IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 29, 2019, accepted August 16, 2019, date of publication August 20, 2019, date of current version August 31, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2936421

Using Network Theory to Explore the Risk Characteristics of Bridge-Tunnel Hybrid Construction

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This work was supported in part by the National Natural Science Foundation of China under Grant 71701213 and Grant 71401181, and in part by the Ministry of Education in China (MOE) Project of Humanities and Social Sciences under Grant 15YJC630008 and Grant 14YJC630136.

ABSTRACT Exploring the characteristics of safety risks is crucial for deeply understanding and promoting traffic construction safety. Bridge and tunnel construction engineering is of high risk, which has been studied separately, while mega traffic engineering projects often combine them, leading to increased complexity. In this study, a research framework is proposed to explore the risk characteristics of bridge-tunnel hybrid construction engineering, which can be applied in other types of hybrid constructions. The real data with respect to 67 typical bridge and 64 tunnel accidents was collected from the database of a large traffic construction enterprise in China. 146 risk factors and 326 trigger relations are extracted to establish bridge and tunnel construction risk subnetworks. Moreover, a whole risk network is established by combing the two subnetworks together,. With the network scale, diameter, and other metrics, the properties of the risk networks are revealed. The critical risk factors in the construction of bridges and tunnels are identified. The results show that most of the accidents are attributed to management and worker factors, while purely environmental factors do not significantly contribute to the occurrence of the accidents. The results provide some prevention and post-remedy safety suggestions for the management of bridge and tunnel construction.

INDEX TERMS Network theory, risk analysis, bridge-tunnel hybrid construction.

I. INTRODUCTION

Transportation infrastructure lays a solid foundation necessary for rapid socioeconomic growth and development. With China's vigorous modernization, the government has gradually increased investment in infrastructure construction. "Safety production", that is, significant accident prevention and control measures, determines to a certain extent the survival and growth of construction enterprises. Because of the complex terrain in China, bridges and tunnels are required together in many places, such as Hongkong-Zhuhai-Macao Bridge Project [1], [2], which introduce significant safety risks to traffic construction. Although local governments are vigorously developing transportation facilities, bridge and tunnel construction are deficient in effective safety management. The blind pursuit of construction progress is also likely to result in significant safety risks.

The risks of bridge and tunnel construction projects have been discussed separately, while most of mega traffic engineering projects involve both of them. Challenges have arisen in identifying critical risk factors. Firstly, it is difficult to explore the complex dependencies among the various risk factors using traditional methods as proposed in the previous studies [3]–[6]. Secondly, some studies have used questionnaires [7] to combine data from historical accidents with expert subjective judgments without taking into account the effects of workers' operations or the natural environment. Thirdly, although most of the current literature [8], [9] only focuses on a single type of engineering, crucial traffic engineering often involves the combination of bridges and tunnels.

Herein, an analytical framework is proposed to explore the risk characteristics of complex traffic construction projects, which take bridge-tunnel hybrid construction projects as an example in this paper. In this framework, bridge- and tunnel-exclusive and mutual risk factors were identified from

The associate editor coordinating the review of this article and approving it for publication was Weisi Guo.

the accident case database of a large traffic construction enterprise in China. We established bridge construction risk subnetwork (BCRN) and tunnel construction risk subnetwork (TCRN), respectively, to explore the unique causes of each accident type and combined them to establish the whole risk network (WRN) in order to explore the mutual problems of construction safety management. Based on the network scale, diameter, density, degree distribution, and other metrics from the network theory reveal that BCRN, TCRN, and WRN are small-world and scale-free networks. The critical risk factors are identified based on node metrics such as degree and betweenness to provide some construction safety suggestions including pre-prevention and post-remedy ones.

This paper is novel in the following aspects. Firstly, different from the traditional methods, this paper proposes an analytical framework based on heterogeneous risk network for exploring the common and unique characteristics of complex traffic construction projects. Secondly, to validate the effectiveness, with the data from actual accident cases, we analyze the risk features of bridge-and-tunnel hybrid construction projects in China, then the critical risk factors are identified with the node measurements. Thirdly, based on the results of the case study, we observe that worker and management risk factors are the main critical risk factors for bridge-tunnel hybrid construction projects. The weather and geological factors are main environment risk factors for bridge and tunnel constructions respectively. Finally, this paper suggests insightful managerial suggestions for bridge-and-tunnel hybrid construction projects.

The remaining article is arranged as follows. Section 2 reviews the related literature. Section 3 describes the generation of accident chains, the establishment of the risk network, and the selection of the relevant metrics. Section 4 is a case study, which introduces the data source analyses, the properties of the risk network, and the identifies of the critical risk factors-thus providing safety suggestions to management. Section 5 summarizes the key findings of the present study.

II. LITERATURE REVIEW

Case analysis is a conventional method of modeling construction safety. A systematic review of previous cases is very important for analyzing and understanding construction safety [10]. Meliá *et al.* [6] used four samples to analyze the relationship between safety response and perception probability. By collecting data for 100 cases of building accidents and using ergonomics methods, Haslam *et al.* [5] proposed a series of human-induced accident models. By studying the original characteristics of fatal occupational injuries among Spanish construction workers in the United States, Dong and Platner [3] concluded that the risk faced by Spanish construction workers in the workplace was significantly higher than that of non-Hispanic construction workers. From 224 construction death cases analyzed by a group of experts, Gambatese *et al.* [11] revealed that there was a significant relationship between fatal accidents at construction sites and the conceptual design of building safety. Rozenfeld *et al.* [12] carried out a detailed quantitative analysis of 699 possible out-of-control incidents and developed a structured hazard analysis and a method of assessing construction activities, called construction job safety analysis (CJSA). According to the influencing factors, Chi *et al.* [4] classified and coded 621 fatal high-altitude falls, formulated accident scenarios, and proposed preventive measures. Aksorn and Hadikusumo [13] identified critical success factors (CSFs) for the data from 16 safety projects obtained from the literature and previous studies, which were validated by building safety professionals. From the perspective of accidents, Mitropoulos *et al.* [14] focused on the sources of danger in the construction industry. However, case analysis method only focuses one specific accident case lacking universality.

Risk analysis methods can be categorized as qualitative or quantitative. The former includes fault tree analysis (FTA), the comprehensive fuzzy evaluation method (CFEM), check lists, etc., while the latter includes job risk analysis (JRA) methods, influence diagrams, neural networks (NNs), support vector machines, decision trees, etc., [15]. A prevalent method of analyzing accidents is the accident chain. Li and Wang [16] found the accident chain for a complex environment through interactions between the causes of accidents to better identify the root causes of accidents. Reason [17] believed that false psychological precursors might lead to accident chains. Caffaro *et al.* [18] dissected the behavior of Italian tractor operators and concluded that falls played a key role in the agricultural accident chain through which they also proposed preventive training interventions for part-time farmers who occasionally used agricultural machinery. Caffaro *et al.* [19] also proposed preventive training interventions for part-time farmers who occasionally use agricultural machinery. Rao and Marais [20] developed a method of identifying high-risk accident chains based on historical aviation accident data to reduce the occurrence of such accidents. Lindberg *et al.* [21] used an accident chain to propose six quality criteria for accidents and post-accident feedback. Kelman [22] concluded that the accident chains of disasters were actually multiple, complex, and interwoven. Sun *et al.* [23] used the human factor analysis and classification system to establish a reasonable and applicable human error investigation index system and discussed the accident chain and the priority of the importance of human factors. Ouyang *et al.* [24] used an accident chain to propose a control-theory-based system of theoretical accident models and processes (STAMPs). Yang *et al.* [25] considered synergies and multiple dominoes to establish an accident chain. However, the accident chain could not consider the complex network dependence among the risk factors, so it was difficult to identify the critical risk factors.

As an emerging science, complex networks have numerous network metrics, which provide rich theories and methods of identifying the key risks and for carrying out targeted risk management [26], [27]. By reviewing 63 papers on social network analysis (SNA) published in eight peer-reviewed journals between 1997 and 2015, Zheng *et al.* [28] revealed the current state of the application of SNA in construction project management (CPM). Instead of analyzing individual accidents, Zhou *et al.* [9] used network theory to explore the complexity of a subway construction accident network. Deng *et al.* [8] selected coal-mining accidents as data to analyze an accident chain and integrated the accident chains into a global network. From the perspective of complex network theory, Zhou *et al.* [29] discussed the time series characteristics of hidden accidents in subway construction and the underlying mechanisms. By combining multidimensional data mining and a complex network, Zhou *et al.* [30] also proposed a method of modeling and analyzing a shield tunneling performance network. Wehbe *et al.* [31] used SNA to assess the safety performance and network resilience to risk by studying the security interactions between construction teams. Xiong *et al.* [7] used a questionnaire survey of 586 scaffolding workers in Wuhan as the basis of SNA to identify potential leaders among the workers. Yuan *et al.* [32] studied the social risks and stakeholders from the perspective of networks to provide a better method of analyzing risk for China's high-density urban construction projects.

From above, the existing literature begins to consider the complex interaction relationships among risk factors in the construction projects. However, most of them only concern a single type of projects. Actually, there must simultaneously exist mutual characteristics among different engineering projects. A more comprehensive analysis might help us understand the common or unique characteristics of multiple project classes. In addition, the literature on case studies and the literature on risk network are relatively independent. Moreover, most of the previous literature generally focus on one single category of risk factors, e.g., human factors, However, risk factors from different categories may directly affect the subsequent specific safety reinforcement measures. Actually, as the accident cases collected become richer and richer, a risk analysis framework based on risk network for multiple project classes is necessary and useful for researchers and managers to understand the complex risk characteristics of hybrid constructions.

III. ANALYTICAL FRAMEWORK

To analyze the risk characteristics of bridge and tunnel engineering projects, an analysis framework, as shown in Figure 1, is proposed. First, we decompose the acquired accident cases into accident chains. Then, we use network theory to establish risk networks for all the cases according to different classifications including the BCRN, TCRN, and WRN. Finally, various network indicators are selected to analyze all the networks and give corresponding safety suggestions to management.

The details of the framework are described as follows:

A. ACCIDENT CHAIN GENERATION

Typical cases of bridge and tunnel accidents are selected from the database. Each accident is triggered by a sequence of events at unique stages. Therefore, each accident case could be decomposed into several chronological characteristic stages, which subsequently are abstracted as risk factors that could be chronologically combined to establish an end-to-end accident chain.

For example, in a typical extrusion accident in bridge construction, worker carelessness triggered violations in operating procedure, which in turn triggered template overturn thereby ultimately leading to the extrusion accident. The following accident chain is obtained by abstracting the unique stages as risk factors:

$$\begin{aligned} \text{Worker carelessness} &\rightarrow \text{Violations in operating procedure} \\ &\rightarrow \text{Template overturn} \\ &\rightarrow \text{Extrusion accident} \end{aligned}$$

For a typical landslide accident in tunnel construction, rain is a precondition coupled with workers' violations in operating procedure resulting in unstable massif, thereby triggering a landslide accident. The following accident chain is obtained by abstracting unique stages as risk factors:

$$\begin{aligned} \text{Rain} &\rightarrow \text{Violations in operating procedure} \\ &\rightarrow \text{Unstable massif} \rightarrow \text{Landslide} \end{aligned}$$

Clearly, both accident chains contain the risk factor "violations in operating procedure". Some risk factors will appear in different accident chains, and the same risk factors can combine all the accident chains into a risk network.

B. RISK NETWORK GENERATION

All accident risk factors and the trigger relations between them can form a risk network as follows.

$$\mathcal{G} = \{\mathcal{N}_b, \mathcal{N}_t, \mathcal{N}_b, \mathcal{E}_{trigger}\},$$

where $\mathcal{G}_b = \{r_1, r_2, \ldots, r_i, \ldots, r_b, 1 \leq i \leq b\}$ is the node set of bridge-exclusive risk factors, represented by triangle nodes in the network, $\mathcal{G}_t = \{r_1, r_2, \ldots, r_i, \ldots, r_t, 1 \leq i \leq t\}$ is the node set of tunnel-exclusive risk factors, represented by circle nodes in the network, $\mathcal{G}_m = \{r_1, r_2, \ldots, r_i, \ldots, r_m, 1 \leq i \leq m\}$ is the node set of mutual bridge and tunnel risk factors, represented by square nodes in the network, and $\mathcal{E}_{trigger} = \{\langle r_i, r_j \rangle | i \neq j\}\}$ is the edge set of risk trigger relations.

Here, $\langle r_i, r_j \rangle$ means risk factor j is triggered by risk factor i, so the trigger relation between the risk factors is directional. Edge sets contain elements defined by an adjacency matrix, $A = [a_{ij}]_{n \times n}$, which describes the risk trigger relation:

$$a_{ij} = \begin{cases} 1, & \text{if risk } j \text{ is triggered by risk } i \\ 0, & \text{otherwise.} \end{cases}$$

Through the node set of bridge-exclusive risk factors, $\mathcal{N}_b$, the node set of tunnel-exclusive risk factors, $\mathcal{N}_t$, the node set of mutual bridge and tunnel risk factors, $\mathcal{N}_m$, and the edge set of risk trigger relations, $\mathcal{E}_{trigger}$, we established the BCRN and TCRN, respectively. Since there is a node set of mutual bridge and tunnel risk factors, $\mathcal{N}_m$, we can combine the BCRN, $\mathcal{G}_b =$

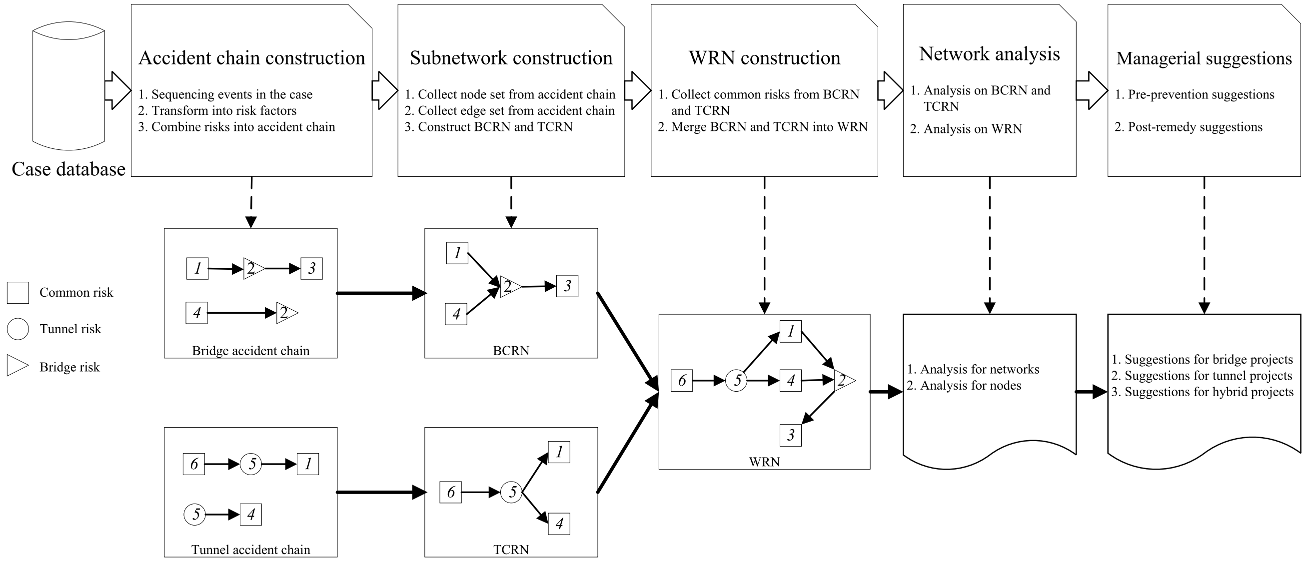


FIGURE 1. Analytical framework of bridge-tunnel hybrid construction risk network.

$\{\mathcal{N}_b, \mathcal{N}_m, \mathcal{E}_{trigger}\}$ and TCRN $\mathcal{G}_t = \{\mathcal{N}_t, \mathcal{N}_m, \mathcal{E}_{trigger}\}$ into the WRN $\mathcal{G}_w = \{\mathcal{N}_b, \mathcal{N}_t, \mathcal{N}_m, \mathcal{E}_{trigger}\}$.

C. PERFORMANCE METRICS SELECTION

Boas *et al.* [33] published a comprehensive overview of the major concepts and recent achievements in the study of complex network structures and dynamics, and summarized their related applications in many different disciplines. We refer to this paper to introduce the most important network metrics in the risk network.

1) METRIC OF OVERALL NETWORK PERFORMANCE

a: NETWORK SCALE (n)

The network scale, n, refers to the number of nodes in the network. Therefore, the scales of the BCRN, TCRN, and WRN are

$$n(\mathcal{G}_b) = |\mathcal{N}_b| + |\mathcal{N}_m|,$$
$$n(\mathcal{G}_t) = |\mathcal{N}_t| + |\mathcal{N}_m|,$$

and

$$n(\mathcal{G}_w) = |\mathcal{N}_b| + |\mathcal{N}_t| + |\mathcal{N}_m|,$$

respectively. In the current construction network, the network scale will not be too large owing to the limited types of construction accidents.

b: NETWORK DIAMETER (D)

The network diameter, D, is the longest geodesic distance between any two nodes in the same component of the network. In the construction risk network, the larger the network diameter, the more characteristic stages there are in accidents, meaning that the causes of accidents are more complex and that there is more safety management space to prevent accidents.

c: NETWORK DENSITY (ρ)

Since, the construction risk network is directional, the risk network of scale n has $n(n-1)$ possible trigger relations. If the actual number of trigger relations in the network is m, then the network density is equal to $\rho = m/(n(n-1))$. Therefore, the densities of the BCRN, TCRN, and WRN are

$$\rho(\mathcal{G}_b) = |\mathcal{E}_{trigger}|/(n(\mathcal{G}_b)(n(\mathcal{G}_b) - 1)),$$
$$\rho(\mathcal{G}_t) = |\mathcal{E}_{trigger}|/(n(\mathcal{G}_t)(n(\mathcal{G}_t) - 1)),$$

and

$$\rho(\mathcal{G}_w) = |\mathcal{E}_{trigger}|/(n(\mathcal{G}_w)(n(\mathcal{G}_w) - 1)),$$

respectively. The higher the density of the traffic construction accident network, the closer the connection between the risk factors and the easier the accident will be triggered.

d: PATH LENGTH (L)

In a network, the minimum number of edges connecting any two nodes is defined as the path length of the two nodes, and the average path length of all the node pairs in the network is defined as the path length of the network. The shorter the path length, the faster the accident is triggered. Therefore, timely measures should be implemented to prevent accidents.

e: CLUSTERING COEFFICIENT (C)

The clustering coefficient of a node is defined as $C_i = \frac{2l_i}{d_i(d_i-1)}$, where l_i represents the number of edges connected between adjacent points of node r_i, and d_i represents the degree of node r_i and is defined as the number of adjacent edges of node r_i. For a network of scale n, the average network-clustering coefficient is $C = \frac{\sum_1^n (C_i)}{n}$. The average clustering coefficients of the BCRN, TCRN, and WRN are

$$C(\mathcal{G}_b) = \frac{\sum_1^{n(\mathcal{G}_b)} (C_i)}{n(\mathcal{G}_b)},$$

$$C(\mathcal{G}_t) = \frac{\sum_{1}^{n(\mathcal{G}_t)}(C_i)}{n(\mathcal{G}_t)},$$

and

$$C(\mathcal{G}_w) = \frac{\sum_{1}^{n(\mathcal{G}_w)}(C_i)}{n(\mathcal{G}_w)},$$

respectively. The larger the average clustering coefficient is, the more concentrated the network is, meaning that some critical risk factors exist.

2) METRICS OF NODE

a: DEGREE

The degree of a node is the number of other node directly connected to it. If a node is directly connected to many nodes, that node has a high degree. In a directed graph, the degree of a node is divided into in- and out-degrees. The in-degree of a node is the number of other nodes entering into that node; that is, the number of direct relations obtained from the node. In the construction risk network, the greater the in-degree of the risk factor, the more frequently the corresponding accident is triggered and the more post-remedy measures must be implemented. The degree of exit of a node is the number of relations directly emitted from the node. In the construction risk network, the larger the out-degree of a risk factor, the more types of accidents that can be triggered by the risk factor and the more pre-prevention measures should be implemented.

b: BETWEENNESS

Betweenness measures the extent to which a node lies on paths between other nodes. In the construction risk network, the larger the betweenness of risk factors, the greater its influence on other risk factors; therefore, corresponding safety management measures should be implemented.

IV. CASE ANALYSIS

A. DATA SOURCES

With the assistance of the project management and safety quality supervision departments, a database of bridge and tunnel construction accidents is established, 67 and 64 typical bridge and tunnel accidents are selected, respectively, and 146 risk factors are excavated. Among them, 67 are bridge-exclusive risk factors, 48 are tunnel-exclusive risk factors, and 31 are mutual bridge and tunnel risk factors. Some accident information is detailed while some is sketchy. For accidents with detailed information, we excavate more detailed risk factors such as hydrogen sulfide poisoning. When the source of the poison is uncertain, it is directly identified as poisoning. Similarly, due to the lack of raw data and the complexity of environmental factors, there are more geological risk factors cannot be extracted, which are collectively referred to as Inadequate geological prospecting.

By using of *Gephi*, a network analysis and visualization software, we get the network figures of BCRN, TCRN and WRN, as shown in Figure 2. In the BCRN and TCRN, the node's size increased with increasing out-degree of the risk factor, and in the WRN, it increased with increasing betweenness. As in the classification of coal mining risk factors by Deng *et al.* [8], the risk factors in the present work are roughly divided into five categories: Worker, Machine, Technology, Management, and Environment, as indicated by different colors in the risk network. "Worker" refers to the risk attributed to worker errors. "Machine" refers to the risk attributed to damaged equipment and tools. "Technology" refers to the risk attributed to working under conditions less than ideal for the technology used. "Management" refers to the risk attributed to managerial negligence. "Environment" refers to the adverse effects of the natural environment. By classifying and analyzing the risk factors, the similarities and differences between bridge and tunnel construction risks in complex traffic engineering models could be determined and targeted suggestions for preventing accidents could be put forward.

TABLE 1. Property of the risk networks.

	n	D	ρ	L	C
BCRN	96	10	0.02	3.675	0.065
TCRN	79	8	0.025	2.837	0.083
WRN	146	12	0.015	4.076	0.08

TABLE 2. The number of categorical risk factors.

	Worker	Management	Machine	Technology	Environment
BCRN	29	15	44	3	5
TCRN	13	11	21	4	30
WRN	36	18	55	5	32

B. RESULTS AND DISCUSSION

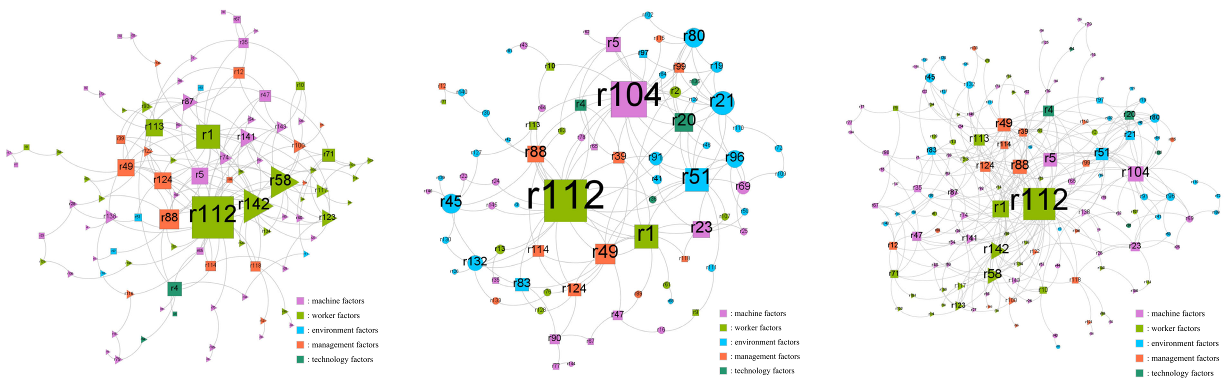
1) RISK NETWORK PROPERTIES

As shown in Table 1, the BCRN shows 96 risk factors, including 67 bridge-exclusive risk factors and 29 mutual bridge and tunnel risk factors. The TCRN shows 79 risk factors, among which 50 are tunnel-exclusive risk factors. Because bridge construction is more complex than tunnel construction, there are more bridge-exclusive risk factors. The WRN is formed by combining the 146 risk factors. Table 2 shows the number of categorical risk factors in these three networks.

The diameters of the BCRN, TCRN, and WRN are 10, 8, and 12, respectively. The diameter of the BCRN is longer than that of the TCRN, indicating that bridge construction has more space available than tunnel construction for deploying safety measure to prevent accidents. The triggering process of risk accidents is longer in hybrid engineering models than in single-type ones, meaning that safety management could play a greater role in hybrid engineering projects.

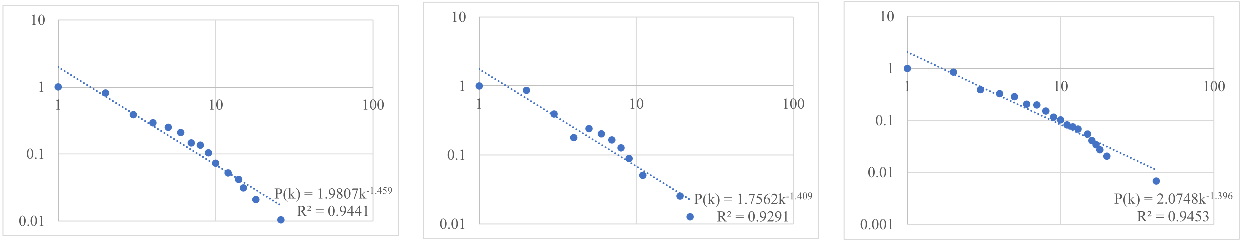
The densities of the BCRN, TCRN, and WRN are 0.020, 0.025, and 0.015, respectively. The densities of large-scale networks are usually lower than those of small-scale ones. The densities of networks of different scales cannot be directly compared.

Watts and Strogatz [34] proposed the "small-world network" model, which has a short path length and a high average clustering coefficient. The path lengths of the BCRN,



(a) BCRN (b) TCRN (c) WRN

FIGURE 2. Risk networks.



(a) Degree distribution of BCRN (b) Degree distribution of TCRN (c) Degree distribution of WRN

FIGURE 3. Degree distribution.

TCRN, and WRN are 3.675, 2.837, and 4.076 and their corresponding average clustering coefficients are 0.065, 0.083, and 0.08, respectively; therefore, the BCRN, TCRN, and WRN are all small-world networks. In such kind of networks, the path length is short, indicating that the risk factor trigger speed is fast. The analysis of the average clustering coefficient indicated that the construction risk network is concentrated and that the critical risk factors could be found through some methods. If the critical risk factors can be eliminated, the safety performance will be significantly improved.

Complex networks following a power-law distribution are called "scale-free networks" [35], which means some node's degree value is more than the others. As shown in Figure 3, the BCRN, TCRN, and WRN show the degree distribution functions: $P(k) = 1.9807k^{-1.459}$ ($R^2 = 0.9441$), $P(k) = 1.7562k^{-1.409}$ ($R^2 = 0.9291$), and $P(k) = 2.0748k^{-1.396}$ ($R^2 = 0.9453$), respectively, indicating that the three networks are approximative scale-free networks. It means that in practical application a few critical risk factors with high degree can be identified in these three risk networks.

2) NODE ANALYSIS

Through the analysis of the nodes in the risk networks, the deep causes of accidents can be determined and suggestions for construction safety can be provided to management. The detailed information of critical risk factors concerned in this paper is shown in the APPENDIX.

TABLE 3. Top 20 risk factors by the order of the out-degree.

	BCRN		TCRN		WRN	
Rank	Risk id	Value	Risk id	Value	Risk id	Value
1	r112	22	r112	14	r112	36
2	r1	13	r51	9	r1	19
3	r58	9	r1	9	r49	14
4	r49	9	r49	8	r51	11
5	r88	6	r21	7	r4	10
6	r4	6	r20	6	r88	10
7	r124	6	r124	5	r58	9
8	r113	6	r88	5	r124	8
9	r123	5	r23	4	r113	8
10	r39	4	r83	4	r21	7
11	r5	4	r4	4	r20	7
12	r141	4	r96	4	r39	7
13	r117	3	r39	4	r5	7
14	r93	3	r114	3	r83	5
15	r118	3	r80	3	r23	5
16	r114	3	r5	3	r114	5
17	r35	3	r45	2	r123	5
18	r100	3	r90	2	r118	4
19	r138	3	r2	2	r141	4
20	r10	2	r91	2	r96	4

a: OUT-DEGREE

The top 20 nodes of the BCRN, TCRN, and WRN are listed by the order of the out-degree, as shown in Table 3.

Most of the bridge and tunnel accidents are triggered by mutual risk factors, which showed significant similarities among them. The identified mutual risk factors are violations in operating procedure, worker carelessness, imperfect regulation, inadequate training, inadequate protection, unscientific design, unstable pillars, management negligence,

TABLE 4. Top 20 risk factors by the order of the in-degree.

	BCRN		TCRN		WRN	
Rank	Risk id	Value	Risk id	Value	Risk id	Value
1	r142	17	r104	17	r104	18
2	r58	8	r112	9	r142	17
3	r87	7	r45	6	r112	10
4	r112	6	r80	5	r5	10
5	r88	6	r23	4	r47	9
6	r5	6	r5	4	r88	8
7	r71	6	r132	4	r58	8
8	r141	5	r69	4	r71	7
9	r47	5	r47	4	r87	7
10	r124	4	r51	3	r45	6
11	r113	4	r1	3	r113	5
12	r12	4	r21	3	r23	5
13	r74	4	r20	3	r141	5
14	r143	4	r88	3	r12	5
15	r123	3	r96	3	r80	5
16	r117	3	r91	3	r51	4
17	r100	3	r49	2	r124	4
18	r138	3	r83	2	r10	4
19	r1	2	r114	2	r74	4
20	r4	2	r90	2	r132	4

TABLE 5. Top 20 risk factors by the order of the betweenness.

	BCRN		TCRN		WRN	
Rank	Risk id	Value	Risk id	Value	Risk id	Value
1	r112	1217	r112	393	r112	3491
2	r58	805	r88	184	r58	1700
3	r88	395	r23	147	r88	1410
4	r124	305	r21	144	r23	1059
5	r113	260	r104	132	r51	1032
6	r5	232	r51	113	r5	767
7	r4	223	r20	99	r124	566
8	r51	197	r96	98	r28	518
9	r1	190	r1	81	r4	503
10	r114	173	r49	64	r113	490
11	r100	141	r30	57	r1	445
12	r123	137	r83	54	r21	427
13	r117	130	r69	41	r20	401
14	r118	100	r140	40	r114	388
15	r116	91	r45	39	r138	326
16	r71	90	r110	39	r96	303
17	r138	82	r132	38	r49	273
18	r6	79	r39	37	r39	268
19	r142	78	r5	36	r118	233
20	r35	72	r80	33	r117	226

violations of code of conduct, etc. In these critical risk factors, worker and management factors still dominate. In tunnel construction, many risks such as topography, landforms, meteorology, hydrology, ecology, strata, lithology, and geological structures are often involved. Therefore, in addition to mutual factors such as management and worker errors, environmental factors are major triggers of tunnel accidents.

b: IN-DEGREE

The top 20 nodes of the BCRN, TCRN, and WRN are ranked by the order of the in-degree, as shown in Table 4.

Apart from the risk factors which need pre-prevention, falling, falling into water, extrusion, and falling objects are the consequences of most bridge construction accidents. Fire, falling rocks, dynamite explosion, electricity leakage, extrusion, and water leakage are the consequences of most tunnel construction accidents. Collapse, falling, extrusion, falling into water, fire, and cable accidents are the consequences of most hybrid construction accidents. The characteristics of bridge and tunnel construction make their corresponding accident consequences quite different.

c: BETWEENNESS

The top 20 nodes of the BCRN, TCRN, and WRN are listed by the order of the betweenness, as shown in Table 5.

It can be seen that the risk factors that most significantly influence bridge construction are still worker and management factors, which are common to many other types of projects [18], [19], [23]. Unstable pillars and unscientific design significantly influenced bridge construction safety management. Among the mutual environmental factors, rain significantly influenced bridge construction safety management mainly because bridge construction is extremely sensitive to changes in water level, so sudden rainfall would increase the water level and make the construction site wet and slippery, thereby introducing significant safety risks to bridge construction. In addition to worker and management factors, adverse geological conditions, rain, water and poisonous gas leakages, wind, and other environmental factors have a greater impact on tunnel construction than on bridge construction. Management and worker factors accounted for the highest proportion of hybrid construction accidents. Moreover, most of the construction workers are migrant workers, who have lower security awareness. The ever-changing construction environments and processes also increase the potential for safety hazards, which in turn significantly impact construction safety.

C. MANAGERIAL ADVICES

1) ADVICE TO MANAGEMENT FOR BRIDGE CONSTRUCTION SAFETY

Bridge construction units should set up clearly visible warning signs outside danger zones and regularly educate personnel about safety protocols to prevent the occurrence of events when entering the danger zones. During each working shift, someone should be appointed to ensure that the workers are wearing their safety belts and life jackets, and unqualified personnel should be prohibited from entering the worksite. For accidents involving unstable barycenter, overturned templates, and unstable outriggers, any damaged parts must be reinforced immediately, and nearby workers must be evacuated timely to prevent any secondary disasters.

2) ADVICE TO MANAGEMENT FOR TUNNEL CONSTRUCTION SAFETY

Compared with bridge construction, tunnel construction is more easily affected by the natural environment. In case of any tunnel construction accidents, the first task is to evacuate all the workers. Then, the corresponding measures should applied for different environment risk factors. For example, in case of gas outburst, any leaks should be filled immediately to avoid poisoning or blasting. When dynamite explodes or electricity leaks, any injured people should be treated immediately to prevent secondary disasters. When there is water leakage, water should be drained from the work area immediately.

3) COMPREHENSIVE SUGGESTIONS TO MANAGEMENT

From the foregoing analysis, many factors affect construction safety, and the interactions among them are complex. Therefore, the establishment of a sound construction safety management system should be the first priority to prevent construction accidents. Simultaneously, corresponding countermeasures must be formulated against all the potential safety hazards faced during construction. Construction units should often undertake mandatory safety training to educate all the personnel about all the firmly established safety protocols. Construction units can take certain disciplinary measures against personnel who violate operating procedures and the standard code of conduct, thereby preventing any corresponding negative consequences. Construction units should establish a strict pre-job screening and training system to strictly prohibit workers deemed unqualified for the job. Finally, construction units should standardize these measures and put them into effect on construction sites.

V. CONCLUSION

Learning from past accidents can improve engineering safety with little cost. Recently, lots of literature on the analysis of accident cases has begun to investigate the risk characteristics of different accidents [26]–[31]. However, most of them assume that the risk factors of a single type of projects are independent upon each other. In fact, mutual characteristics or risk factors exist between different engineering projects, which form heterogeneous risk networks. Moreover, different types of projects may coexist in mega construction engineering projects, e.g., the Hongkong-Zhuhai-Macao Bridge Project, which directly leads to the realistic demand of risk analysis on hybrid constructions.

To promote the safe production of bridges-tunnel hybrid construction, the accident database of a large construction enterprise in China is used to decompose the acquired accident cases into accident chains and establish the BCRN, TCRN, and WRN. The network scale, diameter, density, and other metrics are selected to reveal the properties of the construction risk network. We show that the risk network has small-world and scale-free characteristics. Taking the degree (out- and in-degrees) and betweenness as metrics, the critical risk factors in the accident network are identified, respectively. We can observe that worker and management factors are the most critical risk factors for hybrid construction, which is in line with most of the single-type constructions. For environment factors, bridge construction should pay more attention on weather conditions, while tunnel construction should focus on geological conditions. Finally, corresponding preventive and post-remedy measures are put forward for bridge, tunnel, and hybrid constructions, respectively. Additionally, the proposed analytical framework can also be applied in other single or hybrid construction projects by changing the data source. In this paper, we take the bridge-tunnel hybrid construction as the case study. With the accumulation of data from different types of projects, the results will achieve have high applicability and reliability.

The same risk factors may appear in numerous accidents; therefore, the frequency of occurrence of the risk factors and the corresponding trigger relations should be appropriately weighted. The identification of the critical risk factors in a weighted construction risk network is the main direction of our future work. Moreover, we find that construction risk networks are small-world networks, which means any subtle changes in edges or nodes can dramatically affect network performance and network security. Designing safety-enhancing strategies that can significantly improve the management level according to the properties of risk networks will also deserve future research.

APPENDIX
INFORMATION OF CRITICAL RISK FACTORS CONCERNED IN THIS PAPER

Risk id	Risk name	Attribution	Type
r1	Worker carelessness	Mutual	Worker
r2	Blasting	Tunnel	Worker
r4	Unscientific design	Mutual	Technology
r5	Unstable pillars	Mutual	Machine
r6	Misstep and tilt	Bridge	Worker
r10	Overload	Mutual	Worker
r12	Inappropriate handling	Mutual	Management
r20	Inadequate geological prospecting	Mutual	Technology
r21	Adverse geological conditions	Mutual	Environment
r23	Cable accident	Mutual	Machine
r28	Overturned crane	Bridge	Machine
r30	Poisonous gas leakage	Tunnel	Environment
r39	Management negligence	Mutual	Management
r45	Fire	Tunnel	Environment
r47	Extrusion	Mutual	Machine
r49	Imperfect regulation	Mutual	Management
r51	Rain	Mutual	Environment
r58	Entering danger zone	Bridge	Worker
r69	Electricity leakage	Tunnel	Machine
r71	Falling into water	Mutual	Worker
r74	Template overturn	Bridge	Machine
r80	Falling rocks	Tunnel	Environment
r83	Wind	Mutual	Environment
r87	Overturn	Bridge	Machine
r88	Inadequate protection	Mutual	Management
r90	Brake failure	Mutual	Machine
r91	Unstable massif	Tunnel	Environment
r93	Dismantling components	Bridge	Worker
r96	Water leakage	Tunnel	Environment
r100	Inspection negligence	Bridge	Management
r104	Collapse	Mutual	Machine
r110	Gas outburst	Tunnel	Environment
r112	Violations in operating procedures	Mutual	Worker
r113	Welding violation	Mutual	Worker
r114	Violations of code of conduct	Mutual	Management
r116	No postponement	Bridge	Management
r117	Not wearing life jacket	Bridge	Worker
r118	No warning sign	Mutual	Management
r123	Not wearing seat belt	Bridge	Worker
r124	Inadequate training	Mutual	Management
r132	Dynamite explosion	Tunnel	Environment
r138	Unstable outrigger	Bridge	Machine
r140	Poisoning	Tunnel	Environment
r141	Unstable barycenter	Bridge	Machine
r142	Falling	Bridge	Worker
r143	Falling objects	Bridge	Machine

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