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Research on Construction Workers' Safety Risk Sharing in Tunneling Projects Based on a Two-Mode Network: A Case Study of the Shangwu Tunnel

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Abstract: There is a high level of construction safety risk shared among construction workers in tunneling projects due to collaboration on the narrow and semi-enclosed construction site. However, no one has reported on this. Therefore, this paper proposes a new network model to explore risk-sharing features among construction workers based on a two-mode network. That model represents a new personnel safety management tool to provide suitable risk mitigation for tunneling projects. First, the work breakdown structure (WBS)–risk breakdown structure (RBS) method was employed to identify construction activities, risk resources, and construction safety risk factors (CSRFs). Subsequently, the two-mode WBS–RBS matrix was further established. The construction workers' sets were determined based on the organization breakdown structure (OBS)–WBS method and a two-mode OBS–WBS matrix was established. By applying the construction activities in the WBS tree carrying the CSRFs as the link, a two-mode OBS–RBS network was established by converting the two-mode WBS–RBS and OBS–WBS matrices. Hence, taking CSRFs allocated by several construction workers as a basis for network generation, the construction workers' risk-sharing network was further established. Centrality analysis identified the network characteristics and determined the most important construction workers in risk network. For example, this model was employed to explore the whole network characteristics of the Shangwu Tunnel and identify the workers in key positions in the risk-sharing network. Expert interviews demonstrated the model's rationality and practicality. The results show that each construction worker's safety risk-sharing degree in the Shangwu tunnel differed and reached varying levels. However, the staff from the engineering management department were in the key position of the risk-sharing network. Collectively, this model can help construction workers understand their risk-sharing degree to improve their safety awareness and adjust their attitude toward safety accordingly. Moreover, this strategy provides project managers with the necessary information to more effectively allocate safety resources and to be cognizant of the safety quality of each construction worker according to the different risk-sharing degrees.

Keywords: tunnelling project; construction worker; construction safety; risk-sharing relationship; two-mode network; characterization analysis

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1. Introduction

In recent decades, tunnel engineering has experienced unprecedented development due to the increasing exploration of the underground world [1]. Tunnels have been widely adopted in transportation infrastructures due to their superiority in reducing travel time and improving operation. More world-class tunnel projects have been planned, constructed, and operated, including the 57-km Gotthard Base Tunnel under the Sant' Gerda mountain in Switzerland, the 55-km Brenner Base Tunnel connecting Italy and Austria, the 57-km Mont Cenis Railway Tunnel linking France and Italy, and the 18-km Fehmarn Immersed Tube Tunnel connecting Denmark and Germany [2–5].

Most tunnel projects, especially those with thick overburden, and great depth and length, face daunting challenges of risk events caused by the complex geological conditions, hazardous underground construction environment, and complicated construction technology [6]. These events will likely result in countless casualties [7]. Indeed, major safety accidents are reported with tunneling projects almost annually in all associated countries. For example, in India, two construction workers died in an accident at the Greenko RE tunnel on 21 July 2023 [8]. Additionally, on 18 April 2023, one worker died and two others were injured in association with the Sevoke-Rangpo Tunnel project in India; collectively, there have been ten lives lost since work began in 2017 [9]. On 11 April 2023, a collapse at a construction site in Shuangjiang district, Yunnan province, China trapped seven workers [10]. Meanwhile, a gas explosion in the Genoa Junction tunnel in Italy caused the death of one worker with another suffering injuries [11]. Hence, research on construction safety risks is significant in railway tunneling projects.

When analyzing the causes of these accidents, construction workers in tunneling projects have a higher level of risk-sharing relationships than other engineers. More specifically, the tunnel construction site is narrow and semi-enclosed [12], which may cause serious injuries or fatalities [13]. Moreover, given that numerous construction workers collaborate to complete the same task simultaneously, they are constrained by the same work surface. Once a risk event occurs, the workers cannot readily disperse or leave the area, becoming trapped at the site and experiencing an increased probability of casualties. Additionally, certain activities have complex processes and require the collaboration of multiple professional construction workers [14]. For example, to complete the initial tunnel supports, steel workers, welders, and electricians install anchor rods, steel frames, and hang steel mesh, respectively. The concrete workers and wet spray machine operators accomplish the concrete pouring work. The safety officer and technicians perform on-site duties. The quality inspector and surveyor provide reasonable support opportunities based on the measurement results. Hence, construction workers have risk-sharing relationships while completing their corresponding construction activities.

The construction workers are designated as either construction managers or on-site construction operators [15]. Two major study types have assessed the safety risk of construction workers during tunneling projects. One applies the "Construction Worker" as the research object and regards them as the victims, for which the probability of casualties caused by safety loss is evaluated. The other takes "Construction Safety Risk" as the research object and regards "construction workers" as the "human factor" to explore their effect on safety loss. However, neither considers the risk-sharing influence due to construction workers' cooperative tasks, information exchange, and joint operation in the same workspace. Besides, the construction safety risk factors (CSRFs) associated with the various construction activities are diverse and variable. Most studies neglect the impact that this difference has on workers' risk exposure or on safety risk events. Additionally, prior work on risk-sharing analysis in tunneling projects has focused primarily on financial or contract risk among stakeholders. Overall, research on safety risk sharing among construction workers on tunneling projects is sparse.

However, understanding the risk-sharing relationships with other workers is important for risk mitigation. In particular, it can help construction workers correct safety attitudes and enhance safety awareness [16,17]. For example, if a focal construction worker has a clear understanding of the safety risk to themselves and those who share the same risk, the conscious adjustment of their working practices might improve the overall safety atmosphere of the team. Additionally, once aware of the focal construction worker in the key risk-sharing position, the construction safety managers can optimize the resource allocation of construction workers and improve personnel protection measures. For certain countries or regions, like China, the construction of railway tunnels has implemented standardized management; hence, most construction workers have a general and conceptual understanding of construction safety risk-sharing. However, for countries without standardized construction management in railway tunneling projects, projects using new

technology, new materials, or new equipment, or new projects within extremely complex construction conditions, a cognitive bias may exist for construction workers to handle the risk-sharing relationships solely based on their construction experience. Therefore, it is necessary to explore a new management strategy to establish risk-sharing relationships among construction workers intuitively and objectively.

Accordingly, this study aims to develop a new model, as a construction personnel safety management tool, to explore the construction safety risk-sharing relationships among construction workers based on a two-mode network. This model first uses the work breakdown structure (WBS)—risk breakdown structure (RBS) method to identify the CSRFs, and establish the two-mode WBS–RBS matrix simultaneously. The organization breakdown structure (OBS)–WBS method is then utilized to determine the construction workers' set, and establish the two-mode OBS–WBS matrix. Subsequently, relationships between construction workers and CSRFs are obtained using the construction activities in WBS trees as links. Furthermore, based on the data structure attribute, the two-mode OBS-RBS matrix can be converted to a one-mode OBS matrix to represent the risk-sharing relationships among construction workers. Centrality analysis facilitates the exploration of risk sharing among construction workers and the identification of critical construction workers who are in the key position of the network. A case study of the Shangwu tunnel is presented to demonstrate the feasibility and effectiveness of the proposed method.

The remainder of the paper is organized as follows. Section 2 reviews the literature on construction workers' safety risk analysis in railway tunnel projects. Section 3 presents the research method and proposes a risk-sharing model based on a two-mode network. Section 4 presents a case study demonstrating the evaluation results. Section 5 discusses the validity of the model and case results, revealing areas requiring future work. Section 6 concludes the paper.

2. Literature Review

2.1. Construction Workers and Safety Risk Analysis in Railway Tunnelling Project

Risk analysis is an indispensable process in railway tunnel construction as it is conducive to scientific decision-making to reduce the occurrence of engineering accidents, improve employees' risk management awareness, and enhance tunnel projects' risk management performance [18]. Risk analysis for tunnel projects date back to 1978 and initiated an upsurge in studies on risk assessment [19,20]. Research on construction workers and construction safety risk of railway tunnel projects is roughly divided into two categories. One takes the "Construction Worker" as the research object; they are regarded as the victims, and the probability of casualties is explored. The other type takes "Construction Safety Risk" as the research object and "construction workers" as the "human factor" to explore its effect on safety loss.

Safety events can directly lead to construction workers being trapped, injured, or even dying [21]. Therefore, research that takes construction workers as the research object seeks to determine the probability of casualties by analyzing risk exposure time, injury severity, injury type, work position, etc. [22]. For example, Chen et al. [23] used construction worker exposure time to assess dust pollution. They found that the construction workers involved in tunneling and excavating have the highest health risk. Aneziris et al. [24] determined the work position and injury severity of 17 construction worker types. They found that the workers responsible for completing liner installation have the highest probability of fatality, while those positioned under unstable rock have the most serious casualties. Albert et al. [25] analyzed hazard recognition of construction workers through a multiple baseline testing approach and found that improved hazard recognition is of great significance for protecting construction workers. Additionally, Antwi-Afari [26] reviewed work-related musculoskeletal disorders among construction workers and found that the disorders are highly associated with construction.

Other studies seek to propose appropriate risk mitigation strategies to avoid injuries to construction workers through risk analysis. For instance, Terheijden et al. [27] employed

accident prediction scenarios to compare registered process disturbances with regular processes. They found that suitable safety design and correct use of risk mitigation measures are key to reducing safety risks. Meanwhile, Spangenberg et al. [28] assessed the injury types among construction workers between 1991 and 2000 in Denmark and found that the highest hospitalization rates associated with tunneling projects are due to toxic gases and dust inhalation. They believe that taking the construction workers' safety during the early decision-making stages of the project is a critical measure to reducing their occupational safety risks. Wang et al. [12] proposed an improved YOLOX approach to improve the identification of personnel protective equipment to prevent casualties among construction workers.

The actions of construction workers significantly impact the occurrence of safety risk events [29]. According to statistics from the Emergency Management Department of China, 88% of safety risk events on construction sites in subway tunneling projects are related to human error [30,31]. Accordingly, most scholars take construction workers as human factors and apply causation analysis to explore how the workers affect safety loss. Common theories include the trajectory intersection theory, evident theory, complex systems theory, etc. For example, Jiang et al. [32] applied the trajectory intersection theory and divided risk factors into two categories: people and objects. They reported that the interaction between human factors (e.g., physical and mental conditions), safety management quality, and object factors (e.g., equipment, excavation technology, and geological environment) could lead to tunnel collapse events. Meanwhile, Zhang et al. [33] used system dynamics theory and divided the risk factors into people, equipment, environment, and management. They found that construction workers' weak safety awareness is a key factor causing the risk events of tunneling projects. Zhang et al. [34] applied the accident cause theory and divided the risk factors into five aspects: environment, technology, materials and equipment, management, and personnel. They reported that the professional degree, safety awareness, and hypoxia fitness of construction workers impact the risk events in tunneling projects.

2.2. Risk Sharing of Tunneling Projects

Risk sharing, referring to the chance of loss or peril, are divided, allocated, or apportioned in the construction industry [35]. Research on risk sharing in tunneling projects dates back to the early 1920. Antill [36] states that it is necessary to add an equitable latent conditions clause in tunnel contracts to allocate the risks of tunnel contractors reasonably. In 1979, the Swiss Engineers' and Architects' Association issued a specification, called Norm SIA 198 that further regulates the contract risk sharing among stakeholders of tunnel project [37]. From 1980 to 2000, the International Tunnelling Association (ITA) continuously improved contract documentation for underground construction projects to establish a more reasonable risk-sharing mechanism among stakeholders [38,39]. Since 2000, a rise in the public–private partnership (PPP) model of tunneling projects has led to financial and contract risk sharing becoming two main research objects [40]. For example, Guo et al. [41] used real option analysis to establish a systematic approach for improving the profit-risk allocation during the concession period of PPP projects. Song et al. [42] applied the Wutongshan tunnel in build–operate–transfer (BOT) mode as an example to verify a bargaining–game model with complete information. This model can evaluate the compensation for projects with incomplete contracts to establish a reasonable risk allocation mechanism. Other research on risk sharing includes geological risk, schedule risk, etc. For example, Yan et al. [43] used computer simulation technology to explore the risk distribution of cavities in tunneling projects. They applied the liner stability and water inflow rates as the risk index to assess the risk of karst cavities to tunneling works.

Game modeling, sensitivity analysis, and the ISM model, are the primary methods to analyze risk sharing among stakeholders in tunnel projects. For example, Sanchez [44] used game modeling to educate the owners on the potential benefits of risk sharing in

construction contacts. Meanwhile, Zhou et al. [45] applied the ISM model to analyze the relationship between risk factors that can impact the PPP scheme for underground projects.

2.3. Research Gap

Overall, research on construction workers and safety risk analysis in tunneling projects is relatively mature; however, studies have not specifically addressed the difficulty of quantifying the construction workers' safety risk-sharing degree due to work cooperation and shared work surfaces.

To elaborate, efforts in construction worker-related safety risk in tunneling projects are largely undertaken in isolation, with little crossover between different research objects. While one takes construction workers as research objects, the other applies construction safety risk as the object. Although the former acknowledges that construction workers face different construction safety, they overlook the potential impact workers have on the construction safety risks due to the activities they carry out in the tunneling project. Meanwhile, the latter emphasizes that construction workers have a great effect on construction safety risks, however, ignores the impact that different construction workers have on safety risks due to the different construction activities carrying various CSRFs. Moreover, no studies have reported the risk-sharing influence on construction workers' safety risk, although it exists due to their work cooperation, information exchange, and joint operation at the same working face. Regarding risk sharing in tunneling projects, research has focused primarily on financial or contract risk among stakeholders, whereas safety risk sharing among construction workers remains unexplored.

3. Research Design

3.1. Research Method: Two-Mode Network

This study explores the risk-sharing relationship among construction workers in tunneling projects using a two-mode network. This network, as part of social network analysis (SNA), comprises the relationships between two nodes' sets. Hence, it is an efficient and novel tool to analyze interactions among different nodes from two sets. Two research paradigms are employed when applying a two-mode network to risk analysis.

A two-mode network can be used to explore the risk relationships between two different nodes directly. For example, Yang et al. [46] used a two-mode network centrality analysis to explore the relationships between CSRFs and safety risk events. They found R15 (unstable components) and R16 (biased component positioning) have strong relationships with collapse in building construction projects. Chen et al. [47] used a two-mode network centrality analysis to explore the relationships between safety risk factors and safety accidents. They reported that service interruption has a high-risk coupling relationship with collapse accidents in the urban utility tunnel projects. Meanwhile, Ke et al. [48] used the same method and reported that weak safety awareness and standardized construction workers are the key factors influencing blasting in open-pit mines.

A two-mode network can be converted to a one-mode network. For example, Yuan et al. [49] used a two-mode network to represent the relationships between social risk factors and stakeholders in high-density urban areas in China. They then converted this two-mode network to a one-mode risk factor network and a one-mode stakeholder network to determine the critical factors and stakeholders, respectively. Yu and Zhang [50] also used degree and betweenness analysis to assess the impact of stakeholders' CSRFs in the risk network. They found that the critical risk factors in metro construction are construction site managers' behaviors, construction personnel's lack of safety protection, designers' insufficient detailed surveys, and the government's inadequate supervision by SNA.

The model design employed in the current study is based on the second conversion method. To elaborate, safety loss is caused primarily by many CSRFs arising from construction activities, as the internal risk resource, and construction environments, as the external resource. The construction activity carrying CSRFs is completed by construction workers [51]. Accordingly, a two-mode network can present the relationships between con-

struction workers and construction activities, or between construction activities and CSRFs. Furthermore, taking these construction activities as links, the two-mode network can be converted to present the relationships between construction workers and CSRFs. Finally, these construction workers have a risk-sharing relationship when mapped to the same CSRFs. This process can be realized by converting the two-mode network to a one-mode network (See Figure 1).

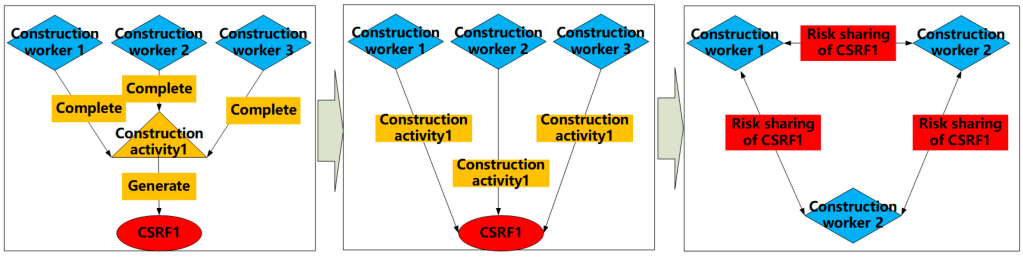


Figure 1. Principle of railway tunnel construction workers risk-sharing network.

3.2. Model Design

3.2.1. Model Framework

According to the abovementioned principle, the risk-sharing network can be established when all risk-sharing relationships among construction workers are determined. Here, a model based on a two-mode network is proposed for exploring the risk-sharing relationships among construction workers. Centrality analysis can help explore the risk-sharing characteristics at the network and node levels. The most important construction workers who are in the key position of the network are determined. Figure 2 illustrates the proposed safety risk-sharing structure and the research process. The software, named UCINET V6.237, was used to handle this modeling process. Net-draw was employed to visualize all matrixes and networks in the model.

3.2.2. Risk-Related Identification

The commonly used project management tools, OBS, WBS, and RBS, were utilized to identify the CSRFs and construction workers. First, the WBS–RBS method was used to identify the CSRFs of the railway tunnel project. Then, the OBS–WBS method was applied to determine the construction workers' set.

Step 1: CSRFs identification

The WBS tree was used to describe the hierarchical structure of construction activities by decomposing the construction activities layer by layer into a minimum, operable, independent work package [52]. The RBS method was used to decompose the potential risk carried by construction activities into the minimum risk units, as CSRFs, at the end of the RBS tree. Therefore, the CSRFs' set was established. This method can identify the CSRFs during the whole construction process to avoid risk emission crossover, as follows:

(1) Risk event (E_o) identification: The resulting set of risk events was obtained after case analysis, experts' interviews, etc., where $E = \{E_h | h \in [1, o]\}$.

(2) Risk resource (C_i) identification: The WBS tool was used to decompose the construction activities into work packages, where $C = \{C_i | i \in [1, l]\}$.

(3) CSRF (F_j) identification: The work package C_i in the WBS tree is related to F_j in the RBS tree. Therefore, the CSRFs' set was established, where $\mathrm{F} = \{F_j | j \in [1, n]\}$. The two-mode WBS-RBS matrix A was established synchronously (See Equation (1)):

$$A = \{(C, F, R_{CF}, W_{R_{CF}})\} \quad (1)$$

where C is the nodes set representing work packages, as risk resources; F is the nodes set representing CSRFs; R_{CF} is the edges set representing construction activity C carrying F; $W_{R_{CF}}$ represents the weight of R_{CF}. Let us assume that the weight of $W_{R_{CF}}$

defaults to 1 or 0; when $W_{R_{CF}} = 1$, the F_j is sourced from C_i; when $W_{R_{CF}} = 0$, F_j is not sourced form C_i.

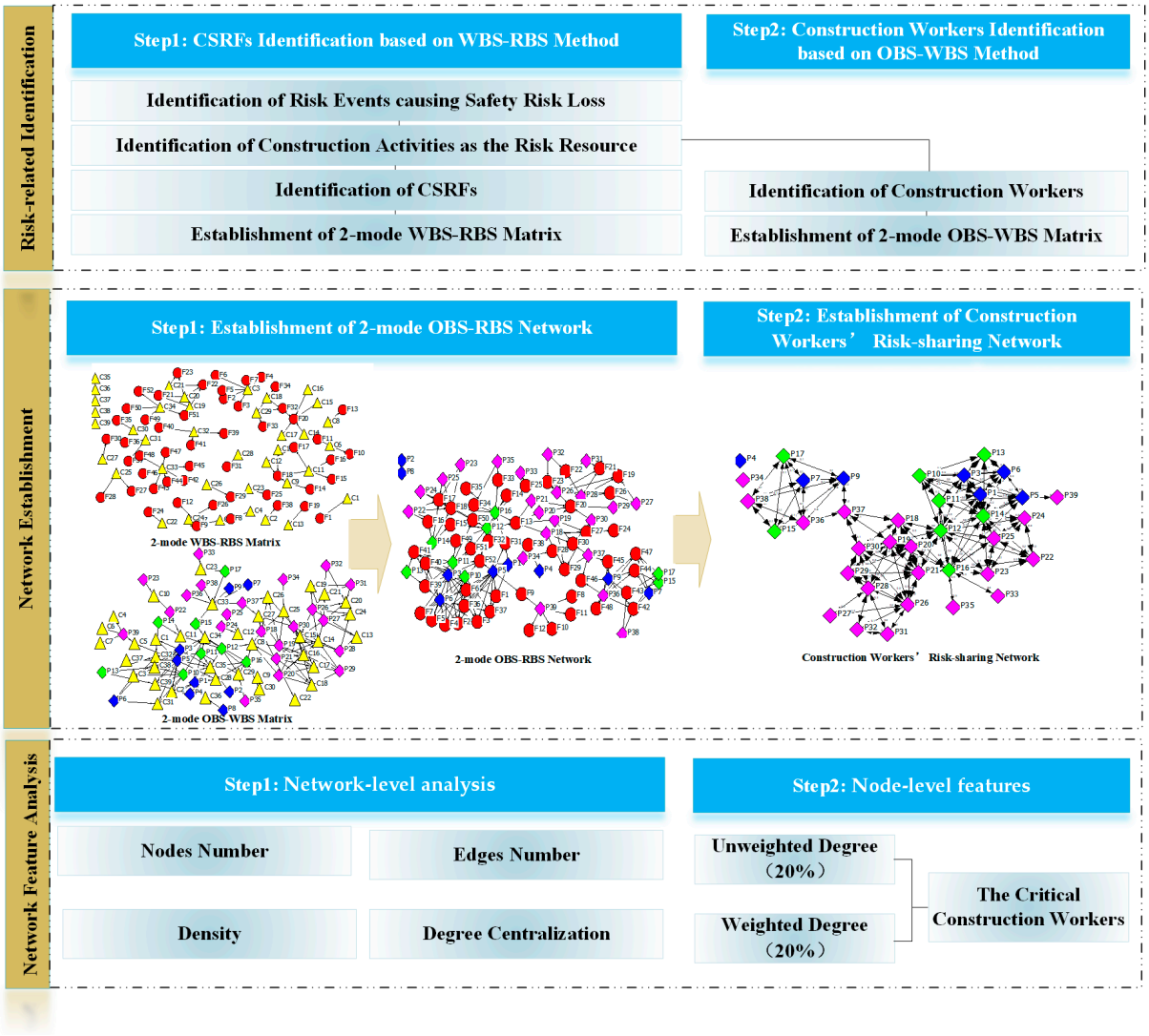


Figure 2. The model framework of the railway tunnel construction workers risk-sharing network.

Figure 3 is a schematic diagram showing the identification process of CSRFs based on the WBS–RBS analysis. Meanwhile, the two-mode WBS–RBS matrix is visualized. The yellow triangles represent the construction activities, designated $C_1 - C_5$, with size 5. The red circle represents the CSRFs, designated $F_1 - F_5$, with size 5. The black lines represent the construction activities generated by CSRFs.

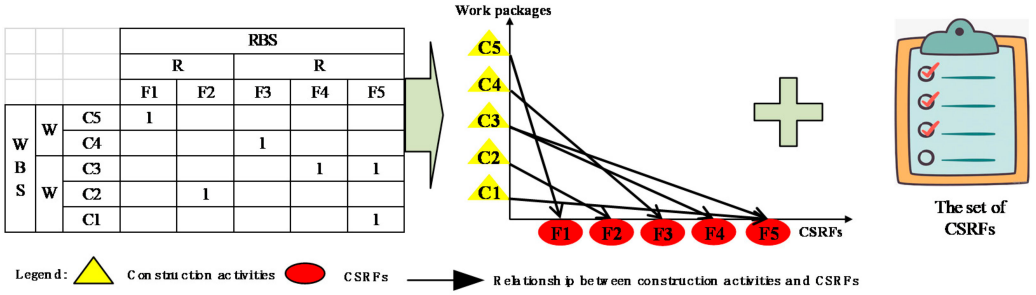


Figure 3. Determination of the CSRFs' set based on WBS–RBS analysis (hypothetical data).

Step 2: Construction worker identification

The OBS–WBS method represents the construction workers involved in tunnel construction on the horizontal axis and the work packages on the vertical axis. The decomposed work packages are assigned to the construction workers according to their job responsibilities and professional skills. Therefore, when the relationships between work packages and the corresponding construction workers are determined, the two-mode OBS–WBS matrix is established. The construction workers' set is determined synchronously (see Figure 2). This method can combine construction workers from different professions and departments in a complete OBS tree from top to bottom. Let us call it: $P = \{P_k, P_q \,|k, q \in [1, m]\}$. The two-mode OBS–WBS matrix B is established synchronously (see Equation (2)):

$$B = \{(P, C, R_{PC}, W_{R_{PC}})\} \tag{2}$$

where C is the nodes set representing work packages, as the risk resource; P is the nodes set representing construction workers; R_{PC} is the edges set representing the relationships between P and C; $W_{R_{PC}}$ is the weight of R_{PC}. Let us assume that the weight of $W_{R_{PC}}$ defaults to b or 0. When $W_{R_{CF}} =$ b, the P_k completes C_i; when $W_{R_{CF}} = 0$, F_j does not complete C_i.

The value of b is typically determined for different tunnel projects according to the actual situations. In this study, we used the average distribution method to determine b. That is, we assumed $b = 1/y$, meaning the construction activity C_i was completed by y construction workers. If $b = 1$, the construction activity C_i was completed by only one worker.

Figure 4 presents a schematic diagram to show the identification process of construction workers based on the OBS–WBS analysis. Meanwhile, the two-mode OBS–WBS matrix was visualized. The yellow triangles represent the construction activities, designated $C_1 - C_5$, with size 5. The blue diamond represents the construction workers, designated $P_1 - P_5$, with size 5. The black lines represent the relationships between construction workers and construction activities as the construction workers compete in construction activities. The size of the black lines corresponds to the number of construction workers competing in the focal construction activity. Take C_1 as an example, two construction workers, P_4 and P_5, complete C_1 together, hence, the weight of the relationship between P_4 and C_1 is $1/2$, same as P_5.

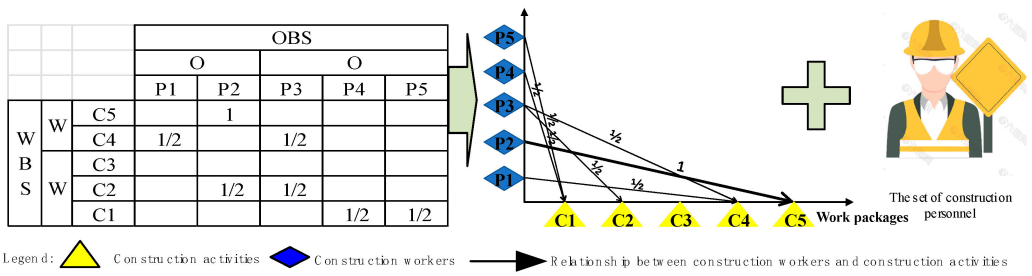


Figure 4. Determination of construction worker set based on OBS–WBS analysis (hypothetical data).

3.2.3. Risk-Sharing Network Establishment

The construction workers' risk-sharing network D was transformed from A and B, combined with data structure attributes of the two-mode network. The relationships between construction workers and CSRFs was first determined. When several construction workers had the same relationship with the focal CSRF, the workers shared the CSRF by completing corresponding construction activities. Therefore, the risk-sharing relationship among the construction workers could be determined. The determination process comprises converting the two-mode OBS–RBS matrix C to a one-mode OBS matrix D based on the data structure attribute. The detailed process is as follows:

Step 1: Two-mode OBS–RBS matrix establishment

The relationship between construction workers and CSRFs is visualized by the two-mode OBS–RBS matrix C (see Figure 5). The two-mode WBS–RBS matrix A and two-mode OBS–RBS matrix B are combined to form the two-mode OBS–RBS matrix C where:

$$C = \{(P, F, R_{PF}, W_{R_{PF}})\} \tag{3}$$

and P is the nodes set representing construction workers; F is the nodes set representing CSRFs; R_{PC} is the edges set representing the mapping relationships between P and F; $W_{R_{PC}}$ represents the weight of R_{PC}, as shown in Equation (4):

$$W_{P_kF_j} = \sum_{i=1}^{l} \left(W_{P_kC_i} \times W_{C_iF_j} \right) \tag{4}$$

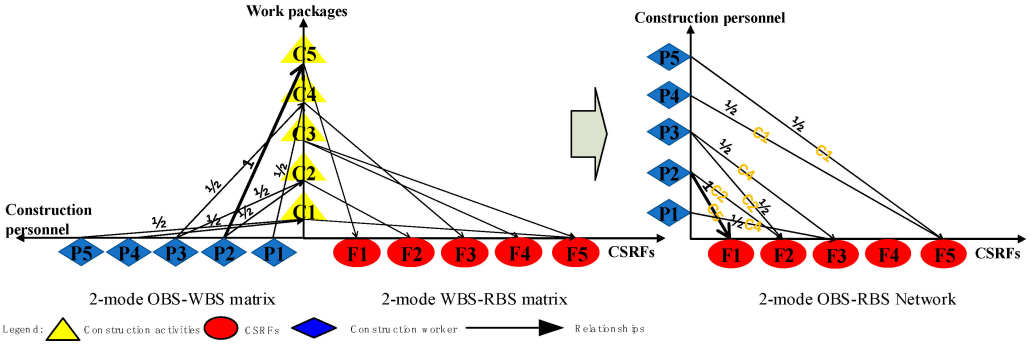


Figure 5. Determination process of the mapping relationships between construction workers with size 5 and CSRFs with size 5.

If $W_{P_kF_j} > 0$, the construction worker P_k completes C_i carrying F_j; If $W_{P_kF_j} = 0$, the construction worker P_k completes C_i, and does not carry F_j; Therefore, Equation (4) is converted to Equation (5):

$$W_{P_kF_j} = \begin{cases} \sum_{i=1}^{l} W_{P_kC_i} \times W_{C_iF_j}, if\ W_{C_iF_j} = 1\ in\ A\ and\ W_{P_kC_i} = 1\ in\ B \\ 0, if\ W_{C_iF_j} = 0\ in\ A\ or\ W_{P_kC_i} = 0\ in\ B \end{cases} \tag{5}$$

Step 2: One-mode risk-sharing network establishment

The two-mode OBS–RBS matrix C can be further converted to the construction workers' risk-sharing relationship matrix D, as shown in Equation (6) (See Figure 6):

$$D = \{(P, R, W)\} \tag{6}$$

where P is the nodes set representing construction workers; R is the edges' set representing the risk-sharing relationships between P_k and P_q; W represents the weight of R. Let us assume that the weight of W defaults to w or 0, as in Equation (7):

$$W_{kq} = \begin{cases} w,\ P_k\ has\ a\ risk-sharing\ relationship\ with\ P_q; \\ 0, P_k\ does\ not\ have\ a\ risk-sharing\ relationship\ with\ P_q; \end{cases} \tag{7}$$

where $k, q \in [1, m]$, represents m construction worker; w represents the weight of the risk-sharing relationship between P_k and P_q, and $w > 0$. If $W_{kq} = w$, the construction workers P_k and P_q have the same relationship with F_j; if $W_{kq} = 0$, the construction workers P_k or P_q do not have the same relationship with F_j. Therefore, Equation (7) is converted to Equation (8):

$$W_{kq} = \begin{cases} (W_{P_kF_j} W_{P_qF_j})/2, if\ W_{P_kF_j} > 0\ and\ W_{P_qF_j} > 0\ in\ C; \\ 0, if\ W_{P_kF_j} = 0\ or\ W_{P_qF_j} = 0\ in\ C; \end{cases} \tag{8}$$

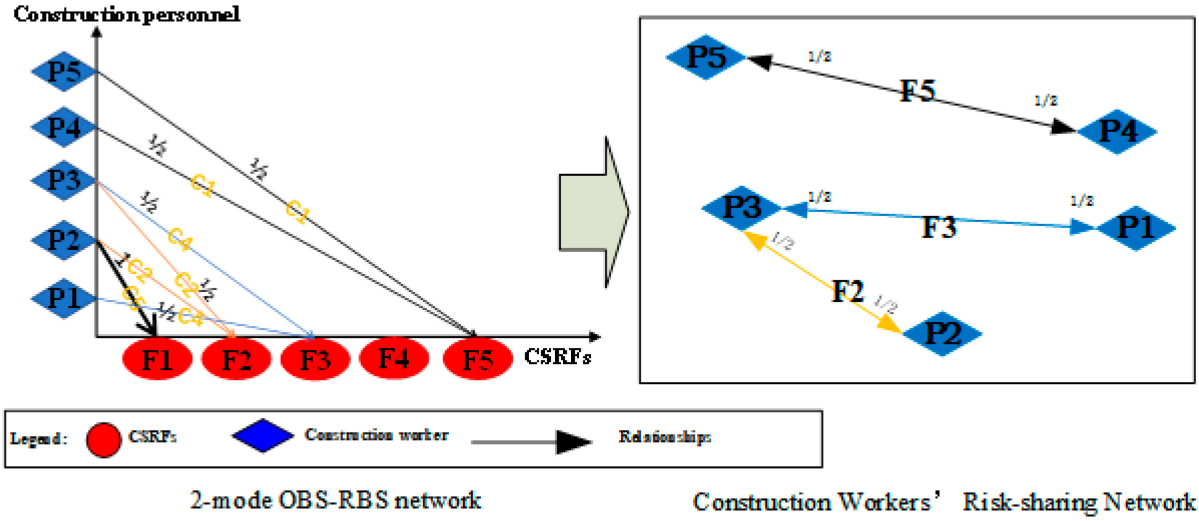


Figure 6. Determination process of the risk-sharing relationships among construction workers with size 5.

P_k and P_h may have several risk-pooling relationships since P_k and P_q complete numerous construction activities with several CSRFs. Therefore, we assume P_k and P_q have several of the same relationships with $F_1, F_2, \ldots, F_j$. If $j = n$, P_k and P_q share all risk-sharing relationships. Therefore, Equation (8) is converted to Equation (9):

$$W_{kq} = \begin{cases} \sum_{j=1}^{n} (W_{P_kF_j} W_{P_qF_j})/2, if\ W_{P_kF_j} > 0\ and\ W_{P_qF_j} > 0\ in\ C; \\ 0, if\ W_{P_kF_j} = 0\ or\ W_{P_qF_j} = 0\ in\ C; \end{cases} \quad (9)$$

3.2.4. Network Feature Analysis

We used degree centrality analysis to explore the risk-sharing features of the one-mode risk-sharing relationship network D.

Step 1: Network-level analysis

Node number (m), edge number (W), density (ρ) and degree centralization (ND_w) can describe the whole network analysis [53]. The node number represents the number of construction workers participating in the network. The edge number represents the number of risk-sharing relationships. Density represents the whole network's sparsity. The greater the density (ρ), the higher the participation degree of construction workers in the risk-sharing network, as demonstrated by Equation (10):

$$\rho = 2W/m(m-1) \quad (10)$$

Degree centralization (ND_w) reflects the concentration of this risk-sharing network. That is, a larger ND_w indicates that few construction workers are engaged in more construction activities carrying more CSRFs, as represented by Equation (11):

$$ND_w = \frac{\sum_{k=1}^{m} (MAX(D_w) - D_w(P_k))}{MAX[\sum_{k=1}^{m} (MAX(D_w) - D_w(P_k))]} \quad (11)$$

Step 2: Node-level features

Degree centrality is used to explore the critical construction workers who share the most CSRFs. The weighted degree centrality and unweighted degree centrality can help determine the performance of the single node. The weighted degree (top20%) and unweighted degree (top 20%) intersection identifies the critical construction workers in this risk-sharing network.

The weighted degree centrality represents the risk-sharing degree of the focal construction worker with others. The weighted degree centrality of P_k is:

$$D_w = \sum_{q=1}^{m} W_{kq} \quad (12)$$

The unweighted degree centrality represents the number of risk-sharing relationships of the focal construction worker. The unweighted degree centrality of P_k is:

$$D_{uw} = \sum_{q=1}^{m} R_{kq} \quad (13)$$

where R_{kh} represents exiting of the risk-sharing relationship between P_q and P_k. If $W_{kq} > 0$, $R_{kq} = 1$; if $W_{kq} = 0$, $R_{kq} = 0$.

Taking P_3 in Figure 5 as an example, the unweighted degree centrality of P_3 is 2, hence 2 construction workers, P_1 and P_2, have a risk-sharing relationship with P_3. The weighted degree centrality of P_3 is 1, meaning the risk-sharing degree of P_3 is 1/2 + 1/2 = 1.

4. Case Study: Application of the Proposed Risk-Sharing Model to the Shangwu Tunnel Project

To demonstrate an application of the proposed risk-sharing network model, a case study is provided.

4.1. Tunnel Background

The Shangwu tunnel is located in Jiangxi, China and is 1062 m. It is a typical railway tunneling project with a typical mining method. The excavation and support construction techniques are traditional. It has a standard organizational structure, standardized construction process, clear division of labor, and cooperation among construction workers. Moreover, the construction risk events are relatively typical according to the risk assessment report. Therefore, this case study can offer valuable references for construction safety risk-sharing research for similar tunnels around the world.

4.2. Risk-Related Identification Result

4.2.1. Identification of CSRFs

To determine the CSRFs' set, the expert risk assessment team of the Shangwu tunnel conducted a comprehensive evaluation using the WBS–RBS method described in Section 3.2.2. The detailed steps are as follows:

Step 1: Identification of the safety risk events, including E_1 collapse, E_2 water and mud inrush, E_3 gas explosion and E_4 rock falling.

Step 2: Identification of the risk resources. After analyzing the standardized construction management materials, including the implementation construction plan, special construction plan, construction schedule table, etc., the construction safety risk resource tree was established based on the WBS analysis, comprising 39 work packages, designated $C_1 - C_{39}$ (see Figure 7).

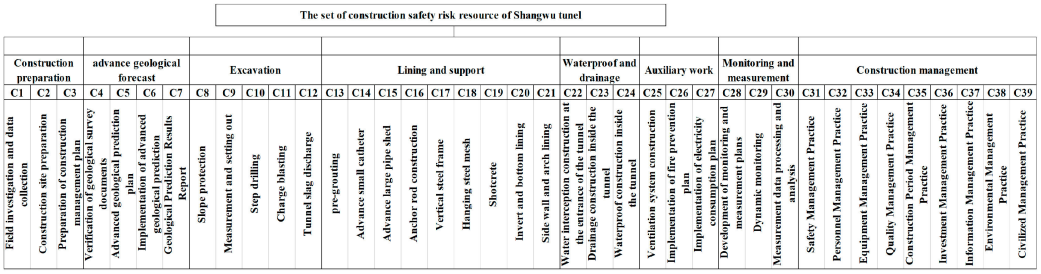


Figure 7. Set of construction activities as a safety risk resource of the Shangwu tunnel based on WBS analysis.

Step 3: Based on the risk resources determined in stage 2, 52 CSRFs, designated $F_1 - F_{52}$ were identified by referring to the Interim Regulations on Risk Assessment and Management of Railway Tunnels [18], the official risk assessment report of the Shangwu tunnel and a literature review (see Table 1).

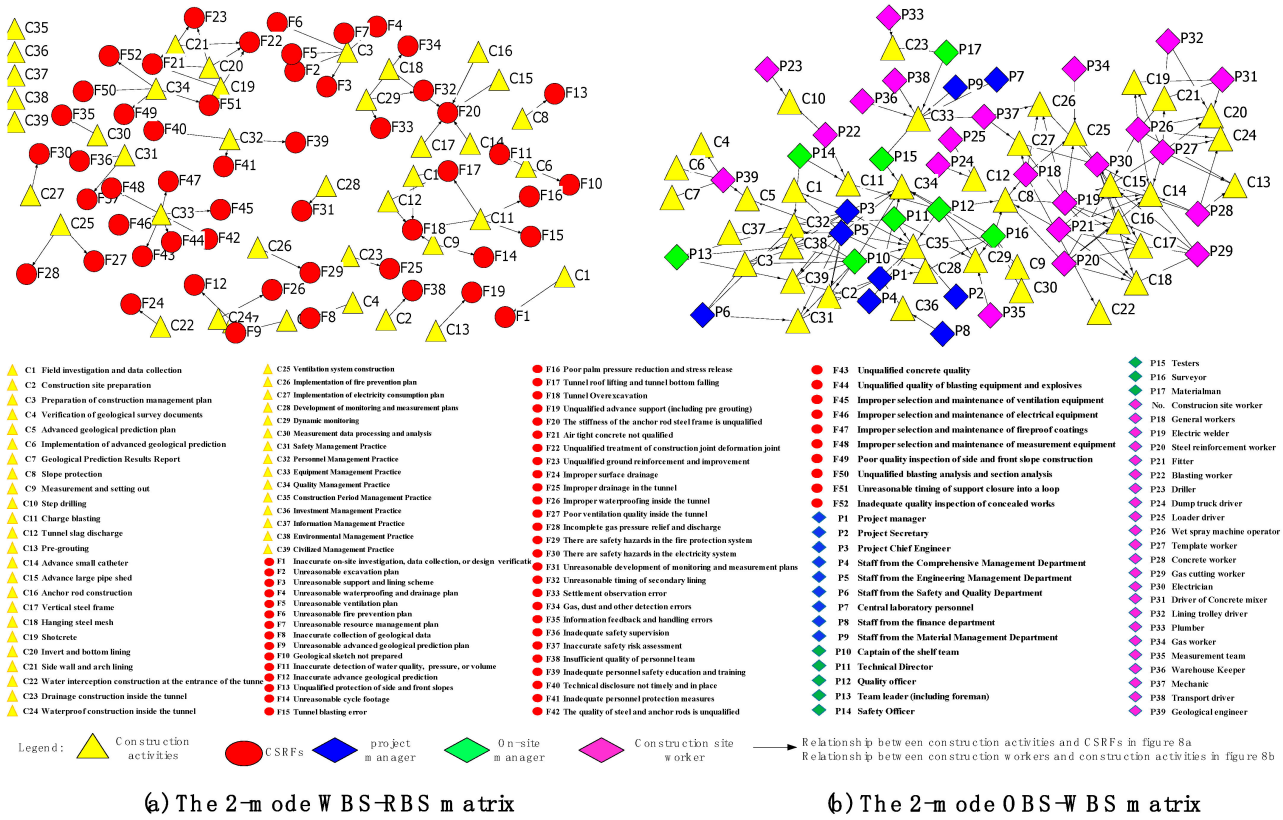
Table 1. Set of CSRFs in the Shangwu tunnel based on WBS–RBS analysis.

			No.	CSRF
Set of CSRFs in the Shangwu tunnel	Construction preparation		F_1	Inaccurate on-site investigation, data collection, or design verification [18,54]
			F_2	Unreasonable excavation plan [54,55]
			F_3	Unreasonable lining support plan [54,55]
			F_4	Unreasonable waterproofing plan [54,55]
			F_5	Unreasonable ventilation plan [54,55]
			F_6	Unreasonable fire prevention plan [54,55]
			F_7	Unreasonable resource management plan [54,55]
	Advance Geological Forecast		F_8	Inaccurate collection of geological data [33,54,56,57]
			F_9	Unreasonable advanced geological prediction plan [33,54,57]
			F_{10}	Unqualified geological sketch [33,54,57]
			F_{11}	Inaccurate detection of water quality, pressure, or volume [33,54,57]
			F_{12}	Inaccurate advance geological prediction [33,54,57]
	Excavation		F_{13}	Unqualified protection of side and front slopes [33,54,57]
			F_{14}	Unreasonable cycle footage [33,54,57]
			F_{15}	Errors in blasting [33,54,57,58]
			F_{16}	Poor palm pressure reduction or stress release [33,54,57,59]
			F_{17}	Unqualified roof lifting or tunnel bottom falling [33,54,57]
			F_{18}	Over excavation [33,54,57]
	Lining and support		F_{19}	Unqualified advanced support (including pre grouting) [33,54,57,58]
			F_{20}	Unqualified stiffness of the anchor rod steel frame [33,54,57,58]
			F_{21}	Unqualified air-tight concrete [33,54,57,58]
			F_{22}	Unqualified construction or deformation joint [33,54,57,58]
			F_{23}	Unqualified ground reinforcement or improvement [33,54,57–59]
	Waterproof and drainage		F_{24}	Improper surface drainage [33,54,57,58]
			F_{25}	Improper drainage in the tunnel [33,54,57,58]
			F_{26}	Improper waterproofing inside the tunnel [33,54,57,58]
	Auxiliary work	Ventilation shaft	F_{27}	Poor ventilation quality inside the tunnel [54,57]
			F_{28}	Incomplete gas pressure relief and discharge [54,57]
		fire prevention	F_{29}	Safety hazards in the fire protection system [57]
			F_{30}	Safety hazards in the electrical system [56,57]
	Monitoring and measurement		F_{31}	Unreasonable monitoring and measurement plans [54]
			F_{32}	Unreasonable timing of secondary lining [54]
			F_{33}	Error in settlement observation [54,56]
			F_{34}	Gas, dust, and other detection errors [54]
			F_{35}	Information feedback and handling errors [54,56]
	Construction management	Construction safety	F_{36}	Inadequate safety supervision [54,58]
			F_{37}	Inaccurate safety risk assessment [54,58]
			F_{38}	Insufficient quality of personnel team [54,58]
		Construction personnel	F_{39}	Inadequate personnel safety education and training [54,58]
			F_{40}	Technical disclosure not timely or in place [54]
			F_{41}	Inadequate personnel protection measures [54]
		Construction equipment	F_{42}	Unqualified steel and anchor rods' quality [54,55,59]
			F_{43}	Unqualified concrete quality [54,55,59]
			F_{44}	Unqualified blasting equipment and explosives [54,55,58,59]
			F_{45}	Improper ventilation equipment [55,58,59]
			F_{46}	Improper electrical equipment [55]
			F_{47}	Improper fireproof coatings [54,55]
			F_{48}	Improper measurement equipment [55]
		Construction quality	F_{49}	Poor inspection of side and front slope construction {Ministry of Railways, 2007 #3}
			F_{50}	Unqualified blasting analysis and section analysis [54]
			F_{51}	Unreasonable timing of support closure into a loop [54,59]
			F_{52}	Inadequate quality inspection of concealed works [56]

Step 4: Combination of the WBS and RBS trees; each CSRF was matched with the work packages. The two-mode WBS–RBS matrix was then conducted. Net-draw was used to

visualize the matrix, showing the relationships between construction activities and CSRFs (see Figure 8a).

Figure 8 shows the two-mode WBS–RBS matrix and two-mode OBS-WBS matrix of the Shangwu tunneling project. The yellow triangles represent the construction activities, designated $C_1 - C_{39}$, with size 39. The red circles represent the CSRFs, designated $F_1 - F_{52}$, with size 52. The colored diamonds represent the construction workers ($P_1 - P_{39}$), with blue representing project managers, green representing on-site managers, and purple representing on-site construction workers. The black lines with unidirectional arrows represent the relationships among nodes, those in Figure 8a represent the construction activities that generate CSRFs, those in Figure 8b represent the construction workers' complete construction activities.



(a) The 2-mode WBS-RBS matrix (b) The 2-mode OBS-WBS matrix

Figure 8. Two-mode WBS-RBS network and two-mode OBS–WBS network of the Shangwu tunnel project.

4.2.2. Identification of Construction Workers

Based on Section 3.2.2 and the OBS–WBS method described above, the detailed steps for identifying construction workers are as follows:

Step 1: Based on the construction activities, as risk resources, determined in Section 3.2.1, 39 construction workers, designated $P_1 - P_{39}$ were identified by analyzing the standardized construction workers management materials, including the construction workers activity division table, personnel work manual, labour contract, etc.

Step 2: The construction workers from different departments and professions were integrated and the OBS tree was established. More specifically, they were divided into construction management personnel and construction site workers according to the environmental and hygiene standards of the construction site (see Figure 9) [60]. The construction management personnel included project managers and on-site managers.

Step 3: The OBS and WBS trees were combined; each construction worker was matched to the work packages. The two-mode OBS–WBS matrix was conducted and the weight $W_{R_{PC}}$, representing the participation degree of a construction worker in a construction

activity, was determined according to Section 3.2.2. The matrix was visualized with Netdraw, revealing the relationships between construction workers and construction activities (see Figure 8b).

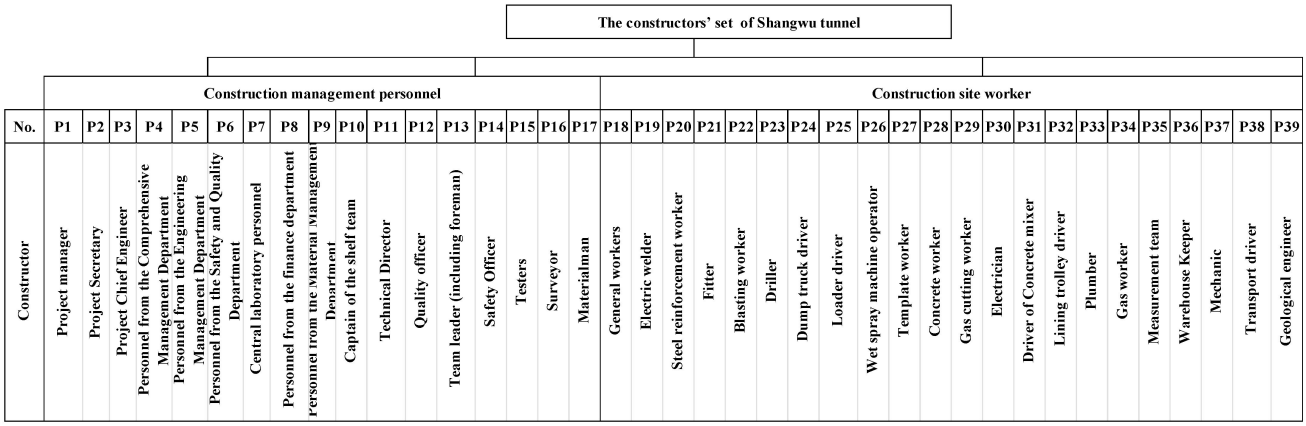


Figure 9. Set of construction workers the Shangwu tunnel based on OBS-WBS analysis.

4.3. Risk-Sharing Network Result

The two-mode OBS–RBS matrix was obtained following the procedure described in Section 3.2.1 (See Figure 10a). Corresponding risk-sharing relationships among construction workers were then established using the UCINET V6.237 software following the procedure described in Section 3.2.2. NET-DRAW was then employed to visualize the one-mode construction workers' risk-sharing network (see Figure 10b). The black lines with unidirectional arrows in Figure 10a represent construction workers who shared CSRFs as they completed construction activities carrying these CSRFs. The black lines with bidirectional arrows in Figure 10b represent the risk-sharing relationships among construction workers.

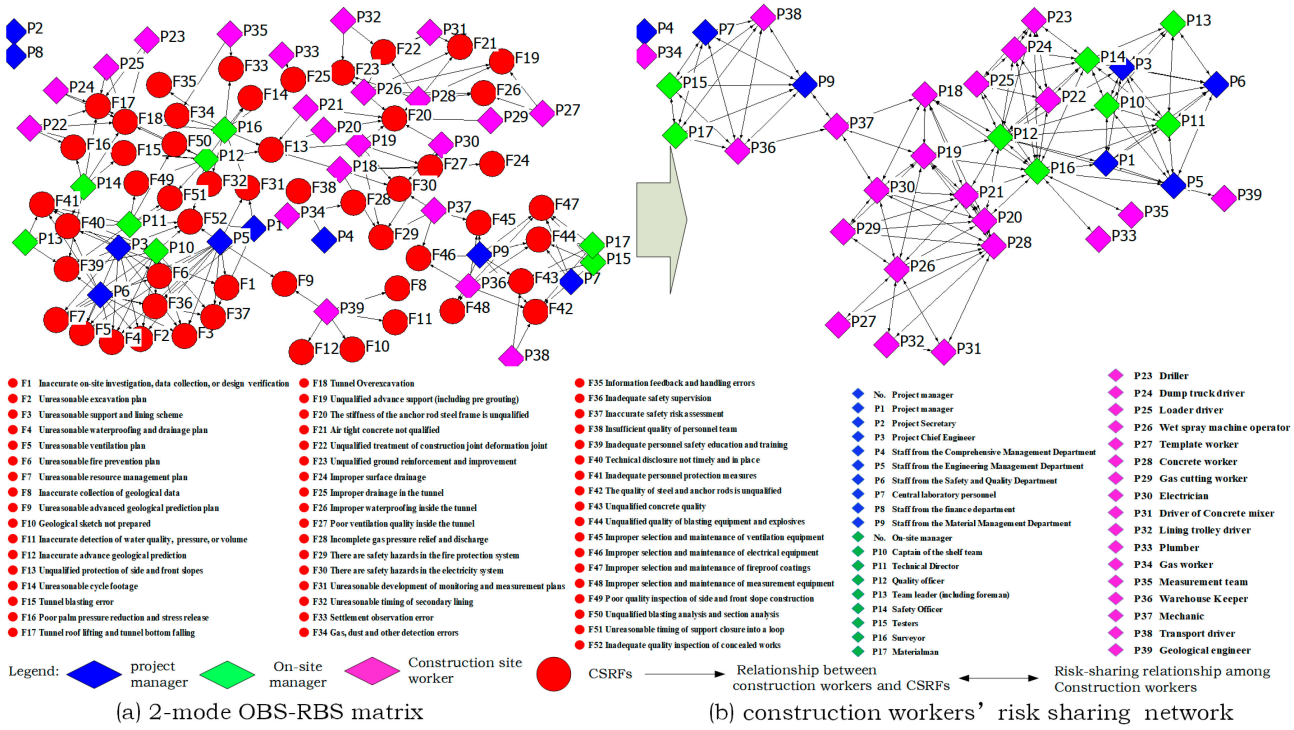


Figure 10. Process for generating the construction workers' risk-sharing network of the Shangwu Tunnel-Visualization based on NET-DRAW.

4.4. Feature Analysis Results

4.4.1. Network-Level Feature

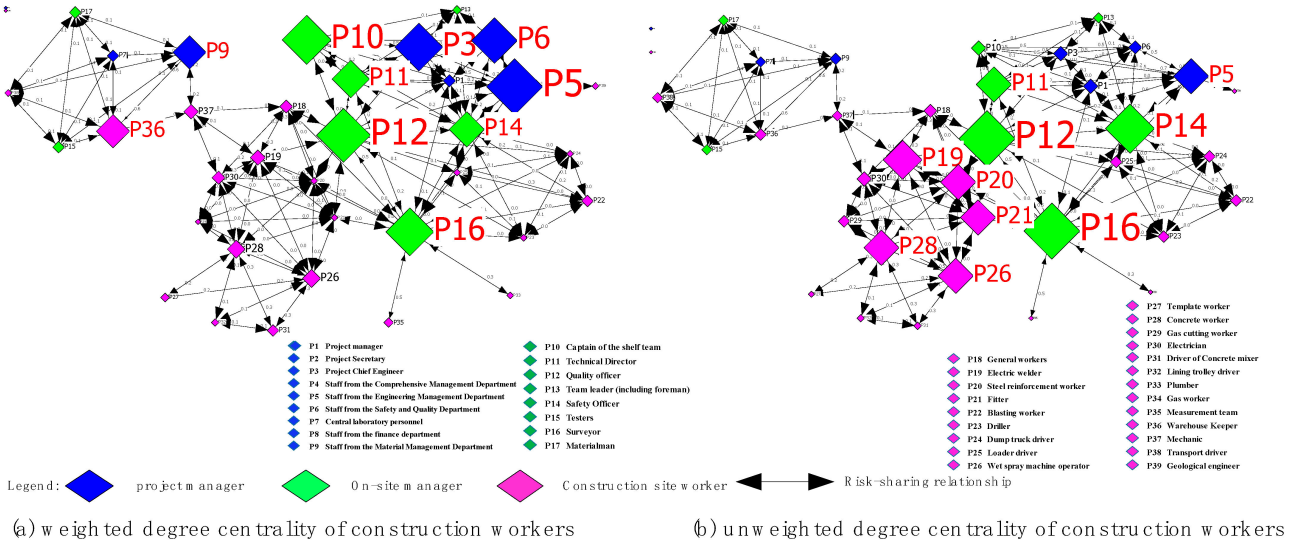
Table 2 shows all of the network features based on the node number, relationship number, density, and degree centralization. There are 37 construction workers sharing safety risks with 118 risk-sharing relationships on the Shangwu tunneling project. The network density is 0.174, indicating the structure of the network is normal sparse. The degree of centralization is 0.256, indicating that a few construction workers are in the critical position in the network.

Table 2. Weighted and unweighted centrality of construction workers.

			Construction Worker	Rank	D_w	Rank	D_{uw}
OBS tree for the Shangwu tunnel	construction manager	project manager	P_1 Project manager	17	0.68	11	8
			P_2 Project secretary	37		37	
			P_3 Project chief engineer	4	1.93	12	8
			P_4 Staff from the Comprehensive Management Department	36	0.00	36	0
			P_5 Staff from the Engineering Management Department	1	2.31	5	9
			P_6 Staff from the Safety and Quality Department	6	1.86	15	7
			P_7 Central laboratory personnel	20	0.60	24	5
			P_8 Staff from the finance department	37		37	
			P_9 Staff from the Material Management Department	9	1.29	17	6
		on-site manager	P_{10} Captain of the shelf team	3	2.00	13	8
			P_{11} Technical director	7	1.50	6	9
			P_{12} Quality officer	2	2.21	1	15
			P_{13} Team leader (including foreman)	25	0.42	25	5
			P_{14} Safety officer	8	1.38	3	13
			P_{15} Testers	21	0.60	26	5
			P_{16} Surveyor	5	1.93	2	15
			P_{17} Materialman	22	0.60	27	5
	construction site worker		P_{18} General workers	16	0.74	16	7
			P_{19} Electric welder	13	0.88	4	10
			P_{20} Steel reinforcement worker	27	0.29	7	9
			P_{21} Fitter	28	0.29	8	9
			P_{22} Blasting worker	18	0.65	18	6
			P_{23} Driller	29	0.28	19	6
			P_{24} Dump truck driver	30	0.28	20	6
			P_{25} Loader driver	31	0.28	21	6
			P_{26} Wet spray machine operator	11	1.10	9	9
			P_{27} Template worker	24	0.44	32	2
			P_{28} Concrete worker	12	1.10	10	9
			P_{29} Gas cutting worker	35	0.15	22	6
			P_{30} Electrician	15	0.74	14	8
			P_{31} Driver of concrete mixer	19	0.61	30	3
			P_{32} Lining trolley driver	26	0.33	31	3
			P_{33} Plumber	33	0.25	33	1
			P_{34} Gas worker	37	0.00	37	0
			P_{35} Measurement team	23	0.50	34	1
			P_{36} Warehouse keeper	10	1.29	23	6
			P_{37} Mechanic	14	0.82	28	5
			P_{38} Transport driver	32	0.28	29	5
			P_{39} Geological engineer	34	0.25	35	1

4.4.2. Node-Level Features

The degree centrality analysis is suitable for determining which construction workers are the most critical. Figure 11 presents the results of the weighted and unweighted degrees of each construction worker in this risk-sharing network. The size of the critical construction workers (top 20%) is proportional to its rank (See Figure 11). Table 2 lists all construction workers' degree centrality through the Shangwu tunnel. Overall, different construction workers have different risk-sharing degrees; however, the on-site managers share the most CSRFs and have the most risk-sharing relationships.



(a) weighted degree centrality of construction workers (b) unweighted degree centrality of construction workers

Figure 11. Node-level features of the construction workers' risk-sharing network on the Shangwu tunneling project.

As shown in Figure 11a, from the perspective of the weighted degree of construction workers, P_5 (staff from the engineering management department) must be carefully considered as their risk-sharing degree with other construction workers is the largest at 2.31. Hence, P_5 has the greatest impact on construction safety risk. Additionally, P_{12} (quality officer) had a weighted degree of 2.21, indicating that they complete corresponding construction activities with relatively more CSRFs. Other construction workers within the top 20% included P_{10} (captain of the shelf team), P_3 (project chief engineer), P_{16} (surveyor), P_6 (staff from the safety and quality department), P_{11} (technician director), and P_{14} (safety officer).

As shown in Figure 11b, from the perspective of the unweighted degree, P_{12} (quality officer) and P_{16} (team leader) must be given priority as they have 15 risk-sharing relationships with other construction workers. Meanwhile, P_{14} (safety officer) has 13 risk-sharing relationships and P_{19} (electric welder) has 12. Additionally, P_5 (staff from the engineering management department), P_{11} (technical director), P_{20} (steel reinforcement worker), and P_{21} (fitter) had nine risk-sharing relationships with other construction workers.

By taking the intersection of the weighted and unweighted degrees, five critical construction workers were identified: P_5 (staff from the engineering management department), P_{11} (technical director), P_{12} (quality officer), P_{14} (safety officer), and P_{16} (surveyor).

5. Discussion on the Model and Results

5.1. Expert Interview for Model Validation

Expert interviews were conducted to validate our risk-sharing network model. We included nine experts from the Shangwu tunnel project for this model validation, including the chief engineer, three engineers from the engineering management department, and five on-site team leaders. The interview began with a Power Point (PPT) presentation showing the risk-sharing model and the case analysis steps adopted. The experts then expressed their opinions about the model rationality and result validity through the interview questions (see Appendix A). Overall, the interviewed experts think that the model is reasonable and universal. The case analysis results are broadly in accordance with their construction experience, as detailed below.

Regarding the model rationale, the experts agreed that the logic for the establishment process is reasonable. Specifically, using the WBS–RBS analysis to identify the CSRFs and the OBS-WBS analysis to determine the construction workers' set are common project management tools [61,62]. For example, You et al. [62] applied a WBS–OBS analysis to determine the CSRFs of the subway tunnel shield construction. Therefore, the internal logic for using these two methods is reasonable. Regarding the establishment process

of the risk-sharing network among construction workers, all of the experts agreed that the work cooperation and information exchange could generate risk sharing among construction workers' activities [63]. Therefore, if the relationships between the construction activities and CSRFs, and between the construction workers and construction activities can be accurately identified, the relationship between construction workers and CSRFs can be determined. Moreover, when several construction workers share the same CSRFs, the risk-sharing relationship among them can be identified. Therefore, the logic for establishing the construction workers' risk-sharing network is reasonable. The experts also agreed that the conversion process is easy to understand based on the information presented in Figures 3 and 4. In the other risk analysis field, scholars had already used the two-mode network to explore risk relationships between stakeholders and risk factors. For example, Yuan et al. [49] used a two-mode network to represent the relationships between social risk factors and stakeholders in high-density urban areas in China. They then converted the two-mode network to a one-mode risk factor network and one-mode stakeholder network to determine the critical factors and stakeholders, respectively. Finally, regarding weighted and unweighted degree centrality, experts said that although there is a lack of knowledge about network theory, the indicators to show the risk-sharing relationship are simple and easy to understand. In addition, several researchers have applied centrality analysis to risk-sharing research. For example, Eissa et al. [64] used degree centrality to identify the important stakeholders and corresponding risk factors in research on cooperation risk allocation. Additionally, Attanasio and Krutikova [65] used degree centrality to explore whether the rejection of perfect risk sharing can be related to our measure of information quality.

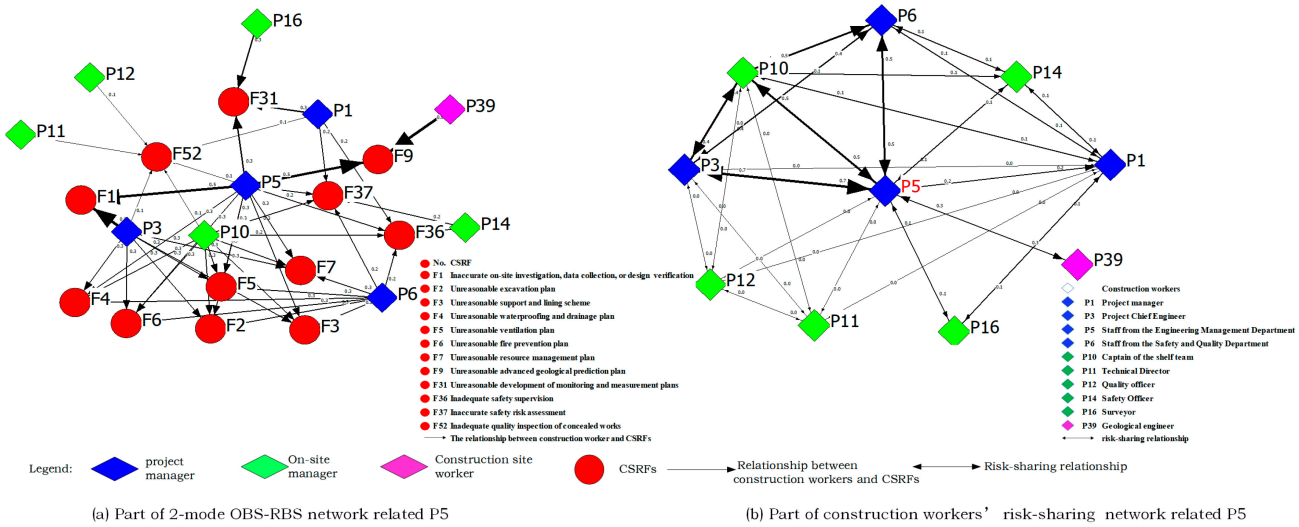
Regarding result rationality, the experts expressed that the results align with their construction experiences. Specifically, the construction activities, CSRFs, and construction workers' sets are partially adjusted based on the standardized management materials of the Shangwu tunnel and a literature review. This can ensure the input data is objective and accurate. They also thought that the structure of the construction workers' risk-sharing network was rational. For example, P_2 (project secretary) is responsible for land expropriation, demolition, and party affairs. P_8 (staff from the finance department) is in charge of the capital plan, contract development, and cost control. Both have no impact on construction safety, and the likelihood of their risk exposure was relatively zero. Besides, P_5 (staff from the engineering management department) holds the key position of the risk-sharing network and is responsible for construction site preparation, implementation of the construction plan, and quality management. These activities carry various CSRFs. Finally, the staff under the on-site risk management level, including P_{11} (technical director), P_{12} (quality officer), P_{14} (safety officer), and P_{16} (surveyor), have important roles in the risk-sharing network. Indeed, others have expressed similar sentiments. For example, Tsai et al. [66] reported that on-site managers take on many responsibilities associated with information exchange and work cooperatively with other workers, making them more prone to risk sharing. Meanwhile, Shin [67] stated that the on-site management personnel and others must actively and systematically cooperate to reduce the possibility of construction safety accidents.

Some of the experts provided their opinions on the applicability of this model. They stated that WBS, RBS, and OBS are common project management tools in engineering practice. Meanwhile, determining construction activities, CSRFs, and construction workers is objective, indicating that this model is operable and practical. Besides, it is not only used in tunnel construction projects but also widely in other construction projects, such as bridges, roadbeds, railways, highways, and residential buildings; hence, the model has strong universality.

5.2. Risk Mitigation Suggestions Based on Case Study Results

Experts have verified that the risk-sharing degree and the risk-sharing relationships among construction workers of the Shangwu Tunnel are reasonable. Thus, according to the analysis results, risk mitigation measures are provided to project managers.

Regarding safety attitude improvements, it is recommended that the project safety manager adopt a two-mode network to present the relationships between construction workers and CSRFs, or a one-mode network to present the risk-sharing among construction workers locally or comprehensively. The two-mode OBS–RBS network will help construction workers intuitively understand the impact of CSRFs they may face, improving their safety cognition and adjusting their safety attitude [16]. The one-mode risk-sharing relationship network will help construction workers intuitively understand their risk-sharing relationships with each other, particularly with those working at the same surface, consciously enhancing the team atmosphere and improving work harmony. For example, P_5 (staff from the engineering management department) can identify the potential CSRFs generated by their construction activities according to the two-mode OBS–RBS network, improving their safety cognition. P_5 can also readily determine which workers share construction safety risk with them according to the construction workers' risk-sharing network. Consequently, P_5 can focus on work cooperation with P_1, P_3, P_6, P_{10}, P_{11}, P_{12}, P_{14}, P_{16}, and P_{39} (See Figure 12).



(a) Part of 2-mode OBS-RBS network related P5

(b) Part of construction workers' risk-sharing network related P5

Figure 12. A portion of the two-mode OBS–RBS network and construction workers' risk-sharing network related to P_5 (staff from the engineering management department) on the Shangwu tunneling project.

Regarding attention suggestions, construction managers at different levels of the organizational structure should treat their workers' work quality differently. For example, if a worker has more risk-sharing relationships with others, or, their risk-sharing degree is high, they can influence others' activities carrying shared CSRFs. Hence, they have the greatest impact on the construction safety risk of tunneling projects. A typical case is that P_5 (staff from the engineering management department) has a risk-sharing relationship with nine other workers (P_1, P_3, P_6, P_{10}, P_{11}, P_{12}, P_{14}, P_{16}, and P_{39}). Based on the relationship strengths, they should pay particular attention to P_6, P_{10}, and P_{13} (See Figure 11b). Similarly, P_1 (project manager) should prioritize P_5 (staff from the engineering management department) as they not only have the highest risk-sharing degree but also have relatively more risk-sharing relationships with other workers. Meanwhile, P_{13} (team leader) should pay more attention to the worker quality of P_{20} (steel reinforcement worker), P_{21} (fitter), P_{26} (wet spray machine operator) and P_{28} (concrete worker). Overall, the construction managers must focus on those workers in critical positions on the risk-sharing network.

Regarding safety protection measures, some on-site workers' construction activities are dangerous. The procedures that trigger safety risk events are the construction activities carrying CSRFs for on-site workers. Therefore, for on-site construction workers, designated P_{19}–P_{39}, certain safety resources should be allocated according to the risk-sharing degree. For example, P_{20} (steel reinforcement worker), P_{21} (fitter), P_{26} (wet spray machine operator) and P_{28} (concrete worker) should be allocated more safety protection resources.

5.3. Further Research on Construction Safety Risk Sharing

For future research, attention should be paid to the research directions below:

(1) In this paper, the measurement of risk-sharing relationships' strength depends solely on the participation degree of construction workers in a certain activity carrying CSRFs. However, there are more suitable ways to determine the risk-sharing relationships' weight, including the artificial neural network (ANN). Therefore, this related study can improve the current research on risk management in the future.

(2) This risk-sharing network only explores construction workers' risk-sharing features. However, construction workers not only have risk-sharing relationships due to work cooperation but also have risk-transmission relationships due to process connection and causal analysis. A typical case is that a driller has a risk-transmission relationship with a blaster during railway tunnel excavation practice. If the driller is not following the drawings when carrying out the drilling operations, the position of the drilling hole may be inaccurate. This will place the blaster in a dangerous situation since unqualified drilling positions may lead to the failure of blasting operations in excavation. Therefore, a risk transmission among construction workers should be developed in future studies.

(3) The related study of construction workers' risk relationships in risk management is rare. Hence, we consider it valuable to study whether the risk relationships of construction workers are related to their organizational, communicative, or social relationships. For example, if the risk relationships among construction workers are highly related to their organizational relationships, we can modify the organizational structure to reduce the probability of risk transmission. We can also provide quadratic assignment procedure (QAP) analysis in SNA as an effective solution. The QAP analysis explores the relationships between two different relationships [68,69]. Therefore, these related studies will enrich the risk management theory.

6. Conclusions

The risk allocation based on the construction workers' work cooperation, information communication, and co-jointed work has become a common barrier to effective risk assessment for planning risk mitigation by project managers. This framework and procedures to identify risk-sharing relationships among construction workers are presented in this paper. A construction workers' risk-sharing network based on the two-mode network, as a personnel safety management tool, can handle the vagueness and subjectivity in risk analysis of tunneling projects. It confirms that the risk sharing based on construction workers' activities cannot be ignored.

Specifically, the WBS–RBS method is used to identify CSRFs and determine the relationships between construction activities and CSRFs (i.e., the two-mode WBS-RBS matrix) simultaneously; the OBS–WBS method is then utilized to determine the construction workers' set and the relationships between construction workers and construction activities (i.e., the two-mode OBS–WBS matrix). Then, taking construction activities in then WBS trees as links, the two-mode OBS–RBS matrix is created by converting the two-mode WBS–RBS matrix and two-mode OBS–WBS matrix. Based on the data structure attribute of the two-mode network, the two-mode OBS–RBS matrix can further converted to a one-mode OBS matrix to represent the risk-sharing relationships among construction workers. From network-level analyses (i.e., nodes, relationships, density, and degree centralization) and node-level variables (i.e., unweighted and weighted degree centrality), the indices and

network diagrams are produced from UCINET and NETDRAW, respectively, leading to the identification of the critical construction workers. Finally, we applied the proposed model to the Shangwu projects, and corresponding risk mitigation measures were suggested.

Additionally, a two-mode network is as a more useful analysis model to explore the safety risk-sharing features among construction workers in tunneling projects. Indeed, the risk allocation in construction workers' activities must be closely considered. However, few studies have evaluated safety risk sharing among construction workers in the engineering field. This direction is worthwhile for further studies.

Finally, for the limitation of this research, it may be inappropriate that the measurement of risk-sharing relationships' strength only depends on the participation degree of construction workers in a certain activity carrying CSRFs. Future research is expected to improve this aspect.

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Data Availability Statement: This study was conducted using data sets and analyses that are reasonably accessible from the corresponding author.

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

Appendix A. Verification of Risk-Sharing Model Questionnaire

Appendix A.1. Verification of Construction Risk Assessment Methodology

1. Do you think the set of CSRFs constructed in this tunnel project is reasonable?
2. Do you think it is reasonable to identify the risk-sharing relationship of CSRFs based on the work cooperation of construction activities carrying CSRFs?
3. Can you understand the proposed process for building this construction workers' risk-sharing network?
4. Do you think it is reasonable to use graph network analysis to build and analyze this risk-sharing network? What needs to be improved?

Appendix A.2. Verification of Construction Risk Assessment Results

1. Do you think the indices of construction risk-sharing features produced for this tunnel project are reasonable?
2. Do you think the overall feature analysis of the construction risk-sharing results is reasonable?

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