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EXPLORING THE RISK TRANSMISSION CHARACTERISTICS AMONG UNSAFE BEHAVIORS WITHIN URBAN RAILWAY CONSTRUCTION ACCIDENTS

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Abstract. Various construction accidents are proven to be caused by multiple unsafe behaviors (e.g., wrong use of PPE), but the risk transmission among different behaviors remains unclear. This paper provides insight into risk transmission through behavioral risk chain that leads to accidents from a system safety perspective. To better understand the coupling mechanism of various unsafe behaviors, integrate different behavioral risk chains and present the risk transmission process, a directed-weighted complex network (DWCN) method was adopted. Historical urban railway construction accidents in China are investigated to extract behavioral risk chain. A DW-BRCNA is applied to integrated behavioral risk chain and the behavioral risk transmission characteristics are explored and clarified by the five network properties, including degree and degree distribution, node strength and node strength distribution, average path length and diameter, weighted clustering coefficient and betweenness centrality. The results show that DW-BRCNA has the characteristics of a small-world, scale-free and hierarchical network, indicating that some unsafe behaviors are of greater importance in the process of risk transmission through behavioral risk chains. In addition, risk transmission in critical behavioral risk chains is more potentially to lead to accidents. This study proposed a new perspective of accident causation analysis from risk transmission among unsafe behaviors. It explains the risk transmission characteristics by a DWCN method based on behavioral risk chains. The findings also provide a practical guidance for developing control strategies on sites to prevent risk transmission and reduce accidents.

Keywords: unsafe behavior, behavioral risk chain, complex network, accident prevention, urban railway construction.

Introduction

Worldwide construction is one of the most dangerous industries as people are susceptible to workplace accidents, injuries, and even fatalities (Fang et al., 2020). In many countries, construction industry has one of the highest numbers of fatal injuries and incident rates compared with other industries (Health and Safety Executive, 2021; Winge & Albrechtsen, 2018). In China, the situation is scarcely any better as the fatalities in the construction sector have ranking first among all industrial production sectors since 2012 (Ministry of Emergency Management of the People's Republic of China, 2018). In the construction industry, urban railway construction is high risk due to congested construction sites and complex geological and hydrological conditions. The situation expressed a requirement for further understanding the impact of factors on construction accidents for developing preventive strategies.

Accident causation analysis is a critical way to understand and learn from previous accidents (Liu et al., 2019). The existing accident causation models considered several factors (e.g., unsafe behaviors, unsafe conditions, inadequate management) as a system perspective, and many scholars devoted to explaining the interactions among these factors. Although the unsafe behavior is regarded as one of the leading factors of accidents (Heinrich et al., 1950), rarely studies explore how risks transmit among unsafe behaviors and finally leading to accidents. Risks transmission among unsafe behaviors can be seen in various scenes. For instance, a driver overdrunk and then drove a car without wearing a safety belt, and the risks propagate between two unsafe behaviors continuously in order of "overdrinking → not wearing safety belt" and finally led to a serious traffic accident. According

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to this instance, traffic managers could easily know the risk transmission between these two unsafe behaviors and then develop control strategies. In the urban railway construction, the situation is much more complicated owing to the characteristics of construction such as migrant workers and complex environment (Valipour et al., 2017). Many historical accidents which involve multiple unsafe behaviors and transmissions of behavioral risks among them could hardly be explained by even experienced engineers/managers. According to investigation of historical accident cases, unsafe behaviors in an accident usually happened subsequently, forming a behavioral risk chain in chronological order. For example, as seen in Figure 1, two behavioral risk chains can be extracted: (a) not wearing personal protective equipment (PPE) → climbing to the top of a shield machine and (b) not wearing personal protective equipment (PPE) → entering into dangerous area of lifting. It can be seen that "not wearing personal protective equipment (PPE)" plays a critical role in risk transmission in both behavioral risk chains. Effective control of this behavior can greatly degrease risk transmission through behavioral risk chain and reduce accident rate in construction. Therefore, exploring the risk transmission characteristics among various behaviors based on behavioral risk chain and finding out critical unsafe behaviors are important to cut down behavioral risk transmission and prevent accidents in construction.

To better understand the coupling mechanism of various unsafe behaviors, integrate different behavioral risk chains and present the risk transmission process, a directed-weighted complex network (DWCN) method was adopted. Complex network (CN) is widely used to explore systematic issues based on chain, such as disaster chains of urban transit system (Chen et al., 2021), behavior chains for online participation in social network (Fogg & Eckles, 2007) and accident chains in subway construction (Zhou et al., 2014). Therefore, in this study, a DWCN method based on behavioral risk chain is proposed and demonstrated using collected urban railway construction accident reports.

1. Literature review

1.1. Factors influencing unsafe behaviors in construction

Unsafe behavior has been judged to be one of the leading causes of accident since Heinrich proposed the accident cause chain (Heinrich et al., 1950). In order to reduce human error related incidences, studies have been conducted to explore what factors could influence workers' safety behaviors at construction sites (Choudhry & Fang, 2008). Due to the complexity of construction, factors affecting unsafe behavior in the construction industry are multifarious (Guo et al., 2018). Various types of factors were found to have influence on unsafe behavior in varying degree and could be important factors to address to prevent unsafe behavior from emerging, including (i) individual factors, like individual age (Amponsah-Tawiah & Mensah, 2016), sociocognitive processes (Choi & Lee, 2018), personal background and socioeconomic status (Shuang et al., 2019), job stresses (Wu et al., 2018); (ii) organizational factors (Jitwasinkul & Hadikusumo, 2011), like unreasonable regulations (Mohammadfam et al., 2017), safety atmosphere and policy (Chan et al., 2017; Kim et al., 2019); (iii) environmental factors, like temperature and noise (Lu & Davis, 2016). Exploration of the factors leading to unsafe behavior is conducive to preventing individual unsafe behaviors from arising. In the accident cause theory, human unsafe behavior, as an important link in the accident cause chain, is one of the dominoes that directly lead to the accident (Heinrich et al., 1950; Stewart, 2001). Due to this, safety management studies are gradually shifting their focus from effectively controlling accident causes to cutting off the coupling relationships among accident causes (Eshtehardian & Khodaverdi, 2016).

1.2. Impact of risk transmission on behavior

Risk transmission can lead to a complex impact on the evolution of cooperative behaviors (Dui et al., 2020). It has been widely studied in complex system reliability such as electric power systems, epidemics, and interdependent

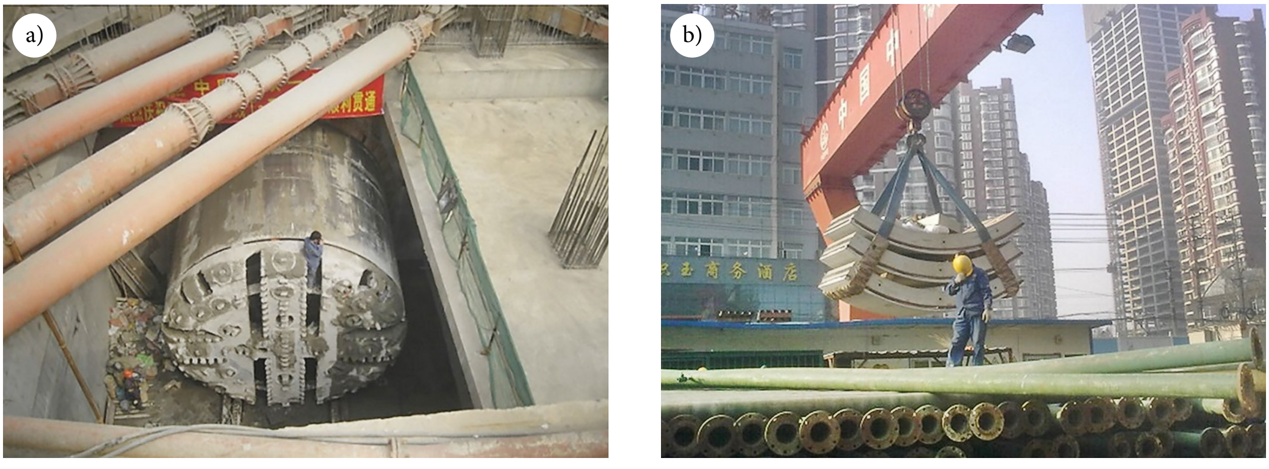


Figure 1. Behavioral risk chains: a – not wearing personal protective equipment: climbing to the top of a shield machine; b – not wearing personal protective equipment: entering into dangerous area of lifting

networks (Dong & Cui, 2015). Xing and Levitin (2010) studied the risk isolation and transmission effects. Levitin et al. (2019) analyzed the influence of the risk transmission on the mission abort policy in warm standby system. Just like the interactions among potential hazards in work activities, one unsafe behavior does not singly happen (Zhou et al., 2014) and an accident is usually caused by multiple unsafe behaviors (Yin et al., 2017). Once unsafe behavior has occurred, behavioral risk can be passed among unsafe behaviors by different workers. Behavioral risk is often the result of a sequence of previous unsafe behaviors, or the cause of a sequence of following unsafe behaviors. According to the chronological order among different unsafe behaviors in an accident, once unsafe behavior has occurred, behavioral risk can be passed through various unsafe behaviors by different workers. The superposition effect of accidents caused by unsafe behaviors is reflected by the risk transmission through behavioral risk chain (Guo et al., 2020).

1.3. Complex network (CN) applications in accident analysis

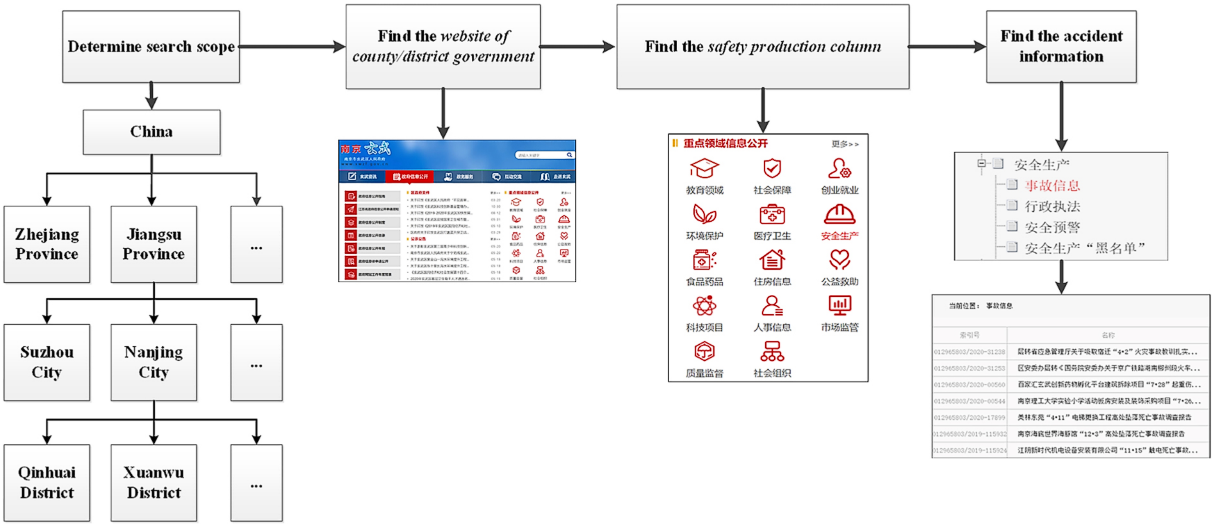
The CN method was used to identify salient properties of diverse complex systems, such as neuroanatomical connectivity (Rubinov & Sporns, 2010), power grids (Pagani & Aiello, 2013) and air transport (Wang et al., 2011). It is widely applied in accident analysis as it considers the co-occurrence of risks through their causal correlation (Akgul et al., 2017; Li et al., 2016), and can also determine the critical risks and key risk transmission paths according to density and centrality of network (Yang & Zou, 2014). In construction, this method has been used for accident analysis such as characterizing the time series of near-miss accidents (Zhou et al., 2017), exploring the complexity of a construction accident network (Zhou et al., 2014), and understanding the causes of accidents in a complex situation (Zhou & Irizarry, 2016). Considering the characteristics of CN, this method could potentially be used to explore risk transmission among factors in complex systems and has successfully applied on some aspects in construction (e.g., Tang et al., 2018). Since unsafe behaviors are critical factors leading to accidents, CN method can also help to explore the risk transmission characteristics through behavioral risk chain within accidents and capture the complexity of the correlation among unsafe behaviors.

2. Methodology

To explore the interactions among unsafe behaviors within construction accidents, a case study approach is adopted (Yin, 2017). The research questions to be asked in this study are: (i) What are the behavioral risk chains existed in construction accidents? (ii) How do these chains act as a network to affect construction safety? (iii) What is the impact of interactions among unsafe behaviors on construction accidents? To answer these questions, the unit of analysis is initially identified in which the cases are selected from historical accident records of urban railway construction in China. The urban railway construction is a typical high-risk construction type worldwide owing to the complex environment (e.g., narrow spaces, poor lighting, and complex geological and hydrological conditions) (Singh, 2020; Yuan et al., 2019). In China, the situation is much serious since the characteristics of short history and rapid development (Ding & Xu, 2017). Additionally, workers engaged into construction tasks without sufficient safety experience (Yu et al., 2014). Therefore, many accidents are caused by multiple unsafe behaviors and the cases are representative to explore the interactions among unsafe behaviors within construction accidents.

2.1. Data collection

Historical accident data in urban railway construction of China is from government websites since accident records are much reliable as the accidents have been carefully investigated by experts. Government websites, such as the Ministry of Housing and Rural-Urban Development and the Work Safety Administration, in certain provinces provide detailed accident investigation reports. An example of the accident search process is shown in Figure 2. Accord-



索引号	名称
012965803/2020-31238	层转省应急管理厅关于吸取宿迁“4•2”火灾事故教训扎实...
012965803/2020-31253	区安委办层转《国务院安委办关于京广铁路湖南郴州段火车...
012965803/2020-00560	百家汇玄武创新药物孵化平台建筑拆除项目“7•28”起重伤...
012965803/2020-00544	南京理工大学实验小学活动板房安装及装饰采购项目“7•26...
012965803/2020-17899	美林东苑“4•11”电梯更换工程高处坠落死亡事故调查报告
012965803/2019-115932	南京海底世界海豚馆“12•3”高处坠落死亡事故调查报告
012965803/2019-115924	江阴新时代机电设备安装有限公司“11•15”触电死亡事故...

Figure 2. An example of the accident search process

ing to the regulation on investigating and reporting accidents related to goods producing, construction accidents should be recorded with detailed reports. Detailed reports of accident cases are found in the safety information section of government websites. In addition, accident cases can be directly searched on government websites using keywords such as construction accidents, accident reports and accident investigations. By means of this process, a total of 287 cases of urban railway construction accidents in China were obtained from these websites. The amount of data is relatively small for three main reasons: (i) many accident reports are released only for short time and are then removed from government websites; (ii) some nonfatal accidents with low economic losses are not disclosed on the websites; and (iii) many accidents are recorded via a simple process, thus, chains of unsafe behaviors cannot be extracted. Only accidents with detailed reports are selected in this study. As the unsafe behavior is the study object, accidents caused by unsafe conditions or the environment are not considered. Although the amount of accident data is not large, many representative accidents of urban railway construction in China are included. These accident cases occurred in China between 2008 and 2020. Moreover, each investigation report provides all the information related to an accident/incident in detail, such as the occurrence process, accident causes and workers' unsafe behaviors.

2.2. Complex network

The CN method is used to explore the interactions among unsafe behaviors within construction accidents. To build the network, the unsafe behaviors involved in historical accidents are extracted to generate behavioral risk chains and the chains sharing the same unsafe behaviors are crossed to form the network structure. Since unsafe behaviors are arranged in chronological order, the connections between unsafe behaviors in chains are directed to form directed edges in the network. The weight of each edge is identified by the number of connections between unsafe behaviors. Compared to the previous studies (Guo et al., 2020, 2021), the weighted network is more reliable because the interaction strength among unsafe behaviors could be described (Zhou et al., 2015). Hence, a directed weighted network is built, which is called a directed weighted-behavioral risk chain network of accidents (DW-BRCNA).

Basic network properties, including degree and degree distribution, node strength and node strength distribution, average path length and diameter, weighted clustering coefficient and betweenness centrality, are selected to analyse the structure of the DW-BRCNA. A directed weighted network with N nodes can be represented mathematically as an N×N adjacency matrix A with elements (Barrat et al., 2004):

$$A_{ij} = \begin{cases} a_{ij} \cdot w_{ij} & \text{if node } i \text{ points to node } j \\ 0 & \text{otherwise} \end{cases}, \tag{1}$$

where a_{ij} takes a value of 1 if node i points to node j and 0 otherwise, and w_{ij} specifies the weight on the edge if node i points to node j ($w_{ij} = 0$ otherwise).

(1) Degree and degree distribution.

Degree is a measure of centrality of a node in the network. The all degree of node i is the number of edges incident with the node, which is expressed as k_i. In directed networks, the all degree is defined as follows:

$$k_i = k_i^{in} + k_i^{out}, \tag{2}$$

where k_i^{in} is the in-degree (number of incoming links: $k_i^{in} = \sum_j a_{ji}$) of node i and k_i^{out} is the out-degree (number of outgoing links: $k_i^{out} = \sum_j a_{ij}$) of node i.

The cumulative degree distribution $P(k)$ is defined as the fraction of nodes with a degree greater than or equal to k and is calculated using the formula:

$$P(k) = \sum_{k'=k}^{\infty} p(k'), \tag{3}$$

where $p(k)$ is the probability of a randomly selected node being degree k.

(2) Node strength and node strength distribution.

Degree has generally been extended to the sum of weights when analysing weighted networks (Opsahl et al., 2010) and labelled node strength. In directed weighted networks, the all node strength is defined as follows:

$$s_i = s_i^{in} + s_i^{out}, \tag{4}$$

where s_i^{in} is the sum of incoming weights of node i and s_i^{out} is the sum of outgoing weights of node i.

The node strength distribution, denoted as $P(s)$, is similar to the degree distribution.

(3) Average path length and diameter.

The shortest path length reflects the smallest sum of the edge lengths among all the possible paths connecting two nodes in the network. In our network, the edge length is defined as the reciprocal of the weight ($1/w_{ij}$) to better apply Dijkstra's algorithm to identify the shortest paths. The implementation of Dijkstra's algorithm is formally defined as:

$$d_{ij}^{w} = \min\left(\frac{1}{w_{ih}} + ... + \frac{1}{w_{hj}}\right). \tag{5}$$

The average path length is the average topological distance between any two nodes and is defined as the mean geodesic length over all nodes (Boccaletti et al., 2006):

$$L = \frac{1}{N(N-1)} \sum_{i,j \in N,\ i \neq j} d_{ij}^{w}, \tag{6}$$

where d_{ij}^{w} is the length of the geodesic from node i to node j and N represents the number of nodes in the network.

The maximum value of d_{ij}^{w} is called the diameter, which is defined as the longest of all the calculated shortest paths in a network.

(4) Weighted clustering coefficient.

The clustering coefficient reflects the probability that two randomly selected neighbors of a node are connected. In a directed weighted network, the weighted clustering coefficient of a given node is defined as:

$$c_i^w = \frac{1}{k_i(k_i-1)} \sum_{j,k\in N,\, j\neq k} \left(w'_{ij} w'_{jk} w'_{ik}\right)^{1/3}, \qquad (7)$$

where k_i is the total degree of node i and w'_{ij}, defined as $w'_{ij} = w_{ij} / \max(w_{ij})$ ($\max(w_{ij})$, is the maximum weight of the edges connected to node i), which represents the normalized weight of the edge connecting node i to node j.

(5) Betweenness centrality.

Betweenness centrality measures the extent to which a node acts as an intermediary in the interaction between other nonadjacent nodes. The betweenness centrality b_i of node i is defined as follows:

$$b_i = \sum_{j,k\in N,\, i\neq j\neq k} \frac{n_{jk(i)}}{n_{jk}}, \qquad (8)$$

where n_{jk} is the number of shortest paths connecting node j and node k and $n_{jk(i)}$ is the number of shortest paths connecting node j and node k and passing through node i.

The consideration of weights and directions in directed weighted complex networks leads to complex calculation procedures. Traditional computing tools, such as Pajek, are unable to meet the requirement since they could not analyse weighted networks. Thus, NetworkX, a Python package for the creation, manipulation, and study of the structure, dynamics, and functions of complex networks, is imported and modified to analyse the network properties of the DW-BRCNA. In addition, to better observe the network structure, Matplotlib is adopted to visualize the model of the DW-BRCNA.

3. Process

3.1. Identify unsafe behaviors

A list of unsafe behaviors is constructed based on relevant safety standards, operating procedures and a previous study to define the nodes in the network (Guo et al., 2020). The unsafe behaviors in the list are extracted mainly from the Classification Standard for Casualty Accidents of Enterprise Workers (GB 6441-1986) (National Standards Bureau, 1986), which includes 49 unsafe behaviors. Other guidelines on safety standards and operating procedures in China, such as the Technical Code for Safety of Working at Height of Building Construction (JGJ 80-2016) (Ministry of Housing and Urban-Rural Development of the People Republic of China, 2016), Code for Construction and Acceptance of Crane Installation Engineering (GB 50278-2010) (National Standards Bureau, 2011), and Quality and Safety Check Points of Urban Rail Transit Engineering (National Standards Bureau, 2011), are also used as references. A total of 151 unsafe behaviors across 24 classes in urban railway construction are identified. Then, the unsafe behaviors are encoded as four characters with the first two characters representing the type code and the last two characters representing the name code (see the Table A.1 in the Appendix for detailed classification information and the codes of unsafe behaviors). Examples of the identified unsafe behaviors are shown in Table 1.

Table 1. Examples of identified unsafe behaviors on the list

Type	Code	Name	Code
Installation and demolition operation	17	Erecting or dismantling scaffolding against procedures	1702
Tunnel operation	19	Not supplying air to deep well as required	1910

3.2. Identify the behavioral risk chains

To denote these interrelationships of unsafe behaviors by edges in the network, a directed behavioral risk chain is employed to arrange unsafe behaviors as nodes in chronological order. The detailed accident reports provide information to identify behavioral risk chains. An example behavioral risk chain of an accident is shown in Table 2.

Table 2. An example of behavioral risk chain extraction

Accident process	Accident cause	Behavioral risk chain	Code
A worker operated a Komatsu shield machine to drill in the right line of the tunnel. During the drilling process, he found the screw conveyor of the shield machine was stuck with something, so he asked his colleagues to open the point inspection port of the screw conveyor. However, the shield machine could be checked from only one inspection port, and the leader suspected that foreign matter was stuck in the upper inspection port. Therefore, gas welding was used for cutting. After cutting, the high-pressure water column rushed out, and the water head pressure was approximately 20 m. When the accident occurred, the workers in the shield machine escaped immediately.	Direct causes: 1. The team leader of the shield machine operated against rules and ordered the operator to open the point inspection port of the shield machine without permission. 2. After the point inspection port was opened, no effective control measures were taken, resulting in excessive water and sand gushing. 3. Complex geological conditions. Indirect causes: 1. Relevant system was not strictly implemented. 2. The construction organization design was unreasonable, and the construction sequence of the tunnel was improper.	Not addressing problems in the surrounding environment in time and effectively → violating operation process; → operating equipment running at high speed; → not formulating effective response measures for abnormal performance of shield construction; → issuing improper commands; → operation error	1407→ 1801→ 1606→ 1901→ 2402→ 1605

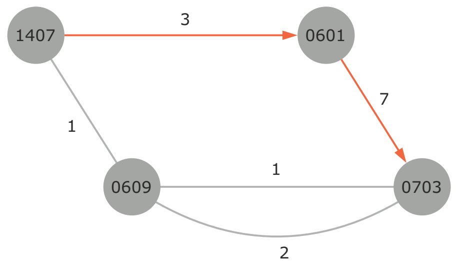


Figure 3. Subset of nodes and their relationships

Accidents caused by a single unsafe behavior cannot form chains and are thus eliminated from the analysis. Finally, 157 behavioral risk chains consisting of 100 nodes in urban railway construction are extracted to establish a network. The nodes are represented by the codes of the unsafe behaviors involved.

Moreover, to illustrate how to determine the weights of these edges, a subnet of 4 nodes ("0601", "0609", "0703", "1407") and their relationships is shown in Figure 3. The weight of an edge is 1 when a node connects to another node a single time, such as edge "1407" to "0609". In addition, an edge weight greater than 1, such as that of edge "1407" to "0601" with a weight of 3, reflects that the latter unsafe behavior occurs behind the former multiple times.

3.3. Establish DW-BRCNA

The aforementioned approach to identify the behavioral risk chain is applied to all accident cases. Then, all the chains are integrated by CN method to establish the model of DW-BRCNA, and the visualized result is shown in Figure 4. Various correlations of unsafe behavior can be simplified into DW-BRCNA, which consists of 100 nodes and 252 directed weighted edges. The node size is positively correlated with the degree of this node. The edge color and edge widths represent the weight of this edge. The wider the edge, the darker the color, the greater the weight.

4. Results

The network properties could assist in identifying the most important information in the DW-BRCNA, such as key nodes, crucial chains, interactions of nodes and the topological characteristics of the network. The analysis results are presented in the rest of this section.

4.1. Node degree

In directed networks, all degree has two components: in-degree and out-degree. The degree indicates the importance of a node in the network. Figure 5 shows the nodes with all degree greater than or equal to 10. The unsafe behaviors "2402", "1407" and "0703" have relatively high in-degrees, with values of 19, 13 and 12, respectively. These unsafe behaviors are susceptible to other unsafe behaviors and represent the direct causes of accidents. The unsafe behaviors "1801", "2402", "1406", "1407", and "1502" have relatively high out-degrees of 21, 19, 16, 13, and 10. These unsafe behaviors are more likely to influence others in the network and represent indirect causes of accidents. According to the degree analysis results, unsafe behaviors in urban railway construction are largely related to the environment and management.

4.2. Node strength

Node strength takes both the number and weights of edges connected to a node into consideration; thus, node strength reflects the centrality of a node in the DW-BRCNA. All node strength consists of two components: in-strength and out-strength. The average all node strength

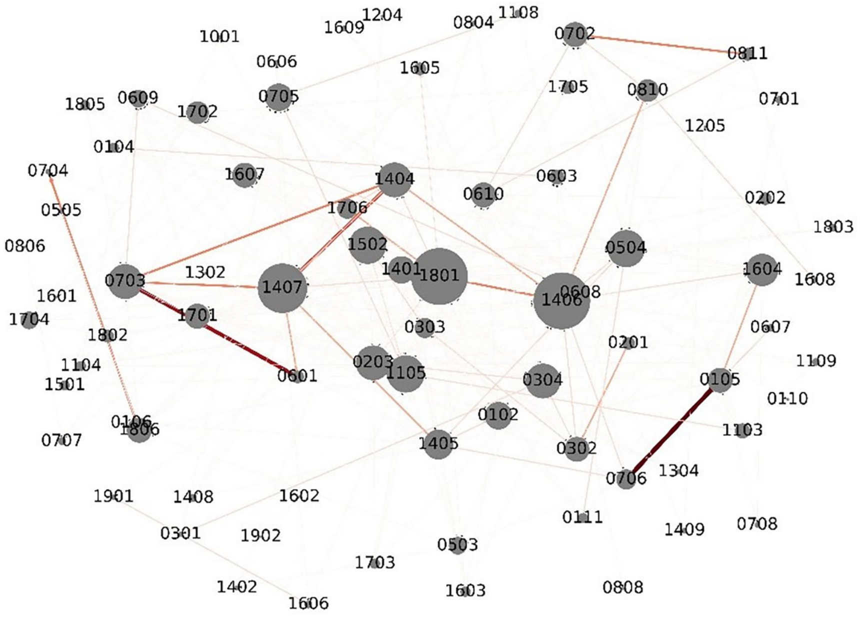


Figure 4. Establishment of the model of DW-BRCNA

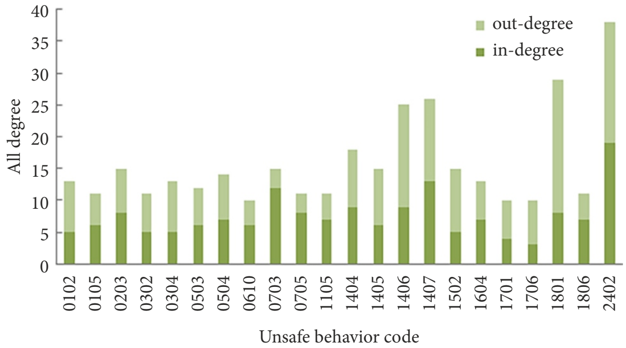


Figure 5. Nodes with all degree greater than or equal to 10

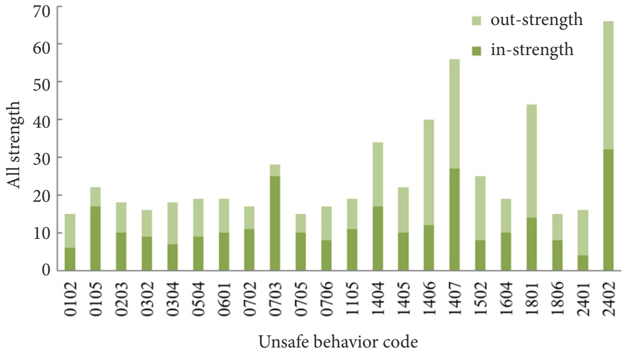


Figure 6. Nodes with all strength values greater than 14

in this network is 9.42, indicating that every unsafe behavior could affect or be affected more than 9 times. The nodes with all strength values greater than 14 are shown in Figure 6. Compared to node degree, a new node "1404" has a high all node strength of 34. Therefore, this kind of unsafe behavior should also gain increased attention.

4.3. Node degree distribution and node strength distribution

The cumulative degree distribution (Figure 7a) and cumulative node strength distribution (Figure 7b) of DW-BRCNA follow power-law distributions that approximately follow exponential functions $P(k)\sim 3.1033k^{-1.306}$ ($R^2 = 0.6725$) with $\lambda = 1.306$ and $P(s)\sim 3.028k^{-1.125}$ ($R^2 = 0.8844$) with $\lambda = 1.125$. Considering the weights of the edges, the variable s (node strength) has greater explanatory power and a better curve fitting effect. The distributions deviate from the power-law distribution for large values of k and s, indicating that this network is a scale-free network (Barabási & Albert, 1999). These nodes with high degrees and high node strengths make the network robust to random attacks. If controlled effectively, the network will become vulnerable and transform into a set of isolated subnetworks. Lots of behavioral risk chains can be cut down and risk transmission through behavioral risk chain can be interrupted. Thus, collaborative control over unsafe behaviors with high degrees and high node strengths can effectively decrease the probability of construction accidents.

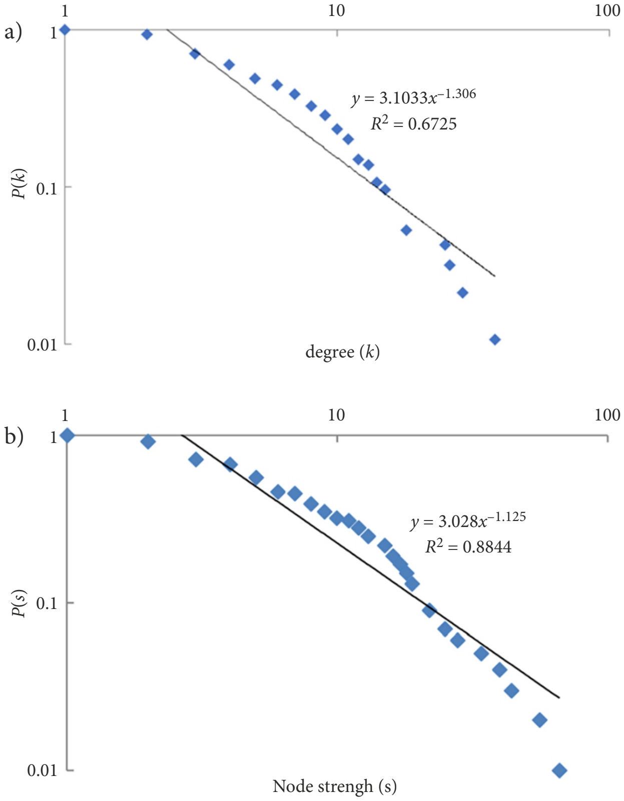


Figure 7. Distributions: a – the cumulative degree distribution; b – the cumulative node strength distribution

4.4. Average path length and diameter

Shortest paths play an important role in the transport and communication between nodes and in the characterization of the internal structure of a complex network. The average path length is a measure of the typical separation between two nodes and is defined as the mean geodesic length over all pairs of nodes. The average path length in DW-BRCNA is 2.77, which means that the physical length between two unsafe behaviors is less than 3. That is, an unsafe behavior leading to an accident will only require passing through distance of less than 3.

The diameter, which represents the longest of all the calculated shortest paths in a complex network, is 6.5 in the DW-BRCNA. The pair of nodes with the longest topological distance in the DW-BRCNA: "0609" to "2206". This path of relationships (0609→1109→1103→0603→1407→2301→2203→2206) is likely to be ignored by workers and managers due the long distance and low connection frequency. However, "0609" could lead to "2206" after the propagation of a series of unsafe behaviors and then lead to accidents.

4.5. Weighted clustering coefficient

The weighted clustering coefficient is a measure of the degree to which nodes in a complex network tend to cluster together. In a directed weighted network, some neighbors of nodes are more important than others, so the weights

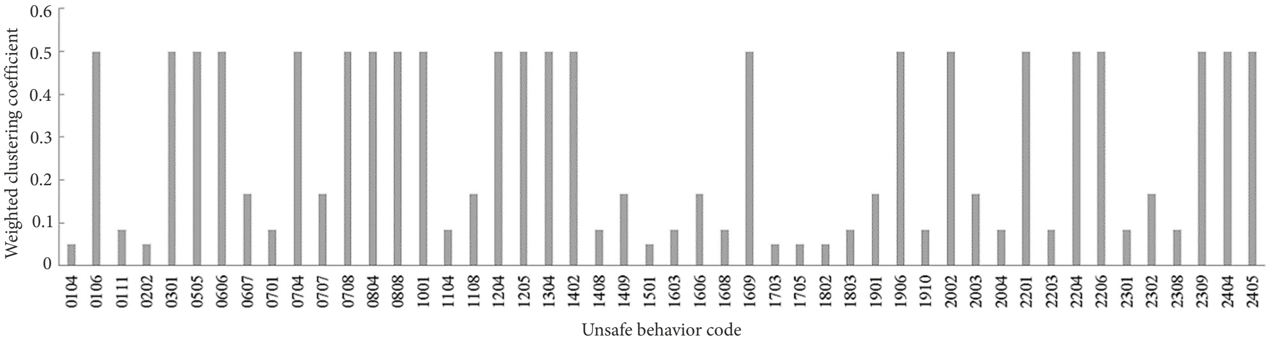


Figure 8. Weighted clustering coefficients

directions of edges are taken into consideration in the DW-BRCNA. The nodes with a degree of 1 are eliminated in the analysis. As shown in Figure 8, in this network, 22 nodes have a maximum clustering coefficient of 0.5. Nodes with larger clustering coefficients have stronger connections with neighboring nodes and form clusters in the network. Controlling the unsafe behaviors in the center of the clusters can reduce the occurrence of other related unsafe behaviors in the cluster.

Furthermore, secondary and derived accidents could be prevented by controlling unsafe behaviors with high clustering coefficients.

The average weighted clustering coefficient of the network is 0.1615, which is much higher than that of a random network of the same size, with a value less than 0.04. Large clustering coefficient and short average path length are characteristics of a small-world network (Watts & Strogatz, 1998). In this kind of network, a chain can be formed between two seemingly unrelated nodes by passing through a few other nodes. In other words, unsafe behavior could lead to seemingly unrelated unsafe behavior due to connections with other unsafe behaviors, thereby resulting in accidents. Therefore, collaborative control over multiple unsafe behaviors could avoid the formation of chains between unsafe behaviors.

The function of the weighted clustering coefficient with respect to node strength is plotted and expressed by $C(s)$ to explore the hierarchy in the DW-BRCNA, as shown in Figure 9. A significant linear relationship is observed between the weighted clustering coefficients and node strength ($C(s) \sim s^{-1}$), indicating that the DW-BRCNA has a hierarchical topology to a certain extent. The hierarchical topology of the complex network reflects that many nodes are connected to nodes with greater strength that are scattered, leading to low clustering (Ravasz & Barabási, 2003). In contrast, nodes adjacent to nodes with low strength are highly interconnected and form small groups of nodes. These nodes are organized in a hierarchical manner into increasingly larger groups. The hierarchical properties of DW-BRCNA indicate that unsafe behaviors in the clusters should be controlled to take precautions against their rapid diffusion effect in causing secondary and derived accidents.

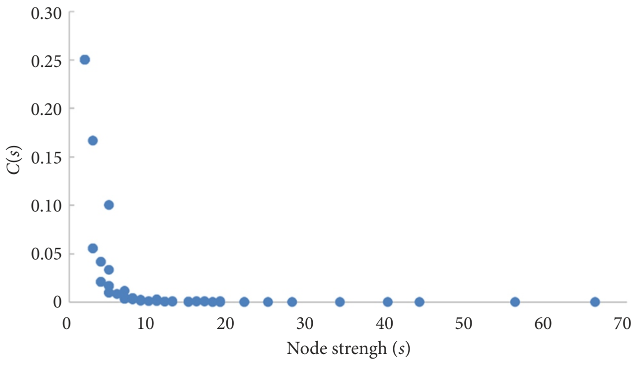


Figure 9. The function of the weighted clustering coefficient with respect to node strength

4.6. Betweenness centrality

Betweenness centrality is another standard measure of node centrality. Betweenness centrality, which is obtained by counting the number of shortest paths passing through a node, was originally introduced to quantify the importance of a node in a complex network. The higher the betweenness centrality is, the more influential the node in the transport in the network. The weights and directions of edges are considered in the calculation of betweenness centrality in the DW-BRCNA. Fourteen nodes with values greater than 0.05 are adopted in the analysis of betweenness centrality, as shown in Figure 10. Node "2402" is the most important unsafe behavior with a value of 0.395, indicating that nearly 40% of the shortest paths pass through this node in the network. The following nodes are "1406", "1801" and "1407", with values of 0.324, 0.270 and 0.223,

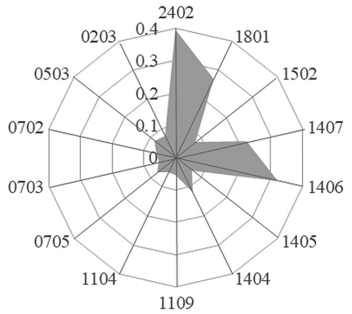


Figure 10. Betweenness centrality

respectively. These three unsafe behaviors also play an important role in the propagation of unsafe behavior in the DW-BRCNA. The results show that proper commands and supervision of managers are critical during the life cycle of urban railway construction. Effectively controlling the related behaviors, such as "2402", could significantly increase the average path length and diameter of the network, thereby decreasing the transmission and diffusion efficiency of unsafe behaviors and avoiding accidents.

5. Discussions

Through calculating the network properties of DW-BRCNA, the topological characteristics of this network are found out. The topological characteristics reflect the risk transmission characteristics through behavioral risk chain:

(i) The DW-BRCNA has small-world properties, meaning that the probability of a newly occurring unsafe behavior being connected to each existing unsafe behavior is not the same. The probability of a connection to an unsafe behavior with high degree is much higher than that of with low degree. Thus, unsafe behaviors with high degree are more easily to propagate risk transmission to other unsafe behaviors. In BW-BRCNA with small-world properties, collaborative control of unsafe behavior with high degree can block the behavioral risk chain of most unsafe behaviors, causing low risk transmission efficiency.

(ii) The DW-BRCNA has scale-free properties, which means that unsafe behavior could lead to seemingly unrelated unsafe behavior. Just as shown in Figure 4, some nodes with low degree may be connected to edges with large weights. This kind of path bears great risk transmission efficiency. Once the former unsafe behavior occurred, the latter unsafe behavior on this path has a high probability of occurrence. In this situation, cutting off paths with high weights can greatly reduce the risk transmission efficiency through behavioral risk chain.

(iii) The DW-BRCNA has hierarchical properties. Unsafe behaviors in hierarchical network are more likely to connect to scattered unsafe behaviors with high strength, leading to low clustering. In contrast, adjacent unsafe behaviors with low strength are highly interconnected with each other and form small groups of unsafe behaviors. This kind of unsafe behaviors are usually not noticed due to its low incidence, but risk transmission in such highly clustered unsafe behaviors may occur repeatedly with superposition effect. If ignored in safety management, these unsafe behaviors can become the end of risk transmission and the direct cause of some accidents.

These findings indicate that some unsafe behaviors play an important role in the process of behavioral risk transmission through behavioral risk chains. According to the calculation results of network properties, critical unsafe behaviors in risk transmission have been figured out. Several unsafe behaviors, including 2402 (Issuing improper commands), 1407 (not handling problems in the surrounding environment effectively and in a timely manner), 0703 (Remaining or working in unstable or unsafe areas), 1406 (Not supervising during dangerous operations), 1502 (Engaging in high-risk special operations without a certificate), 1404 (Taking no effective support and reinforcement measures) and 1801 (Violating operation process) are supposed to be focused on during construction process. In addition, the construction site should be equipped with safety management supervisors and more efforts should be put to promote their perception of environmental risks and ability to analyse and command when facing complex construction conditions.

Conclusions

Unsafe behaviors in construction accidents have received substantial attention, but the risk transmission among different behaviors remains unclear. This paper provides insight into risk transmission through behavioral risk chain that leads to accidents from a system safety perspective. Historical urban railway construction accidents in China are investigated to extract behavioral risk chain. A DW-BRCNA is applied to integrated behavioral risk chain and the behavioral risk transmission characteristics are explored and clarified by the five network properties. The results show that the DW-BRCNA is a small-world, scale-free, hierarchical network, which indicates some unsafe behaviors are of great importance in the generation and propagation of behavioral risks. The risk transmission would be faster and more serious if these unsafe behaviors co-occur to form the chains. From the theoretical aspects, this study promotes accident causation analysis. The risk transmission through behavioral risk chain could potentially lead to construction accidents, and this study provides a further explanation that some unsafe behaviors are in the critical positions during the risk transmission. Additionally, the formation of the identified chains increases the probability of risk transmission. These explanations enrich the reasons why accidents are caused by multiple unsafe behaviors. From the practical aspects, this study provides guidance for developing control strategies for unsafe behaviors in urban railway construction of China, which can also be extended to other countries. In the DW-BRCNA, the key nodes and identified chains represent the unsafe behaviors which should be primarily controlled and collaboratively controlled. The managers/engineers could develop control strategies according to the characteristics of these unsafe behaviors. This method could eliminate personal biases of managers/engineers in developing control strategies.

Some limitations have been addressed during this research, in terms of both the proposed methodology and the study itself. (i) This study focused on the static characteristics of the DW-BRCNA. In practice, the interaction among unsafe behaviors, especially the propagation of the behavioral risk chain, is uncertain and dynamic. Further study should model the behavioral dynamics combined with complex network and explore behavioral risk transmission from the perspective of dynamic network. (ii) The number of accidents may influence the complexity and structure of DW-BRCNA constantly thus more cases concerning different accident types and construction project types should be collected to explore the subtle relationships among unsafe behaviors. (iii) A broader range of causal factors including organisational factors, environmental factor and individual factors should be considered. Take multilayer network method into consideration to form a more comprehensive system for accident analysis.

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Author contributions

Shengyu Guo and Bing Tang conceived the study and were responsible for the design and development of the data analysis. Bing Tang and Wei Lu were responsible for data collection and analysis. Bing Tang and Pan Zhang was responsible for programming. Shengyu Guo and Bing Tang were responsible for data interpretation. Bing Tang wrote the first draft of the article.

Disclosure statement

Authors confirm that all of the content, figures (charts, photographs, etc.), and tables in the submitted manuscript work are original work created by the authors and no any competing financial, professional, or personal interests from other parties.

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APPENDIX

Table A.1. The list of unsafe behaviors and their codes

Code	Unsafe behavior	Code	Unsafe behavior
01	Neglect security warning	1306	Not keeping distance between inflammable and explosive objects and electrical equipment
0101	Working after drinking	14	Inadequate protective measures
0102	Ignoring warning signs and warning signals	1401	Inadequate protection measures at the caves and edges
0103	Operating when moving fast	1402	Not setting safety net as required
0104	Starting or shutting down machines with no signal	1403	Not setting handrail rope as required
0105	Not lookout timely	1404	Taking no effective support and reinforcement measures
0106	Overspeed, overload or overrun	1405	Fail to set safety warning signs in dangerous areas
0107	Putting hands into the punching machine	1406	Not supervising during dangerous operations
0108	Putting the head (or hands, etc.) out of the cab	1407	not handling problems in the surrounding environment effectively and in a timely manner
0109	Throwing things at high altitude	1408	Not setting the escape way as required or block the escape
0110	Carrying workers against regulations	1409	Not setting gas detection alarm or other equipment in confined space
02	Cause the safety device to fail	15	Special operation
0201	Not inspecting the safety devices of machinery and equipment periodically	1501	Not having physical examination before special operation
0202	Not installing safety devices as required	1502	Engaging in high-risk special operations without a certificate
0203	Causing the safety device to fail due to adjustment error	16	Mechanical equipment operation
03	Use unsafe devices	1601	Forgetting to turn off the device
0301	Using equipment without safety devices	1602	Not locking the switch, causing unexpected turning, power on, leakage, etc
0302	Using equipment with failed safety devices	1603	Illegal operation of mechanical equipment
0303	Using machinery and equipment without inspection and acceptance	1604	Illegal driving of motor vehicles
0304	Not inspecting machinery and equipment before construction	1605	Operation error
04	Operate with hand instead of tools	1606	Operating equipment running at high speed
0401	Removing chips by hand	1607	Starting, stopping and moving mechanical equipment without permission
0402	Holding workpieces by hand for machining	1608	Overloading mechanical equipment
0403	Operating with hands instead of manual tools	1609	Not setting complete equipment maintenance regulations

Continue of Table A1

Code	Unsafe behavior	Code	Unsafe behavior
05	Improper placement	17	Installation and removal
0501	Piling up beyond the limit height	1701	Not fastening workpieces firmly
0502	Storing large formwork without protective measures	1702	Erecting or dismantling scaffolding against procedures
0503	Storing in improper location	1703	Not install or remove mechanical equipment according to specifications
0504	Not fastening firmly during transportation or lifting	1704	Not building construction platform required
0505	Stacking not unevenly	1705	Not setting up or removing formwork support system according to specification
06	Enter hazardous sites	1706	Not installing or removing the support system as required
0601	Entering into areas easy to collapse	1707	Not removing negative ring, portal and connecting passage segments as required
0602	Approaching leakage place without safety facilities	18	Illegal operation
0603	Accessing to tanks, mixers or wells without permission	1801	Violating operation process
0604	Overrunning a signal	1802	Arranging reinforcement against specification
0605	Getting on and off when speeding at switchyard	1803	Pouring concrete against specifications
0606	Starting underground operation without tapping surrounding rock	1804	Not clearing the hole after drilling operation
0607	Walking through the dangerous area instead of the safe passage	1805	Constructing too fast
0608	Entering a confined space without prior proof	1806	Overloading of construction platform, scaffold, support or formwork
0609	Accessing to dangerous places for rescue blindly	19	Tunnel operation
0610	Entering into dangerous area of lifting and hoisting	1901	Not formulating effective response measures for abnormal performance of shield construction
07	Stay in unsafe position	1902	Not setting up anti-sliding measures
0701	Staying within the operating radius of machinery and equipment	1903	Not cleaning up the sundries and mud in the construction area timely
0702	Working under lifting objects	1904	Not formulating the operating procedures for opening the shield machine
0703	Remaining or working in unstable or unsafe areas	1905	Opening shield machine against specifications
0704	Working on overloaded platform	1906	Not setting up communication facilities between the air injection area or the inside and outside of the tunnel
0705	Climbing or sitting in unsafe positions	1907	Not carrying out advance support and reinforcement of stratum as required
0706	Staying in the vehicle running area	1908	Not setting up climb ladder as required
0707	Operating under high voltage transmission line	1909	Not fixing track and foundation as required
0708	Stepping on the equipment in operation	1910	Not supplying air to deep well as required
08	Lifting	20	Foundation pit and trench operation
0801	Using deformed or damaged gantry crane track foundation	2001	Not supporting timely in foundation pit and trench
0802	Using gantry crane track with excessive wear on top or side of rail	2002	Stacking materials and tools near pit edge
0803	Setting gantry crane track with large deviation	2003	Not taking reliable anti-skid measures at the pit edge
0804	Using substandard wire rope	2004	Sloping too steeply
0805	No special protective measures in areas covered by tower crane operation	21	Blasting operation
0806	Erecting a tower crane within the safe distance of an overhead line without protective measures	2101	Not setting up effective warning measures before blasting
0808	Placing objects on the hoisted objects	2102	Not evacuating irrelevant personnel before blasting
0809	Not installing wall attachment device in the high-altitude hoisting	2103	Charging process operation error
0810	Improper operation of crane	22	Electricity

End of Table A1

Code	Unsafe behavior	Code	Unsafe behavior
0811	Lifting operation when there are people in the operation radius	2201	Not setting special switch box or the electrical components as requirement
09	Other operations during machine operation	2202	Not protecting the working cable from mopping and soaking
0901	Cleaning the machine when it is running	2203	Not setting protection of circuit from overload, leakage and short circuit
10	Distraction behavior	2204	Hinge equipment without protection circuit overload, leakage and short circuit
1001	Falling without external force	2205	Not using safety voltage as required in hazardous area
11	Use of personal protective equipment	2206	Laying power lines against specifications
1101	Not wearing protective gloves	2207	Not setting up power supply line according to the specification
1102	Not wearing safety shoes	2208	Connecting wires without permission
1103	Not wearing safety helmet	2209	Not replacing aging and damaged electrical equipment in time
1104	Not wearing respiratory protective equipment	2210	Not interlock the power supply of generator set with the power supply of external power lines
1105	Not wearing safety hardness	23	Fire safety
1106	Not wearing working cap	2301	Building temporary facilities with unsatisfactory fire performance
1107	Not wearing goggles or mask	2302	Not setting up fire water supply system and fire-fighting equipment as required
1108	Wrong use of safety protection equipment	2303	Using damaged and invalid fire-fighting equipment
1109	Not preparing personal protection equipment as required	2304	Illegal use of open fire on site
12	Unsafe attire	2305	Illegal use of high-power electrical appliances
1201	Wearing oversized clothing when working near equipment with rotating parts	2306	Not cleaning up the oil leakage of mechanical equipment in time
1202	Wearing chemical fiber and other non-anti-static clothes or spiked shoes for blasting operation	2307	Hot work near inflammables
1203	Wearing gloves when handling equipment with rotating parts	2308	Not setting up isolation measures between the hot work area and inflammable materials
1204	Wearing uninsulated clothing and expose parts during electrical operation	2309	Improper use of fire-fighting facilities
1205	Not wearing flame-retardant labor protection garment	24	Other operation
13	Handling of inflammables and explosives	2401	Not setting drainage ditch and impervious layer as required
1301	Not classifying and storing inflammables and explosives	2402	Issuing improper commands
1302	Storing combustible materials in tunnel or other unsafe places without fire prevention measures	2403	Improper use of ladders
1303	Useing inflammables and explosives without permission	2404	No pin point or delayed pin point after operation, no site clearing or incomplete site clearing
1304	No safety isolation measures between gas cylinder and inflammable and explosive materials	2405	Improper rescue
1305	Not using explosion-proof electrical equipment in inflammable and explosive places	2406	Not equipped with lighting system as required