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Safety Risk Evaluation of Metro Shield Construction When Undercrossing a Bridge

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Abstract: The government of China has planned numerous metro projects, and with more metros, undercrossing of bridges can hardly be avoided. Metro shield construction when undercrossing a bridge (MSCUB) frequently takes place in complicated natural and social contexts, which often makes the construction process more susceptible to safety accidents. Therefore, it is crucial to look into the safety risk during MSCUB. This paper identified the safety risk factors during MSCUB by using a literature review and expert group evaluation, proposed a novel safety risk assessment model by integrating confirmatory factor analysis (CFA) and fuzzy evidence reasoning (FER), and then selected a project case to test the validity of the suggested model. The study results show that (a) a safety risk factor list for MSCUB was identified, including four first-level safety risk factors and thirty-seven second-level safety risk factors; (b) the proposed safety risk assessment model can be used to measure the risk values of the overall safety risk of a worksite, the first-level safety risk factors, and the second-level safety risk factors during MSCUB; (c) environment-type safety risk factors and personnel-type safety risk factors have higher risk values during shield construction when undercrossing a bridge; (d) when compared with worker-type safety risk factors, manager-type safety risk factors are the higher risks. This study can enrich the theoretical knowledge of MSCUB safety risk assessment and provide references for safety managers for conducting scientific and effective safety management on a construction site when constructing metro shields undercrossing a bridge.

Keywords: shield construction safety risks assessment; metro undercrossing a bridge; safety risk factor list; safety assessment model; confirmatory factor analysis; fuzzy evidence reasoning

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1. Introduction

China, being the second-largest economy in the world, is quickly becoming an urbanized and industrialized nation [1]. To provide jobs and raise living standards for its citizens, the government has gradually passed laws on and increased investment in infrastructure construction [2–4]. City planners are frequently required to plan a metro system, since it has excellent traffic efficiency, safety, stability, and energy savings [5,6]. Although metros are generally constructed underneath major city streets to minimize the risk of ground loads and minimize risk [7,8], cities are extremely intricate systems of human settlements, frequently containing roads, trains, and rivers, and thus, it is difficult for the metro to avoid undercrossing a bridge [8,9]. Metro shield construction when undercrossing a bridge (MSCUB) is an extremely risky construction context. The shield construction process will disturb the surrounding soil; on the one hand, it will lead to the settlement of neighboring bridge piles and the creation of additional stresses, which may cause damage to the bridge or aggravate the already existing damage, affecting the normal use of the bridge or leading to a collapse [10,11]; on the other hand, it will cause a sudden change in the stress of the traversing soil layer and instability in the excavation palisade surface, which is very likely to cause collapses or gushing water events [12,13]. Consequently, there is a pressing necessity to investigate safety risks during MSCUB.

Numerous scientific studies have been carried out on metro shield construction safety, with the primary goals of identifying the associated safety risks (factors) and assessing them. Previous research has investigated the safety risk factors based on different aspects, such as Pan et al. [14], who examined shield construction safety risk factors according to the classic paradigm of "personnel-equipment-material-technique-environ ment", identifying personnel-type, equipment-type, environment-type, and management-type risk factors; Liu et al. [15], who employed a questionnaire survey to identify shield construction safety risks, with a safety risk list covering tunnel excavation, segment assembly, special procedures and conditions, grouting, lead excavation, and slag removal. As for safety risk assessment, previous scholars often used the analytic hierarchy process [16], cloud model [16], fault tree analysis [17], Bayesian network [18,19], backpropagation (BP), neural network [20–22], etc. For instance, Wu and Zou [22] integrated the entropy weight method and cloud model to evaluate the static safety risk of underwater shield tunneling and a Bayesian network approach was utilized by Chung et al. [23] to evaluate safety risks during tunnel shield construction. To date, although MSCUB is extremely risky, few researchers have delved into the safety risks under this construction scenario.

To fill the gaps in existing research, this paper looks into safety risk evaluations of MSCUB. The main purposes of this study are to (1) provide a systematic and feasible list of safety risk factors for MSCUB based on a literature review and expert group evaluation; (2) propose a quantitative method to evaluate the safety risk factors of MSCUR; (3) and select a case to validate the proposed quantitative approach.

2. Literature Review

With the development of shield machine manufacturing technology, more and more metro tunnels are opting for a shield construction, as this tunnelling technique is characterized by greater safety, smaller environmental impact, and a higher level of automation [6,24]. Metro tunnels are generally designed to be built under the city, so the construction of metro tunnels is often confronted with various complex environmental contexts (e.g., crossing complex overburden layers, adjacent to rivers, existing pipelines, and tunnels). The existing literature has examined the safety risks of shield construction in some complicated situations, involving tunnelling under a complex overburden [6,25,26], tunnelling under an existing building [27–29], tunnelling under an existing tunnel [30,31], and tunnelling under existing pipelines [32]. These studies' topics are mostly concentrated on two areas, i.e., identifying safety risk factors and evaluating safety risks.

2.1. Identifying Safety Risk Factors of Metro Shield Construction

The identification of safety risk factors is a prerequisite for safety risk assessment. Based on various perspectives, previous research has looked into the safety risk factors of metro shield construction [29,32]. Some researchers adopted the "equipment-environment-management" identification paradigm, because they thought that the external environment, shield equipment, and onsite management were the most important safety concerns [25,26,30,33]. For instance, Hu et al.'s [25] investigation into the safety risks of metro shield construction under a soft overburden layer identified geologically complex conditions, underground water conditions, minimum overburden layer thickness, minimum radius of curvature, construction speed, distance from the surrounding environment, and onsite construction management as safety risk factors. A summary of the associated safety risk factors, including geological and hydrological conditions, shield construction parameters, tunnel conditions, bridge conditions, and organization and management risks, was provided by Zhai et al. [33] in their analysis of the safety risks of metro shield construction when adjacent to an existing bridge. Others have stated that metro shield construction is a complicated system and that it is important to consider the "personnel-equipment-environment" system while solving this complex system issue. For instance, Liu et al. [6] and Chen et al. [5] investigated the safety risks of metro shield construction when undercrossing intricate overburden strata and identified the safety risk factors using the "personnel-equipment-environment" architecture. The "personnel-equipment-environment-management" approach is more methodical. Wu et al. [34] and Pan et al. [14] identified the safety risk factors based on the aforementioned framework. Additionally, a more methodical paradigm called the "personnel-equipment-material-technique-environment" framework exists. Based on this paradigm, Li et al. [35] and Fan and Wang [36] examined the safety risks of metro shield construction and gathered the safety risk factors.

2.2. Evaluating Safety Risks of Metro Shield Construction

The risk assessment calculation method is illustrated by the safety risks assessment model. The weight-determining method and the measurement of safety risks are the two most important considerations when establishing the assessment model, because there are numerous safety risks within the index framework. According to past studies, the analytic hierarchy process (AHP) was chosen as the weight-determining method. For instance, Li et al.'s [35] investigation of the safety risks during slurry-balancing shield construction employed AHP to compute the weights of safety risks. To reduce the subjective element when determining the weights, more objective procedures were gradually implemented. Zhai et al. [33] chose a combinatorial weighting method by integrating G1 and CRITIC in their investigation of safety risks of shield construction when adjacent to an existing bridge. Fan and Wang [36] applied the ISM-DEMATEL and Shapley value method to determine the weights of safety risks in order to consider the relationships between different safety risks.

Many quantitative methods for measuring safety risks can be found in existing studies. The evaluation of shield construction safety concerns frequently uses the fuzzy comprehensive evaluation approach [35,37]. For instance, Ren et al. [37] used a fuzzy comprehensive evaluation method to evaluate all the safety concerns for construction when a building was nearby. Another extensively used strategy is the matter–element approach [27,36]. By linking the risk and its risk criteria, this method has advantages in terms of determining the risk rating [4]. Currently, to lessen the influence of uncertainty, Bayesian networks [30,38] and cloud models [26,34] have also been used to measure safety risks. Wu et al. [30] combined fuzzy Bayesian and evidence theory to assess the safety risks of metro shield construction when passing through existing tunnels. Wu et al. [34] selected a cloud model to evaluate the shield construction safety risks. Furthermore, Chen et al. [26] applied extension cloud theory and optimal cloud entropy to assess the safety risks of shield construction when close to existing structures. Additionally, by simulating the probability sampling process and the dynamic interactions between various safety risks, Monte Carlo [33] and systematic dynamic (SD) [14] were also applied to the shield construction safety risks evaluation.

3. Identification of Safety Risk Factors of MSCUB

3.1. The Framework for Identification of Safety Risk Factors

The paradigms outlined in the literature review above can offer theoretical frameworks to detect the safety risk factors during MSCUB, although few studies have examined the risk assessment of shield construction in this construction scenario. As previously highlighted, the framework of "personnel-equipment-material-technique-environment" [34,36] is a widely accepted and more methodical paradigm in the area of shield construction safety risks. However, we believe that non-standard materials should not be utilized in construction after several inspection rounds, and the damage of materials during the construction process is often caused by irregular construction arrangements, which should be included in the personnel-type, equipment-type, and technique-type safety risk factors. In addition, most previous research also did not include material-related safety risks (factors) [5,6,14,34]. Hence, we took no account of the material-type safety risks and adopted the "personnel-equipment-technique-environment" framework to identify the safety risk factors. Figure 1 displays the framework for identifying safety risk factors for MSCUB.

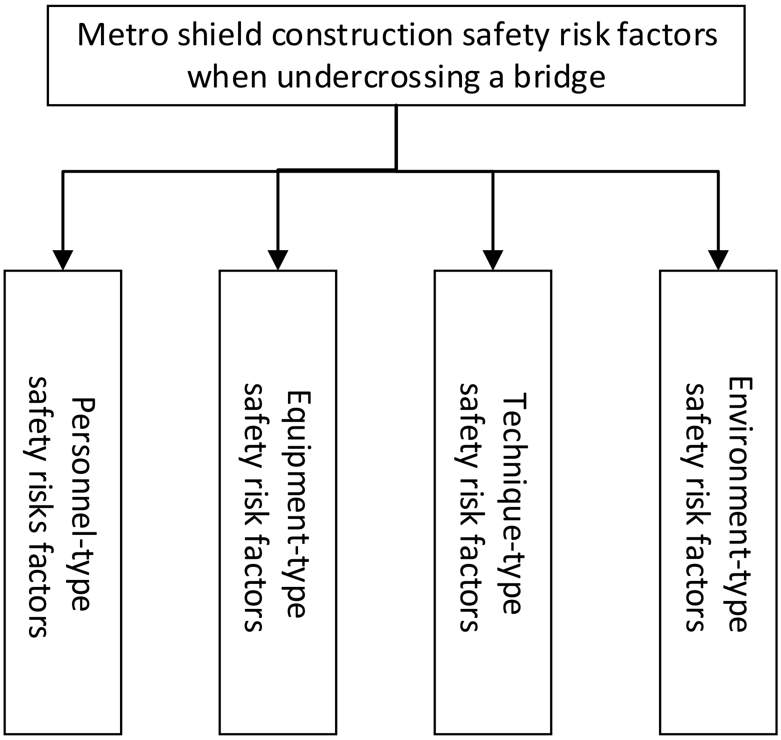

Figure 1. Safety risk factors identification framework of MSCUB.

3.2. The Identification Process of the Safety Risk Factors

This paper employed a two-step approach to identifying the safety risk factors during MSCUB based on the aforementioned framework. First, we conducted a review of the literature to identify the relevant safety risk factors. Second, we put together a panel of experts to evaluate and improve the list of safety risk factors.

Step 1. Safety risk factors identification based on the literature review.

We selected CNKI and Scopus as retrieval databases and our search criteria were ("safety risks" AND "shield construction") OR ("shield construction" AND "bridge") OR ("safety risks" AND "metro construction") OR ("metro construction" AND "bridge") OR ("safety risks" AND "subway construction"), OR ("subway construction" AND "bridge"). A total of 84 English papers and 75 Chinese papers were found in the initial search. Following a thorough analysis of these papers, 54 papers—31 in English and 23 in Chinese—were kept. The retained papers were mined for the initiating safety risk factors.

Step 2. Safety risk factors evaluation and improvement based on expert group.

Twenty safety management specialists were invited to evaluate and improve the safety risk factors identified during the preliminary procedure. The 20 experts were randomly selected from the expert database of the Zhengzhou Metro Group Co. Ltd. Before selecting, the expert group members were required to include two professor-level specialists, five senior engineers, and thirteen site engineers and all the members should have a least five years of experience in shield construction. After the aforementioned two steps, we determined the potential safety risk factors that could arise during MSCUB. The safety risk factor list is displayed in Table 1.

Table 1. Safety risk factor list for MSCUB.

First-Level Safety Risk Factors		Second-Level Safety Risk Factors
Personnel-type	Worker-type	W1: Physical and psychological unhealth; W2: Poor safety awareness; W3: Weak safety ability.
	Manager-type	M1: Lower safety management awareness; M2: Weaker safety management competency; M3: Lower safety management intentions; M4: Insufficient safety communication; M5: Inadequate safety inspection.
Equipment-type		EQ1: Malfunction of cutter head equipment; EQ2: Malfunction of thrust cylinder equipment; EQ3: Malfunction of screw conveyor; EQ4: Malfunction of segment erector; EQ5: Malfunction of grouting equipment: EQ6: Malfunction of electrical equipment.
Technique-type		TE1: Improper bridge pier reinforcement technical scheme; TE2: Inadequate geological and hydrological investigation scheme; TE3: Improper construction monitoring technical scheme; TE4: Improper excavation technical scheme; TE5: Improper grouting and reinforcement technical scheme; TE6: Sealed water-proof technical scheme; TE7: Improper emergency plan.
Environment-type	Natural environment-type	NE1: Soft clay layer; NE2: Silt soil layer; NE3: Complex soil layer; NE4: High-pressure underground water; NE5: Subterranean boulders; NE6: Subterranean voids.
	Bridge condition	BC1: Relatively close position of bridge piles and tunnel; BC2: Friction bridge pile type; BC3: Large bridge pile diameter; BC4: Poor bridge pile integrity; BC5: Poor bridge safety condition.
	Management environment-type	ME1: Poor safety climate; ME2: Incomplete safety institutions; ME3: Incomplete safety organization; ME4: Unclear safety rights and responsibility; ME5: Inadequate safety training and education.

4. Evaluation Model for Safety Risks of MSCUB

We established a model for evaluating the safety risks of MSCUB. Confirmatory factor analysis (CFA) [39,40] and fuzzy evidence reasoning (FER) [41,42] were both included in the evaluation model. The aforementioned weights of the safety risk factors were determined using the CFA method, and the risk value of the safety risk factors and the overall worksite safety risk were measured using the FER method.

4.1. Weights Calculation Based on Confirmatory Factor Analysis

CFA is a widely used data analysis method, and this method belongs to the group of factor analysis methods. CFA seeks to validate the viability of a pre-identified common factor structure (i.e., dimension structure) as opposed to exploratory factor analysis, which is used to identify a common factor structure from the messy data [43,44].

To gather data for CFA, a questionnaire survey was carried out [45]. Appendix A shows the questionnaire adopted in this paper. The questionnaire survey was carried out by using the Wenjuanxing platform [46]. The online questionnaires were distributed to onsite managers who had collaborated with the researchers. After the validity test, 197 responses from a total of 232 questionnaires were kept.

The data collected were initially loaded into SPSS 23 to test the reliability [47,48]. Cronbach's alpha was 0.942 [49], indicating that the collected data were highly reliable and internally consistent.

The data adhered to the normal distributions, as demonstrated by the substantial p-value ($p < 0.001$) obtained through Bartlett's test of sphericity [50]. The KMO value of 0.921 demonstrated adequate sample adequacy for factor analysis as well as significant correlations between the items [39,51].

Following that, a CFA was carried out on the AMOS 23 using the collected data [52,53]. The concept model is displayed in Figure 2. The standard path coefficients can be obtained after the CFA and are displayed in Table 2. The relationship strength between various variables is indicated by the standard path coefficients [54–57]. As a result, we determined the weights for the safety risk factors based on the standard path coefficients, which are displayed in Table 3.

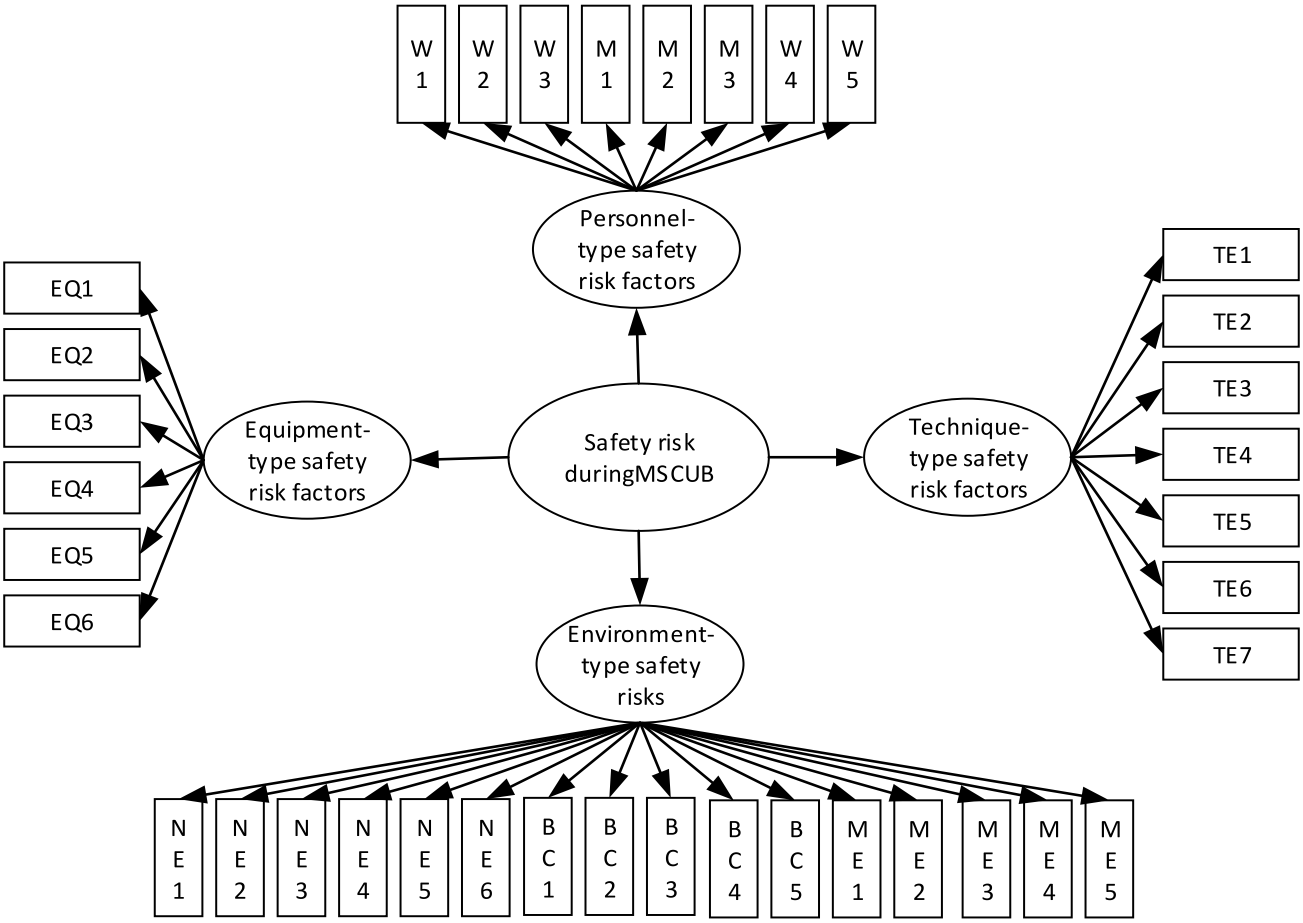

Figure 2. Concept model for CFA.

Table 2. Standard path coefficients of the CFA.

RP	SPC	*p*	RP	SPC	*p*	RP	SPC	*p*
PTSRF→W1	0.406	***	TTSRF→TE1	0.699	***	ETSRF→BC2	0.674	***
PTSRF→W2	0.711	***	TTSRF→TE2	0.531	**	ETSRF→BC3	0.642	***
PTSRF→W3	0.592	***	TTSRF→TE3	0.627	***	ETSRF→BC4	0.732	***
PTSRF→M1	0.570	***	TTSRF→TE4	0.779	**	ETSRF→BC5	0.755	***
PTSRF→M2	0.605	***	TTSRF→TE5	0.756	**	ETSRF→ME1	0.732	***
PTSRF→M3	0.739	***	TTSRF→TE6	0.587	***	ETSRF→ME1	0.835	***
PTSRF→M4	0.706	***	TTSRF→TE7	0.473	***	ETSRF→ME1	0.732	***
PTSRF→M5	0.727	***	ETSRF→NE1	0.747	***	ETSRF→ME1	0.813	***
ETSRT→EQ1	0.625	***	ETSRF→NE2	0.741	***	ETSRF→ME1	0.625	***
ETSRT→EQ2	0.682	**	ETSRF→NE3	0.673	***	SRMSCUB→PTSRF	0.785	***
ETSRT→EQ3	0.409	***	ETSRF→NE4	0.723	***	SRMSCUB→ETSRF	0.564	***
ETSRT→EQ4	0.622	**	ETSRF→NE5	0.547	***	SRMSCUB→TTSRF	0.648	**
ETSRT→EQ5	0.768	**	ETSRF→NE6	0.543	***	SRMSCUB→ETSRF	0.946	**
ETSRT→EQ6	0.594	***	ETSRF→BC1	0.769	***	-	-	

Notes: RP denotes relationship path; SPC denotes standard path coefficient; PTSRF denotes personnel-type safety risk factors; ETSRF denotes equipment-type safety risk factors; TTSRF denotes technique-type safety risk factors; ETSRF denotes environment-type safety risk factors; SRMSCUB denotes safety risk of MSCUB; "***" denotes that the *p*-value is less than 0.05; and "**" denotes that the *p*-value is less than 0.1.

Table 3. Weights of different safety risk factors.

Safety Risks Factor	Weight	Safety Risks Factor	Weight	Safety Risks Factor	Weight
W1	0.238	TE1	0.157	BC2	0.189
W2	0.416	TE2	0.119	BC3	0.180
W3	0.346	TE3	0.141	BC4	0.205
M1	0.170	TE4	0.175	BC5	0.211
M2	0.181	TE5	0.170	ME1	0.196
M3	0.221	TE6	0.132	ME2	0.223
M4	0.211	TE7	0.106	ME3	0.196
M5	0.217	NE1	0.188	ME4	0.218
EQ1	0.169	NE2	0.186	ME5	0.167
EQ2	0.184	NE3	0.169	PTSRF	0.267
EQ3	0.111	NE4	0.182	ETSRF	0.192
EQ4	0.168	NE5	0.138	TTSRF	0.220
EQ5	0.208	NE6	0.137	ETSRF	0.321
EQ6	0.161	BC1	0.215	-	-

4.2. Measuring the Safety Risk (Factors) Using FER

Step 1: Representing a single safety risk factor using triangular fuzzy numbers.

The safety risk value of a safety risk factor R can be expressed as $R = P \times S$, that is, the production of the occurrence probability of a safety risk factor P and the consequence severity of a safety risk factor S. Quantitative evaluation of the risk value of a safety risk factor is frequently challenging due to the impact of uncertainty. Applying qualitative descriptions to express the risk level of a safety risk factor is a useful and efficient strategy. The occurrence probability of a safety risk factor can be qualitatively expressed in a verbal scale as "extremely low", "low", "relatively high", "high", and "extremely high". The consequence severity of a safety risk factor can also be described using "no impact," "minor," "large", "dangerous", and "catastrophic." In this paper, the verbal evaluation levels of P and S can be transformed into triangular fuzzy numbers, and the corresponding relationship is displayed in Table 4.

Table 4. Relationship between verbal evaluation level and the triangular fuzzy number.

Level	Occurrence Probability	Consequence Severity	The Triangular Fuzzy Number
1	Extremely low	No impact	(0.00, 0.00, 0.25)
2	Low	Minor impact	(0.00, 0.25, 0.50)
3	Relatively high	Large impact	(0.25, 0.50, 0.75)
4	High	Dangerous	(0.50, 0.75, 1.00)
5	Extremely high	Catastrophic	(0.75, 1.00, 1.00)

Assuming that two triangular fuzzy numbers $\widetilde{P} = (l_P, m_P, u_P)$ and $\widetilde{S} = (l_S, m_S, u_S)$ are used to express the occurrence probability P and the consequence severity S, subsequently, Formula (1) can be utilized to express the corresponding safety risk value of the safety event [58,59].

$$\widetilde{R} = (l_P l_S, m_P m_S, u_P u_S) \tag{1}$$

Step 2: Establishing the fuzzy belief structure for the predefined risk levels of the safety risk factors.

Assuming that N evaluation levels exist for each safety risk factor and the corresponding membership functions are known, we can establish the fuzzy belief structure for the risk evaluation levels of a safety risk factor, which is expressed by Formula (2).

$$FBS(R) = \{(FH^n, \beta^n), n = 1, 2, 3, \cdots, N\} \tag{2}$$

In Formula (2), FH_n denotes the fuzzy evaluation levels; N denotes the number of risk evaluation levels; β_n denotes the belief level of a safety risk factor at fuzzy evaluation levels; additionally, $\beta_n \geq 0$ and $\sum_{n=1}^{N} \beta_n \leq 1$.

This study assumed that a safety risk factor has five different evaluation levels, and its membership functions follow the fuzzy triangular numbers (see in Table 5); subsequently, the fuzzy belief structure of the risk evaluation levels of a safety risk factor can be expressed using Formula (3), and the membership functions of the five risk evaluation levels are displayed in Figure 3.

$$FBS(R) = \{(FH^n, \beta^n), n = 1,2,3,4,5\} \quad (3)$$

Table 5. Definition of safety risk evaluation level and risk parameter description.

No.	Level of Safety Risk	Definition	Membership Functions
1	Extremely low (EL)	The safety risk is acceptable.	(0.00, 0.00, 0.25)
2	Low (L)	The safety risk is acceptable, and if the safety risk cost is acceptable, measures should be taken to reduce the risk.	(0.00, 0.25, 0.50)
3	Medium (M)	If technology is feasible, measures must be taken to reduce the risk.	(0.25, 0.50, 0.75)
4	High (H)	Measures must be taken to reduce the risk.	(0.50, 0.75, 1.00)
5	Extremely high (EH)	Measures must be taken to reduce and control the risk.	(0.75, 1.00, 1.00)

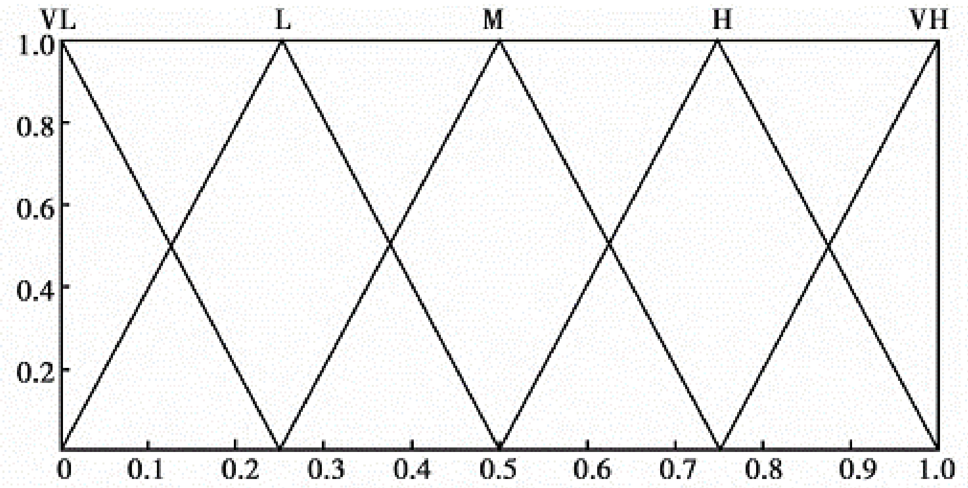

Figure 3. The membership functions of the five risk evaluation levels.

Step 3: Computing the belief structure of each safety risk factor.

Through this step, we can compute the belief structure of each safety risk factor (β_n) based on its triangular fuzzy values ($\widetilde{R}$). The computing criteria are as follows:

(1) Create the membership curve based on $\widetilde{R}$.
(2) Locate the points where the membership curve of $\widetilde{R}$ and the five-level membership curves in Figure 3 cross.
(3) Compute the ordinates of the intersection points to express the belief values of the corresponding fuzzy evaluation level. If there are no intersection points, the belief

value of this fuzzy evaluation level is zero. If there are two intersection points, the larger ordinate is selected as the belief value of this fuzzy evaluation level.

(4) Next, standardize the five belief values after sequentially determining the belief values of a safety risk factor. As a result, the belief structure of a safety risk factor $Z(R)$ can be gained, which is expressed by Formula (4).

$$Z(R) = \{\beta_{EL}, \beta_L, \beta_M, \beta_H, \beta_{EH}\} \quad (4)$$

Step 4: Calculating the belief structure of the upper-level safety risk factors and overall work site safety risk based on ER.

Assuming that there exists a risk evaluation problem RE with L risk indexes r_i (i = 1, 2, ..., L), the weights of these indexes r_i are ω_i and that every risk index follows the fuzzy belief model $FBS(D_i) = \{(FH^n, \beta_i^n)\}$, we can calculate the mass number of each risk index, as presented in Formulas (5)–(8) [60].

$$m_i^n = \omega_i \beta_i^n, n = 1, 2, 3, \cdots, N; i = 1, 2, 3, \cdots, L \quad (5)$$

$$m_i^H = 1 - \sum_{n=1}^{N} m_i^n, i = 1, 2, 3, \cdots, L \quad (6)$$

$$\overline{m}_i^H = 1 - \omega_i, i = 1, 2, 3, \cdots, L \quad (7)$$

$$\widetilde{m}_i^H = \omega_i \left(1 - \sum_{n=1}^{N} \beta_i^n\right), i = 1, 2, 3, \cdots, L \quad (8)$$

In the above formulas, m_i^n denotes the basic fuzzy belief value of risk index r_i at the fuzzy risk level of FH^n, and m_i^H denotes the uncertain risks due to a lack of information, which includes $\overline{m}_i^H$ and $\widetilde{m}_i^H$.

Let $m_{I(i)}^n$ denote the belief degree to the nth evaluation level of an upper-level risk index that the first i lower-level indexes support; $m_{I(i)}^H$ denotes the retained probability after all the first i lower-level risk indexes have been assigned to all the evaluation levels; thus, the recursive processes of $m_{I(i)}^n$ and $m_{I(i)}^H$ are expressed in Formulas (9)–(12) [60,61].

$$m_{I(i+1)}^n = K_{I(i+1)}(m_{I(i)}^n m_{i+1}^n + m_{I(i)}^n m_{i+1}^H + m_{I(i)}^H m_{i+1}^n) \quad (9)$$

$$\widetilde{m}_{I(i+1)}^n = K_{I(i+1)}(\widetilde{m}_{I(i)}^H \widetilde{m}_{i+1}^H + \widetilde{m}_{I(i)}^H \overline{m}_{i+1}^H + \overline{m}_{I(i)}^H \widetilde{m}_{i+1}^H) \quad (10)$$

$$\overline{m}_{I(i+1)}^n = K_{I(i+1)}(\overline{m}_{I(i)}^H \overline{m}_{i+1}^H) \quad (11)$$

$$K_{I(i+1)} = \Big(1 - \sum_{n=1}^{N} \sum_{\substack{t=1 \\ t \neq n}}^{N} m_{I(i)}^n m_{i+1}^t\Big)^{-1}, i = 1, 2, 3, \cdots, L-1 \quad (12)$$

Then, the fuzzy belief values of an upper-level risk index β^n can be computed by using Formula (13).

$$\beta^n = \frac{m_{I(L)}^n}{1 - \overline{m}_{I(L)}^H}, n = 1, 2, 3, \cdots, N \quad (13)$$

Step 5: Determining the risk levels of a safety risk factor or overall worksite safety risk.

Based on the aforementioned processes, we can calculate the fuzzy belief values of all the first-level safety risk factors and the overall worksite safety risk. Subsequently, we can find the maximum belief value of β^n, and the risk level of the safety risk factor or overall worksite safety risk is the level where the maximum belief value is located.

5. Case Validation

5.1. Project Overview

The tunnel section between Zhengzhou Sports Center station and Longzihu Central Station of Zhengzhou Rail Transit Line 1 Phase II Project is constructed using the shield method, with an outer diameter of 6 m. The interval tunnel mileage section K006+129.000-K006209.000 underpasses the Zhengzhou–Kaifeng intercity railway Zhengzhou Grand Bridge, with bridge pier numbers 121 and 122. The left and right lines of the tunnel pass through the 121~122 piers are, respectively, at 83°~86° to the Zhengzhou–Kaifeng intercity railway Zhengzhou Grand Bridge. The inner diameter of the shield tunnel is 5.4 m, the outer diameter is 6.0 m, the thickness of the pipe segment is 0.30 m, the width of the pipe segment is 1.5 m, and the double-sided wedge is 0.045 m.

5.2. Identifying the Safety Risk Factors Based on the Expert Group

The tunnel section between Zhengzhou Sports Center station and Longzihu Central Station includes a very dangerous tunnel portion that underpasses the Zhengzhou–Kaifeng intercity railway Zhengzhou Grand Bridge. The project management department invited a 15-person expert group to participate before undercrossing the Zhengzhou Grand Bridge. The specialists were tasked with identifying the safety risk factors associated with undercrossing the Zhengzhou Grand Bridge and then assessing the likelihood of the occurrence and the severity of the identified safety risk factors.

After conducting an onsite investigation, the experts examined the project documents and questioned the project managers about a few project-related questions. Then, individual safety risk factor checklists were given to each expert (see Appendix B). All of the pre-identified safety risk factors in Table 1 are covered by the safety risk factor checklist. The experts noted the safety risk factors they deemed important, together with the associated likelihood of their occurrence and severity of the consequences. On-site supervisors gathered all of the checklists and computed the average value of the likelihood that each risk would occur and the severity of its consequence. Table 6 lists the safety risk factors that the expert group identified, and Table 7 lists the calculated results.

Table 6. The list of safety risk factors identified by experts.

Safety Risk Factor Category		Safety Risk Factors
Personnel-type	Worker-type	W2: Poor safety awareness; W3: Weak safety ability.
	Manager-type	M2: Weaker safety management competency; M4: Insufficient safety communication; M5: Inadequate safety inspection.
Equipment-type		EQ2: Malfunction of thrust cylinder equipment; EQ3: Malfunction of screw conveyor; EQ5: Malfunction of grouting equipment: EQ6: Malfunction of electrical equipment.
Technique-type		TE1: Improper bridge pier reinforcement technical scheme; TE3: Improper construction monitoring technical scheme; TE4: Improper excavation technical scheme; TE5: Improper grouting and reinforcement technical scheme; TE6: Sealed water-proof technical scheme.
Environment-type	Natural environment-type	NE1: Soft clay layer; NE4: High-pressure underground water; NE5: Subterranean boulders.
	Bridge condition	BC1: Relatively close position of bridge piles and tunnel; BC2: Friction bridge pile; BC3: Large bridge pile diameter; BC5: Poor bridge safety condition.
	Management environment-type	ME2: Incomplete safety institutions; ME4: Unclear safety rights and responsibility; ME5: Inadequate safety training and education.

Table 7. The levels of occurrence probability and consequence severity of safety risk factors based on expert assessment.

Safety Risk Factor	Occurrence Probability Level	Consequences Severity Level
W2: Poor safety awareness	3 (Relatively high)	4 (Dangerous)
W3: Weak safety ability	3 (Relatively high)	3 (Large impact)
M2: Weaker safety management competency	4 (High)	3 (Large impact)
M4: Insufficient safety communication	3 (Relatively high)	5 (Catastrophic)
M5: Inadequate safety inspection	3 (Relatively high)	4 (Dangerous)
EQ2: Malfunction of thrust cylinder equipment	3 (Relatively high)	4 (Dangerous)
EQ3: Malfunction of screw conveyor	2 (Low)	4 (Dangerous)
EQ5: Malfunction of grouting equipment	3 (Relatively high)	4 (Dangerous)
EQ6: Malfunction of electrical equipment	3 (Relatively high)	3 (Large impact)
TE1: Improper bridge pier reinforcement technic scheme	3 (Relatively high)	5 (Catastrophic)
TE3: Improper construction monitoring technical scheme	3 (Relatively high)	3 (Large impact)
TE4: Improper excavation technical scheme	3 (Relatively high)	3 (Large impact)
TE5: Improper grouting and reinforcement technical scheme	3 (Relatively high)	4 (Dangerous)
TE6: Sealed water-proof technical scheme	3 (Relatively high)	5 (Catastrophic)
NE1: Soft clay layer	3 (Relatively high)	4 (Dangerous)
NE4: High-pressure underground water	4 (High)	4 (Dangerous)
NE5: Subterranean boulders	3 (Relatively high)	3 (Large impact)
BC1: Relatively close position of bridge piles and tunnel;	3 (Relatively high)	4 (Dangerous)
BC2: Friction bridge pile	4 (High)	4 (Dangerous)
BC3: Large bridge pile diameter	3 (Relatively high)	4 (Dangerous)
BC5: Poor bridge safety condition	3 (Relatively high)	3 (Large impact)
ME2: Incomplete safety institutions	3 (Relatively high)	5 (Catastrophic)
ME4: Unclear safety rights and responsibility	3 (Relatively high)	4 (Dangerous)
ME5: Inadequate safety training and education	3 (Relatively high)	3 (Large impact)

5.3. Calculating the Risk Values of the Safety Risk Factors Based on CFA and ER

The triangular fuzzy numbers of the safety risk factors can be determined using the aforementioned transformation rule (see Table 4), and the results are shown in Table 8. We computed the belief structure of the safety risk factors by using the transformation rules described in Step 3, and the transformative results are displayed in Table 9. In addition, the risk levels of safety risk factors were also determined (see Table 9).

Table 8. The triangular fuzzy values of the safety risks.

Safety Risk Factor	Fuzzy Occurrence Probability	Fuzzy Consequences Severity Level	Fuzzy Values of Safety Risks
W2: Poor safety awareness	(0.25, 0.50, 0.75)	(0.50, 0.75, 1.00)	(0.125, 0.375, 0.750)
W3: Weak safety ability	(0.25, 0.50, 0.75)	(0.25, 0.50, 0.75)	(0.063, 0.250, 0.563)
M2: Weaker safety management competency	(0.50, 0.75, 1.00)	(0.25, 0.50, 0.75)	(0.125, 0.375, 0.750)
M4: Insufficient safety communication	(0.25, 0.50, 0.75)	(0.75, 1.00, 1.00)	(0.188, 0.500, 0.750)
M5: Inadequate safety inspection	(0.25, 0.50, 0.75)	(0.50, 0.75, 1.00)	(0.125, 0.375, 0.750)
EQ2: Malfunction of thrust cylinder equipment	(0.25, 0.50, 0.75)	(0.50, 0.75, 1.00)	(0.125, 0.375, 0.750)
EQ3: Malfunction of screw conveyor	(0.00, 0.25, 0.50)	(0.50, 0.75, 1.00)	(0.00, 0.188, 0.500)
EQ5: Malfunction of grouting equipment	(0.25, 0.50, 0.75)	(0.50, 0.75, 1.00)	(0.125, 0.375, 0.750)
EQ6: Malfunction of electrical equipment	(0.25, 0.50, 0.75)	(0.25, 0.50, 0.75)	(0.063, 0.250, 0.563)
TE1: Improper bridge pier reinforcement technical scheme	(0.25, 0.50, 0.75)	(0.75, 1.00, 1.00)	(0.188, 0.500, 0.750)
TE3: Improper construction monitoring technical scheme	(0.25, 0.50, 0.75)	(0.25, 0.50, 0.75)	(0.063, 0.250, 0.563)
TE4: Improper excavation technical scheme	(0.25, 0.50, 0.75)	(0.25, 0.50, 0.75)	(0.063, 0.250, 0.563)
TE5: Improper grouting and reinforcement technical scheme	(0.25, 0.50, 0.75)	(0.50, 0.75, 1.00)	(0.125, 0.375, 0.750)
TE6: Sealed water-proof technical scheme	(0.25, 0.50, 0.75)	(0.75, 1.00, 1.00)	(0.188, 0.500, 0.750)

Table 8. *Cont.*

Safety Risk Factor	Fuzzy Occurrence Probability	Fuzzy Consequences Severity Level	Fuzzy Values of Safety Risks
NE1: Soft clay layer	(0.25, 0.50, 0.75)	(0.50, 0.75, 1.00)	(0.125, 0.375, 0.750)
NE4: High-pressure underground water	(0.50, 0.75, 1.00)	(0.50, 0.75, 1.00)	(0.250, 0.563, 1.000)
NE5: Subterranean boulders	(0.25, 0.50, 0.75)	(0.25, 0.50, 0.75)	(0.063, 0.250, 0.563)
BC1: Relatively close position of bridge piles and tunnel	(0.25, 0.50, 0.75)	(0.50, 0.75, 1.00)	(0.125, 0.375, 0.750)
BC2: Friction bridge pile	(0.50, 0.75, 1.00)	(0.50, 0.75, 1.00)	(0.250, 0.563, 1.000)
BC3: Large bridge pile diameter	(0.25, 0.50, 0.75)	(0.50, 0.75, 1.00)	(0.125, 0.375, 0.750)
BC5: Poor bridge safety condition	(0.25, 0.50, 0.75)	(0.25, 0.50, 0.75)	(0.063, 0.250, 0.563)
ME2: Incomplete safety institutions	(0.25, 0.50, 0.75)	(0.75, 1.00, 1.00)	(0.188, 0.500, 0.750)
ME4: Unclear safety rights and responsibility	(0.25, 0.50, 0.75)	(0.50, 0.75, 1.00)	(0.125, 0.375, 0.750)
ME5: Inadequate safety training and education	(0.25, 0.50, 0.75)	(0.25, 0.50, 0.75)	(0.063, 0.250, 0.563)

Table 9. The belief structure and risk level of the safety risk factors.

Safety Risk Factor	Belief Structure					Risk Level
	EL	L	M	H	EH	
W2: Poor safety awareness	0.114	0.341	0.363	0.183	0.000	M
W3: Weak safety ability	0.205	0.477	0.265	0.053	0.000	L
M2: Weaker safety management competency	0.114	0.341	0.363	0.183	0.000	M
M4: Insufficient safety communication	0.051	0.257	0.461	0.231	0.000	M
M5: Inadequate safety inspection	0.114	0.341	0.363	0.183	0.000	M
EQ2: Malfunction of thrust cylinder equipment	0.114	0.341	0.363	0.183	0.000	M
EQ3: Malfunction of screw conveyor	0.300	0.467	0.233	0.000	0.000	L
EQ5: Malfunction of grouting equipment	0.114	0.341	0.363	0.183	0.000	M
EQ6: Malfunction of electrical equipment	0.205	0.477	0.265	0.053	0.000	L
TE1: Improper bridge pier reinforcement technical scheme	0.051	0.257	0.461	0.231	0.000	M
TE3: Improper construction monitoring technical scheme	0.205	0.477	0.265	0.053	0.000	L
TE4: Improper excavation technical scheme	0.205	0.477	0.265	0.053	0.000	L
TE5: Improper grouting and reinforcement technical scheme	0.114	0.341	0.363	0.183	0.000	M
TE6: Sealed water-proof technical scheme	0.051	0.257	0.461	0.231	0.000	M
NE1: Soft clay layer	0.114	0.341	0.363	0.183	0.000	M
NE4: High-pressure underground water	0.000	0.184	0.366	0.300	0.15	M
NE5: Subterranean boulders	0.205	0.477	0.265	0.053	0.000	L
BC1: Relatively close position of bridge piles and tunnel	0.114	0.341	0.363	0.183	0.000	M
BC2: Friction bridge pile	0.000	0.184	0.366	0.300	0.150	M
BC3: Large bridge pile diameter	0.114	0.341	0.363	0.183	0.000	M
BC5: Poor bridge safety condition	0.205	0.477	0.265	0.053	0.000	L
ME2: Incomplete safety institutions	0.051	0.257	0.461	0.231	0.000	M
ME4: Unclear safety rights and responsibility	0.114	0.341	0.363	0.183	0.000	M
ME5: Inadequate safety training and education	0.205	0.477	0.265	0.053	0.000	L

Formulas (5) and (12) can then be used to calculate the normalization coefficient (i.e., K_I) and belief structure (i.e., m_I^n) of the first-level safety risk factors and the overall worksite safety risk. The calculated results are presented in Table 10. Hence, the risk level of the first-level safety risk factors and the overall worksite safety risk can be obtained by using Formulas (13) (see Table 10).

As can be seen in Table 10, the risk levels of 16 safety risk factors are at the medium level, and others are at the low level. As for worker-type safety risk factors, poor safety awareness is riskier than weak safety ability. Of the manager-type safety risk factors, insufficient safety communication is the riskiest one. For equipment-type safety risk factors, malfunction of thrust cylinder equipment and malfunction of grouting equipment are at the medium level, and the remaining ones fall on the low level. Improper bridge pier reinforcement technical scheme and improper grouting and reinforcement technical scheme in the technique-type safety risk factors have higher risk values. In terms of natural environment-type safety risk factors, a soft clay layer and high-pressure underground water are the risker factors. For the bridge condition, relatively close position of bridge piles and tunnel, friction bridge pile, and large bridge pile diameter hold higher risk values. In addition, incomplete safety institutions and unclear safety rights and responsibilities are riskier than inadequate safety training and education.

Table 10. The normalization coefficient, belief structure, and risk level of the first-level safety risks and the overall worksite safety risk.

First-Level Safety Risk Factors/Overall Worksite Safety Risk	NC (K_I)	Belief Structure (m_I^n)					Risk Level
		EL	L	M	H	EH	
Worker-type safety risk factor	0.138	0.080	0.560	0.330	0.030	0.000	L
Manager-type safety risk factor	0.276	0.007	0.300	0.615	0.078	0.000	M
Personnel-type safety risk factor	0.102	0.001	0.451	0.541	0.007	0.000	M
Equipment-type safety risk factor	0.820	0.023	0.740	0.233	0.004	0.000	L
Technique-type safety risk factor	3.040	0.001	0.480	0.516	0.003	0.000	M
Natural environment-type safety risk factor	0.595	0.012	0.464	0.500	0.024	0.000	M
Bridge condition	1.105	0.000	0.433	0.543	0.024	0.000	M
Management environment-type safety risk factor	0.406	0.000	0.440	0.532	0.028	0.000	M
Environment-type safety risk factor	0.302	0.000	0.394	0.604	0.002	0.000	M
Overall worksite safety risk	0.269	0.000	0.475	0.524	0.001	0.000	M

Notes: NC denotes the normalization coefficient.

As is displayed in Table 10, the overall worksite safety risk is at the medium level, which indicates that the project management team has an average degree of management competency in terms of the safety risks of MSCUB. Almost all the first-level safety risk factors are graded as medium-level risk, except for the equipment-type safety risk factor, which is at the low level. Of the first-level safety risk factors, environment-type safety risk factors as a whole have the highest values, the personnel-type safety risk factors and the technique-type safety risk factors follow closely behind. As for the personnel-type safety risk, the manager-type safety risk is higher than the worker-type safety risk, which indicates that management personnel should be given more attention. For the environment-type safety risk factors, the bridge condition has the maximum risk value, which indicates that managers should develop special plans for bridge safety management in advance to prevent safety accidents related to this. In addition, the management-type safety risk factor ranks second; thus, more safety experiences should be collected and more safety training should be carried out to develop a more perfect safety management system for safety risk management during MSCUB.

6. Discussion and Management Implications

This paper identified a list of MSCUB safety risk factors, which consists of 37 second-level safety risk factors and 4 first-level safety risks, including personnel-type, equipment-type, technique-type, and environment-type safety risk factors. In the available literature, safety risk factors are classified using the same taxonomy. To illustrate, Lu et al. [62] and Zhou et al. [63] separated safety risk factors into hydrogeological safety risk factors, equipment safety risk factors, construction technology safety risk factors, and personnel safety risk factors by adhering to this type of classification. As was previously mentioned, the taxonomy does not include material-type safety risk factors because, in practice, non-standard materials cannot be brought onto construction sites due to the strict three-level review system, and damage to materials at work sites is frequently brought on by inadvertent working procedures, during which personnel-type, equipment-type, and technique-type safety risks can cover the related risks. Additionally, as management-type safety risk factors are essentially environment-type notions or variables, we put them in the environment-type safety risk factors [64]. This approach was used by Liu et al. [6] and Chen et al. [5] to determine the safety concerns during tunnel shield construction. Based on a literature review and expert evaluations, the safety risk factors were determined. Our safety risk factor list for MSCUB is more comprehensive than the lists from earlier studies. For instance, Wu et al. [13] investigated the safety risks when metro construction occurred adjacent to a bridge and identified tunnel characteristics, soil conditions, bridge condition, and the construction method and management as first-level safety risk factors, ignoring the personnel-type and equipment-type safety risk factors.

This study integrated fuzzy evidence reasoning (FER) and confirmatory factor analysis (CFA) to provide a novel method for assessing the safety risk of MSCUB. The existing literature has introduced CFA- or SEM-kind approaches that can calculate the association degree between some lower-level variables and an upper-level latent variable as well as provide a mechanism for calculating their weights [56,65]. These approaches have the benefit of making variable weights more objective through large-scale statistical analysis of survey data. The safety risk analysis frequently employs FER as a method of analysis [66,67]. This method can combine many pieces of information to draw a comprehensive evidential inference and partially alleviate the semantic vagueness and uncertainty brought on by expert evaluation [66,68]. As a result, when compared with previous evaluation models for assessing shield construction safety risk, such as AHP and FCE, the new proposed assessment model can produce results that are more accurate and scientific, which can serve as a more solid foundation for the prevention and management of safety risks.

The proposed CFA-FER model was applied to a case, i.e., Zhengzhou Rail Transit Line 1 Phase II Project undercrossing Zhengzhou Grand Bridge, to test its feasibility. The computation procedures and findings demonstrate that the suggested approach can assess the safety risks associated with MSCBA. The case study demonstrates that environment-type safety risk factors have the maximum risk values, of which bridge conditions are riskier safety risk factors. The results were in line with earlier research. For instance, it was highlighted by Zheng et al. [69], Liu et al. [8], and [12] that bridge piles are the central aspect to management when constructing subways undercrossing a bridge. Additionally, manager-type safety risk factors are more dangerous than worker-type risk factors. The results of earlier studies can also be used to explain this discovery. Safety managers play a key role in safety management of the traditional two-agent management approach [70,71]. The managers' neglect and the ineffectiveness of the safety management system were the main causes of the workers' low safety awareness and frequent unsafe behaviors [64,72,73].

Some management measures for improved on-site safety management can be developed based on the analysis given above. The primary safety risk factors when constructing shields for undercrossing a bridge are the bridge conditions. Other actions can be taken in advance to lessen the detrimental impact. Project managers can (a) reinforce the bridge piles and bridge to assure its stability; (b) conduct further in-depth geological and hydrological surveys; (c) grout in advance to ensure the stability of surrounding soil; and (d) control the excavation speed and continually track the bridge's change in spatial location. Second, it was determined that management-type safety risk factors and worker-type safety risk factors were the generally greater safety risks. Senior and front-line managers can take the following actions: (a) consider the engineering reality and China's indigenous management context when formulating management regulations; (b) establish a strict reward and punishment system; (c) clearly define managers' responsibilities and obligations; and (d) strengthen the supervision of the construction process.

7. Conclusions

This paper used a literature review and expert group evaluation to identify the safety risk factors of MSCUB, proposed a new safety risk assessment model by integrating CFA and FER, and utilized a case to demonstrate the feasibility of the suggested method. The findings of the study are as follows:

(1) A practically feasible list of safety risk factors for MSCUB is established and consists of four first-level safety risks and thirty-seven second-level safety risk factors. The first-level safety risks include personnel-type, equipment-type, technique-type, and management-type safety risks.

(2) An integrated safety risks assessment model was proposed to quantitatively assess the safety risks of MSCUB, and the model was validated as feasible in evaluating the risk values of the safety risk factors, first-level safety risks, and the overall worksite safety risk.
(3) A case study showed that the overall worksite safety risk is at the medium level, and that environment-type safety risk factors and personnel-type safety risk factors have higher risk values when constructing a shield to undercross a bridge. Additionally, manager-type safety risk factors, as a whole, are higher than worker-type safety risk factors.
(4) Two limitations to this research exist. Firstly, the paper neglects the relationships among the second-level safety risk factors. Follow-up research can establish new methods to evaluate the safety risks, considering the causality and coupling relationships among the safety risk factors. Secondly, the paper only selects one case to apply the proposed approach to; thus, we suggest more project cases can be analyzed in the future to validate its generality.

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Appendix A

Table A1. The Questionnaire for Data Collection.

Safety Risks	Not Important	Slightly Important	Important	Relatively Important	Extremely Important
W1: Physical and psychological unhealthy					
W2: Poor safety awareness					
W3: Weak safety ability					
M1: Lower safety management awareness					
M2: Weaker safety management competency					
M3: Lower safety management intentions					
M4: Insufficient safety communication					
M5: Inadequate safety inspection					
EQ1: Malfunction of cutter head equipment					
EQ2: Malfunction of thrust cylinder equipment					
EQ3: Malfunction of screw conveyor					
EQ4: Malfunction of segment erector					
EQ5: Malfunction of grouting equipment					
EQ6: Malfunction of electrical equipment					

Table A1. *Cont.*

Safety Risks	Not Important	Slightly Important	Important	Relatively Important	Extremely Important
TE1: Improper bridge pier reinforcement technical scheme					
TE2: Inadequate geological and hydrological investigation scheme					
TE3: Improper construction monitoring technical scheme					
TE4: Improper excavation technical scheme					
TE5: Improper grouting and reinforcement technical scheme					
TE6: Sealed water-proof technical scheme					
TE7: Improper emergency plan					
NE1: Soft clay layer					
NE2: Silt soil layer					
NE3: Complex soil layer					
NE4: High-pressure underground water					
NE5: Subterranean boulders					
NE6: Subterranean voids					
BC1: Relatively close position of bridge piles and tunnel					
BC2: Friction bridge pile					
BC3: Large bridge pile diameter					
BC4: Poor bridge pile integrity					
BC5: Poor bridge safety condition					
ME1: Poor safety climate					
ME2: Incomplete safety institutions					
ME3: Incomplete safety organization					
ME4: Unclear safety rights and responsibility					
ME5: Inadequate safety training and education					

Appendix B

Table A2. The Safety Risk Factors Checklist for Experts' Evaluation.

Safety Risk Factors	Occurrence Probability Grade	Consequences Severity Grade
W1: Physical and psychological unhealthy		
W2: Poor safety awareness		
W3: Weak safety ability		
M1: Lower safety management awareness		
M2: Weaker safety management competency		
M3: Lower safety management intentions		
M4: Insufficient safety communication		
M5: Inadequate safety inspection		

Table A2. *Cont.*

Safety Risk Factors	Occurrence Probability Grade	Consequences Severity Grade
EQ1: Malfunction of cutter head equipment		
EQ2: Malfunction of thrust cylinder equipment		
EQ3: Malfunction of screw conveyor		
EQ4: Malfunction of segment erector		
EQ5: Malfunction of grouting equipment		
EQ6: Malfunction of electrical equipment		
TE1: Improper bridge pier reinforcement technic scheme		
TE2: Inadequate geological and hydrological investigation scheme		
TE3: Improper construction monitoring technical scheme		
TE4: Improper excavation technical scheme		
TE5: Improper grouting and reinforcement technical scheme		
TE6: Sealed water-proof technical scheme		
TE7: Improper emergency plan		
NE1: Soft clay layer		
NE2: Silt soil layer		
NE3: Complex soil layer		
NE4: High-pressure underground water		
NE5: Subterranean boulders		
NE6: Subterranean voids		
BC1: Relatively close position of bridge piles and tunnel		
BC2: Friction bridge pile		
BC3: Large bridge pile diameter		
BC4: Poor bridge pile integrity		
BC5: Poor bridge safety condition		
ME1: Poor safety climate		
ME2: Incomplete safety institutions		
ME3: Incomplete safety organization		
ME4: Unclear safety rights and responsibility		
ME5: Inadequate safety training and education		

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