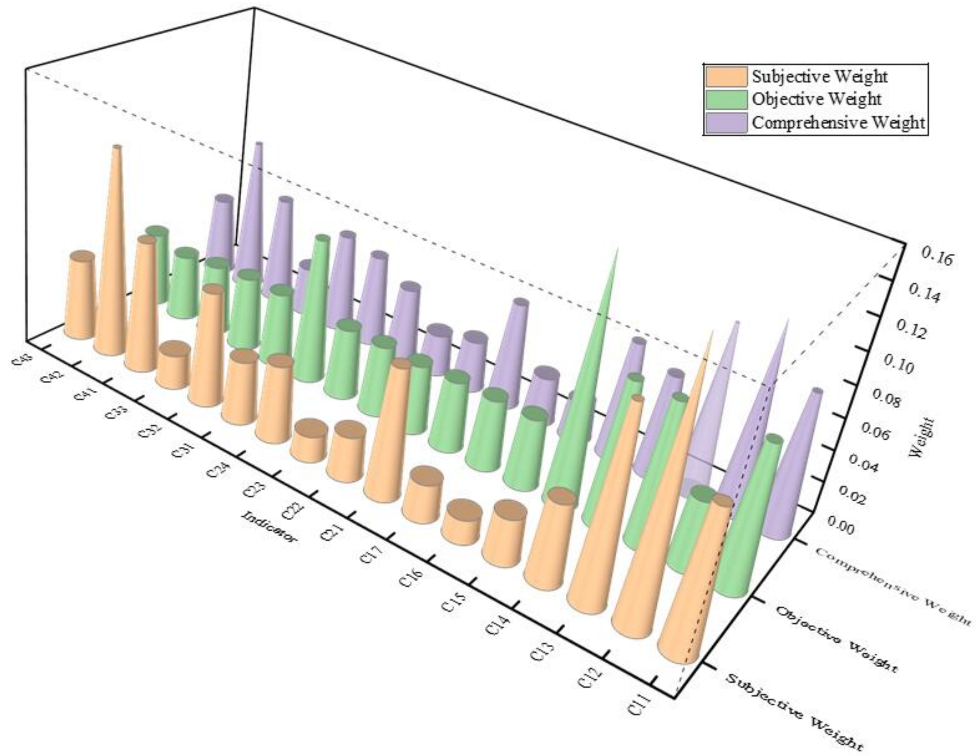

Figure 5. Elsiyah high-grade highway construction risk evaluation indicator system

3.2 Calculation of Construction Risk Level

3.2.1 Single factor fuzzy comprehensive evaluation

(1) Scoring the safety risk evaluation factor set U according to the established risk evaluation level set V. Based on the results of the Delphi survey, the scoring results of 20 experts on the risk levels of various risk indicators during the construction period of the Elsiyah project are shown in Table 5.

(2) Based on the experts' scoring of the secondary indicators at the criterion level, determine the fuzzy relation matrix of the factor layer regarding the criterion layer using Eqs. (14) and (15):

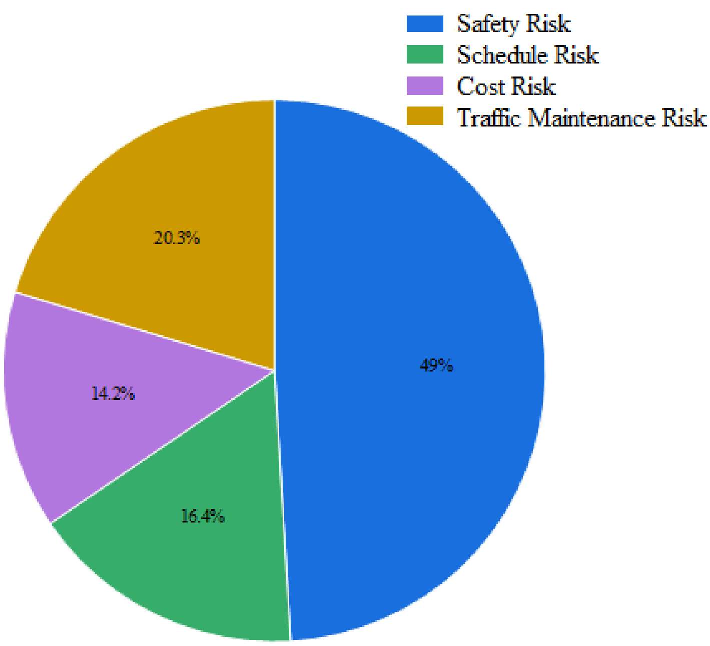

Figure 6. Elsiyah high-grade highway construction risk evaluation indicator system

Table 5. Scoring results of risk evaluation factors

Evaluation Factor		Low Risk	Relatively Low Risk	Moderate Risk	Relatively High Risk	High Risk
Safety Risk	C11 Prolonged Heavy Rainfall	0	1	3	7	9
	C12 Soft Weak Foundation with Black Silty Mud	0	0	2	6	12
	C13 Weathered Shale Slope Instability	0	1	5	6	8
	C14 Groundwater and River Water Intrusion	1	2	5	8	4
	C15 Landslide and Debris Flow Disasters	2	3	4	9	2
	C16 Heavy Vehicle Load	6	4	3	2	3
	C17 Improper Bridge Design and Construction	2	4	7	5	2
Schedule Risk	C21 Adverse Weather Conditions	3	2	4	6	5
	C22 Construction Equipment Replacement	2	5	6	4	3
	C23 Delayed Supply of Construction Materials	4	6	3	4	3
	C24 Design Changes	2	4	6	5	3
Cost Risk	C31 Repair of Substandard Projects	3	3	6	7	1
	C32 Improper Design	1	1	8	6	4
	C33 Post-operation Maintenance	4	5	7	3	1
Traffic Maintenance Risk	C41 High Traffic Flow	1	2	5	6	6
	C42 Road Construction	0	2	4	8	6
	C43 Road Interruption by Geological Disasters	1	1	6	5	7

B_1: Safety Risk

$$B_1 = \begin{pmatrix} 0 & 0.05 & 0.15 & 0.35 & 0.45 \\ 0 & 0 & 0.1 & 0.3 & 0.6 \\ 0 & 0.05 & 0.25 & 0.3 & 0.4 \\ 0.05 & 0.1 & 0.25 & 0.4 & 0.2 \\ 0.1 & 0.15 & 0.2 & 0.45 & 0.1 \\ 0.3 & 0.2 & 0.15 & 0.1 & 0.15 \\ 0.1 & 0.2 & 0.35 & 0.25 & 0.1 \end{pmatrix} \tag{19}$$

B_2: Schedule Risk

$$B_2 = \begin{pmatrix} 0.15 & 0.1 & 0.2 & 0.3 & 0.15 \\ 0.1 & 0.25 & 0.3 & 0.2 & 0.15 \\ 0.2 & 0.3 & 0.15 & 0.2 & 0.15 \\ 0.1 & 0.2 & 0.3 & 0.25 & 0.15 \end{pmatrix} \tag{20}$$

B_3: Cost Risk

$$B_3 = \begin{pmatrix} 0.15 & 0.15 & 0.3 & 0.35 & 0.05 \\ 0.05 & 0.05 & 0.4 & 0.3 & 0.2 \\ 0.2 & 0.25 & 0.35 & 0.15 & 0.05 \end{pmatrix} \tag{21}$$

B_4: Traffic Maintenance Risk

$$B_4 = \begin{pmatrix} 0.05 & 0.1 & 0.25 & 0.3 & 0.3 \\ 0 & 0.1 & 0.2 & 0.4 & 0.3 \\ 0.05 & 0.05 & 0.3 & 0.25 & 0.35 \end{pmatrix} \tag{22}$$

(3) According to the combined weighting method mentioned above, determine the local weights of the factor layer indicators:

$WB_1 = (0.173, 0.237, 0.211, 0.126, 0.144, 0.049, 0.060)$

$WB_2 = (0.389, 0.192, 0.151, 0.268)$

$WB_3 = (0.385, 0.413, 0.202)$

$WB_4 = (0.317, 0.453, 0.230)$

(4) Calculate the single-factor fuzzy comprehensive evaluation set for the criterion layer:

Using a weighted average type comprehensive evaluation model, the single-factor fuzzy comprehensive evaluation vectors for each risk category are obtained as follows:

Fuzzy Comprehensive Evaluation Vector for Safety Risk:

$C_{\text{Safety Risk}} = B_1 WB_1 = (0.041, 0.075, 0.191, 0.330, 0.357)$

Fuzzy Comprehensive Evaluation Set for Schedule Risk:

$C_{\text{Schedule Risk}} = B_2 WB_2 = (0.135, 0.186, 0.238, 0.252, 0.15)$

Fuzzy Comprehensive Evaluation Set for Cost Risk:

$C_{\text{Cost Risk}} = B_3 WB_3 = (0.119, 0.129, 0.351, 0.289, 0.112)$

Fuzzy Comprehensive Evaluation Set for Traffic Maintenance Risk:

$C_{\text{Traffic Maintenance Risk}} = B_4 WB_4 = (0.027, 0.089, 0.239, 0.334, 0.312)$

3.2.2 Overall fuzzy comprehensive evaluation

(1) Construct the Fuzzy Comprehensive Evaluation Judgment Matrix

Construct the overall fuzzy comprehensive evaluation judgment matrix using the single-factor fuzzy evaluation vectors mentioned above:

$$R= \begin{pmatrix} 0.041 & 0.075 & 0.191 & 0.330 & 0.357 \\ 0.135 & 0.186 & 0.238 & 0.252 & 0.15 \\ 0.119 & 0.129 & 0.351 & 0.289 & 0.112 \\ 0.027 & 0.089 & 0.239 & 0.334 & 0.312 \end{pmatrix} \tag{23}$$

(2) Calculate the Overall Comprehensive Evaluation Vector

Using the combined weight W of the criterion layer indicators determined by the previous combined weighting method and the overall fuzzy judgment matrix R, perform fuzzy synthesis operation to calculate the overall fuzzy comprehensive evaluation vector B.

$W = (0.490, 0.164, 0.142, 0.203)$

$B = WR = (0.064609, 0.103639, 0.230981, 0.311868, 0.27877)$

(3) Determine the Overall Risk Level of the Project

Construct the score value vector S using the starting scores assigned to the five levels “Low Risk, Relatively Low Risk, Moderate Risk, Relatively High Risk, High Risk” in the construction safety risk comment set.

$$S = \begin{pmatrix} 1 \\ 3 \\ 5 \\ 7 \\ 9 \end{pmatrix} \tag{24}$$

$$F = B \times S = 6.22 \tag{25}$$

To accurately grasp the specific risk levels of different types of risks during the project construction and propose targeted risk control measures, calculate the risk values and corresponding risk levels for each criterion layer indicator as shown in Table 6.

Table 6. Risk values and risk levels for each criterion layer indicator

Risk Category	Safety Risk	Schedule Risk	Cost Risk	Traffic Maintenance Risk
Risk Value	6.744	4.997	5.292	6.635
Risk Level	Relatively High Risk	Moderate Risk	Moderate Risk	Relatively High Risk

According to Tables 3 and 6, the overall project risk, safety risk, and traffic maintenance risk are all relatively high, requiring implementation of risk reduction measures and preparation of emergency plans. The project's schedule risk and cost risk are moderate, necessitating some preventive measures to reduce the risks.

4 Discussion

(1) Among the four types of risks at the criterion layer, Safety Risk > Traffic Maintenance Risk > Cost Risk > Schedule Risk. Safety risk and traffic maintenance risk are at a relatively high-risk level. For safety risk, the Elsiyah Highway is extensively distributed with adverse geological conditions. Geological survey results show that risk areas account for over 20% of the total length of the route, mainly comprising strongly weathered shale and slate, along with numerous black muddy soil sections with extremely poor strength. Frequent geological disasters such as rockfalls, collapses, and landslides are common due to atmospheric and rainwater influences. For traffic maintenance risk, as part of the "Chile-Brazil" international transport corridor, the Elsiyah Highway plays a vital role in Bolivia's transport network. Therefore, maintaining traffic flow during construction is crucial despite challenges posed by weather, geographical environment, and heavy vehicle loads (over 50% of the traffic comprises heavy freight vehicles). The evaluation results conform to the actual situation, necessitating effective risk management and control measures, such as building retaining structures, replacing shallow black muddy soil layers, using half-width construction methods, and temporarily hardening some road surfaces for traffic maintenance. Cost and schedule risks are at a moderate level, requiring further implementation of preventive measures. It is advisable to optimize and enhance existing construction techniques and structural designs in line with actual construction situations.

(2) Combining subjective and objective weights leverages expert experience and on-site survey and monitoring data while effectively avoiding negative impacts caused by experts' recognition levels and personal preferences. This enhances the objectivity and practicality of the evaluation results. Applying mathematical theories reduces the impact of uncertainties, constructing an AHP-EWM-FUZZY model for a more accurate assessment of construction risks. The research findings are applicable to risk evaluations of other highway construction projects due to their generalizability. The study utilizes widely applied and recognized methods in subjective weighting, objective weighting, and handling fuzziness and uncertainty, making the model easily understandable and applicable for broader use.

(3) The construction unit of the Elsiyah high-grade highway precisely identified 13 high and relatively high-risk segments out of 28 based on this study's findings, and determined factors causing significant risks in these segments. It is important to note that while the results indicate the direction of risk control, further specific measures should be taken in accordance with actual site conditions. For instance, controlling rainwater is unrealistic, so focus should be on managing risks associated with the black muddy soil foundation. Additionally, risk control strategies should be adapted to local conditions. For instance, some sections laid along valleys are limited by road width and cannot adopt half-width construction methods. In such cases, adding detour segments might be necessary to maintain traffic flow. Overall, based on the research findings and actual conditions, the Elsiyah construction unit implemented targeted measures, including optimizing routes, half-width construction, temporary road surface hardening, drainage system improvements, and using new types of slope support. The highway was successfully opened on November 23, 2023, and the research results provided theoretical and technical support for the smooth construction of the project.

(4) The accuracy of the evaluation results largely depends on the rationality of the evaluation indicator system. This study's evaluation indicator system was primarily constructed based on the characteristics of the Elsiyah high-grade highway. When applying the model to risk evaluation and control of other similar projects, it is necessary to further optimize and improve the indicator system based on specific project characteristics. The proposed method for establishing the indicator system is generalizable, still allowing for the use of Hall's three-dimensional structure and system safety theory to summarize and classify factors, and then using the Delphi method for selection and identification of major risk factors. The challenge remains in identifying and selecting major risk factors, as the final results based on the Delphi method are influenced by the expertise and level of the experts, requiring them to have a clear understanding of the project characteristics and considerable evaluation experience.

5 Conclusion

By identifying and analyzing risks in high-grade highway construction from three dimensions: different construction times, different structural types, and different sources of risk, a new approach for scientifically and accurately establishing a risk indicator system is provided. Considering the challenges in conducting risk evaluation for actual construction projects, a risk evaluation model is proposed. Calculating evaluation indicator combined weights based on game theory principles and constructing a comprehensive evaluation model using fuzzy mathematics theory overcomes the drawbacks of single weighting methods and effectively reduces the impact of fuzziness, offering a more accurate assessment method. Taking the Elsiyah high-grade highway project as an example, the risk evaluation model constructed in this study calculated the project construction risks. The calculation results align well with the actual project, guiding the construction process and verifying the scientific nature and practicality of the constructed model.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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