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Coupled Analysis of Safety Risks in Bridge Construction Based on N-K Model and SNA

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Abstract: Bridge construction accidents are often caused by a variety of factors, so it is particularly important to explore the role mechanism of bridge construction accident risk factors to effectively prevent construction safety accidents and ensure the smooth construction of bridges. We collect the causes of bridge construction accidents in China from 2006 to 2023, take 126 typical cases as research samples, analyze the primary risk factors of bridge construction from four aspects (human factors, equipment factors, management factors, and environmental factors), establish a library of secondary risk factors with reference to the literature research, introduce the theory of risk coupling, and analyze the coupling mechanism and types of risk factors of bridge construction accidents. The N-K random Boolean network model (N-K model) quantifies the coupling relationship between risk factors, assesses the risk level, and uses social network analysis (SNA) to analyze the network of bridge construction accident risk factors. The results indicate that the more factors involved in risk coupling, the greater the safety risks in bridge construction. Human factors are susceptible to the influence of other elements, and environmental and management factors can directly or indirectly impact other factors. In addition, operational errors, a lack of supervision and management, inadequate safety inspections, poor management personnel, and insufficient technical capabilities are also key risk factors that need to be prevented and controlled.

Keywords: bridge construction; risk factors; coupling analysis; N-K random Boolean network model (N-K model); social network analysis (SNA)

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1. Introduction

Bridges are an indispensable part of the transportation infrastructure system, providing access for transportation across natural barriers such as mountains, canyons, rivers, etc., to provide people with more convenient transportation. Its complex construction process, harsh operating environment, and uncertainty make the construction process very unpredictable, and construction safety faces multiple risks and challenges. Studying the safety risk factors of bridge construction is essential to improve the life safety of every participant and to improve the quality of bridge construction.

In recent years, scholars at home and abroad have conducted relevant research in the field of safety risks in bridge construction [1–3]. Wang et al. [4] established a hierarchical holographic modeling (HHM) safety risk framework with six dimensions: risk source, construction unit, control error, risk loss, safety accident, and participant. They applied social network analysis (SNA) to comprehensively identify the key safety risk factors in bridge construction projects. In the construction process of large bridges, various uncertain factors such as environmental conditions and construction loads exist. To reduce the theoretical calculation errors in monitoring and controlling indicators during the construction of high bridge piers with large spans of continuous rigid-frame bridges, Zhou et al. [5] introduced the Bayesian dynamic updating method to reevaluate the predicted results of the theoretical model. Li et al. [6] constructed a bridge construction accident risk early warning model integrating the rough set (RS), sparrow search algorithm (SSA), and least squares support vector machine (LSSSVM) to predict the construction safety risk of bridge projects. Wang et al. [7] comprehensively used a combination of the expert scoring method, fuzzy analytic hierarchy process (F-AHP), and grey entropy correlation analysis (GECA) to identify significant sources of risk during bridge construction. Wu et al. [8] employed the 4M1E approach to dissect the risk factors affecting the construction phases of bridges. They also proposed the use of artificial intelligence algorithms for risk assessment in the bridge construction process. Li et al. [9] proposed a bridge construction risk assessment model based on dynamic weights-two-dimensional cloud model to dynamically assess the bridge construction risk in the special environment of Sichuan-Tibet Railway. Ji et al. [10] introduced an improved fuzzy analytic hierarchy process (FAHP) factor analysis method to assess safety risks during the construction phase of large and complex bridges. Subsequently, they performed a risk assessment of bridge construction using the operational decomposition structure–risk decomposition structure assessment method and the fuzzy hierarchical synthesis method. Research on the safety risk management of bridge construction has primarily focused on identifying and assessing risk factors. However, studies investigating the complex interactions among these risk factors are limited. The coupling of multiple risk factors can potentially lead to unforeseen safety incidents. Conducting research on the interactions among safety risk factors in bridge construction is of vital significance. It allows for a deeper understanding of the sources of risk in bridge construction and aids in the formulation of effective risk control measures.

Recent research has emphasized the importance of adopting systematic and integrated approaches to risk management. This entails analyzing the mutual dependencies and feedback loops among various risk factors. Notably, many scholars have explored the coupling effects of multiple risk factors in the construction safety of other engineering structures, particularly based on the N-K model. Fang et al. [11] carried out a study on the analysis of the coupled evolution of subway tunnel construction safety risks based on the N-K model. Pan et al. [12] analyzed the impact of the coupling of multiple risk factors on the safe construction of tunnels by constructing an N-K model. Jiang et al. [13] investigated the risk coupling mechanism of the construction of deep foundations in the vicinity of existing underpass tunnels based on the dynamic Bayesian network and the N-K model. Hai et al. [14] simulated the integrated tube corridors based on the Potential Dirichlet Allocation Algorithm, the N-K model, and the system dynamics model construction safety risk evolution process. Pan et al. [15] studied the system coupling of tunnel construction safety risk in a subway shield zone based on the coupling degree theory in physics. Guo et al. [16] carried out a risk analysis of tunnel construction with the N-K and coupling degree models, and the results showed that there is a strong coupling relationship between complex geology and tectonic factors. Upon analyzing the literature, it is evident that the N-K model has found widespread applications in risk management, such as subway construction and tunnel development. Its effectiveness in analyzing interrelationships among various factors has also been validated. However, there remains a significant research gap in applying this model to the realm of bridge construction safety.

Currently, more scholars have used SNA to study the association between risk factors, which breaks through the previous assumption that risk is regarded as an isolated unit and better reflects the complexity and interdependence of risk factors [17–19]. Zhou et al. [20] used SNA and the N-K model comprehensively to study the risk factors of tower crane safety in construction projects and put forward prevention and control suggestions. Shao et al. [21] used SNA to visualize the risk factor relationship of new energy vehicle combustion and explosion and analyzed the centrality and accessibility of each node in the risk factor network. Based on the social network theory (SNA) and social capital theory, Wang et al. [22] revealed the emergence mechanism of project resilience by targeting survey data from 247 construction engineering practitioners. Chen et al. [23] employed various measurement methods of social network analysis (SNA) to identify core risk factors and analyze the risk diffusion effects in urban underground engineering. The research findings were validated through incidents in Chinese urban subway systems from 2017 to 2019. Wu et al. [24] screened the safety risk indicators of large-scale deep drainage tunnel projects based on SNA and assigned objective weights to them, effectively solving the problem of the strong correlation between risk factors. The SNA method offers a fresh perspective and tools for risk management. By constructing a network structure of risk factors, it can unveil interactions, information propagation, and influence paths among risks. This facilitates a more precise evaluation of potential risk impacts. Despite the wide application of SNA in other domains, its utilization in the context of bridge construction accident risk factors remains relatively limited. Introducing the SNA method into studies concerning bridge safety is of significant importance.

In summary, this paper adopts a comprehensive approach to studying bridge construction risk factors and their coupling. First, case data and literature research are collected to construct a model of bridge construction risk factors and their coupling mechanism to comprehensively understand the complexity of risk. Second, the N-K model is used to quantify the degree of coupling of construction risk factors to reduce subjective bias and provide an objective basis for risk assessment. Meanwhile, SNA is used to emphasize the relationship network and important nodes between risk factors, revealing the propagation path and influence degree of risk factors. The results of this study will provide a decision basis for the prevention and control of bridge construction risks, develop more effective risk management strategies, reduce the probability of accidents, and improve the safety and reliability of bridge construction.

2. Theory

2.1. Bridge Construction Accident Risk Factor Identification

In order to quantitatively analyze the characteristics of bridge construction accident risk factor coupling, the process of collecting and organizing bridge construction accident cases is as follows:

1. Based on the National Railway Bureau, the emergency management bureaus of provinces, cities, counties, and districts, the people's government network, the "Railway Bureau of Construction Safety Production Accident Early Warning and Card Control" monograph [25], and other information channels, find and organize a total of 153 cases of bridge construction accidents in our country that occurred from 2006 to 2023 (Appendix A).
2. Statistically analyze the accident occurrence factors based on the accident investigation reports or the causes of accidents collated and published by experts.
3. In order to ensure the reliability and accuracy of the study, assess the data quality of each case, screen and eliminate the cases with insufficient or unreliable data, and ultimately collect 126 cases of typical bridge construction accidents.

Through the analysis of literature studies [12,20,26–31], according to the theory of system engineering, bridge construction accident risk factors can be broadly classified into four categories: human factors, equipment factors, management factors, and environmental factors. Human factors, caused by the actions, behaviors, and restrictions of people involved in the construction process, is the most important one; equipment factors are risk factors arising from the use of equipment, machinery, and tools in the construction process; management factors are factors such as mismanagement, management deficiencies, and a lack of supervision that exist in the construction process; and environmental factors are the natural environment, the environment of the construction site, and the social environment that exists in the construction process that will also have a certain impact on the safety risk.

There are many risk factors affecting the safety of bridge construction; through the analysis of accident cases and literature, based on the four primary risk factors of man-made, equipment, management, and environment, 25 secondary risk factors are organized and obtained (see Table 1).

Table 1. Risk factors for bridge construction accidents.

Primary Risk Factor	Secondary Risk Factor
Human Factors	Fatigue operation R1 Non-compliant operation R2 Weak safety awareness R3 Insufficient technical ability R4 Operational error R5 Poor management competence R6 Equipment aging R7
Equipment Factors	Equipment failure R8 Inadequate equipment maintenance R9 Inappropriate equipment selection R10 Defects in equipment and material quality R11 Improper material storage R12 Improper material usage methods R13
Management Factors	Loopholes in regulations and rules R14 Ineffective implementation of management systems R15 Lack of supervision and management R16 Insufficient safety training R17 Inadequate safety inspections R18 Unreasonable construction plans R19
Environmental Factors	Severe weather conditions R20 Poor geological and hydrological conditions R21 Unfavorable working environment in the construction area R22 Complex traffic conditions along the perimeter R23 Risk of natural disasters R24 Complex underground pipeline conditions R25

2.2. Coupling Mechanism of Bridge Construction Risk Factors

According to the self-organization theory, coupling is the universal paradigm of things, which involves the nonlinear interaction between two systems [32]. Coupling refers to the degree or manner in which two or more systems or components interact and influence each other [33], and the term "coupling" is widely used in computer science, physics, engineering, and other fields. In risk management, there may be a coupling mechanism between different risk factors; that is, changes in one risk factor may have an impact on other risk factors, thus affecting the evolution of the whole risk state. The coupling effects among bridge construction accident risk factors arise from the complexity and diversity of interactions and influences between different factors. These relationships are not simply linear but encompass nonlinearity, asymmetry, and instability, leading to potential uncertainties, risks, and even safety accidents. Consequently, the coupling effects among bridge construction accident risk factors constitute a complex systemic issue, demanding a comprehensive analysis and assessment of the interactions between various risk factors. It necessitates the establishment of an integrated risk assessment model and the formulation of corresponding risk control measures to reduce the likelihood and impact of construction safety risks.

Risk factor coupling relationships are categorized according to the number and attributes of bridge construction accident risk factors, i.e., single-factor coupling, two-factor coupling, and multi-factor coupling [13,28,34]. Single-factor coupling refers to the interdependence and association among one or more components within the same safety risk factor category. For example, within the human factors category, the lack of safety awareness and non-compliant actions by construction personnel can lead to construction accidents. Dual-factor coupling pertains to the correlation between two safety risk factor categories from different domains. For instance, the combination of an unreasonable construction plan from the management factors category and adverse weather conditions from the environmental factors category can result in construction accidents. Multifactor coupling involves the interaction among three or more safety risk factors, spanning different categories. For instance, the combined effects of various factors like mechanical failures from equipment, operational errors from human factors, inadequate supervision from management factors, and complex terrain from environmental factors can potentially lead to severe construction accidents. The risk coupling model is shown in Figure 1.

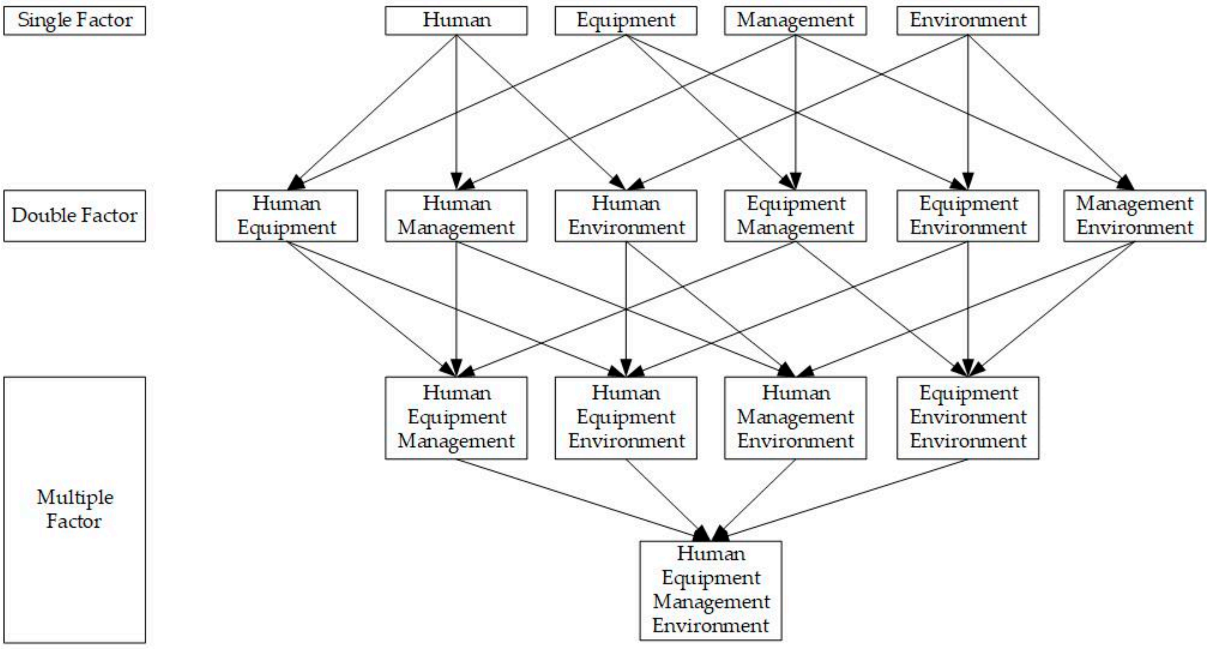

Figure 1. Risk coupling model.

3. Methods

3.1. Specific Analysis Process

In this paper, we combine the N-K model with the SNA model. The groundwork is to construct a risk factor library for bridge construction accidents and analyze the form of coupling. Then, the N-K model is utilized to quantify the risk factor coupling and assess the possibility of risk events. However, the N-K model may not be able to consider the actual relationship and propagation path between factors. At the same time, the adjacency matrix is built based on the factor library, and the SNA is used to calculate the centrality to obtain the key risk factors and find out the propagation path. However, the SNA model may ignore the coupling strength and specific influence mechanisms between factors. By combining them, the interactions between risk factors can be better understood, subjective bias can be reduced, and a more comprehensive perspective on risk management can be provided. The research process is illustrated in Figure 2.

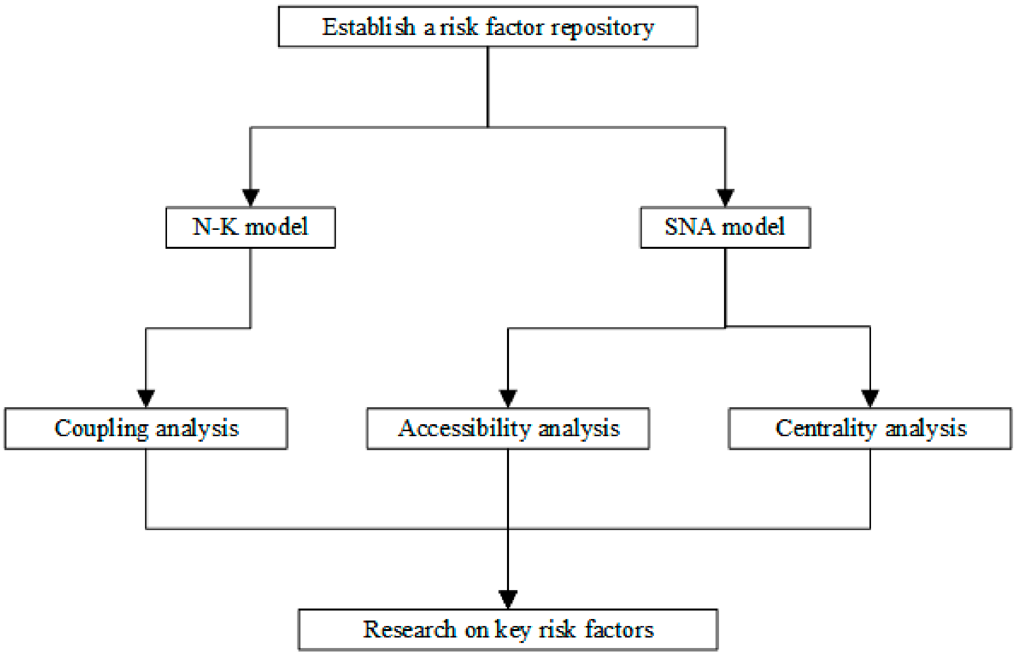

Figure 2. Methodology flowchart.

3.2. N-K Model Risk Coupling Model Construction

The N-K model is a mathematical model proposed by biologist KAUFFMAN [35] to study the interactions and interdependencies between factors in complex systems, which helps to identify the key risk factors and their interactions in a structured and systematic way and is an important extension of the traditional analytical approach [36]. In order to study the coupling relationship between elements in a complex system, the interaction information T in information theory can be utilized to measure the correlation and mutual information between two elements, reflecting the degree of connection between them. When the value of T is higher, it indicates that the coupling relationship between these two elements is stronger, and the mutual influence is greater. Therefore, by calculating the interaction information T, we can better understand the interrelationships and action mechanisms between the elements in the system and provide important references for the optimization and control of the system.

The N-K model has two important parameters N and K; N represents the number of elements in the system, and the K value indicates the number of dependencies or interactions between elements in the system. If each element in the system has n possible states, there are n^N possible combinations of N elements. These elements will be connected to each other in a certain way to form a network. The interaction relationship between the elements is also known as interdependence and can be described by K. The value of K ranges from 0 to $N - 1$ where $K = 0$ means that there is no interaction relationship between the elements while $K = N - 1$ means that each element has an interaction relationship with all other elements.

In assessing the risk state formed by the coupling effect, it can be judged by calculating the interaction information T between the factors involved in the coupling, and the larger the value of T, the greater the risk of such a form of coupling, and thus the greater the possibility of accidents occurring. The following A, B, C, and D denote the human factors, equipment factors, management factors, and environmental factors affecting bridge construction safety, respectively. The coupling values of the four categories of risk factors (human, equipment, management, and environment) are represented as $T_{11}(A)$, $T_{12}(B)$, $T_{13}(C)$, and $T_{14}(D)$, respectively, and the total coupling risk value is represented as T_1. The bivariate coupling values for the six categories of interactions, namely human and equipment, human and management, human and environment, equipment and management, equipment and environment, and environment and management, are denoted as $T_{21}(A,B)$, $T_{22}(A,C)$, $T_{23}(A,D)$, $T_{24}(B,C)$, $T_{25}(B,D)$, and $T_{26}(C,D)$, respectively, and the total coupling risk value is represented as T_2. The triple-factor coupling values of human–equipment–management, human–equipment–environment, human–management–environment, and equipment–management–environment are represented as $T_{31}(A,B,C)$, $T_{32}(A,B,D)$, $T_{33}(A,C,D)$, and $T_{34}(B,C,D)$, respectively, and the total coupling risk value is represented as T_3. The four-factor coupling value of human–equipment–management–environment is represented as $T_4(A,B,C,D)$, and the total coupling risk value is represented as T_4. The specific calculation formulas are as follows:

$$T(A,B,C,D) = \sum_{h=1}^{H}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} P_{hijk}\bullet \log_2(P_{hijk}/(P_{h***}\bullet P_{*i**}\bullet P_{**j*}\bullet P_{***k})) \\ h = 1,2,\ldots,H; i = 1,2,\ldots,I; j = 1,2,\ldots,J; k = 1,2,\ldots,K; \tag{1}$$

In Equation (1), h, i, j, and k represent the human, equipment, management, and environment factors involved in the coupling analysis, respectively. The "*" symbol indicates an unknown state for that particular factor. $P_{\mathrm{h}***}$, $P_{*\mathrm{i}**}$, $P_{**\mathrm{j}*}$, and $P_{***\mathrm{k}}$ represent the probabilities of the human factor being in state h, the equipment factor being in state i, the management factor being in state j, and the environment factor being in state k, respectively. P_{hijk} represents the probability of the four risk factor coupling occurring when the human factor is in state h, the equipment factor is in state i, the management factor is in state j, and the environment factor is in state k. By calculating the joint probability of h, i, j, and k occurring together, we can determine the coupling risk value between factors and take appropriate preventive measures to ensure the smooth progress of bridge construction.

Based on Equation (1), the calculation formulas for multi-factor and two-factor coupling are as follows:

$$T_{31}(A,B,C) = \sum_{h=1}^{H}\sum_{i=1}^{I}\sum_{j=1}^{J} P_{hij}\bullet \log_2(P_{hij}/(P_{h***}\bullet P_{*i**}\bullet P_{**j*})) \tag{2}$$

$$T_{32}(A,B,D) = \sum_{h=1}^{H}\sum_{i=1}^{I}\sum_{k=1}^{K} P_{hik}\bullet \log_2(P_{hik}/(P_{h***}\bullet P_{*i**}\bullet P_{***k})) \tag{3}$$

$$T_{33}(A,C,D) = \sum_{h=1}^{H}\sum_{j=1}^{J}\sum_{k=1}^{K} P_{hjk}\bullet \log_2(P_{hjk}/(P_{h***}\bullet P_{**j*}\bullet P_{***k})) \tag{4}$$

$$T_{34}(B,C,D) = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} P_{ijk}\bullet \log_2(P_{ijk}/(P_{*i**}\bullet P_{**j*}\bullet P_{***k})) \tag{5}$$

$$T_{21}(A,B) = \sum_{h=1}^{H}\sum_{i=1}^{I} P_{hi}\bullet \log_2(P_{hi}/(P_{h***}\bullet P_{*i**})) \tag{6}$$

$$T_{22}(A,C) = \sum_{h=1}^{H}\sum_{j=1}^{J} P_{hj}\bullet \log_2(P_{hj}/(P_{h***}\bullet P_{**j*})) \tag{7}$$

$$T_{23}(A,D) = \sum_{h=1}^{H}\sum_{k=1}^{K} P_{hk}\bullet \log_2(P_{hk}/(P_{h***}\bullet P_{***k})) \tag{8}$$

$$T_{24}(B,C) = \sum_{i=1}^{I}\sum_{j=1}^{J} P_{ij}\bullet \log_2(P_{ij}/(P_{*i**}\bullet P_{**j*})) \tag{9}$$

$$T_{25}(B,D) = \sum_{i=1}^{I}\sum_{k=1}^{K} P_{ik}\bullet \log_2(P_{ik}/(P_{*i**}\bullet P_{***k})) \tag{10}$$

$$T_{26}(C,D) = \sum_{j=1}^{J}\sum_{k=1}^{K} P_{jk}\bullet \log_2(P_{jk}/(P_{**j*}\bullet P_{***k})) \tag{11}$$

3.3. Construction of the SNA Model

SNA is a quantitative analysis method based on mathematical methods and tools such as graph theory [30], which is widely used in the fields of social sciences, organizational management, and information sciences. It focuses on the interrelationships between nodes and information transfer paths, which can reveal the role relationship between bridge construction risk factors and assess the influence and propagation effect of risk factors. Based on combing and analyzing the collected causes of bridge construction accident cases, a preliminary bridge construction accident risk factor relationship library was constructed. On this basis, combined with expert interviews, the association between risk factors was further improved, and the final risk factor adjacency matrix was obtained (Appendix B). In the adjacency matrix, element 1 indicates that there is a connection between the corresponding two factors, and element 0 indicates that there is no connection between the two factors.

SNA employs various metrics, and in this study, we primarily focus on closeness centrality and betweenness centrality. Closeness centrality measures the quick connectivity of a node with other nodes in the network. It is calculated based on the average shortest path length between a node and all other nodes in the network. Nodes with high closeness centrality are considered to be in central positions, enabling rapid dissemination of information or resources to other nodes. Betweenness centrality measures the extent to which a node acts as a bridge or intermediary in the network. It quantifies the number of times a node appears on the shortest paths between other nodes. Nodes with high betweenness centrality play a crucial role in connecting different parts of the network and controlling the flow of information or resources. For a complex network with n nodes, the closeness centrality C_C of node i is calculated using Equation (12), and the betweenness centrality C_B is calculated using Equation (13). In these equations, $d(n_i, n_j)$ represents the shortest path length between node n_i and node n_j, $g_{jk}(n_i)$ denotes the number of geodesic paths passing through node n_i, and g_{jk} represents the total number of geodesic paths from node n_j to node n_i.

$$C_C = \left[\sum_{j=1}^{n} d\left(n_i, n_j\right)\right]^{-1} \tag{12}$$

$$C_B = \sum_{j<k} g_{jk}(n_i)/g_{jk} \tag{13}$$

4. Results

4.1. Analysis of the Results of N-K Model Calculations

In the computation of the N-K model, the coupling of risk factors in the recorded accident cases is first categorized and calculated. The detailed information is presented in Table 2. In the table, "p" represents the number of occurrences, "P" indicates the frequency, and the likelihood of a factor contributing to the occurrence of an accident is denoted by 1 or 0. Specifically, "1" signifies that the factor led to the accident occurrence, while "0" indicates that the occurrence of the accident was unrelated to that factor. For example, p_{1000} means that the number of accidents caused by human factors (126 typical bridge construction accidents collected as mentioned in Section 2.1) is 17, and P_{1000} means that the probability of an accident caused by human factors is 0.1349.

From Table 2, we can learn that the human–management aspect has the highest number of accidents and the highest probability. This indicates that in bridge construction, factors such as poor management, inadequate supervision, and carelessness of personnel become common causes of accidents under the interaction between human and management. Secondly, the number of accidents in the human–equipment–management aspect is relatively high, and the probability is also relatively high. This may imply that the interactions between the actions of personnel, the condition of equipment, and management practices at the construction site are intertwined, and together affect the probability of accidents. The combination of multiple factors results in a higher percentage of accidents than a single factor. In the construction process, we not only need to strengthen the control of single factors but also need to pay more attention to the interaction between multiple factors.

Table 2. Statistics of bridge construction accidents in China from 2006 to 2023.

Type of Coupling	Risk Factor	Accident Count	Accident Frequency
Single Factor	Human	$p_{1000} = 17$	$P_{1000} = 0.1349$
	Equipment	$p_{0100} = 19$	$P_{0100} = 0.1508$
	Management	$p_{0010} = 2$	$P_{0010} = 0.0159$
	Environment	$p_{0001} = 6$	$P_{0001} = 0.0476$
Double Factor	Human–Equipment	$p_{1100} = 4$	$P_{1100} = 0.0317$
	Human–Management	$p_{1010} = 38$	$P_{1010} = 0.3016$
	Human–Environment	$p_{1001} = 1$	$P_{1001} = 0.0079$
	Equipment–Management	$p_{0110} = 3$	$P_{0110} = 0.0238$
	Equipment–Environment	$p_{0101} = 1$	$P_{0101} = 0.0079$
	Environment–Management	$p_{0011} = 1$	$P_{0011} = 0.0079$
Multiple Factor	Human–Equipment–Management	$p_{1110} = 20$	$P_{1110} = 0.1587$
	Human–Equipment–Environment	$p_{1101} = 1$	$P_{1101} = 0.0079$
	Human–Management–Environment	$p_{1011} = 9$	$P_{1011} = 0.0714$
	Equipment–Management–Environment	$p_{0111} = 2$	$P_{0111} = 0.0159$
	Human–Equipment–Management–Environment	$p_{1111} = 2$	$P_{1111} = 0.0159$

Based on the previous Equation (1) in Section 3.2, to determine the risk value T for each risk coupling interaction, we need to obtain the probabilities P for single-factor, double-factor, and multiple-factor scenarios. Taking P_{1***}, P_{*01*}, and P_{*011} as examples, the calculation process is as follows:

$$P_{1***} = P_{1000} + P_{1100} + P_{1010} + P_{1001} + P_{1110} + P_{1101} + P_{1011} + P_{1111}$$
$$= 0.1349 + 0.0317 + 0.3016 + 0.0079 + 0.1587 + 0.0079 + 0.0714 + 0.0159 = 0.7302$$
$$P_{*01*} = P_{0010} + P_{1010} + P_{0011} + P_{1011} = 0.0159 + 0.3016 + 0.0079 + 0.0714 = 0.3968$$
$$P_{*011} = P_{0011} + P_{1011} = 0.0079 + 0.0714 = 0.0794$$

The calculation process for all risk coupling factor probabilities is the same as mentioned earlier, and the results are shown in Table 3.

Table 3. Coupling probability of safety risk factors for construction accidents of sample bridges.

Type of Coupling	Coupling Probability			
Single Factor	$P_{0***} = 0.2698$	$P_{*0**} = 0.5873$	$P_{**0*} = 0.3889$	$P_{***0} = 0.8175$
	$P_{1***} = 0.7302$	$P_{*1**} = 0.4127$	$P_{**1*} = 0.6111$	$P_{***1} = 0.1825$
Double Factor	$P_{00**} = 0.0714$	$P_{0*0*} = 0.2063$	$P_{0**0} = 0.1905$	$P_{*00*} = 0.4524$
	$P_{*0*0} = 0.3175$	$P_{**00} = 0.2143$	$P_{11**} = 0.5476$	$P_{1*1*} = 0.1032$
	$P_{1**1} = 0.1032$	$P_{*11*} = 0.2143$	$P_{*1*1} = 0.0476$	$P_{**11} = 0.1111$
	$P_{01**} = 0.1984$	$P_{0*1*} = 0.0635$	$P_{0**1} = 0.0794$	$P_{*01*} = 0.3986$
	$P_{*0*1} = 0.1349$	$P_{**01} = 0.0714$	$P_{10**} = 0.5159$	$P_{1*0*} = 0.1825$
	$P_{1**0} = 0.6270$	$P_{*10*} = 0.1984$	$P_{*1*0} = 0.3651$	$P_{**10} = 0.5000$
Multiple Factor	$P_{000*} = 0.0476$	$P_{00*0} = 0.0159$	$P_{0*00} = 0.1508$	$P_{*000} = 0.1349$
	$P_{100*} = 0.1429$	$P_{010*} = 0.1587$	$P_{001*} = 0.0238$	$P_{10*0} = 0.4365$
	$P_{01*0} = 0.1746$	$P_{00*1} = 0.0556$	$P_{1*00} = 0.1667$	$P_{0*10} = 0.0397$
	$P_{0*01} = 0.0556$	$P_{*100} = 0.1825$	$P_{*010} = 0.3175$	$P_{*001} = 0.0556$
	$P_{110*} = 0.0397$	$P_{011*} = 0.0397$	$P_{101*} = 0.3730$	$P_{11*0} = 0.1905$
	$P_{01*1} = 0.0238$	$P_{10*1} = 0.0794$	$P_{1*10} = 0.4603$	$P_{1*01} = 0.0159$
	$P_{0*11} = 0.0238$	$P_{*110} = 0.1825$	$P_{*011} = 0.0794$	$P_{*101} = 0.0159$
	$P_{111*} = 0.1746$	$P_{11*1} = 0.0238$	$P_{1*11} = 0.0873$	$P_{*111} = 0.0317$

Based on the risk coupling calculation Formulas (1)~(11) in Section 3.2 and the coupling probabilities of different safety risk factors shown in Table 3, the risk coupling values T are calculated, and the results are shown in Table 4.

Table 4. The coupling value T of safety risk factors of sample bridge construction accidents.

Coupling of Risk Factors	Risk Coupling Value T	Sorting by Magnitude
Human–Equipment	T_{21}(A,B) = 0.1154	6
Human–Management	T_{22}(A,C) = 0.1593	5
Human–Environment	T_{23}(A,D) = 0.0207	8
Equipment–Management	T_{24}(B,C) = 0.0180	9
Equipment–Environment	T_{25}(B,D) = 0.0160	10
Management–Environment	T_{26}(C,D) = 0.0004	11
Human–Equipment–Management	T_{31}(A,B,C) = 0.2833	2
Human–Equipment–Environment	T_{32}(A,B,D) = 0.2140	3
Human–Management–Environment	T_{33}(A,C,D) = 0.1865	4
Equipment–Management–Environment	T_{34}(B,C,D) = 0.0417	7
Human–Equipment–Management–Environment	T_4(A,B,C,D) = 0.4507	1

Based on the measurement of risk coupling effects and the analysis of coupling interaction combinations, we conducted an in-depth analysis and research on the coupling results of each factor. The conclusions are as follows:

1. The greater the number of factors involved in the coupling, the higher the risk of bridge construction accidents. From Table 3, it can be observed that the four-factor coupling T_4 is the largest, being 59% higher than the maximum three-factor coupling value T_{31}. Three-factor coupling values are generally larger than two-factor coupling values, with the maximum three-factor coupling value T_{31} being 78% higher than the maximum two-factor coupling value T_{22}. The calculated results align with the actual situation of safety risks in construction sites. Avoiding multiple-factor couplings as much as possible during bridge construction is an effective measure to reduce the probability of accidents.
2. In the three-factor risk coupling, the coupling value of human–equipment–management T_{31} is the largest, followed by the coupling value of human–equipment–environment T_{32}. To some extent, it indicates that human and equipment factors are easy to couple with other factors, which has a greater impact on the construction safety of bridge construction and needs to be paid special attention to and be controlled. At the construction site, necessary measures should be taken to ensure the cooperative operation of personnel and equipment, reduce the probability of coupling with other factors, and ensure construction safety and efficiency. The coupling value T_{31} is 32% higher than T_{32}, the coupling value T_{32} is 15% higher than T_{33}, and the coupling value T_{33} is 347% higher than T_{34}. The data indicate that three-factor risk coupling without human involvement, i.e., only equipment–management–environment involvement, has a much smaller probability of accidents.
3. In the two-factor risk coupling, the human–management coupling value T_{22} is the largest, followed by the human–equipment coupling value T_{21}, and then the human–environment coupling value T_{23}. It is obvious that the coupling value increases due to the involvement of human factors, which indicates that human behaviors are crucial for bridge construction safety during the bridge construction process. The coupling value of management–environment is the smallest, indicating that the interaction between these two factors is relatively weak. However, this does not mean that environmental risks can be ignored, and those responsible should take measures to assess and mitigate these risks. The coupling value T_{22} is 38% higher than T_{21}, while the coupling value T_{21} is 457% higher than T_{23}. The data indicate that among all two-factor risk couplings, the human–management and human–equipment factor couplings are more likely to cause bridge construction accidents.

4.2. Analysis of SNA Model Calculation Results

In order to further analyze the association relationship between risk factors, we imported the constructed risk factor adjacency matrix into the application of social network analysis software UCINET 6.0 and binarized it. Subsequently, with the help of NetDraw 2.161 software, we visualized and presented the obtained risk factor association network, as shown in Figure 3. The figure is a directed complex network, and the pointing of the arrows indicates the induced relationships between risk factors.

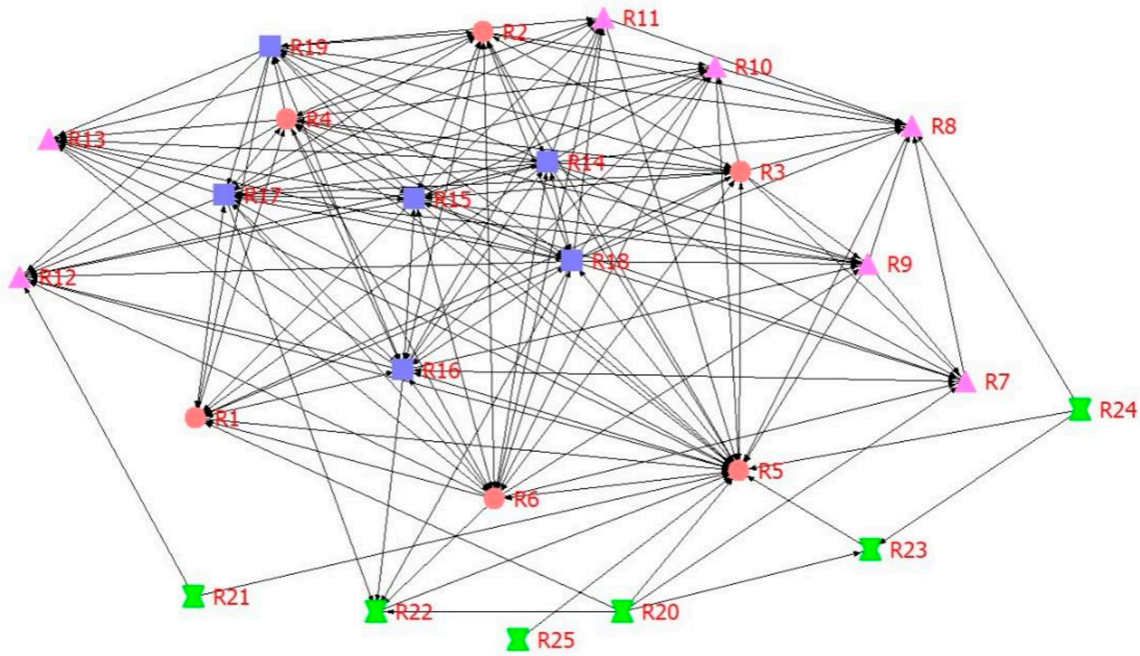

Figure 3. Bridge construction accident risk factor network diagram.

Through this visualization, we were able to observe the interactions between risk factors more clearly. Based on the connections in the network and the direction of the arrows, the propagation path of the risk can be traced. A causal relationship indicates that a change in one factor may directly cause a change in another factor. For example, a poor choice of equipment R10 may lead to an operational error R5. An interaction relationship indicates that two factors may influence each other. For example, poor managerial skills R6 may lead to operational errors R5, and operational errors R5 may lead to the occurrence of poor managerial skills R6. A mediating relationship indicates that some factors may mediate between other factors. For example, loopholes in regulations R14 may lead to operational violations R2, and operational violations R2 may lead to poor equipment selection R10.

Through the analysis of centrality and power in the UCINET 6.0 software network using the processed adjacency matrix, the closeness centrality and betweenness centrality of each node in the risk network graph were obtained. The specific data can be found in Table 5. As the risk factor network is a directed network, when calculating the closeness centrality of nodes, both out-degree and in-degree are considered, representing the degree of proximity between nodes. A higher in-degree closeness centrality indicates that the risk factor is more easily influenced and induced by other risk factors. On the other hand, a higher out-degree closeness centrality suggests that the risk factor can quickly trigger other risk factors, leading to a higher potential risk. The betweenness centrality measures the importance of a node in connecting other nodes in the network, indicating its role in information and influence dissemination. A higher betweenness centrality implies that the risk factor plays a significant bridging role in the transmission and diffusion of risks.

Table 5. Closeness and betweenness of each risk node in a risk network.

Risk Factor	Closeness		Betweenness
	In-Closeness	Out-Closeness	
Fatigue operation R1	48.00	15.19	5.59
Non-compliant operation R2	47.06	16.00	3.86
Weak safety awareness R3	60.00	15.79	21.79
Insufficient technical ability R4	63.16	16.22	29.59
Operational error R5	96.00	15.29	204.05
Poor management competence R6	61.54	16.44	30.03
Equipment aging R7	48.00	14.81	5.20
Equipment failure R8	54.55	13.79	0.60
Inadequate equipment maintenance R9	47.06	14.12	0.99
Inappropriate equipment selection R10	48.00	13.95	0.68
Defects in equipment and material quality R11	47.06	13.95	0.68
Improper material storage R12	48.98	13.79	0.00
Improper material usage methods R13	48.00	13.79	0.00
Loopholes in regulations and rules R14	44.44	16.44	2.19
Ineffective implementation of management systems R15	47.06	16.22	3.74
Lack of supervision and management R16	63.16	16.44	58.33
Insufficient safety training R17	64.86	16.22	27.91
Inadequate safety inspections R18	61.54	16.67	38.67
Unreasonable construction plans R19	43.64	15.89	1.06
Severe weather conditions R20	4.00	19.83	0.00
Poor geological and hydrological conditions R21	4.00	16.00	0.00
Unfavorable working environment in the construction area R22	45.28	13.79	0.00
Complex traffic conditions along the perimeter R23	4.35	15.79	0.00
Risk of natural disasters R24	4.00	19.05	0.00
Complex underground pipeline conditions R25	4.00	15.79	0.00

Through the analysis of the in-degree, out-degree, and betweenness centrality indicators of closeness centrality in SNA, in-depth research and analysis were conducted on each factor, leading to the following conclusions:

1. In-Closeness: The top 5 risk factors are operational errors R5, insufficient safety training R17, insufficient technical competence R4, lack of supervision and management R16, and poor management R6. This means that human unsafe behaviors are influenced to a higher degree by the other risk factors, which may directly lead to accidents or exacerbate the level of risk.
2. Out-Closeness: The top 5 risk factors are adverse weather conditions R20, natural disaster risk R24, inadequate safety inspections R18, poor level of management personnel R6, and loopholes in rules and regulations R14. This indicates that natural disasters and management factors have the ability to directly or indirectly influence other risk factors and play a key role in propagating and spreading risk.
3. Betweenness: The top 5 risk factors include operational errors R5, lack of supervision and management R16, inadequate safety inspections R18, poor level of management personnel R6, and insufficient technical capabilities R4. This indicates that construction personnel and management personnel play an important role in the transmission of risk information and the dissemination of impacts and that they connect other nodes in the risk network and have an important impact on stability, and safety has an important influence.

5. Discussion

In this section, we discuss the limitations of the current research methods and propose the integration of advanced optimization algorithms to address these shortcomings. We highlight the advantages of advanced optimization algorithms for enhancing problem-solving efficiency, handling multi-objective and multi-constraint problems, and addressing uncertainty and their versatility across various domains.

5.1. Addressing Current Method Limitations

The primary research methods in this study, the N-K model and SNA, provided valuable insights into the complex relationships among risk factors affecting bridge construction safety. However, they fall short in certain aspects as follows.

In the aspect of resource optimization and decision support, the current methods do not adequately address resource optimization and decision support aspects, which are crucial for efficient and effective bridge construction management.

In the aspect of handling multiple conflicting objectives, when multiple conflicting objectives are involved, the current methods lack the ability to provide satisfactory solutions, limiting their applicability in real-world scenarios.

Additionally, in the aspect of uncertainty, bridge construction is susceptible to various uncertainties, such as weather and material availability, for which the current methods cannot offer robust solutions.

5.2. Advantages of Advanced Optimization Algorithms

We propose the integration of advanced optimization algorithms into the research framework to overcome these limitations. Advanced optimization algorithms offer several key advantages.

First, these algorithms can significantly improve the efficiency of problem solving, especially when dealing with large-scale problems or complex objective functions. For example, adaptive algorithms can intelligently adjust the search strategy according to the nature of the problem to adapt to different types of decision problems, thus improving the speed and accuracy of problem solving. Studies have already demonstrated the self-adaptive fast fireworks algorithm adaptive polyploid memetic algorithm (APMA) in large-scale black-box optimization [37] and the successful application of the adaptive multimeme algorithm in truck scheduling problems [38].

Second, advanced optimization algorithms have the ability to handle multi-objective and multi-constraint problems. They are able to efficiently solve multi-objective optimization problems where there are multiple conflicting objectives and also find feasible solutions while considering multiple constraints. This is of great practical importance for solving complex decision-making problems in the real world, such as supply chain optimization or engineering design problems. Previous research has successfully solved vehicle path problems using meta-heuristics [39] and multi-objective models through exact optimization methods and heuristic optimization approaches to minimize the severity of hazards and traffic delays caused by accidents [40].

Moreover, advanced optimization algorithms can deal with uncertainty and variability. They can dynamically adjust strategies during the decision-making process to ensure the robustness and reliability of solutions. For example, the diffusion meme optimizer (DMO) has been proposed for reactive berth allocation and scheduling at seaports, providing critical managerial insights by handling unforeseen events and assisting in berth plan recovery [41]. Additionally, a high-dimensional particle swarm optimization algorithm embedded with machine learning techniques has been applied to solve the berth allocation problem (BAP) with uncertain ship handling times [42].

Lastly, advanced optimization algorithms are not limited to specific domains; they have been successfully applied in various fields, including medicine, finance, data analysis, and artificial intelligence. Their versatility makes them valuable tools for tackling a wide range of challenging decision problems with extensive potential applications. Scholars have expanded their research into broader applications of these algorithms and continue to explore new possibilities. For instance, one study improved the performance of hyper-heuristic algorithms in discrete optimization by introducing an ant colony hyperheuristic algorithm called "Hyperheuristic Ant Colony Optimization (HACO)" [43].

6. Conclusions

Based on an in-depth analysis of typical bridge construction accidents in China and the utilization of the N-K model and SNA, we have arrived at significant findings regarding bridge construction safety. Additionally, we offer insights into potential future research directions. The conclusions are as follows.

The application of the N-K model reveals that the coupling of multiple factors is the fundamental cause of accidents in bridge construction safety. Notably, there is a positive correlation between the number of coupled factors and the magnitude of safety accident risks. Among various combinations, the coupling value is most pronounced in four-factor combinations, followed by three-factor combinations, which generally surpass two-factor combinations. Consequently, mitigating multi-factor coupling emerges as an effective strategy for reducing accident occurrences. Furthermore, the incidence of accidents exhibits a stronger association with the interactions within the human–equipment–management system than with environmental factors. Specifically, accidents are significantly more likely to be triggered by interactions between human–equipment and human–management factors than by the individual factors themselves.

In accordance with the results from the SNA model, it becomes evident that operational errors, insufficient supervision and management, inadequate safety inspections, suboptimal managerial skills, and limited technical capabilities display higher intermediary centrality within the risk network. Proactively addressing these risk factors has the potential to disrupt connections within the risk network effectively, thereby lowering the likelihood and impact of risk incidents.

An analysis of the SNA's in-degree closeness centrality underscores the susceptibility of human unsafe behavior to the influence of other risk factors. Complementing this, N-K calculations reveal that coupling values related to human factors are relatively high, indicating a predisposition for human factors to manifest in risk factor combinations. Consequently, the probability of accidents escalates when human factors are involved in these couplings, emphasizing the paramount importance of human factors in ensuring bridge construction safety.

In the future, the study in this work can be furthered in the following ways: First, from the perspective of the application of advanced optimization algorithms, we recommend integrating advanced optimization algorithms into the current research framework to address deficiencies in resource optimization and decision support. This will contribute to better management of bridge construction risks and provide decision support, especially in scenarios involving multiple conflicting objectives and uncertainty factors. Second, from the perspective of continued study of human factors, due to the significance of human factors in bridge construction safety, future research can delve deeper into these factors to develop more effective interventions and training methods, ultimately reducing the risk of human errors. Third, from the perspective of practical application, the practical application of research findings is paramount. We encourage the utilization of research outcomes to enhance real-world bridge construction safety management practices, thereby reducing accident occurrences and minimizing losses. Hence, these future research directions hold the potential to further enhance the practicality and applicability of bridge construction safety, offering more sustainable and secure solutions for future construction projects.

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Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Bridge safety incident case summaries.

Number	Date	Name of the Incident	Accident Casualties	Type of Coupling
1	29 August 2006	Construction Collapse of Xiamen Tongan Bay Bridge Project	17 injured	Equipment–Management–Environment
2	21 October 2006	A railroad Yangjiazhai station girder stretcher breakage bridge crane overturning accident	6 dead, 15 injured	Human–Equipment–Management
3	30 March 2007	Accident of formwork falling off of a continuous girder across the fifth ring road on a railroad ring road bridge	1 dead, 1 injured	Human–Management–Environment
4	13 August 2007	Fenghuang County, Hunan Province, Dixi Tuojiang Bridge "8.13" particularly significant collapse accident	64 dead, 22 injured	Human–Equipment–Management
5	9 September 2007	A railroad Longjiang Bridge No. 11 pier template mold explosion accident	3 dead, 4 injured	Human–Equipment–Management
6	12 November 2007	A railroad Lingjiang special bridge beribboned girder dislodgement accident	3 dead	Human–Management–Equipment
7	19 November 2007	A railroad Tianxingzhou bridge pier body explosion mold fall accident	1 dead	Human–Equipment
8	27 May 2008	A railroad bridge abutment pit collapse accident	3 dead	Human
9	21 June 2008	A railroad oujiang bridge mobile mold collapse accident	7 dead, 19 injured	Human–Equipment–Management–Environment
10	21 August 2008	Collapse of in-situ girder of Jinshidang Bridge of a passenger railroad specialization	2 dead, 2 injured	Human–Management
11	19 August 2009	A railroad Jiading girder yard gantry crane overturning accident	4 dead, 2 injured	Equipment–Environment
12	22 August 2009	Bored pile collapse of a railroad bridge over Hutuo River	2 dead	Human–Management–Environment
13	11 September 2009	A railroad Caijiawan Han River Bridge mold explosion accident	1 dead, 3 injured	Equipment–Management
14	3 October 2009	A railroad bridge bearing platform burst mold accident	1 dead	Human–Equipment

Table A1. *Cont.*

Number	Date	Name of the Incident	Accident Casualties	Type of Coupling
15	20 October 2009	Collapse of continuous girder support of a railroad bridge over Yinlong River	5 dead, 1 injured	Equipment
16	26 October 2009	Mechanical Injury Accident of Li Jiatun No.2 Special Bridge of a Passenger Specialized Vehicle	1 dead, 1 injured	Human–Management
17	29 October 2009	Accident of falling objects during the construction of Liulaijing continuous girder of a railroad line	1 dead, 1 injured	Human–Equipment–Management
18	18 November 2009	A railroad Haihang Bridge formwork tipping accident	1 dead, 5 injured	Human–Management
19	26 November 2009	A railroad bridge crane overturning accident	1 dead, 2 injured	Human–Management
20	3 January 2010	Kunming Accountable New Airport Approach Bridge Project Bracket Partial Collapse Incident	7 dead, 34 injured	Human–Equipment–Management
21	20 February 2010	Crane rollover accident at No.2 bridge of a passenger railroad special-purpose building	2 dead, 7 injured	Human–Equipment–Management
22	23 May 2010	A railroad Daitanzhai bridge bridge crane overturning accident	5 dead, 4 injured	Equipment
23	23 May 2010	A railroad hub Nanchang oversized bridge pier body rebar tipping accident	2 dead, 1 injured	Environment
24	12 June 2010	A railroad Beijiang Bridge west approach pier 12 mold explosion accident	1 dead, 2 injured	Human–Equipment
25	18 July 2010	Hanging basket overturning accident of a railroad bridge across the North Royal Line	2 dead, 3 injured	Human–Equipment–Management
26	18 July 2010	Sichuan G318 Qiujiang Second Bridge	No casualties shown	Environment
27	7 August 2010	A railroad Xiaodongjiang Bridge No. 107 pier burst mold accident	1 dead, 3 injured	Human–Equipment–Management
28	12 October 2010	Personnel fall accident on a railroad’s Kokayat Bridge	1 dead	Human
29	17 October 2010	A railroad Beijiang Bridge T-beam falling accident at the laying and framing entrance	1 dead	Human–Equipment–Management
30	22 November 2010	A railroad Yangtze River bridge north bank gantry crane overturning accident	1 dead, 4 injured	Human
31	24 January 2011	Temporary Arch Collapse of a Railway Youxi Bridge	2 dead, 2 injured, 1 missing	Equipment
32	24 October 2011	A railroad Hejiagou bridge simple support beam falling accident	1 dead	Equipment
33	21 May 2012	A railroad Beiping Bridge pier 6 burst mold accident	3 dead, 1 injured	Equipment
34	23 May 2012	A railroad hub across the Sui Salt Road cable-stayed bridge protection shed beribboned slipping accident	4 injured	Human

Table A1. *Cont.*

Number	Date	Name of the Incident	Accident Casualties	Type of Coupling
35	19 July 2012	A passenger special-purpose Hanjiatun bridge bridge stabilizer collapse accident	1 dead, 1 injured	Equipment–Management
36	23 August 2012	A railroad Liu Kui Zhai frame middle bridge side wall rebar overturning accident	4 dead, 2 injured	Human–Management
37	4 November 2012	Accident of tilting and dislodging of the bridge crane of a special-purpose bridge in Miaotaitizi.	1 dead, 2 injured	Human
38	22 November 2012	A railroad Shizhu station No. 3 four-lane bridge sorghum fall accident	3 dead, 1 injured	Human–Management–Environment
39	5 January 2013	A railroad Seongchon River bridge fall from height accident	1 dead	Human
40	22 January 2013	Fallen reinforcement of bearing platform of an intercity railroad bridge across a highway	3 dead, 1 injured	Human
41	14 April 2013	Collapse of reinforcing bars of pier No. 8 of the special bridge at Nanfen North Station of a passenger railroad project	3 dead, 4 injured	Equipment
42	7 July 2013	Continuous girder overtopping accident of a railroad bridge at Nanping North Railway Station	3 dead	Equipment
43	18 July 2013	Formwork overturning accident of No.11 pier of Liujia ridge bridge of an intercity railroad	1 dead, 3 injured	Equipment
44	12 October 2013	Chongqing Fengdu Yangtze River Second Bridge "10.12 Accident"	11 dead, 2 injured	Human–Management–Environment
45	10 November 2013	Jiangyan Municipal Construction Engineering Co., Ltd. Shijiaqiao Project "11.10" General Fall from Height Accident	1 dead	Management
46	26 November 2013	A passenger special-purpose big cat slope bridge No. 12 abutment tower crane overturned and collapsed accident	3 injured	Equipment
47	3 December 2013	A intercity railroad Dasha station bridge platform girder bracket collapse incident release	3 dead, 1 injured	Equipment
48	12 January 2014	Fire accident at pier 649 of a intercity railroad bridge across the Tianjin-Taiwan Border Railway special-purpose bridge	3 dead	Environment
49	20 February 2014	Accident of shell collapse of box girder bracket on span 6-7 of Shanghuang Special Bridge of a railroad	1 dead, 1 injured	Equipment

Table A1. *Cont.*

Number	Date	Name of the Incident	Accident Casualties	Type of Coupling
50	27 March 2014	Stable overturning accident of side girder of a railroad bridge over railroad	2 dead, 3 injured	Human–Management
51	31 March 2014	Collapse of a continuous girder side span braced berth girder on Fuhe Bridge of an intercity railroad line	1 dead, 2 injured	Human
52	8 April 2014	A railroad girder yard No. 2 gantry crane demolition tipping accident	3 dead, 2 injured	Human
53	3 May 2014	The "5.3" collapse of a stone arch bridge under construction in Shenzhen Town, Gaozhou City, Maoming, in 2014	11 dead, 16 injured	Human–Management
54	27 September 2014	Fatal accident of falling man in pile hole No. 5 of pier No. 12 of a railroad double-lane bridge over Shixi River	2 dead	Human
55	19 October 2014	A passenger special-purpose flat house bridge concrete tanker rollover accident	3 dead	Equipment
56	29 October 2014	Ru Chen Highway Chishi Bridge The "10-29" large construction fire accident	No casualties shown	Human–Management
57	19 November 2014	Enshi Jinshan Bridge "11.19" work surface collapse accident	1 dead, 10 injured	Management–Environment
58	8 December 2014	Wuzhou-Liuzhou Expressway Longtou Liujiang River Bridge Project "12.8" Drowning Accident	1 dead	Human–Management
59	26 March 2015	A railroad yoke plate river special bridge pier 97-96 bridge crane overturning accident	2 dead, 4 injured	Equipment
60	2 April 2015	A railroad Ziya River bridge pier 270 ~ 271 bridge crane overturning accident	4 dead	Equipment
61	7 November 2015	A railroad elevated station bridge 14 ~ 15 pier bracket pre-compression collapse accident	1 dead	Equipment
62	28 November 2015	Earth collapse accident on the west side of pier No. 10 of Bailongtan Bridge at a railroad junction	1 dead, 2 injured	Environment
63	17 March 2016	Collapse of tower crane on the north side of the sinkhole at pier 29 of a railroad Yangtze River bridge	1 dead, 5 missing	Environment
64	17 March 2016	Suzhou Municipal Government and the Provincial Safety Committee Office agreed to the Hutong Railway Yangtze River Bridge under construction piers "3.17" collapse accident	2 dead, 4 missing	Environment

Table A1. *Cont.*

Number	Date	Name of the Incident	Accident Casualties	Type of Coupling
65	5 June 2016	A passenger special-purpose a special bridge pier 29 rebar collapse accident	2 dead, 2 injured	Equipment
66	27 June 2016	Wuhan Bridge Survey Industrial Engineering Company of Jiujiang Yangtze River Bridge of He'anjiu Railway "6.27" Drowning Accident	1 dead	Human–Management
67	20 August 2016	The "8.20" electrocution accident at the Youyi Bridge construction site of the Wuxi Bridge Construction II bid for the Xingou River Extension and Dredging Project.	1 dead	Human–Management
68	1 January 2017	Investigation of the "1.1" General Fall from Height Accident of China Railway Nine Bridges Engineering Co.	1 dead	Human–Management
69	9 March 2017	A passenger special-purpose Diaohe Bridge No. 45 pier concrete formwork tipping accident	2 dead, 3 injured	Human
70	26 April 2017	Tujia line K224 + 763 shallow foundation disease bridge remediation project "4.26" fall from height fatal accident	1 dead	Human
71	30 May 2017	A passenger specialization Yellow River was the bridge girder gantry crane demolition collapse accident	6 dead, 1 injured	Equipment
72	8 June 2017	A passenger special Wenyu River bridge continuous girder outer formwork falling accident	1 dead	Human
73	30 June 2017	Poisoning accident of a railroad hub liaison line project across the eight steel bridge	2 dead	Equipment
74	19 August 2017	Menghua Railway Ji'an Ganjiang Bridge 19# pier "8-19" large template collapse accident	3 dead, 1 injured	Human–Management
75	11 October 2017	A passenger special Dongjin No. 2 special bridge pier 81 pier formwork tipping accident	2 dead, 4 injured	Human–Equipment–Management–Environment
76	14 October 2017	A passenger special-purpose Chaobai River bridge pier 58-60 pier top fall accident	1 dead	Human
77	17 October 2017	Guizhou bridge construction group limited liability company wuliu high speed ten standard south interchange construction project "10.17" lifting injury general accident	2 dead, 1 injured	Human–Management

Table A1. *Cont.*

Number	Date	Name of the Incident	Accident Casualties	Type of Coupling
78	13 March 2018	Yunnan Sanjiang Road and Bridge Engineering Company "3.13" lifting injury accident	1 dead	Human–Management
79	25 April 2018	Yangchun City "4.25" collapse accident	1 dead, 3 injured	Human–Management–Environment
80	22 May 2018	Slip and fall accident of pre-compacted blocks of full-tower scaffolding at the closing section of a railroad bridge over Longyin Bridge	1 dead, 2 injured	Human–Equipment–Management
81	21 June 2018	Vehicle Injury Accident "2018.6.21" at Chang'an North Road Bridge Construction Site	1 dead	Human–Management
82	13 January 2019	Wuhan Yangsigang Yangtze River Bridge Approach Bridge Project Hanyang Bank "1-13" General Fall from Height Accident	1 dead	Management
83	26 April 2019	The "4.2" landslide accident at the construction site of pier 14 of the Heba Expressway Guijiang Bridge in Dazhuang Village, Zhaoping Town, Zhaoping County, China	2 dead	Environment
84	8 May 2019	Hedong New District Fengtai Bridge 5-8 "local support system collapse accident	1 dead, 1 injured	Human–Management
85	11 July 2019	Chengchuan highway first work area bridge project "7.11" fall from height large accident	3 dead, 1 injured	Human–Management
86	21 July 2019	Crashing accident of a bridge crane on the Jinjiu upstream line of an intercity railroad	2 dead, 3 injured	Human–Management
87	28 July 2019	The "7.28" fatal pipeline construction accident at Inri Bridge in Wancheng Township	1 dead	Human–Management–Environment
88	30 July 2019	"7.30" Fence Tipping Accident at the Intersection of Fuyang Special Bridge and Geng San Line at the High-speed Railway Site in Xishangpu Township, Yingshang County	1 dead	Human–Management
89	3 August 2019	Fall from height of No. 9 portal pier of a two-lane intercity railroad bridge	3 dead	Human–Management
90	23 August 2019	Investigation of the "8.23" Zhao Shijun Object Strike Accident at China Railway Nine Bridges Engineering Co.	1 dead	Human–Management–Environment
91	1 September 2019	Chuzhou City, Quanjiao County Chu Laiquan fast-track bridge across the Xianghe River under construction "2019.9.1" large collapse accident	4 dead, 15 injured	Human–Equipment–Management

Table A1. *Cont.*

Number	Date	Name of the Incident	Accident Casualties	Type of Coupling
92	14 September 2019	Daijiashan Bridge and both sides of the connection project "9.14" general fall from height accident	1 dead, 2 injured	Human–Equipment–Management
93	10 November 2019	Beijing-Shanghai High-speed Railway Suzhou Section Cross-Lake Bridge Project "11.10" Fall from Height Investigation Report on the Accident	1 dead	Human–Management
94	23 November 2019	A railroad hot water ditch two-lane bridge pier 7 fall from height accident	4 dead	Human
95	23 November 2019	A railroad station north down contact line bridge personnel fall accident	2 dead	Equipment
96	12 December 2019	Zhongshan County Fuxing Bridge construction project site "12.12" concrete mixer truck rollover fatal accident	1 dead	Human–Management
97	6 March 2020	Guinan High-speed Railway GNZQ-5 Standard Longtou Two-Lane Special Bridge "3.6" Fall from Height Accident	1 dead	Human–Management
98	12 April 2020	Road and bridge construction in Shanglin Village, Qiaoyin Township, Fengshan County, "4.12" accident	1 dead	Human–Equipment–Management
99	12 July 2020	General production safety accident of "2020.07.12" collapse in Qianrenqiao Town, Shucheng County	1 dead	Human–Management
100	8 October 2020	Shaanxi Ankang Sai'an Engineering Co., Ltd., "10.8" fall accident of Donghe Reservoir common bridge in Hanyin County	1 dead	Human–Management
101	13 October 2020	"10.13" Foshan City Longxiang Bridge approach road project collapse accident	1 dead	Human–Environment
102	1 November 2020	"11.1" Tianjin Nanhuan Lingang Railway Bridge Collapse Railway Traffic Large Accident	8 dead, 6 injured	Human
103	11 December 2020	Chongqing Banan District Emergency Response Bureau Chongqing Qiaoqiang Construction Engineering Co., Ltd. "12.11" general fall from height fatal accident investigation	1 dead	Human–Management
104	16 January 2021	Renwai "1.16" General Highway Construction Project Accident	2 dead	Human–Management–Environment

Table A1. *Cont.*

Number	Date	Name of the Incident	Accident Casualties	Type of Coupling
105	7 March 2021	Zhongwei Xiheyan Yellow River Highway Bridge Project "3.07" Accident	1 dead, 1 injured	Human–Management
106	23 April 2021	Harbin free trade zone infrastructure construction phase two project planning 212, 180 bridge pile foundation project "4.23" object strike accident investigation	1 dead	Human
107	1 May 2021	Huangshan Tanjiaqiao Township, Dongshan Shimamachuan embankment retaining wall Shunjie project "5.1" mechanical injury accident	1 dead	Human–Equipment–Management
108	8 May 2021	Hangzhou-Shaoxing-Taiwan Expressway Shaoxing urban section under construction bridge partial collapse accident investigation report	No casualties	Equipment–Management
109	17 June 2021	Lanxi city old south gate bridge renovation and upgrading project "6.17" general collapse accident	1 dead	Human–Management
110	22 June 2021	Longtan Yangtze River Bridge South Anchor Anchorage Project "6.22" Sinkhole Formwork Collapse Large Accident	3 dead, 12 injured	Human–Management
111	20 July 2021	Shencheng Road and Bridge Construction Group Limited "7.20" Fall from Height Accident	1 dead	Human–Management
112	25 July 2021	Jinwan District, Zhuhai City "7.25" Zhuhai Airport Railway Jinhai Bridge Large accident of box girder collapse in construction section	4 injured, 1 missing	Human–Management
113	1 August 2021	Hangzhou-Jinhua-Quzhou Expressway Reconstruction and Expansion Phase II Project Gaocun Automobile Flyover "8.1" General Fall from Height Accident	1 dead, 4 injured	Human–Management
114	6 August 2021	Yunnan Province S35 Yongjin Expressway Yongren to Dayao section of the civil construction of the eighth division of the bridge Shi "8.06" fall from height accident	1 dead	Human–Management
115	17 August 2021	Zhuzhou City "8.17" Xinhua bridge demolition falling beam accident	No casualties	Human–Equipment–Management
116	17 August 2021	Provincial government approved the closure of Hefei Lujiang County "2021.8.17" large bridge bracket collapse accident	4 dead	Human–Equipment–Management

Table A1. *Cont.*

Number	Date	Name of the Incident	Accident Casualties	Type of Coupling
117	18 August 2021	Dongguan Qiaotou Town “8.18” general collapse accident	2 dead, 2 injured	Human–Equipment–Management
118	24 August 2021	Investigation of “8.24” General Fall from Height Accident of Phoenix Liang Bridge Project of Kaizhou District Hanfeng Lake Comprehensive Tourism Development Project (East Lake Scenic Spot)	1 dead	Human–Management
119	1 November 2021	Wenzhou lucheng district west piece of national and provincial highway highway Linjiang to fengqiao section project Jinao tunnel “11-11” larger roof piece gang accident	3 dead, 1 injured	Equipment–Management–Environment
120	4 November 2021	The “11.04” Production Safety Accident at Dacun Bridge of Danan Expressway	1 dead, 1 injured	Human–Management
121	25 February 2022	The “2.25” collapse of the joint venture between China Railway Sixth Bureau Group Co. Ltd. and Hefei Highway Bridge Engineering Co. Ltd.	1 dead	Human–Management–Environment
122	14 April 2022	The People’s Government of Ji’an City on the Ji’an Ganjiang Bridge Dangerous Bridge Rehabilitation Project “4.7” Drowning and Drowning Accident	1 dead	Human–Management
123	16 April 2022	The “4.16” general production safety accident at the Lianshiwan Bridge in Section B of the Zhongshan Western Ring Road	1 dead	Human–Equipment–Management
124	15 May 2022	Anhui Highway and Bridge Engineering Co., Ltd. “5.15” fall from height incident	1 dead	Human–Management
125	13 July 2022	Yuelu district pingtang street twilight ping xiangjiang river bridge construction site “7.13” fall drowning accident	2 dead	Human–Equipment–Management
126	13 February 2023	Investigation Report on “2.13” Fall from Height Accident of Chongqing Huichuang Construction Engineering Co.	1 dead	Human–Equipment

Appendix B

Table A2. Risk factor adjacency matrix.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24	R25
R1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
R2	0	0	1	1	1	1	0	1	0	1	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0
R3	1	1	0	1	1	1	1	1	1	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
R4	0	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
R5	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
R6	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0	0	0
R7	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
R8	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R9	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R10	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R11	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R12	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R13	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R14	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	0	0	0	0	0	0
R15	1	1	0	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0	0
R16	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0
R17	1	1	1	1	1	1	0	0	1	1	1	1	1	0	1	1	0	1	0	0	0	1	0	0	0
R18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	1	0	0	0
R19	1	1	1	0	1	0	0	1	0	0	1	1	1	0	1	1	1	1	0	0	0	0	0	0	0
R20	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
R21	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
R22	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R23	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R24	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
R25	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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