

Article

An Integrated Pythagorean Fuzzy TOPSIS Framework for Occupational Safety Risk Prioritization in Bridge Construction Projects

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Abstract

With the continuous expansion of government investment in transportation infrastructure, transportation investment has increased, and bridge engineering has flourished. However, safety accidents frequently occur during the construction stage, so the safety situation of bridge construction units remains unfavorable. Bridge construction is a high-risk occupational activity because operations are performed under complex site conditions, variable geological and hydrological environments, long construction periods, and frequent interaction among workers, machinery, materials, technologies, and surrounding environments. Existing bridge construction safety assessment methods have improved hazard identification and risk prioritization; however, many still have difficulty representing uncertainty, hesitation, and subjective judgment in expert-based occupational safety evaluation. To address this problem, this study proposes an integrated Pythagorean fuzzy TOPSIS decision-support framework for occupational safety risk prioritization in bridge construction projects. A safety risk indicator system is established from five dimensions: human, management, material, technical, and environmental factors. Expert judgments are expressed using linguistic variables and converted into Pythagorean fuzzy numbers. The Pythagorean fuzzy weighted average operator is used to aggregate multi-expert evaluation information, and criterion importance is determined from expert-based Pythagorean fuzzy assessments. The model is applied to a bridge reconstruction project, followed by sensitivity analysis and comparison with several existing methods. The results indicate that low work quality, non-standard construction, construction site environment, lack of safety awareness, and insufficient construction technology are the most critical occupational safety risk indicators. The proposed method provides a practical decision-support tool for identifying priority safety risks under fuzzy and uncertain evaluation conditions.

Keywords: bridge construction; occupational safety; safety risk prioritization; Pythagorean fuzzy set; TOPSIS; multi-criteria decision-making; construction management; leading indicators



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1. Introduction

Bridge construction is an essential part of transportation infrastructure development. Bridges are built to cross rivers, valleys, railways, highways, urban roads, and other

physical obstacles, and their construction normally involves complex structural systems, temporary works, heavy machinery, high-altitude operations, wet operations, and long construction periods. Compared with ordinary building projects, bridge construction is more strongly affected by geological conditions, hydrological changes, site mobility, extreme weather, and surrounding traffic or environmental constraints. These characteristics make bridge construction a typical high-risk engineering activity.

Safety risk assessment is therefore a necessary task in bridge construction management. Many accidents in construction projects are not caused by a single factor, but by the interaction of human behavior, equipment condition, management defects, technical complexity, and environmental uncertainty. Previous studies have shown that construction safety performance can be improved by identifying leading indicators, unsafe behaviors, and key risk factors before accidents occur [1–3]. However, bridge construction safety assessment remains difficult because many risk factors are uncertain, qualitative, and difficult to measure directly.

At the level of building safety management systems in construction enterprises, this explains the core value of establishing a complete safety management system for ensuring safe production on construction sites, summarizes the main components of the enterprise safety management system, and clarifies the implementation path for constructing a standardized and regulated safety management system. Finally, it emphasizes that the safety production awareness, sense of responsibility, and safety-related scientific and cultural competence of all employees are the key elements supporting the efficient operation of the safety management system [2,3]. Several studies have attempted to improve bridge and construction safety assessment by using multi-criteria decision-making and uncertainty modeling methods. For example, Wu et al. [4] developed a bridge construction safety risk assessment model in a marine environment by combining CRITIC and TOPSIS. Li et al. [5] proposed a cloud entropy weight method for highway bridge construction safety risk assessment. These studies confirm that bridge construction safety risk assessment requires systematic indicators, structured decision logic, and practical interpretation of risk results.

In practical bridge construction projects, expert judgment is still widely used because complete accident data and quantitative site information are often unavailable. Experts usually evaluate risks through linguistic expressions, such as low, medium, high, or extremely high. Such information contains fuzziness and hesitation. Traditional TOPSIS, proposed by Hwang and Yoon [6], is effective for ranking alternatives according to their distance from the positive and negative ideal solutions, but it is mainly designed for crisp decision data. Fuzzy extensions of TOPSIS have therefore been developed to handle uncertain decision environments [7,8].

Pythagorean fuzzy sets provide a useful framework for representing uncertain evaluation information. Compared with intuitionistic fuzzy sets, Pythagorean fuzzy sets relax the constraint between membership and non-membership degrees, allowing decision-makers to express a wider range of uncertainty and hesitation [8,9]. This feature is suitable for bridge construction safety assessment because experts may not be able to give precise numerical judgments for risk severity, occurrence probability, or uncontrollability. By combining Pythagorean fuzzy sets with TOPSIS, risk indicators can be ranked more flexibly under uncertain expert evaluation conditions.

From a systems safety perspective, bridge construction accidents are not the result of isolated unsafe acts only, but of interactions among workers, management systems, technical procedures, materials, machinery, and the physical environment. The proposed indicator system reflects this socio-technical structure by evaluating human, management, material, technical, and environmental dimensions simultaneously. The ranked indicators

can therefore be interpreted as leading occupational safety indicators because they identify unsafe conditions and management weaknesses before accident occurrence.

This study proposes a Pythagorean fuzzy TOPSIS decision model for safety risk assessment in bridge construction projects. A safety risk indicator system is developed based on five categories: human factors, management factors, material factors, technical factors, and environmental factors. Twelve secondary indicators are evaluated by five experienced experts under three criteria: severity, probability, and uncontrollability. The expert judgments are converted into Pythagorean fuzzy numbers, aggregated using weighted operators, and ranked using a TOPSIS-based closeness index.

The main contribution of this study is threefold. First, a bridge construction occupational safety risk indicator system is constructed according to the characteristics of bridge construction and expert evaluation. Second, Pythagorean fuzzy numbers are used to represent the uncertainty and hesitation contained in linguistic expert judgments. Third, the TOPSIS process is used to rank bridge construction safety risk indicators and support priority-based occupational safety management, including training, competency improvement, procedural control, and site-environment intervention.

This study aligns with integrated occupational safety management in construction by combining hazard identification, human-factor evaluation, expert-based uncertainty modelling, and multi-criteria risk prioritization into a structured decision-support framework. Unlike conventional bridge construction risk assessments that mainly report general risk levels, the proposed model identifies priority occupational safety risks and links them to actionable control measures across worker behavior, training, technical execution, management practices, and site-environment conditions.

The remainder of this paper is organized as follows. Section 2 reviews related works on bridge construction safety risk assessment and fuzzy multi-criteria decision-making methods. Section 3 presents the proposed Pythagorean fuzzy TOPSIS decision model. Section 4 describes the bridge reconstruction case and calculation results. Section 5 discusses the practical implications and limitations of the proposed method. Section 6 presents the conclusions and future research directions.

2. Related Works

2.1. Construction Safety Risk Assessment

Construction safety risk assessment has been widely studied because construction projects involve temporary works, changing site conditions, multiple participants, and high uncertainty. Unlike manufacturing systems, construction sites are not fixed production environments. Workspaces, crews, equipment, and construction procedures change continuously as the project progresses. This dynamic nature increases the difficulty of identifying hazards and controlling unsafe conditions. Previous studies have therefore emphasized the need to evaluate safety risks before accidents occur and to identify leading indicators that can support preventive safety management [1,2].

Many construction safety studies have focused on unsafe behavior, near-miss events, safety climate, and leading safety indicators. Behavior-based safety has been used to observe workers' unsafe actions and transform field observations into measurable safety indicators [3,10]. This type of study shows that effective safety risk assessment should not only identify risk factors but should also help managers understand their priority and practical implications.

In bridge construction, the safety risk problem is more complex because construction operations often involve deep foundations, high-altitude work, hoisting operations, river-crossing construction, large temporary structures, and difficult environmental conditions. Risk factors may come from workers, machinery, materials, methods, management, and the

external environment. Wu et al. [4] assessed bridge construction safety risks in a marine environment using CRITIC and TOPSIS models. Li et al. [5] developed a highway bridge construction safety risk assessment method based on the cloud entropy weight method. These studies indicate that bridge construction safety assessment requires a systematic index structure and a decision-making model that can handle multiple risk criteria.

Bridge construction safety risk assessment is still challenging for two reasons. First, risk factors are often qualitative and cannot be measured directly using complete numerical data. Second, bridge projects are usually unique, and accident data from one project may not be directly applicable to another project. Therefore, expert judgment remains important in bridge safety risk assessment. However, expert judgment is subjective and often expressed in vague linguistic terms. This makes fuzzy decision-making methods suitable for bridge construction safety evaluation because they can transform uncertain expert opinions into structured decision data.

Recent studies published in Buildings further show the relevance of integrated and decision-oriented occupational safety assessment. Yao et al. [11] proposed a bridge construction risk assessment method based on variable weight theory and cloud model theory, while Pham et al. [12] developed a hybrid EFA-AHP approach for prioritizing occupational safety factors in high-rise construction. Zhao et al. [13] proposed a vision-guided dynamic risk assessment framework for long-span bridge construction using DEMATEL-ISM-DBN modelling. These studies confirm that current construction safety research is moving toward integrated frameworks that combine risk identification, uncertainty modelling, prioritization, and practical safety intervention.

2.2. Multi-Criteria Decision-Making in Safety Risk Assessment

Safety risk assessment is naturally a multi-criteria decision-making problem. A safety risk indicator may have high severity but low probability, or high probability but relatively low uncontrollability. Therefore, ranking risk indicators requires the simultaneous consideration of several evaluation criteria. Multi-criteria decision-making methods have been widely used to solve such problems because they can integrate different criteria, weights, and expert preferences into a single decision framework [6,14].

TOPSIS is one of the most widely used multi-criteria decision-making methods. The basic idea of TOPSIS is that the best alternative should be closest to the positive ideal solution and farthest from the negative ideal solution [6]. Because of its simple calculation process and clear ranking logic, TOPSIS has been applied in engineering management, supplier selection, environmental assessment, safety evaluation, and construction decision-making. However, traditional TOPSIS assumes that decision data are crisp and deterministic. In practical safety assessment, this assumption is often unrealistic because expert evaluations usually contain uncertainty, hesitation, and linguistic judgment.

To overcome this limitation, fuzzy TOPSIS and intuitionistic fuzzy TOPSIS have been developed. Chen [15] used fuzzy TOPSIS to solve group decision-making problems under linguistic assessment information. Boran et al. [7] proposed an intuitionistic fuzzy group decision-making method based on TOPSIS. These methods improve traditional TOPSIS by allowing experts to express uncertain preferences. Nevertheless, intuitionistic fuzzy sets still have a relatively restrictive condition because the sum of the membership degree and non-membership degree must not exceed one. In more complex decision environments, experts may need a broader expression space to represent uncertain and hesitant information.

Pythagorean fuzzy sets provide a more flexible extension of intuitionistic fuzzy sets. Yager [9] introduced Pythagorean membership grades for multi-criteria decision-making, where the square sum of the membership degree and non-membership degree is required

to be less than or equal to one. This condition allows a wider representation range than intuitionistic fuzzy sets. Zhang and Xu [8] extended TOPSIS to multi-criteria decision-making with Pythagorean fuzzy sets and showed that Pythagorean fuzzy information can effectively represent uncertainty in decision problems. Therefore, Pythagorean fuzzy TOPSIS is suitable for bridge construction safety risk assessment, where experts may be confident about some risks but hesitant about others.

2.3. Fuzzy Methods for Bridge and Construction Risk Evaluation

Fuzzy methods have been widely used in construction and infrastructure risk assessment because construction risk information is often vague, subjective, and incomplete. Fuzzy AHP, fuzzy TOPSIS, fuzzy comprehensive evaluation, grey-fuzzy methods, and cloud models have all been used to evaluate construction risks. These methods are useful because they allow qualitative risk information to be transformed into quantitative evaluation results. For bridge construction projects, fuzzy methods can help managers rank safety risk factors when complete accident records and direct measurements are unavailable.

Recent bridge construction safety studies show a clear trend toward hybrid risk assessment models. Wu et al. [4] combined CRITIC and TOPSIS to evaluate bridge construction safety risks in marine environments. Li et al. [5] used a cloud entropy power method to assess highway bridge construction safety risks. These models improve the objectivity of risk assessment by combining expert judgment with weighting methods. However, many existing studies still rely heavily on subjective data, and the treatment of hesitation in expert evaluation remains limited. Walczak et al. [16] integrated terrestrial laser scanning (TLS) and fuzzy analytic hierarchy process (FAHP) to diagnose floor deformation in a single-family residential building and select the most suitable repair method. Their model compared three alternatives: floor demolition with substrate replacement, cement grout injection, and geopolymer injection under economic, technical, and environmental criteria, with sensitivity analysis used to test ranking stability. This study supports the relevance of fuzzy MCDM in civil-engineering decision support, although its focus is building repair selection rather than bridge construction occupational safety risk prioritization.

The present study addresses this issue by applying Pythagorean fuzzy TOPSIS to bridge construction safety risk assessment. The safety index system includes five primary factors and twelve secondary indicators. The five primary factors are human factors, management factors, material factors, technical factors, and environmental factors. The three evaluation criteria are severity, probability, and uncontrollability. Five experts are used to evaluate the indicators, and their judgments are aggregated using Pythagorean fuzzy numbers.

Recent occupational safety research in construction emphasizes integrated risk management, hazard identification, training and competency development, human factors, safety analytics, leading indicators, and systems safety. In response, the present study positions bridge construction safety risk assessment as an occupational safety prioritization problem rather than only as a mathematical ranking exercise. This framing is important because the final ranking must guide practical actions such as worker training, competency improvement, procedural compliance, technical supervision, site-environment control, and emergency preparedness.

2.4. Research Gap

The literature shows that construction safety risk assessment has gradually shifted from simple qualitative judgment to structured decision-making models. Existing studies have made important contributions by using behavior-based safety, grey models, cloud models, CRITIC, entropy weighting, and TOPSIS. However, three gaps remain.

First, many bridge construction safety risk assessment methods still use crisp values or ordinary fuzzy values, which may not fully represent hesitation in expert judgments. Second, some studies emphasize weighting or ranking, but do not always explain how expert-derived criterion weights are obtained and used in the final risk-ranking process. Third, bridge construction safety risks are often evaluated using general construction indicators, while the specific characteristics of bridge projects, such as large spans, high-altitude operations, deep foundation works, water-related construction, and complex site environments, require a focused safety risk index system.

To address these gaps, this study develops a Pythagorean fuzzy TOPSIS-based safety risk assessment method for bridge construction projects. The method uses Pythagorean fuzzy numbers to represent expert uncertainty and hesitation, aggregates multi-expert judgments using weighted operators, derives criterion weights from expert-based Pythagorean fuzzy assessments, and ranks safety risk indicators according to their relative closeness to the ideal solutions. The proposed method is then applied to a bridge reconstruction project to identify priority occupational safety risks and provide decision support for site safety management. Table 1 compares the present study with recent bridge construction safety, construction occupational safety, and civil-engineering decision-support studies. The comparison considers application context, method, uncertainty treatment, and main relevance and limitation. The inclusion of building repair decision-support research further clarifies the distinction between fuzzy MCDM models used for structural diagnosis and repair selection and the Pythagorean fuzzy TOPSIS model proposed here for occupational safety risk prioritization.

Table 1. Comparison of recent construction safety and civil-engineering decision-support studies.

Study	Application Context	Method	Uncertainty Treatment	Main Relevance and Limitation
Wu et al. [4]	Bridge construction safety in marine environments	CRITIC-TOPSIS	Objective weighting; limited treatment of expert hesitation	Provides bridge safety risk ranking, but does not jointly represent membership, non-membership, and hesitation.
Li et al. [5]	Highway bridge construction safety	Cloud entropy weight method	Cloud model treatment of fuzziness and randomness	Evaluates bridge construction risk levels, but does not provide Pythagorean fuzzy TOPSIS-based prioritization.
Yao et al. [11]	Bridge construction risk assessment	Variable weight theory and cloud model	Fuzziness, randomness, and variable weight adjustment	Supports bridge risk evaluation, but focuses mainly on risk-level assessment rather than occupational safety indicator ranking.
Pham et al. [12]	Occupational safety in high-rise construction	EFA-AHP	Empirical factor extraction and expert-based weighting	Prioritizes occupational safety factors, but the context is high-rise construction rather than bridge construction.
Zhao et al. [13]	Long-span bridge construction risk assessment	Vision-guided DEMATEL-ISM-DBN	Dynamic causal relations and probabilistic uncertainty	Captures dynamic risk evolution, but requires monitoring data and a more complex modeling structure.
Walczak et al. [16]	Building damage diagnosis and repair-method selection	TLS-FAHP	TLS-based deformation measurement and fuzzy pairwise expert preferences	Demonstrates fuzzy decision support for building repair selection, but focuses on repair-method selection rather than construction safety risk prioritization.
This study	Bridge reconstruction occupational safety risk prioritization	Pythagorean fuzzy TOPSIS	Membership, non-membership, and hesitation in expert linguistic judgments	Ranks bridge construction safety risk indicators under severity, probability, and uncontrollability criteria.

3. Methodology

3.1. Framework of the Proposed Method

This study develops a Pythagorean fuzzy TOPSIS decision model to evaluate safety risks in bridge construction projects. The proposed method is designed for situations in which safety risk information is incomplete, expert judgment is uncertain, and different risk indicators must be ranked under multiple evaluation criteria. The model uses Pythagorean fuzzy numbers to describe linguistic expert assessments and applies TOPSIS to determine the relative priority of safety risk indicators. The overall framework of the proposed Pythagorean fuzzy TOPSIS method is presented in Figure 1.

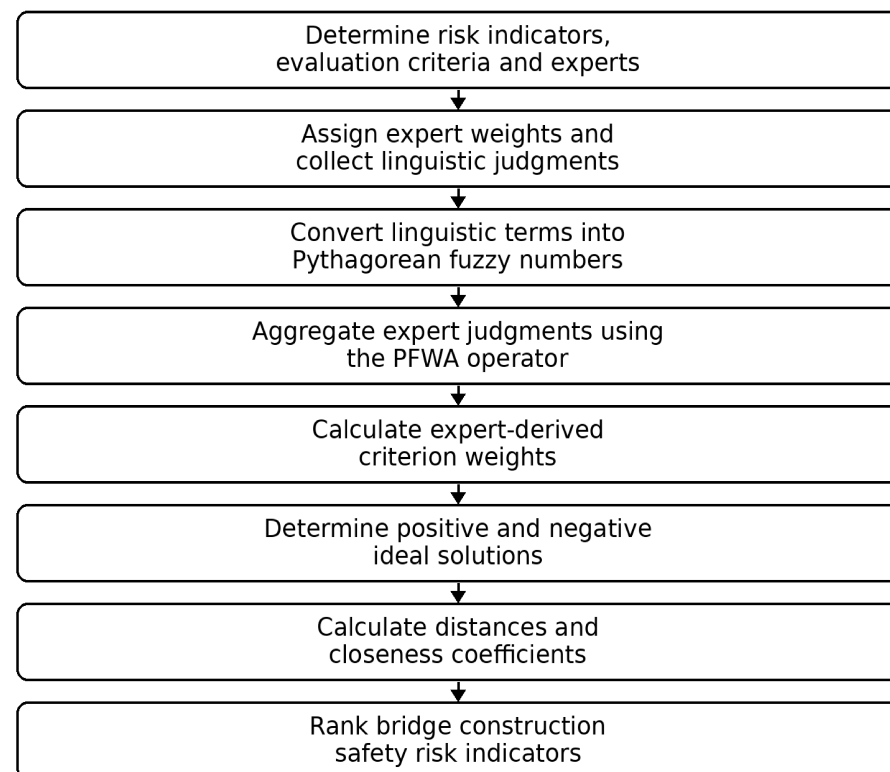


Figure 1. Framework of the proposed Pythagorean fuzzy TOPSIS method.

The assessment procedure consists of eight main steps. First, the safety risk indicators, evaluation criteria, and expert panel are determined. Second, weights are assigned to experts according to their experience, academic qualification, position, and relative influence. Third, expert judgments are collected by questionnaires using linguistic evaluation scales. Fourth, the Pythagorean fuzzy weighted average operator is used to aggregate multi-expert assessments into a group decision matrix. Fifth, the weights of evaluation criteria are obtained from expert judgments and normalized through the score function. Sixth, the positive and negative ideal solutions are determined. Seventh, the distances between each safety risk indicator and the positive and negative ideal solutions are calculated. Finally, the closeness coefficient of each indicator is obtained and used to rank the safety risks.

The proposed method is suitable for bridge construction occupational safety risk assessment for three reasons. First, Pythagorean fuzzy sets can represent membership, non-membership, and hesitation information in expert judgments. Second, TOPSIS provides a clear ranking mechanism based on the ideal-solution concept. Third, the use of expert-derived criterion weights links the model to professional safety judgment while retaining a transparent numerical procedure for risk prioritization.

3.2. Pythagorean Fuzzy Sets

Fuzzy set theory was introduced to model uncertainty using membership functions [17]. Later, intuitionistic fuzzy sets extended ordinary fuzzy sets by considering both membership and non-membership degrees [18]. However, the intuitionistic fuzzy condition restricts the sum of membership and non-membership degrees to be less than or equal to one. In practical decision-making problems, this restriction may limit the ability of decision-makers to express uncertainty and hesitation.

Pythagorean fuzzy sets provide a more flexible representation of uncertain information. Let X be a universe of discourse. A Pythagorean fuzzy set P in X can be expressed as Equation (1).

$$P = \{ \langle x, \mu_P(x), \nu_P(x) \rangle \mid x \in X \} \quad (1)$$

where $\mu_P(x)$ and $\nu_P(x)$ denote the membership degree and non-membership degree of element x , respectively. They satisfy the condition in Equation (2).

$$0 \leq \mu_P^2(x) + \nu_P^2(x) \leq 1 \quad (2)$$

The hesitation degree $\pi_P(x)$ is defined as Equation (3).

$$\pi_P(x) = \sqrt{1 - \mu_P^2(x) - \nu_P^2(x)} \quad (3)$$

Compared with intuitionistic fuzzy sets, Pythagorean fuzzy sets allow a wider decision space because the square sum of membership and non-membership degrees, rather than their direct sum, is constrained. This makes Pythagorean fuzzy sets suitable for expert-based risk assessment problems, where decision-makers may express incomplete confidence or hesitation when evaluating risk severity, probability, and controllability [8,9].

3.3. Linguistic Variables and Pythagorean Fuzzy Numbers

In bridge construction safety assessment, experts often evaluate risks using linguistic terms instead of exact numerical values. Therefore, this study converts linguistic judgments into Pythagorean fuzzy numbers. Two linguistic scales are used. The first scale describes the evaluation level of safety risk indicators, and the second scale describes the importance level of safety evaluation criteria. The correspondence between safety risk indicator levels and their associated Pythagorean fuzzy numbers is presented in Table 2 and the linguistic importance levels and their corresponding Pythagorean fuzzy numbers are presented in Table 3.

Table 2. Correspondence between safety risk indicator levels and Pythagorean fuzzy numbers.

Grade	Linguistic Term	Pythagorean Fuzzy Number
1	Very low	(0.15, 0.90)
2	Low	(0.35, 0.70)
3	Slightly low	(0.45, 0.60)
4	Medium	(0.55, 0.50)
5	Slightly high	(0.65, 0.40)
6	High	(0.75, 0.30)
7	Extremely high	(0.90, 0.10)

The use of linguistic variables reduces the difficulty for experts when expressing safety judgments and allows qualitative risk knowledge to be transformed into structured fuzzy

decision data. This is important for bridge construction projects because many safety risks cannot be evaluated accurately using deterministic numerical data alone.

Table 3. Correspondence between criterion importance levels and Pythagorean fuzzy numbers.

Grade	Linguistic Term	Pythagorean Fuzzy Number
1	Very important	(0.95, 0.20)
2	Important	(0.80, 0.35)
3	Medium	(0.55, 0.50)
4	Unimportant	(0.30, 0.75)
5	Very unimportant	(0.15, 0.90)

3.4. Aggregation of Expert Judgments

Assume that there are m safety risk indicators, n evaluation criteria, and q experts. The safety risk indicator set, criterion set, and expert set are defined as follows:

$$U = \{U_1, U_2, \dots, U_m\}, C = \{C_1, C_2, \dots, C_n\}, E = \{E_1, E_2, \dots, E_q\} \quad (4)$$

Each expert has a corresponding weight $\lambda = (\lambda_1, \lambda_2, \dots, \lambda_q)$, where $\lambda_k \geq 0$ and $\sum \lambda_k = 1$. Let $r_{ijk} = (\mu_{ijk}, \nu_{ijk})$ denote the Pythagorean fuzzy evaluation given by expert E_k for safety risk indicator U_i under criterion C_j . The aggregated Pythagorean fuzzy value r_{ij} is obtained by the Pythagorean fuzzy weighted average operator as follows [19]:

$$r_{ij} = \left(\sqrt{1 - \prod_{k=1}^q \left(1 - (\mu_{ijk})^2\right)^{\lambda_k}}, \prod_{k=1}^q (\nu_{ijk})^{\lambda_k} \right) \quad (5)$$

The aggregated decision matrix is then written as $R = (r_{ij})_{m \times n}$. This matrix represents the group evaluation results of all safety risk indicators under all evaluation criteria.

3.5. Determination of Criterion Weights

The evaluation criteria in this study include severity, probability, and uncontrollability. Severity reflects the potential loss caused by a risk factor in terms of cost, schedule, quality, personnel safety, and project impact. Probability reflects the likelihood that the risk factor may occur during construction. Uncontrollability reflects the degree to which the risk factor is difficult to prevent or control. These three criteria are used because safety risk priority depends not only on how serious a hazard is, but also on how likely it is to occur and how difficult it is to manage.

The subjective weight of each criterion is determined from expert evaluations. Expert judgments on criterion importance are first converted into Pythagorean fuzzy numbers and then aggregated by the Pythagorean fuzzy weighted average operator. The score function is then used to transform each aggregated Pythagorean fuzzy value into a scalar value. For a Pythagorean fuzzy number $p = (\mu, \nu)$, the score function used in this study is defined as Equation (6).

$$S(p) = 1 + \mu^2 - \nu^2 \quad (6)$$

A larger score value indicates a higher importance level. The subjective weight of criterion C_j is calculated by normalizing its score value as Equation (7).

$$w_j^s = \frac{S(C_j)}{\sum_{j=1}^n S(C_j)} \quad (7)$$

In this empirical application, the criterion weights used in the TOPSIS ranking are the normalized expert-derived weights obtained from Equation (7). No additional objective-weighting procedure is introduced into the final ranking, so the calculation remains directly traceable to the reported expert evaluations.

$$w_j = w_j^s \quad (8)$$

where w_j is the final criterion weight used in this case study and w_j^s is the normalized expert-derived subjective weight. Future applications may integrate entropy, CRITIC, or other objective weighting schemes if the corresponding calculations and sensitivity checks are fully reported.

3.6. Pythagorean Fuzzy TOPSIS Model

TOPSIS ranks alternatives according to their relative distance from the positive ideal solution and the negative ideal solution [6]. In this study, each safety risk indicator is treated as an alternative, and each evaluation criterion is treated as a decision criterion. Let $A^+ = (0, 1)$ denote the positive ideal solution and $A^- = (1, 0)$ denote the negative ideal solution. In this study, $(0, 1)$ is used to represent the positive ideal solution because it has the lowest score function. The lower the expert score for a safety evaluation indicator, the lower the risk, and the closer its distance is to $(0, 1)$. The TOPSIS method generally uses $(1, 0)$ to represent the positive ideal solution, which is usually applied to benefit-type indicators. This is exactly opposite to the present study. Based on the actual situation of risk assessment, and for ease of understanding, this study assigns specific practical meanings to $(1, 0)$ and $(0, 1)$. For two Pythagorean fuzzy numbers $p_1 = (\mu_1, \nu_1)$ and $p_2 = (\mu_2, \nu_2)$, the Euclidean distance is defined as Equation (9) [8].

$$d(p_1, p_2) = \sqrt{\frac{(\mu_1^2 - \mu_2^2)^2 + (\nu_1^2 - \nu_2^2)^2 + (\pi_1^2 - \pi_2^2)^2}{2}} \quad (9)$$

The weighted distances from indicator U_i to the positive and negative ideal solutions are calculated as Equations (10) and (11).

$$D_i^+ = \sum_{j=1}^n w_j d(r_{ij}, A_j^+) \quad (10)$$

$$D_i^- = \sum_{j=1}^n w_j d(r_{ij}, A_j^-) \quad (11)$$

The closeness index of safety risk indicator U_i is then calculated as Equation (12).

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (12)$$

In this study, a smaller closeness index indicates a higher safety risk priority. Therefore, the risk indicators are ranked in ascending order of closeness index. The indicator with the smallest closeness index is considered the most critical risk factor requiring priority control.

3.7. Implementation Procedure

The implementation procedure of the proposed method is summarized as follows. Step 1 establishes the bridge construction safety risk indicator system and defines the evaluation criteria. Step 2 selects experts with relevant bridge construction safety experience and determines their weights. Step 3 collects expert judgments using linguistic evaluation

scales. Step 4 converts linguistic terms into Pythagorean fuzzy numbers. Step 5 aggregates multi-expert judgments using the Pythagorean fuzzy weighted average operator. Step 6 calculates expert-derived criterion weights. Step 7 determines the positive and negative ideal solutions. Step 8 calculates the distances between each risk indicator and the ideal solutions. Step 9 computes the closeness index of each risk indicator. Step 10 ranks the safety risk indicators and identifies the priority risks.

This procedure provides a structured and reproducible framework for evaluating bridge construction safety risks. It is particularly useful when risk information is uncertain and expert judgment is the main source of evaluation data.

4. Case Study and Results

4.1. Project Background

The proposed model was applied to a bridge reconstruction project to verify its feasibility in practical safety risk assessment. The project is located in Z City and involves the construction of a new double-lane bridge across the Y River, upstream of the existing bridge. After completion, the existing bridge and the new double-lane bridge will form an eight-lane urban expressway. The total project route length is approximately 1.083 km, including 523.9 m of approach roads, and the standard roadbed width is 36 m.

The project consists mainly of the main bridge, approach bridges, and the new double-lane bridge. The construction process involves a large span, a heavy workload, and a complex surrounding environment. Several high-risk activities are included, such as deep foundation pit excavation, large-volume concrete placement, water-related construction, and high-altitude operations. These construction characteristics increase the uncertainty of safety management and make the project suitable for testing the proposed Pythagorean fuzzy TOPSIS model.

Based on the characteristics of bridge construction and expert consultation, the safety risk assessment system was established from five primary categories: human factors, management factors, material factors, technical factors, and environmental factors. These categories are consistent with the common structure of construction safety risk analysis, where risks are usually associated with workers, management systems, equipment and materials, technical execution, and external site conditions [5,20,21].

4.2. Safety Risk Indicator System

The safety risk indicator system includes 12 secondary indicators. Human factors include lack of safety awareness and low work quality. Management factors include insufficient safety education, improper safety protection signs, and inadequate emergency response measures. Material factors include defective mechanical equipment and sub-standard or insufficient building materials. Technical factors include inappropriate selection of design parameters, insufficient construction technology, and non-standard construction. Environmental factors include natural environmental impact and construction site environment.

Due to the inherent characteristics of bridge construction, various factors influence one another, and construction site conditions are complex. Therefore, constructing a safety evaluation indicator system suitable for the characteristics of bridge construction is a complicated task. Based on relevant national safety laws, regulations, rules, and standards, this study takes the Regulations on the Administration of Work Safety in Construction Projects, the Safety Production Evaluation Standard for Construction Enterprises (JGJ/T77-2003), and the Construction Safety Inspection Standard (JGJ59-99), approved by the Ministry of Construction, as the foundation. It also incorporates the requirements of standards such as the Occupational Health and Safety Management System Specification (GB/T28001-2001).

Following the principles for establishing a basic comprehensive safety evaluation indicator system for bridge construction, and considering the characteristics of bridge construction, after consulting several experts and combining the actual situation of bridge construction, this study divides bridge construction safety evaluation into five major aspects: human factors, management factors, material factors, technical factors, and environmental factors.

- (1) Human factors. In the process of highway bridge construction, human factors are the core elements affecting construction safety. First, weak safety awareness is a prominent and widespread problem. Most construction workers have insufficient understanding of potential safety risks on site and fail to fully recognize the direct relationship between their own behavior and construction safety. For example, during work at height, some workers ignore safety regulations and do not wear basic protective equipment, such as safety belts, as required, which greatly increases the probability of fall-from-height accidents. Second, insufficient professional operation skills also pose a serious threat to construction safety. Some construction workers have not received systematic professional training, and when operating large and complex equipment or carrying out key procedures, they are highly likely to make operational mistakes due to insufficient technical proficiency. Taking the lifting of bridge prefabricated components as an example, if operators do not have a solid understanding of the performance parameters and operating specifications of lifting equipment, the components may become unbalanced and fall during lifting, which not only causes damage to the components but also directly endangers the lives of on-site personnel. Therefore, strengthening safety awareness through regular safety education and improving operation skills through systematic skill training are key measures to resolve safety risks caused by human factors.
- (2) Management factors. Management factors occupy a fundamental position in the prevention and control of safety risks in highway bridge construction, and management loopholes often amplify various safety hazards. First, the absence of safety education and training is the primary weakness at the management level. Some construction enterprises fail to provide comprehensive and systematic safety education for workers, resulting in insufficient safety knowledge and weak risk-identification ability among construction personnel. For example, newly recruited workers are often sent to work hastily without complete pre-job safety training, and they only have a limited understanding of the distribution of hazards on the construction site, safety operating procedures, and emergency response processes, directly becoming a high-risk group for safety accidents. Second, non-standard setting of safety protection signs increases on-site safety risks. The construction site environment is complex, and clear and standardized safety protection signs are needed to guide work behavior and warn against dangerous areas. However, some projects have problems such as missing signs, blurred writing, and incorrect sign placement. For example, in dangerous areas such as edges and openings in bridge construction, if obvious warning signs and protective facilities are not installed, construction workers may mistakenly enter dangerous areas and cause accidents. Third, an imperfect emergency management system is an important management omission. In the face of sudden natural disasters or safety accidents, if enterprises do not formulate targeted emergency plans, or if the plans lack practical operability, emergency response will be delayed and chaotic. For example, heavy rainfall may cause water accumulation at the construction site and slope collapse. If personnel evacuation routes, equipment transfer plans, and emergency rescue procedures are not clarified in advance, casualties and major equipment losses can easily occur. Therefore, improving the safety education system, standardiz-

ing safety sign management, and improving the emergency response mechanism are core links in consolidating the foundation of safety management.

- (3) Material factors. As the material basis for construction activities, material factors directly determine the level of construction safety through their quality and condition. On the one hand, hidden dangers in mechanical equipment are key risk points that cannot be ignored. Large mechanical equipment used in construction, such as cranes, concrete mixing plants, and bridge erecting machines, may experience sudden failures during operation if there are design defects, aging and corroded parts, or inadequate routine maintenance. Taking crane operations as an example, if there is a hidden fault in the braking system, brake failure may occur when lifting heavy objects, causing the heavy objects to fall out of control and resulting in devastating impacts on on-site personnel, equipment, and completed works. On the other hand, substandard construction material quality and supply imbalance may also trigger chain safety risks. Highway bridge projects have strict requirements for construction material quality. If the tensile strength of steel bars is insufficient, the concrete strength does not meet the design standard, or the bearing performance is unqualified, the load-bearing capacity of the bridge structure will be directly reduced, creating hidden risks of collapse. At the same time, untimely supply of construction materials can easily delay construction progress. To catch up with the schedule, some projects may simplify procedures or conduct construction in violation of regulations, further increasing safety risks. Therefore, establishing a full life-cycle management system for mechanical equipment, including entry inspection, regular maintenance, and fault troubleshooting; implementing whole-process quality control of construction materials, including manufacturer qualification review, entry sampling inspection, and use rechecking; and ensuring stable material supply are material guarantees for strengthening construction safety.
- (4) Technical factors. Technical factors run through the entire construction process and play a decisive supporting role in highway bridge construction safety. Omissions in technical links can easily cause fundamental safety hazards. First, improper selection of design parameters can lead to inherent safety defects. If comprehensive and detailed geological investigation is not conducted before engineering design, and if there are deviations in judging key parameters such as foundation bearing capacity and rock-soil stability, structural safety will be directly affected. For example, in bridge foundation design, if geological conditions are misjudged and the designed value of foundation bearing capacity is too low, uneven foundation settlement may occur during construction, which may further cause pier column inclination, beam cracking, and other problems, threatening the overall stability of the bridge. Second, insufficient construction technology restricts the effectiveness of safety control. With the increase in bridge construction under large-span and complex geological conditions, new processes and technologies, such as main cable erection for suspension bridges and segmental beam assembly, are widely applied. If construction workers do not master the core points of new technologies, or if enterprises fail to update technical equipment and optimize construction schemes in time, construction quality and safety may easily become uncontrolled. Taking large-span suspension bridge construction as an example, if operators are unfamiliar with the cable-force adjustment process, uneven cable-force distribution may occur, causing serious problems such as main cable deformation and bridge tower deviation. Finally, non-standard construction operations are the main risk at the level of technical execution. Some construction workers do not strictly follow design drawings, construction specifications, and technical disclosure requirements, and arbitrarily simplify procedures. For example, if concrete pouring

is not carried out with layered vibration according to specifications, defects such as honeycombs, pitted surfaces, and voids may appear inside the concrete, reducing structural durability and load-bearing capacity, and long-term use may lead to structural cracking or even collapse. Therefore, strengthening geological investigation and parameter demonstration at the design stage, enhancing new-technology training and equipment upgrading, and strictly implementing construction specifications and process acceptance are key to building a technical safety assurance system.

- (5) Environmental factors. Environmental factors are complex and sudden, and they have a profound impact on highway bridge construction safety. Therefore, risk prediction and prevention and control should be emphasized. On the one hand, natural environmental risks are significantly uncontrollable. Highway bridge construction is mostly outdoor work and is easily affected by extreme weather and geological disasters. During construction in complex terrain such as mountainous areas and valleys, geological disasters such as landslides, debris flows, and rock collapses may occur suddenly, directly damaging construction facilities and threatening personnel safety. Heavy rainfall can cause water accumulation at construction sites and slope instability, increasing the risks of workers slipping and equipment overturning. Strong winds can affect the safety of work at height, component lifting, and bridge-erecting machine operations. High-temperature and severe cold weather may cause heatstroke and frostbite among construction workers, while also affecting concrete strength development and asphalt paving quality. On the other hand, improper management of the construction site and surrounding environment may also induce safety problems. Unreasonable construction site layout is a common hazard, such as disorderly material stacking occupying fire passages, narrow and muddy construction roads, and temporary facilities being too close to the work area, all of which increase risks for personnel movement and operations. In addition, insufficient coordination of the surrounding environment of the construction site may also cause indirect safety risks. For example, when the construction area is close to residential areas, construction noise and dust pollution may easily trigger complaints from residents or even obstruction of construction, leading to construction interruption or rush-work risks. If the site is close to existing roads or pipelines, and effective protective measures are not taken during construction, pipelines may be damaged or road traffic safety may be affected, causing secondary accidents. Therefore, a comprehensive environmental risk assessment should be carried out before construction. Dynamic monitoring and early warning mechanisms should be formulated for the natural environment, the site layout should be optimized, on-site management should be standardized, and coordination with the surrounding environment should be strengthened. These are effective means to reduce environmental risks.

The evaluation criteria include severity, probability, and uncontrollability. Severity refers to the potential consequences caused by a safety risk, including losses related to cost, quality, schedule, and personnel safety. Probability refers to the likelihood that a safety risk may occur during the construction process. Uncontrollability refers to the difficulty of preventing, controlling, or mitigating the risk once it appears. These three criteria were used because construction safety risks should be assessed not only by their possible consequences, but also by their occurrence likelihood and controllability. Based on the established evaluation scale and the corresponding Pythagorean fuzzy numbers presented in Tables 2 and 3, the bridge construction safety risk indicator system was developed, as shown in Table 4.

Five experts with more than 20 years of experience in bridge construction safety evaluation were invited to participate in the assessment. Their judgments were collected

independently to avoid interaction effects during scoring. In this study, individual weights were determined based on three indicators: experts' educational background, position, and years of work experience. The relevant basic data are shown in Table 5. To further improve the scientific validity and rationality of the evaluation results, this study assigns differentiated weights to the evaluation results of each expert by considering their educational background, job position, and years of work experience. Taking Expert 1 as an example, this expert holds a doctoral degree and has solid professional knowledge in the relevant field, corresponding to 2 points; holds the position of department head and has a high level of familiarity with the relevant work content and business processes, corresponding to 3 points; and has more than 20 years of work experience, with rich practical experience in the field, corresponding to 3 points. In summary, the total score of Expert 1 is 8 points, and the total score of all participating experts is 25 points. Based on this, the evaluation weight of Expert 1 is calculated as 0.32.

Table 4. Bridge construction safety risk indicator system.

Primary Indicator	Secondary Indicator
Human factors	Lack of safety awareness (U1)
Human factors	Low work quality (U2)
Management factors	Insufficient safety education (U3)
Management factors	Improper safety protection signs (U4)
Management factors	Inadequate emergency response measures (U5)
Material factors	Defective mechanical equipment (U6)
Material factors	Substandard or insufficient building materials (U7)
Technical factors	Inappropriate selection of design parameters (U8)
Technical factors	Insufficient construction technology (U9)
Technical factors	Non-standard construction (U10)
Environmental factors	Natural environmental impact (U11)
Environmental factors	Construction site environment (U12)

Table 5. Expert weights.

Expert	Years of Service	Highest Degree	Position	Weight
E1	More than 20 years	PhD	Minister	0.32
E2	More than 20 years	Master	Director	0.20
E3	More than 10 years	Master	Team leader	0.18
E4	More than 10 years	Undergraduate	Team leader	0.16
E5	More than 10 years	Undergraduate	Ordinary employee	0.14

4.3. Aggregated Decision Matrix

The experts evaluated the 12 safety risk indicators according to the three criteria. The linguistic evaluations were converted into Pythagorean fuzzy numbers and aggregated using the Pythagorean fuzzy weighted average operator.

The evaluation results from Questionnaire were summarized, based on which Table 6 was prepared. The Pythagorean fuzzy decision matrix was calculated using Formula (5), and the detailed data are shown in Table 7. The Pythagorean fuzzy decision aggregation matrix is presented in the form of (μ, ν) , where μ represents the membership degree and ν represents the non-membership degree.

Table 6. Summary of safety evaluation indicator assessments based on Pythagorean fuzzy numbers.

Expert	Evaluation Criteria	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12
W1	C1	6	6	3	3	4	2	1	2	5	6	3	5
	C2	6	6	5	2	2	1	2	3	5	6	3	4
	C3	5	7	3	1	4	2	1	2	5	6	3	5
W2	C1	6	6	2	2	5	2	1	2	5	6	3	6
	C2	5	5	4	4	3	2	2	4	6	4	3	5
	C3	5	5	2	2	4	1	3	2	6	6	4	5
W3	C1	6	5	3	2	3	2	1	2	5	7	4	6
	C2	5	5	4	2	2	2	2	5	5	5	3	5
	C3	5	6	2	2	3	2	1	2	5	5	3	5
W4	C1	5	6	2	2	3	3	1	3	5	4	5	5
	C2	4	6	4	2	2	2	1	4	5	4	4	4
	C3	5	7	2	2	3	2	2	2	5	7	4	5
W5	C1	6	5	3	2	4	1	2	3	6	6	4	6
	C2	6	5	4	2	3	2	2	5	5	4	5	6
	C3	5	6	3	4	3	2	2	2	5	5	3	5

Table 7. Aggregated Pythagorean fuzzy decision matrix.

Indicator	C1	C2	C3
U1	(0.6667, 0.3842)	(0.6736, 0.3776)	(0.6736, 0.3776)
U2	(0.7224, 0.3289)	(0.7032, 0.3484)	(0.8307, 0.1875)
U3	(0.4178, 0.6342)	(0.5860, 0.4655)	(0.4003, 0.6521)
U4	(0.3859, 0.6663)	(0.4023, 0.6544)	(0.3470, 0.7237)
U5	(0.5450, 0.5088)	(0.3880, 0.6643)	(0.5061, 0.5457)
U6	(0.3502, 0.7074)	(0.3028, 0.7586)	(0.3215, 0.7361)
U7	(0.1928, 0.8689)	(0.3274, 0.7287)	(0.3023, 0.7696)
U8	(0.3838, 0.6684)	(0.5609, 0.4935)	(0.3500, 0.7000)
U9	(0.7366, 0.3141)	(0.6900, 0.3632)	(0.6500, 0.4000)
U10	(0.7709, 0.2671)	(0.6475, 0.4079)	(0.7626, 0.2759)
U11	(0.5239, 0.5304)	(0.5039, 0.5506)	(0.4900, 0.5619)
U12	(0.7366, 0.3141)	(0.6900, 0.3632)	(0.6500, 0.4000)

The aggregated matrix shows that several indicators have relatively high membership degrees under the three criteria. In particular, U2, U9, U10, and U12 present strong risk characteristics under severity, probability, or uncontrollability. These results indicate that worker performance, construction technology, construction standardization, and site environment are central issues in the safety management of the case project.

4.4. Criterion Weights

Five decision-making experts evaluated the importance of the three evaluation criteria. After summarizing the evaluation data from Questionnaire 3, Table 8 was prepared. The Pythagorean fuzzy aggregated decision matrix of the safety evaluation criteria was obtained through calculation using Formula (5), and the detailed data of this matrix are shown in Table 9. Table 9 specifically lists the aggregated Pythagorean fuzzy values, score function values, and subjective weights. The subjective weights of severity, probability, and uncontrollability were 0.3694, 0.3397, and 0.2909, respectively. Severity has the highest

weight, followed by probability and uncontrollability. This result indicates that experts considered the consequence of a risk event to be the most important criterion in bridge construction safety evaluation. For transparency, the final ranking in this case study uses the expert-derived criterion weights reported in Table 9.

Table 8. Summary of safety evaluation criteria assessments based on Pythagorean fuzzy numbers.

Safety Evaluation Criteria	W1	W2	W3	W4	W5
C1	1	2	1	1	2
C2	1	2	2	2	3
C3	2	2	2	3	3

Table 9. Subjective weights of safety evaluation criteria.

Criterion	Aggregated Pythagorean Fuzzy Value	Score Function Value	Subjective Weight
C1	(0.9209, 0.2419)	1.7895	0.3694
C2	(0.8602, 0.3076)	1.6454	0.3397
C3	(0.7490, 0.3895)	1.4093	0.2909

This keeps the calculation procedure traceable to the reported expert evaluations. In future applications, objective weighting methods such as entropy or CRITIC may be incorporated when the data structure is suitable and the resulting weights are reported explicitly.

4.5. Ranking Results

Based on Equations (10) and (11), the distances between each safety evaluation indicator and the positive and negative ideal solutions can be calculated, and the results are shown in Table 10. According to Equation (12), the closeness value of each safety evaluation indicator can be obtained. Sorting the obtained values from small to large shows that the smaller the closeness value, the higher the corresponding risk level and the higher the priority for risk treatment. The specific calculation results and ranking results are shown in Table 11.

Table 10. Distances of safety evaluation indicators from the positive ideal solution and negative ideal solution.

Evaluation Criteria	C ₁		C ₂		C ₃		D ⁺	D [−]
	D1 ⁺	D1 [−]	D2 ⁺	D2 [−]	D3 ⁺	D3 [−]		
U1	0.7384	0.4984	0.7429	0.4908	0.7429	0.4908	0.7416	0.4931
U2	0.7761	0.4343	0.7629	0.4570	0.8610	0.2939	0.7942	0.4122
U3	0.5324	0.7149	0.6800	0.5795	0.5138	0.7273	0.5954	0.6640
U4	0.4985	0.7373	0.5104	0.7259	0.4289	0.7664	0.4862	0.7404
U5	0.6461	0.6158	0.5008	0.7358	0.6155	0.6484	0.5795	0.6778
U6	0.4509	0.7623	0.3869	0.7959	0.4162	0.7821	0.4152	0.7821
U7	0.2287	0.8776	0.4256	0.7778	0.3705	0.7989	0.3603	0.8151
U8	0.4963	0.7387	0.6582	0.6018	0.4611	0.7617	0.5629	0.6902
U9	0.4963	0.4169	0.6582	0.4719	0.4611	0.5164	0.5629	0.4685
U10	0.8147	0.3751	0.7220	0.5180	0.8090	0.3860	0.7748	0.4441
U11	0.6281	0.6336	0.6108	0.6499	0.6013	0.6613	0.6137	0.6480
U12	0.7860	0.4169	0.7530	0.4719	0.7275	0.5164	0.7566	0.4685

The ranking result is U2 > U10 > U12 > U1 > U9 > U11 > U3 > U5 > U8 > U4 > U6 > U7. The top-ranked indicator is U2 (low work quality), with a closeness index of 0.3417. In bridge reconstruction, quality-control failures are most directly reflected in deep foundation

pit excavation and large-volume concrete placement. For example, during the installation of retaining structures for deep excavations, insufficient precision in applying axial force to steel struts or improper control of layered excavation thickness can readily trigger ground deformation or even collapse of the pit. In mass concrete pours, arbitrary vibrating practices—such as excessive spacing between insertion points or insufficient duration—directly induce honeycombing, surface voids, or cold joints, significantly compromising the structural load-bearing capacity. Moreover, if the inspection and sign-off at critical high-risk construction stages are performed perfunctorily owing to a lack of operator diligence, latent defects from earlier phases may remain undetected until they escalate into serious problems.

Table 11. Final ranking of bridge construction safety risk indicators.

Indicator	Description	Closeness Index	Rank
U2	Low work quality	0.3417	1
U10	Non-standard construction	0.3644	2
U12	Construction site environment	0.3824	3
U1	Lack of safety awareness	0.3994	4
U9	Insufficient construction technology	0.4542	5
U11	Natural environmental impact	0.5136	6
U3	Insufficient safety education	0.5272	7
U5	Inadequate emergency response measures	0.5391	8
U8	Inappropriate selection of design parameters	0.5508	9
U4	Improper safety protection signs	0.6036	10
U6	Defective mechanical equipment	0.6532	11
U7	Substandard or insufficient building materials	0.6934	12

The second-most critical indicator is U10 (non-standard construction), with a closeness index of 0.3644. The detrimental effects of this risk are particularly acute in lifting and hoisting operations as well as work at height. During the erection of large, prefabricated components or steel box girders, any deviation from the approved method statement—for instance, in the positioning of lifting points, the angle of wire ropes, or the temporary bracing scheme—may cause load instability or accidental dropping of the lifted item, potentially resulting in multiple casualties. Similarly, the erection of temporary works and scaffolding that fails to comply with design requirements for step spacing, tie-in density, or foundation reinforcement can lead to overall overturning during high-altitude concreting or rebar placement. On sections that cross over existing roadways, non-standard construction also poses direct threats to the traffic flow underneath.

The third-ranking indicator is U12 (construction site environment), with a closeness index of 0.3824. For bridge projects that span rivers or are situated adjacent to water bodies, environmental influences are mainly manifested through the combined constraints of water-related construction and traffic interface management. In cofferdam works or temporary trestle bridge operations, hydrological variations (e.g., sudden changes in flow velocity or water level) and the confined working area on water severely restrict the manoeuvring of heavy equipment and the handling of materials. In addition, the emergency access routes alongside the river-crossing sections, if encroached upon by temporary material storage, can directly delay rescue operations in the event of an accident. Furthermore, the mixing of diverted public traffic with construction-site traffic at the interface points increases not only the risk of collision during entry and exit of machinery but also the potential hazard zone for falling objects from above.

The fourth and fifth indicators are U1 (lack of safety awareness) and U9 (insufficient construction technology). These two factors constitute deepest sources of risk in highly specialised operations such as dewatering and support of deep excavations, temperature control of mass concrete, and prestressing tension at high elevations. A lack of safety awareness often manifests as workers diminished sensitivity to obvious hazards—such as unprotected edges at height or the swing radius of crane booms—leading them to habitually neglect the use of safety harnesses or the establishment of exclusion zones around lifts. Meanwhile, insufficient technical competence weakens the project team’s capacity to address complex challenges, such as the structural analysis of novel falsework systems or the precise positioning of steel cofferdams in challenging water conditions. When confronted with unusual geometries or adverse working environments, inadequate technical briefings can easily escalate into systemic construction failures.

The lowest-ranked indicators are U6 (defective mechanical equipment) and U7 (sub-standard or insufficient building materials), with closeness indices of 0.6532 and 0.6934, respectively. Although these two categories are generally better controlled, they still warrant vigilance in specific scenarios such as the positioning of large concrete pumps, the threading of extra-long steel strands, and underwater concrete placement. The relatively lower ranking in this case study suggests that the project has established more standardised procedures for the incoming inspection of major lifting machinery, factory-based supervision of concrete raw materials, and acceptance checks for reusable temporary components (e.g., steel tubular scaffolds and Bailey beams). Compared with the inherent variability of human behavior or the ambiguity in technical execution, such physical-asset risks are more amenable to mitigation through systematic ledger-based management and formalized record-keeping.

To strengthen the practical occupational safety contribution of the ranking, the top-ranked indicators were translated into targeted control measures, as shown in Table 12. These measures are not new empirical results; they are practical implications derived from the ranked indicators and standard construction safety-management logic.

Table 12. Priority safety risks and recommended occupational safety control measures.

Rank	Risk Indicator	Safety Meaning	Recommended Occupational Safety Control Measure	Responsible Party
1	Low work quality	Poor task execution, weak compliance with technical instructions, or unstable work performance	Competency assessment, pre-job training, task-specific method briefing, and supervisor inspection	Contractor; safety manager; site supervisor
2	Non-standard construction	Deviation from drawings, specifications, method statements, or safe work procedures	Method-statement approval, checklist inspection, hold-point control, and nonconformance correction	Technical manager; quality manager; safety officer
3	Construction site environment	Unsafe physical conditions related to access, workspace, traffic, storage, temporary facilities, or emergency routes	Site zoning, access control, housekeeping, safe material stacking, temporary traffic control, and emergency-access protection	Site manager; logistics manager; safety officer
4	Lack of safety awareness	Weak hazard perception, shortcut behavior, or insufficient recognition of occupational safety consequences	Toolbox talks, hazard-perception training, behavior-based observation, and daily safety reminders	Safety officer; foreman; subcontractor supervisor
5	Insufficient construction technology	Limited technical capability to manage complex bridge operations and special construction procedures	Technical disclosure, construction-scheme verification, expert review for high-risk operations, and monitoring of key construction parameters	Project engineer; technical manager; construction manager

4.6. Sensitivity Analysis and Comparison of Calculation Results

To explore the influence of fluctuations in the weights of the five decision-making experts on the effectiveness and stability of the risk assessment model, this study conducts a sensitivity analysis of the model by adjusting the expert weight parameters. The initial setting assigns equal weights to the five experts, with an average value of 0.2. The test results show that the ranking results are consistent with those of this study. The model has good robustness against small changes in expert weights, the output evaluation results are effective, and the conclusions are reliable. This also confirms that the five decision-making experts selected in this study have strong representativeness and rationality.

To verify the effectiveness and rationality of this decision-making model, this study compares the calculation results of the proposed method with three classical methods: traditional TOPSIS, fuzzy TOPSIS, and intuitionistic fuzzy TOPSIS [22,23]. The ranking results of the safety evaluation indicators obtained using the four methods are shown in Table 13. Based on the data in the table, the superiority of the proposed method over the other comparison methods can be fully verified. When the traditional TOPSIS method is used for ranking calculation, the safety evaluation indicators U3 and U7 have the same ranking. This method does not introduce a fuzzy linguistic description mechanism, while in actual decision-making scenarios, various types of qualitative evaluation information are difficult to directly quantify and represent using precise numerical values. At the same time, the greater the number of safety evaluation indicators, the higher the probability that the model will produce tied rankings. This is a significant limitation of the traditional TOPSIS method.

Table 13. Ranking of safety evaluation indicators using different methods.

Safety Evaluation Indicators	Proposed Method	TOPSIS	Fuzzy TOPSIS	Intuitive Fuzzy TOPSIS
U1	4	4	4	4
U2	1	1	1	1
U3	7	7	7	7
U4	10	10	10	10
U5	8	7	8	8
U6	11	11	11	11
U7	12	12	12	12
U8	9	9	9	9
U9	5	5	5	5
U10	2	2	2	2
U11	6	6	6	6
U12	3	3	3	3

Although the indicator ranking results obtained by fuzzy TOPSIS and intuitionistic fuzzy TOPSIS are consistent with those of the proposed method, both methods have inherent defects. Among them, fuzzy TOPSIS uses triangular fuzzy numbers to describe the fuzziness and uncertainty of the system, but it only sets a single membership dimension. Therefore, the information description dimension is relatively single and cannot fully cover fuzzy information in complex evaluation scenarios. The intuitionistic fuzzy TOPSIS method completes the calculation based on intuitionistic fuzzy numbers. Although it adds the non-membership dimension and improves the fuzzy information description system, its own constraint conditions have obvious shortcomings. This method clearly requires that “the sum of membership degree and non-membership degree is less than or equal to 1.” This constraint greatly increases the difficulty of expert evaluation and decision-making. In some actual safety evaluation scenarios, the real characteristic information of the evaluation object often has a situation where the sum of membership degree and non-membership

degree is greater than 1, which conflicts with this constraint and leads to limited adaptability of the method to actual scenarios.

Compared with intuitionistic fuzzy sets, Pythagorean fuzzy sets are more suitable for complex and changeable real fuzzy decision-making scenarios and can provide decision-makers with a more flexible assignment space. Their core advantage lies in breaking through the value constraint of intuitionistic fuzzy sets, namely “membership degree + non-membership degree ≤ 1 ,” effectively broadening the valid value range of evaluation information. They can describe the uncertainty characteristics of objects in a more detailed and accurate manner, make the assignment operation of decision-makers more flexible and closer to engineering practice, and effectively make up for the defects and shortcomings of the traditional fuzzy TOPSIS series methods.

4.7. Result Interpretation

The results show that the most important safety risks in the case project are concentrated in human, technical, and environmental dimensions. Low work quality and lack of safety awareness are human-related risks. Non-standard construction and insufficient construction technology are technical execution risks. Construction site environment is an environmental risk. These findings suggest that safety management in bridge construction should not focus only on equipment and materials. More attention should be given to worker competence, technical implementation, site organization, and compliance with construction procedures.

From a management perspective, the ranking results provide a clear basis for prioritizing safety control measures. First, construction units should strengthen pre-job training, technical disclosure, and operational supervision to improve work quality. Second, construction procedures should be standardized, and key operations should be checked against technical specifications. Third, the construction site environment should be continuously inspected, especially in areas involving high-altitude work, water-related construction, material storage, temporary access, and equipment movement. Fourth, safety awareness should be reinforced through daily briefings, behavioral supervision, and accountability mechanisms.

The results are consistent with the general understanding that construction safety is strongly influenced by human behavior and site management conditions. Previous studies have shown that unsafe behavior, weak safety climate, and inadequate safety management are important contributors to construction accidents [3,20,22]. In the present case, the high priority of low work quality and non-standard construction further confirms that bridge construction safety management should focus on controlling operational behavior and technical compliance.

5. Discussion

The case results show that the dominant safety risks in the bridge reconstruction project are mainly related to worker performance, construction standardization, site environment, and technical capability. The highest-risk indicator is low work quality (U2), followed by non-standard construction (U10), construction site environment (U12), lack of safety awareness (U1), and insufficient construction technology (U9). This ranking indicates that the most critical risks are not primarily caused by materials or machinery, but by human, technical, and environmental factors during construction execution. This result is reasonable because bridge construction involves high-altitude operations, deep foundation works, hoisting activities, concrete works, and complex temporary structures, where improper operation and deviation from procedures can quickly lead to unsafe conditions.

The first-ranked indicator, low work quality, reflects the influence of workers' operational competence and task execution on safety performance. In construction projects, unsafe behavior and poor operational performance are closely related to accident occurrence because many safety events originate from workers' decisions and actions at the workplace [22]. In bridge construction, this problem becomes more serious because workers often perform tasks under difficult environmental conditions and strict technical requirements. Therefore, safety management should not treat worker training as a formal procedure only. It should focus on whether workers can correctly understand technical instructions, follow safe operating procedures, and maintain stable performance during complex tasks.

The second-ranked indicator, non-standard construction, shows that compliance with specifications and construction procedures is a central safety issue. Bridge construction depends heavily on process control. Errors in formwork, scaffolding, concrete pouring, reinforcement placement, lifting operations, foundation excavation, and temporary support can create both immediate safety hazards and long-term structural risks. Previous studies have emphasized that construction accidents are often related to deficiencies in planning, supervision, risk control, and procedural implementation [21,23]. Therefore, non-standard construction should be controlled through detailed method statements, technical disclosure, process inspection, and strict acceptance before moving to the next construction activity.

The third-ranked indicator, construction site environment, indicates that site organization and surrounding conditions have a significant influence on bridge construction safety. Bridge construction sites are often constrained by rivers, traffic, nearby structures, narrow working areas, material storage limits, temporary access roads, and variable ground conditions. A disordered site environment may increase the risk of falls, collisions, equipment interference, poor emergency access, and unsafe material handling. This finding is consistent with construction safety studies showing that site conditions and workplace organization are important contributors to accident causation [22]. For the case project, the site environment should be managed through continuous inspection, temporary traffic organization, safe material stacking, clear access routes, and specific control of high-risk work zones.

The fourth-ranked indicator, lack of safety awareness, further confirms the importance of human-related risk control. Safety awareness affects how workers perceive hazards and whether they comply with safe work procedures. Even when safety rules and protective equipment are available, workers with weak safety awareness may ignore potential hazards or take shortcuts under schedule pressure. Safety awareness is also influenced by organizational safety climate, supervisor behavior, and management commitment [3,20]. Therefore, bridge construction managers should strengthen toolbox meetings, pre-task hazard briefings, daily safety reminders, and supervisor-led safety communication. These measures can improve hazard perception and reduce unsafe decision-making during construction.

The fifth-ranked indicator, insufficient construction technology, reflects the technical complexity of bridge construction. With the development of long-span bridges, reconstruction projects, and complex urban bridge systems, construction teams must handle more difficult procedures and higher technical uncertainty. If technical capability is insufficient, construction errors may occur even when workers are willing to follow safety rules. Technical risk control should therefore include construction scheme review, expert demonstration for high-risk operations, equipment suitability analysis, technical training, and monitoring of key construction parameters. This is particularly important for deep foundation excavation, large-volume concrete pouring, water-related construction, high-altitude operations, and special lifting procedures.

By contrast, defective mechanical equipment (U6) and substandard or insufficient building materials (U7) are ranked as relatively low-priority risks in the case project. This does not mean that equipment and materials are unimportant. Rather, it suggests that the project may already have relatively effective controls for equipment inspection, material acceptance, storage, and supply management. Material and equipment risks are often easier to standardize through inspection records, supplier qualification, testing procedures, and maintenance schedules. Human behavior, technical execution, and site environmental control are more variable and therefore more difficult to manage.

The proposed Pythagorean fuzzy TOPSIS method provides a practical way to rank bridge construction safety risks under uncertain expert judgments. Compared with crisp evaluation methods, the use of Pythagorean fuzzy numbers allows experts to express membership, non-membership, and hesitation information. This is useful because experts may not always be fully certain about the severity, probability, or uncontrollability of a risk indicator. Compared with ordinary fuzzy or intuitionistic fuzzy approaches, Pythagorean fuzzy sets provide a broader representation space for uncertain decision information [8,9]. As a result, the proposed method is appropriate for safety risk assessment problems where complete accident data are unavailable and expert judgment remains necessary.

The expert-derived criterion weights are an important feature of the model. In safety risk assessment, expert weights reflect professional understanding of project hazards, accident consequences, and control difficulty. However, subjective weights may also introduce bias if one criterion is overemphasized. Therefore, future extensions should compare the present weighting approach with entropy, CRITIC, or combined weighting methods and should report sensitivity analyses showing how criterion weights affect the final ranking. In the present case study, severity received the highest weight, followed by probability and uncontrollability, indicating that experts considered the possible consequence of risk events to be the most important factor in bridge construction safety evaluation.

Despite these advantages, the proposed method has limitations. First, the evaluation data are mainly derived from expert judgment. Although expert judgment is necessary in projects where complete safety data are unavailable, it may still contain subjective bias. Second, the case study is based on one bridge reconstruction project, so the results may not be directly generalized to all bridge types or construction environments. Third, the model provides a static ranking of risk indicators and does not capture how risk levels change across different construction stages. Bridge construction is a dynamic process, and risk priorities may change during foundation works, substructure construction, superstructure erection, deck construction, and finishing works. Future studies should extend the model by incorporating stage-based evaluation, real-time monitoring data, and sensitivity analysis.

Implications for Safety Training and Worker Competency

These implications help translate the fuzzy TOPSIS ranking into occupational safety management actions. Rather than treating the ranked indicators as abstract numerical outputs, managers can use them to allocate training resources, select inspection priorities, design toolbox-meeting themes, and assign responsibilities to safety officers, site supervisors, and technical managers.

The ranking results have direct implications for safety training and competency development. Low work quality requires task-specific competency assessment, pre-job instruction, and verification that workers can correctly execute critical operations. Non-standard construction requires procedural compliance training based on method statements, drawings, checklists, and hold-point inspections. Lack of safety awareness requires hazard-perception training, toolbox talks, and behavior-based observation. Insufficient construction technology requires technical disclosure, expert review of high-risk schemes,

and supervisor verification during complex operations such as deep foundation excavation, hoisting, formwork installation, water-related construction, and high-altitude work. Construction site environment requires site-specific induction and dynamic hazard briefings because access routes, storage areas, temporary facilities, and emergency paths can change during bridge construction.

From a leading-indicator perspective, the five highest-ranked factors provide early signals of potential occupational safety deterioration. Low work quality and lack of safety awareness indicate behavior-based and competency-related weaknesses. Non-standard construction and insufficient construction technology indicate procedural and technical-control weaknesses. Construction site environment indicates unsafe workplace conditions that may increase exposure before an accident occurs. Monitoring these indicators during daily safety inspections can therefore support proactive intervention instead of reactive accident response.

6. Conclusions

This study proposed an integrated Pythagorean fuzzy TOPSIS decision-support framework for occupational safety risk prioritization in bridge construction projects. The method was developed to address the uncertainty and hesitation that exist in expert-based safety evaluation. A bridge construction safety risk indicator system was established from five dimensions: human factors, management factors, material factors, technical factors, and environmental factors. Twelve secondary indicators were evaluated under three criteria: severity, probability, and uncontrollability. Expert judgments were expressed by linguistic variables, converted into Pythagorean fuzzy numbers, and aggregated through the Pythagorean fuzzy weighted average operator.

The proposed model was applied to a bridge reconstruction project involving complex construction conditions, including deep foundation pit excavation, large-volume concrete placement, water-related construction, and high-altitude operations. The results showed that the most critical safety risk indicator was low work quality (U2), followed by non-standard construction (U10), construction site environment (U12), lack of safety awareness (U1), and insufficient construction technology (U9). These findings indicate that the major safety risks in the case project were mainly associated with human behavior, construction procedure compliance, technical execution, and site environmental control.

The ranking results provide practical guidance for bridge construction occupational safety management. Construction managers should give priority to improving workers' operational quality, strengthening compliance with construction procedures, and optimizing the site environment. In particular, technical disclosure, pre-job safety training, supervisor verification, competency assessment, and strict process inspection should be reinforced. For complex bridge construction activities, such as foundation works, hoisting operations, formwork installation, concrete pouring, and high-altitude operations, safety control should focus on both technical standardization and worker behavior. This is consistent with previous construction safety studies showing that unsafe behavior, weak safety management, and poor site conditions are important contributors to construction accidents [24–26].

The methodological contribution of this study is the integration of Pythagorean fuzzy sets with TOPSIS for bridge construction safety risk prioritization. Pythagorean fuzzy numbers can express membership, non-membership, and hesitation information more flexibly than ordinary fuzzy sets and intuitionistic fuzzy sets [8,9]. This feature is useful in bridge construction safety assessment because experts often evaluate risks under incomplete information and uncertain site conditions. In addition, the transparent use of expert-derived criterion weights keeps the ranking procedure traceable and avoids introducing unsupported numerical adjustments into the final results.

This study has several limitations. First, the assessment data were mainly obtained from expert judgment. Although expert knowledge is valuable in safety risk assessment, future studies should incorporate more field data, accident records, monitoring data, and inspection records to improve objectivity. Second, the case study was based on one bridge reconstruction project. More bridge projects with different structural types, construction methods, and environmental conditions should be examined to verify the general applicability of the proposed model. Third, the current model provides a static ranking of safety risk indicators. Since bridge construction risks change across construction stages, future studies should develop a dynamic Pythagorean fuzzy decision model that can update risk priorities during foundation construction, substructure construction, superstructure erection, deck construction, and finishing works.

The operation of the bridge construction safety evaluation system has typical dynamic characteristics. Its risk control priorities are not constant, but continuously iterate and evolve dynamically as construction procedures progress. During different construction stages, such as pile foundation construction, pier column pouring, and cantilever pouring, the hazard degree, influence scope, and control priority of various safety risk factors will change accordingly. Therefore, bridge construction safety management needs to carry out regular dynamic risk monitoring and optimize and adjust control strategies in a timely manner, so that the evaluation model can recalibrate risk ranking results in real time according to construction progress. This ensures that safety control work accurately focuses on the core risk hazards of each construction stage and effectively implements the safety management goal of “dynamic evaluation and precise prevention and control.”

Future research can extend this study in four directions. First, the proposed model can be combined with dynamic weighting methods to evaluate the variation in safety risks over time. Second, sensitivity analysis can be added to examine the effect of expert weights and criterion weights on the final ranking. Third, objective weighting methods such as entropy or CRITIC can be incorporated when the corresponding weights are fully reported and compared with the expert-derived weights. Fourth, digital construction technologies, such as BIM, sensor monitoring, computer vision, and construction safety databases, can be integrated with fuzzy decision-making models to improve the timeliness and accuracy of safety risk assessment. These extensions would make the model more suitable for real-time safety management in complex bridge construction projects.

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