Heliyon 9 (2023) e12924

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Risk factors influencing tunnel construction safety: Structural equation model approach

Yanqun Yang [a,c], Yu Wang [a,c], Said M. Easa [b,c], Xiaobo Yan [a,*]

[a] College of Civil Engineering, Fuzhou University, Fuzhou, China
[b] Department of Civil Engineering, Toronto Metropolitan University, Toronto, Canada
[c] Joint International Research Laboratory on Traffic Psychology and Behaviors, Fuzhou University, Fuzhou, China

ARTICLE INFO

Keywords:
Tunnel construction
Construction safety
Risk factors
Structural equation model

ABSTRACT

At present, the global tunnel construction industry is developing rapidly, but construction accidents are also common. A large number of casualties and property losses are alarming people. It is urgent to pay attention to the causes of tunnel construction accidents, ensure the safety of construction sites, and reduce tunnel construction accidents. Through literature and case analysis, we have sorted out 35 typical tunnel causative factors for research and analysis, which are divided into 7 types. Based on the variable system, we prepared a measurement questionnaire, and 536 valid questionnaires were collected. The structural equation model (SEM) was used to study the relationship between these variables. The influence mechanism and interaction relationship between the variables are analyzed in depth in terms of influence intensity and path coefficient. The results showed that the following six latent variables significantly influence tunnel construction accidents: human factors, material factors, geological exploration design, technical management, safety management, and natural conditions. Natural conditions have the most significant impact, followed by human factors and safety management. Particular attention should be paid to education, training, and safety management in construction risk control. The structural model and research results are helpful to establish the cause theory of tunnel construction accidents, and guide the formulation of safety management policies for tunnel construction projects, reduce tunnel accidents and ensure construction safety.

1. Introduction

Compared with aboveground engineering, the tunnel construction project is limited by the geological environment, an advanced degree of machinery, the construction method, and other factors; as such, the probability and severity of tunnel construction accidents are higher than other geotechnical construction accidents [1]. Once a tunnel construction site accident occurs, such as gushing water, mud bursting, or collapse of the tunnel face, it will affect the construction progress and even cause casualties and severe economic losses. Therefore, by analyzing and finding the influencing factors of tunnel construction accidents and studying the mutual influence of various factors, how to control the risk source of tunnel construction to improve construction safety has become an urgent theoretical and practical problem.

In the early 1990s, scholars began studying tunnel construction's safety risk. Nowadays, many researchers are also actively

* Corresponding author.
E-mail address: geoyxb@fzu.edu.cn (X. Yan).

https://doi.org/10.1016/j.heliyon.2023.e12924
Received 31 August 2022; Received in revised form 5 January 2023; Accepted 9 January 2023
Available online 12 January 2023
2405-8440/

exploring the factor system that affects tunnel construction safety. It is a standard analysis method to analyze the risk sources of tunnel construction through mathematical modeling. Hu et al. (2021) constructed the safety risk system from risk sources and construction units. They developed a safety risk assessment model for Large-sized deep drainage tunnel project construction based on the materials element expansion method. Yu et al. (2021) used the multi-objective particle swarm optimization algorithm to comprehensively consider the risks faced by the project and the dynamic environment. They used a multi-objective genetic algorithm to optimize the decision scheme. Yu and Wang (2019) analyzed the influence of several participating units on the safety risk of tunnel construction and determined the evaluation index of construction safety risk from the aspects of owners, construction units, and design units. Yang et al. (2021) used the work and resource breakdown structure methods to identify tunnel construction risk and used the fault tree theory to qualitatively and quantitatively analyze the identified risk sources. Lin et al. (2020) combined fuzziness and randomness into the cloud model of risk assessment and constructed a risk-level evaluation model. Zhang et al. (2021) used the fault tree method to identify the correlation between the shield's main construction risks and the shield machine's fault alarm data and established a risk prediction model based on the Bayesian network to control the subsequent risks when such faults occur strictly. The research of these scholars has its focus. Still, the comprehensive exploration from the whole tunnel construction project is the scope of these methods is limited, and they focus on selecting schemes under different factors or different factors. Therefore, it is a critical supplement to the current study of tunnel construction accident factors to explore as completely as possible the influencing factors in the system of tunnel construction accidents and to prove the hypothesis of their relationship.

All these studies have identified and analyzed safety risk factors. However, there are still fewer studies on the relationship between safety influencing factors in tunnel construction. Therefore, we use the SEM model to comprehensively study the interaction between risk factors under tunnel construction conditions. In recent years, the structural equation model (SEM) (a statistical method) has been applied to reveal and test hypothetical models and to discover the interactions that exist between variables [2]. The SEM method can handle complex relationships between variables while estimating all coefficients in the model [3]. The SEM method is also used in various disciplines, including the humanities and engineering. For example, the impact of technological and social lean practices on the performance of SMEs in the automotive industry [4]; the relationship between work attitudes and business values [5]; and the interaction between factors influencing tunnel construction accidents [6]. Therefore, the present study adopted the SEM approach to investigate the risk factors and their relationships that influence tunnel accidents.

This study's activities are shown in Fig. 1. The risk factors (latent and observation variables) and research hypotheses are determined based on existing literature and expert opinions. Next, questionnaires were prepared according to the variable system, and the questionnaire data were collected. The data were analyzed using SPSS software. Then, an SEM was developed using the AMOS software to verify the hypothesized relationships between risk factors for tunnel construction accidents. The analysis of impact intensity and path coefficients revealed the causal relationships and interactions within each variable. The results show the importance and relationships among the risk factors affecting tunnel construction safety and make relevant recommendations to improve tunnel construction safety.

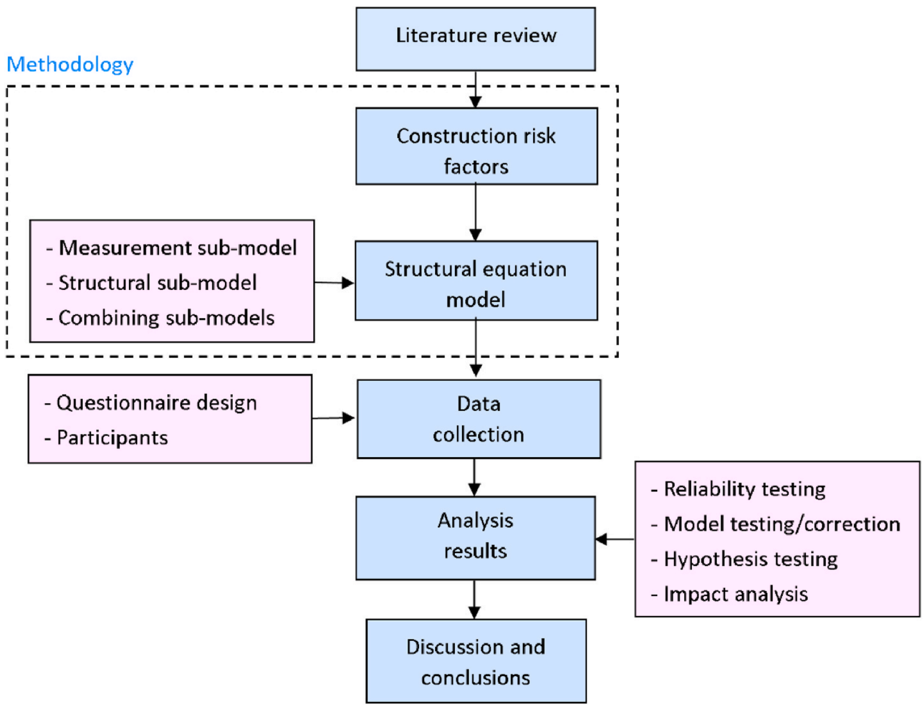

Fig. 1. Study activities.

2. Methodology

2.1. Construction risk factors

2.1.1. Human factors

In Homans' social exchange theory [7], there are four components of any group that are interconnected: activities, interactions, thoughts and emotions, and group norms, and this also applies to tunnel construction projects. BIRD believes that unsafe human behavior is the cause of most accidents [8]. According to statistics, 30% of accidents are purely due to human error, while 60% of accidents occur due to a combination of human causes and natural factors. Human risks are frequent, including poor skills and professionalism, weak safety awareness, and poor physical and mental state. Tunnel construction projects involve personnel, and their professional quality and business ability are directly related to the quality of the project. Studies have shown that the lower the awareness of safety and the more stressful the job, the more likely violations will occur, creating hazards [9]. On the other hand, workers' attitudes toward risk also significantly impact several dimensions of project performance [10]. Therefore, we make the following hypothesis: H1: Human factors have a positive effect on tunnel construction accidents.

2.1.2. Materials factors

There are many construction machinery, materials, and other items at the tunnel construction site. First, the reasonable degree of materials storage at the construction site primarily affects the safety of the site environment. In addition, it is essential to ensure the quality of materials. Machinery and equipment are the main tools of the construction unit, which are vital to realizing the project's construction and are essential for the sustainable development of the construction unit. The large-scale and specialized tunnel construction equipment plays a critical role in the tunnel boring construction progress and project quality, and the quality and operation status of the equipment must be strictly controlled. In addition to mechanical equipment, the quality of construction materials directly affects the quality and safety of the entire construction process. Therefore, we make the following hypothesis: H2 - Materials factors positively affect tunnel construction accidents.

2.1.3. Safety management factors

The focus of tunnel construction safety management is to control the unsafe behavior of people and the unsafe state of things, implement the decisions and goals of safety management, eliminate all accidents, avoid accidental injuries and reduce accidental losses. As analyzed above, tunnel construction technology and mechanical equipment are constantly upgrading. At the same time, it is essential to do an excellent job of digesting and absorbing new technologies and continuously improve the level of operators, technicians and managers through learning and training. On the other hand, it was found that most engineering construction accidents are caused by careless workers and management problems [11]. Accident prevention in construction is not only about developing a list of rules and conducting safety inspections, but also requires a health and safety management system that complies with legal requirements [12,13]. Also, when employees perceive that management cares about their safety, their safety performance will be higher [14]. Frontline managers and supervisors are vital figures in accident prevention [15]. In summary, special training and attention to the technical level, safety awareness and psychological state of personnel can effectively reduce the risk caused by personnel operation errors. Therefore, we make the following hypothesis: H3 - Safety management positively affects the human factor.

As we all know, construction sites are one of the most dangerous places, and safety risks are potentially present in all aspects of the construction process [16]. "Safety first" should be one of the main objectives of any tunnel construction project and must be focused on health, safety and environmental issues to ensure a safe environment at the construction site. The construction site is arranged with various mechanical equipment, construction materials, and other materials. In such a complex environment, there are many sources of risk. Construction accidents such as injuries and explosions caused by improper management of mechanical failures, improper storage of sharp tools, and equipment instability are everywhere [17]. Therefore, we make the following hypothesis: H4–Safety management positively affects material factors.

According to the accident cause theory [18], safety management failures are the root cause of most accidents, and management is the best way to reduce construction accidents. Once the safety management is omitted, it will likely lead to construction accidents [19]. Safety management is an activity to achieve safe production for tunnel construction projects, which directly affects the safety and order of tunnel construction site. Therefore, we make the following hypothesis: H5–Safety management positively affects tunnel construction accidents.

2.1.4. Technical management factors

Current tunnel construction projects are often characterized by large scale, long lead time, and high risks, which require high construction technology and safety management. Furthermore, with the continuous advancement of construction information and automation technology, various new methods and technologies are gradually applied to the construction process, which also increases the difficulty of technical management. During the whole process of tunnel construction, the surrounding rock and support system should be monitored and measured dynamically to adjust the construction parameters in time [20,21], which is vital to guide the construction of the tunnel. Therefore, we make the following hypothesis: H6–Technical management positively affects tunnel construction accidents.

Riella et al. ADDIN EN.CITE <EndNote><Cite><Author>Riella</Author><Year>2015</Year><RecNum>23</RecNum><DisplayText>(Riella, Vendramini, Eusebio, & Soldo, 2015)</DisplayText><record><rec-number>23</rec-number><foreign-keys><key app="EN" db-id="eraptetekvez92ex5xpx2wv1drrdf9s9xwfa" timestamp="1659678324">23</key></

foreign-keys><ref-type name="Book Section">5</ref-type><contributors><authors><author>Riella, Alessandro</author><author>Vendramini, Mirko</author><author>Eusebio, Attilio</author><author>Soldo, Luca</author></authors></contributors><titles><title>The Design Geological and Geotechnical Model (DGGM) for long and deep tunnels</title><secondary-title>Engineering Geology for Society and Territory-Volume 6</secondary-title></titles><pages>991-994</pages><dates><year>2015</year></dates><publisher>Springer</publisher><urls></urls></record></Cite></EndNote>
(2015) [22] proposed tunnel construction accidents are mainly attributed to design and construction errors. Therefore, careful design and timely optimization of the design plans based on geological exploration and monitoring reports are essential to ensure construction quality and safety. Besides, in the technical management of the personnel, regular education, training, and technical briefings can effectively improve the technical level of the personnel. Therefore, we make the following hypothesis: H7–Safety management positively affects technical management.

2.1.5. Natural conditions

The complex natural environment inherently contains a lot of unpredictability and variability, so tunnel construction is also exposed to numerous risk factors that can lead to accidents [23]. Natural conditions are influenced by climate, weather, and other factors, such as alpine regions in the spring temperature rise caused by the melting of permafrost, ice and snow melt water and other phenomena; monsoon regions in the rainy season rainfall caused by the sudden increase in the water content of the surrounding rock caused by mudslides and other phenomena. This variation in the stability of the surrounding rock caused by climate and geographic region may pose significant construction risks and is a major source of safety risk in tunnel construction [24]. The probability of accidents is high under poor geological conditions [25]. In the actual operation process, the survey work is often limited by the topography and geology of the project, resulting in incomplete survey [26]. In summary, we propose the following two hypotheses: H8 - Natural conditions positively affect tunnel construction accidents and H9–Natural conditions positively affect technical management.

2.1.6. Geological exploration and design factors

Geological survey investigates and studies different geological conditions such as rocks, stratigraphic structures, minerals, groundwater and geomorphology in the tunnel construction area. The tunnel design and construction methods are based on the results of the geological survey. The geological exploration for tunnel construction is limited by the technology, cost and natural conditions, and there are problems such as lack of detail and lowexploration accuracy [27]. The geological survey results significantly impact the design and construction links and strongly support the construction project [28]. In particular, the exploration plan design, advanced geological forecast and construction drawing and design should be refined to ensure that the design intent is implemented throughout the construction process. Therefore, we make the following hypothesis: H10–Geological exploration design positively affect tunnel construction accidents and H11–Technical management positively affect geological exploration design.

The surveyor is the critical factor in determining the quality of underground engineering geological survey. In the process of tunnel engineering investigation, a large number of non-professional worker are usually matched with a small number of professional and personnel technicians. However, the overall quality of these investigators, as well as professional knowledge, safety awareness are very serious deficiencies, it is difficult to ensure the quality of the investigation [26]. Therefore, we make the following hypothesis: H12–Human factors positively affect geological exploration design.

Special detection methods and construction techniques are required for areas with poor natural conditions to overcome the impact of poor geological conditions. Especially when the tunnel has to pass through landslide, debris flow, soft soil and other poor geological areas, or other special terrain areas, the necessary engineering and technical measures must be taken to deal with them [29]. Therefore, we make the following hypothesis: H13–Natural conditions positively affect geological exploration design.

2.2. Structural equation model

2.2.1. Measurement sub-model

The measurement sub-model is the confirmatory factor analysis (CFA), which is used to describe the relationship between the observed and latent variables and to measure the observed variables' effect on the latent variables. The measurement sub-model consists of two equations. which represent the relationship between exogenous and endogenous latent variables and measurement variables, respectively. The sub-model is given by

$$\mathrm{x} = \Lambda_{\mathrm{x}} \xi + \delta \quad [1]$$

$$y = \Lambda_y \eta + \varepsilon \quad [2]$$

where, x is an exogenous latent variable; Λ_{x} is the relationship between explicit exogenous variables and exogenous latent variables; ξ is an exogenous latent variable; δ is the error term of the exogenous manifest variable; y is an explicit endogenous variable; Λ_y is the relationship between explicit endogenous variables and endogenous latent variables; η is the relationship between endogenous latent variables; ε is the error term of the endogenous manifest variable. Note that the latent variables cannot be obtained directly, and they need to be described by measurement variables.

As mentioned earlier, many risk factors can affect tunnel construction safety. We finally included 33 observed variables to be measured using the questionnaire. We combined them with expert opinions, as shown in Table 1. Each question item is scored using a 5-point Likert scale from 1 to 5, indicating that the variables were very unrelated, relatively unrelated, uncertain, definitely related, and significantly related to the security event. These questions allowed the respondents to assess the extent to which each factor influenced the safety of the tunnel construction project. The questionnaire items are shown in Table 2.

In addition to the initial 33 risk factors, two additional items, 'objective hazards' (TCA1) and 'subjective hazards' (TCA2), were assigned to determine how respondents weighed the impact of different types of risks on tunnel construction accidents. These two items were also assessed using a Likert scale (i.e., 1 for very unrelated to a safety incident and 5 for very related to a safety incident). Therefore, 35 observed variables were selected to measure the factors influencing tunnel construction safety, as shown in Table 1.

2.2.2. Structural sub-model

The structural sub-model describes the causal structural relationship between latent variables, which can test and estimate whether the causal relationshipss between latent variables are reasonable (also called the causal model). The model is given by

$$\eta = \beta\eta + \Gamma\xi + \varsigma \quad [3]$$

where, η is the relationship between endogenous latent variables; β is the relationship between endogenous latent variables; Γ is the effect of exogenous latent variables on endogenous latent variables; ξ is an exogenous latent variable; ς is the residual term of the structural equation.

Based on the analysis above, six factors, including human factors, can lead to tunnel construction accidents. Moreover, according to Heinrich's chain theory of accident causation [30], an accident is not an isolated event. Instead, a sudden accident at a particular moment may result from a series of factors affecting each other. To assess the interaction between the factors, a preliminary conceptual model was constructed, as shown in Fig. 2.

2.2.3. Combined measurement and structural sub-models

The SEM path diagram of the factors affecting construction accidents was obtained, as shown in Fig. 3, based on the measurement and structural sub-models. Through formula [1–3] and questionnaire data, the causal relationship between variables is measured, and the influence path coefficient is calculated for verification and analysis.

3. Data collection

3.1. Questionnaire design

According to the above variable system, we designed the measurement questionnaire after the revision of expert opinion, finally as shown in Table 2.

3.2. Participants

The questionnaire was released online through the Sojump platform, 581 copies were distributed, 536 valid questionnaires were returned. Among all returned questionnaires, 45 were considered invalid because the scores of each question were precisely the same, with an efficiency rate of 92.3%. The number meets the validity requirement of a sample size greater than 10 times the observed variable [31]. The study was approved by the Human Research Ethics Committee of Fuzhou University. And every respondent signed the informed consent form. The survey respondents were conducted mainly by tunnel construction experts, construction managers, construction technicians, and construction workers, details of which are shown in Table 3.

Table 1
Variables affecting tunnel construction accidents.

Factor (Latent variable)	Observed Variable
Human factors (HF)	Working ability (HF1)、Security awareness (HF2)、Professional quality (HF3)、Health status (HF4)、Mental state (HF5)
Materials factors (MF)	Equipment advancement (MF1)、Equipment operation status (MF2)、Safety devices (MF3)、Quality of construction materials (MF4)、Materials storage (MF5)
Geological exploration design (GED)	Geological Exploration accuracy (GED1)、Drilling design (GED2)、Route design (GED3)、Construction drawing design (GED4)、Implementing the design intent (GED5)
Technical management (TM)	Safety education train (TM1)、Program change (TM2)、Construction organization (TM3)、Quality iInspection (TM4)、Monitoring management (TM5)、Monitoring analysis (TM6)、Geologic analysis (TM7)、Detail design (TM8)、Technical tests (TM9)
Safety management (SM)	System construction (SM1)、System implementation (SM2)、Information receiving (SM3)、Emergency plan system (SM4)、On-site environmental management (SM5)
Natural environment (NC)	Water supply (NC1)、Regional structural (NC2)、Climatic conditions (NC3)、Geologic environment (NC4)
Tunnel construction accident (TCA)	Objective hazard sources (TCA1)、Subjective hazard sources (TCA2)

Table 2
Questionnaire on the impact of tunnel construction accidents.

Number	Observed Variable	Items
1	HF1	What is the degree of obedience to command when tunnel construction site personnel carry out operations, and which is the degree of quality tunnel construction accidents related to operations according to the prescribed processes and methods of operation?
2	HF2	What is the degree to which the level of responsibility and safety awareness of construction site personnel is related to tunnel construction accidents?
3	HF3	What is degree of correlation between whether tunnel construction site personnel have undergone pre-job training, assessment, certification, and business proficiency to meet construction organization and safety management requirements and tunnel construction accidents?
4	HF4	What is the degree of correlation between the age distribution and health of technical and operational personnel on site and tunnel construction accidents?
5	HF5	What is the degree of correlation between the adequacy of rest time and conditions for regulating the physical and mental state of tunnel construction personnel when facing work stress and tunnel construction accidents?
6	MF1	What is the degree of correlation between the degree of massification and specialization of tunnel construction equipment and tunnel construction accidents?
7	MF2	What is the degree of correlation between the quality of inspection work on machinery and equipment and the operational status of major equipment and tunnel construction accidents?
8	MF3	What is the degree of correlation between the installation of escape safety channels and safety signs, the provision of safety protective equipment and spare equipment and tunnel construction accidents?
9	MF4	What is the degree of correlation between the rigor of sampling, testing and retention of all materials on site, the strictness of the acceptance process and tunnel construction accidents?
10	MF5	What is the degree of correlation between the choice of materials management warehouses and materials storage sites, the sorting and storage of all materials (according to e.g. type, origin, size, batch) and tunnel construction accidents?
11	GED1	What is the degree of correlation between the results of combining various types of surveys to accurately discern the level of the surrounding rock and other results and tunnel construction accidents?
12	GED2	What is the degree of correlation between the quantity, point design and quality of completion of pre-drill and physical surveys and tunnel construction accidents?
13	GED3	What is the degree of correlation between the reasonable degree of design route selection, the ability to avoid adverse geological locations and tunnel construction accidents?
14	GED4	When carrying out construction drawing design, which is the correlation between the quality and depth of the design unit's design to meet construction needs and tunnel construction accidents?
15	GED5	What is the degree of relevance of the experience of the design representative assigned to the design unit during on-site construction and the ability to ensure that the construction will carry out the design intent to the tunnel construction accident?
16	TM1	What is the degree of correlation between the quality and implementation of Expanded Education and Training and tunnel construction accidents?
17	TM2	What is the degree of correlation between the construction unit's fulfillment of its responsibility to prepare special construction technology plans for sub-projects and design temporary work plans and tunnel construction accidents?
18	TM3	What is the degree of correlation between whether the construction unit started construction in strict accordance with the construction plan and process and the tunnel construction accident?
19	TM4	What is the degree of correlation between the stringency of quality inspection and acceptance of the implementation of key processes in tunnelling and tunnel construction accidents?
20	TM5	What is the degree of correlation between the test equipment configuration, test qualification, testing frequency and equipment maintenance records and tunnel construction accidents?
21	TM6	What is the degree of correlation between monitoring scope and testing data analysis compliance and integrity and tunnel construction accidents?
22	TM7	What is the degree of correlation between the appropriateness of the advanced geological exploration method, the timeliness and detail of the forecasting work and tunnel construction accidents?
23	TM8	What is the degree of correlation between the timeliness of the design unit in adjusting the construction plan based on monitoring reports and advanced geological forecasts, and tunnel construction accidents?
24	TM9	What is the degree of correlation between the operability of the safety technical handouts and tunnel construction accidents?
25	SM1	What is the degree of correlation between whether a system of sound safety management practices is targeted and tunnel construction accidents?
26	SM2	What is the degree of implementation of the system, such as the main person in charge of safety on site with the degree of correlation with tunnel construction accidents?
27	SM3	What is the degree of correlation between the efficiency of information reception and site handover of personnel in each department and tunnel construction accidents?
28	SM4	What is the degree to which the integrity of the emergency planning system and emergency linkage mechanism is relevant to a tunnel construction accident?
29	SM5	What is the degree of correlation between the effectiveness of control and treatment of environmental problems involving occupational health of personnel, such as dust, noise and food safety, and tunnel construction accidents?
30	NE1	What is the degree of correlation between the water recharge situation at the construction site and tunnel construction accidents?
31	NE2	What is the degree of correlation between the regional structure where the tunnel is located (seismic zone, regional fracture, etc.) and tunnel construction accidents?
32	NE3	What is the degree of correlation between the climatic conditions in the area where the tunnel is located (e.g. alpine region, rainy region) and tunnel construction accidents?
33	NE4	What is the degree of correlation between the geological environment, such as tunnel envelope lithology and geological structure, and tunnel construction accidents?
34	TCA1	What is the degree of correlation between objective hazards (mechanical damage, adverse geology, etc.) and tunnel construction accidents?
35	TCA2	What is the degree of correlation between subjective sources of danger (poor management, weak safety awareness, etc.) and tunnel construction accidents?

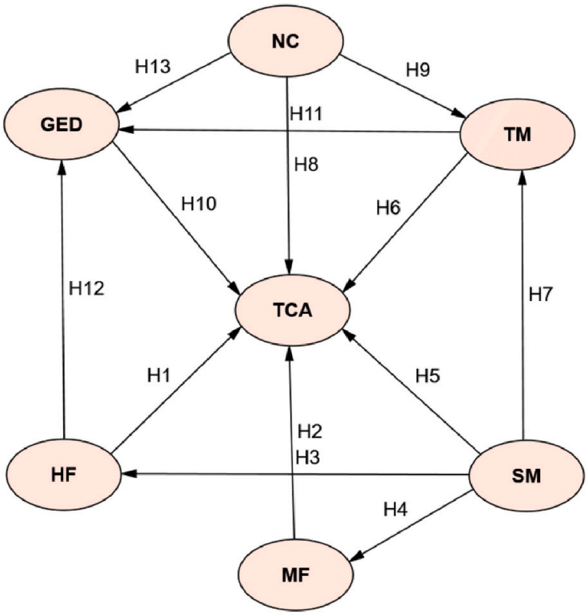

Fig. 2. Structural sub-model of the factors affecting construction accidents.

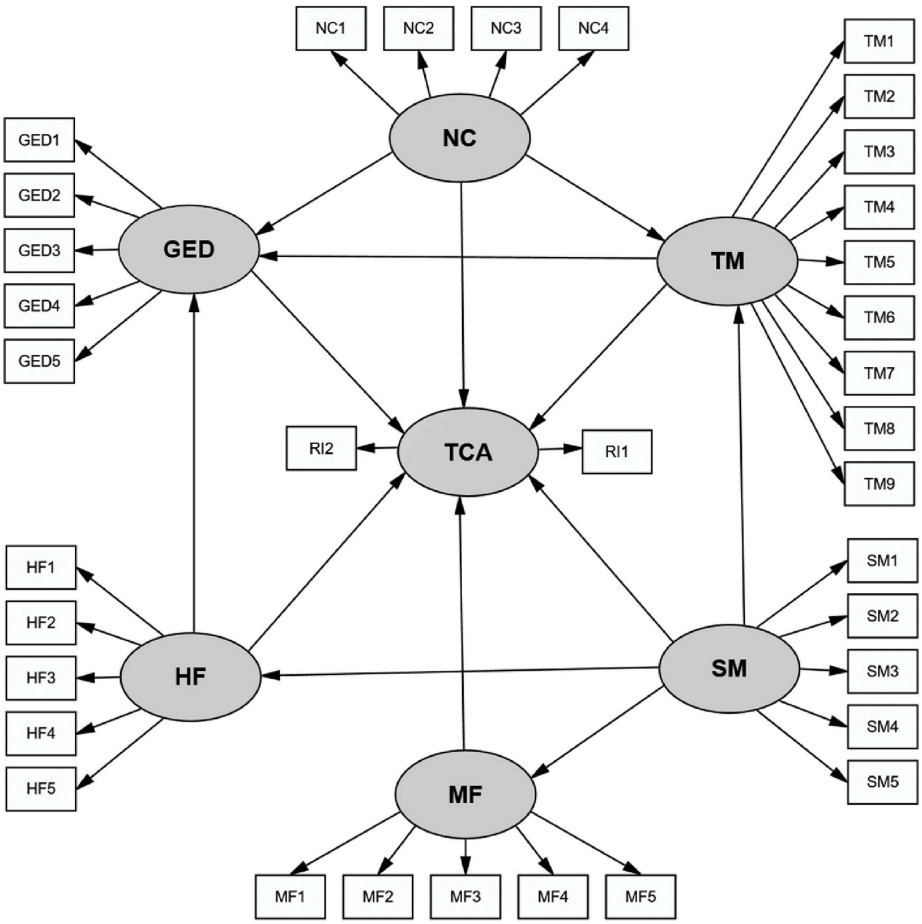

Fig. 3. Paths of the structural equation model.

Table 3
Descriptive statistics results.

Characteristics	Classification	N	%
Sex	Male	493	91.98
	Female	43	8.02
Age	<30	192	35.82
	30–40	157	29.29
	40–50	125	23.32
	>50	62	11.57
Education	College degree and above	190	35.45
	Junior college	113	21.08
	High school	147	27.43
	Middle school and below	86	16.04
Work experience	<1 year	103	19.22
	1–5 years	195	36.38
	6–10 years	181	33.77
	>10 years	57	10.63
Identity	Expert	4	0.75
	Construction manager	82	15.30
	Construction technician	113	21.08
	Construction worker	337	62.87

4. Analysis results

4.1. Reliability testing

SPSS25.0 software was used to measure the internal consistency coefficient of the developed questionnaire. As shown in Table 4, the Cronbachs' alpha coefficients of all seven latent variables were larger than 0.7, indicating that the questionnaire had sufficient internal consistency and high reliability [32]. Next, Bartlett's spherical [33] and KMO tests were used to perform the correlation

Table 4
Confidence validity test.

Latent variable	Observed variables	Cronbachs' α	Factor loading	Contribution rate (%)	Mean
Human factors (HF)	HF1	0.718	0.672	4.361	3.96
	HF2		0.705		
	HF3		0.744		
	HF4		0.607		
	HF5		0.518		
Materials factors (MF)	MF1	0.879	0.721	11.560	4.48
	MF2		0.834		
	MF3		0.858		
	MF4		0.848		
	MF5		0.821		
Geological exploration design (GED)	GED1	0.812	0.561	6.224	3.73
	GED2		0.696		
	GED3		0.784		
	GED4		0.774		
	GED5		0.754		
Technical management (TM)	TM1	0.876	0.477	23.897	4.05
	TM2		0.670		
	TM3		0.615		
	TM4		0.702		
	TM5		0.648		
	TM6		0.683		
	TM7		0.681		
	TM8		0.714		
	TM9		0.866		
Safety management (SM)	SM1	0.879	0.805	7.639	4.55
	SM2		0.816		
	SM3		0.757		
	SM4		0.844		
	SM5		0.808		
Natural conditions (NC)	NC1	0.842	0.727	4.84	4.17
	NC2		0.776		
	NC3		0.748		
	NC4		0.795		
Tunnel construction accidents (TCA)	TCA1	0.761	0.502	2.899	4.22
	TCA2		0.457		

analysis between the variables. The p-value of Bartlett's spherical test was 0.00 (<0.001), and the KMO value was 0.899 (>0.7). According to Kaiser [34], the closer the KMO value is to 1, the higher the correlation of the variables and the more suitable for factor analysis. Therefore, this questionnaire was ideal for factor analysis [35].

Then, factor analysis was conducted using principal component analysis with maximum variance rotation, and seven principal components (HF, MF, GED, TM, SM, NC, TCA) were extracted with a cumulative contribution of 61.420%. The factor loadings of each observed variable were greater than 0.4, indicating that the questionnaire had good structural validity.

Finally, pearson correlation analysis was used to test the relationship between the questionnaire and the mean values of the factors. As shown in Table 5, the mean values of the factors were significantly correlated at the 0.01 significance level, and the correlations among the factors were low to moderately low, indicating good differential validity and a high degree of consistency between the content of the factors tested and the overall content of the questionnaire. In summary, the questionnaire developed in this paper has good reliability and validity.

4.2. Model testing and correction

The test parameters in the proposed model were successfully estimated to assess the fitness of the overall model. However, after the goodness-of-fit test, the GFI and AGFI of the initial volume model failed the fit criteria. In addition, the modification index and critical ration corrections were performed to improve the model's explanatory power. The results are shown in Table 6, where only the AGFI (0.888 > 0.871) was slightly lower than the standard value (0.9). While all other indicators meet their respective criteria, indicating that the modified model fits the data better than the theoretical model. Therefore, the optimized model is considered appropriate.

4.3. Hypothesis testing

The hypothesized relationships were tested by path analysis of the structural equation model. As shown in Table 7, the significance levels of all 13 paths of action were less than 0.01, indicating the acceptance of all hypotheses. Therefore, the occurrence of tunnel construction accidents is profoundly influenced by the following risk factors: human factors, materials factors, geological exploration design, technical management, safety management, and the natural environment. The final structural model was obtained, as shown in Fig. 4.

4.4. Impact analysis

The structural equation model contains variables with multiple influences, and the relationship between the variables is achieved through two or more paths. On the one hand, human factors, materials factors, geological exploration design, technical management, safety management, and natural conditions directly affect tunnel construction accidents. On the other hand: (a) safety management indirectly affects geological exploration design by affecting technical management and in turn construction accidents in mountain tunnels, (b) safety management indirectly affects mountain tunnel construction accidents by affecting human factors, (c) natural conditions indirectly affect mountain tunnel construction accidents by affecting technical management, and (d) technical management, geological exploration and design, and human factors are intermediate variables. Therefore, each latent variable's direct, indirect, and total effects on construction accidents in mountain tunnels were calculated to provide an in-depth analysis of the degree of interaction between the variables. The interaction between the variables explains the model, and the results are shown in Table 7. The direct effect is the impact of each potential variable on the tunnel construction accident, and the value is the path coefficient directly pointing to TCA in Fig. 4. The indirect effect refers to the influence of a factor on TCA indirectly by influencing another factor. The calculation method is the product of all path coefficients. The total effect is the sum of direct impact and indirect impact.

5. Discussion

This paper has considered the effects of multiple factors, and analyzed tunnel construction accidents using the structural equation approach. We proposed a variable system of factors influencing tunnel construction accidents and constructed a structural equation model. Furthermore, the path coefficient and influence relationship between the influencing factors are obtained.

As shown in Table 8, the six influencing factors on tunnel construction accidents are, in descending order, natural conditions,

Table 5
Correlation matrix between the mean values of the factors.

Latent Variable	HF	MF	GED	TM	SM	NC	TCA
HF	1						
MF	0.147[a]	1					
GED	0.385[a]	0.02	1			Symmetrical	
TM	0.339[a]	0.128[a]	0.388[a]	1			
SM	0.170[a]	0.268[a]	0.01	0.259[a]	1		
NC	0.308[a]	0.119[a]	0.360[a]	0.500[a]	0.260[a]	1	
TCA	0.408[a]	0.214[a]	0.444[a]	0.474[a]	0.292[a]	0.518[a]	1

[a] $P < 0.01$.

Table 6
Model fit indexes.

Fit indexes	Absolute suitability index				Value Added Suitability Index		
	CMIN/DF	GFI	AGFI	RMSEA	IFI	TLI	CFI
Before amendment	2.081	0.887	0.871	0.045	0.928	0.922	0.928
After correction	1.851	0.902	0.888	0.040	0.944	0.939	0.944
Fitting criteria	<3.0	>0.9	>0.9	<0.08	>0.9	>0.9	>0.9

Table 7
Hypothesis path test results.

Hypothesis	Action path	Standardized path coefficient β	Significance level P	Conclusion
H1	human factors → geological exploration design	0.34	***	accepted
H2	human factors → tunnel construction accidents	0.19	***	accepted
H3	geological exploration design→ tunnel construction accidents	0.25	***	accepted
H4	natural environment→ geological exploration design	0.23	***	accepted
H5	natural environment→ technical management	0.52	***	accepted
H6	natural environment→ tunnel construction accidents	0.35	***	accepted
H7	technical management→ geological exploration design	0.21	***	accepted
H8	technical management→ tunnel construction accidents	0.15	**	accepted
H9	safety management→ technical management	0.17	***	accepted
H10	safety management→ tunnel construction accidents	0.14	**	accepted
H11	safety management→ human factors	0.17	**	accepted
H12	safety management→ materials factors	0.30	***	accepted
H13	materials factors→ tunnel construction accidents	0.14	**	accepted

**$p < 0.01$; ***$p < 0.001$.

human factors, safety management, geological exploration design, technical management, and materials factors. Natural conditions such as poor rock stability and ground settlement at the construction site cause the highest collapses and water surges, so natural conditions significantly impact tunnel construction accidents. In addition to natural conditions, safety management has a relatively sizeable indirect impact on other factors, and special attention should be paid to the effect of safety management in construction risk control.

As shown in Fig. 4, natural conditions significantly impact technical management ($\beta = 0.52$) and geological exploration design ($\beta = 0.23$). The unique natural conditions led to many potential risk events that severely impacted the drilling design and indoor experiments for the survey work [36,37]. Such construction risks caused by natural factors often require preliminary investigation through exploration work and then unique design for hazardous points to reduce construction accidents indirectly. Therefore, the site selection for the tunnel project should be based on a comprehensive investigation of the local surrounding rock conditions, geological formations, and other natural factors to reduce the difficulty of subsequent technical work. The impact of natural conditions on technical management lies in monitoring analysis and geological analysis, the results of which are essential guidelines for specialized work such as the selection of construction methods.

In addition, human factors ($\beta = 0.34$) and technical management (also affect the geological survey and design ($\beta = 0.21$). Although natural conditionsnatural conditions natural conditions limit the results of geological survey limit the results of geological survey limit the results of geological survey, some difficulties caused by natural conditions can be overcome through the efforts of professional survey and design personnel. The changes of surrounding rock cracks before and during tunnel construction can be accurately measured, and appropriate construction schemes can be designed with the cooperation of professional designers to reduce unexpected collapse accidents. On the other hand, the advanced tunnel geological survey instruments, equipment, technologies, and means are constantly updated, requiring workers to have excellent technical literacy and practical operation quality. Therefore, professional tunnel engineers should make technical delivery to the team in all construction links and strictly follow the critical tunnelling processes, especially the hidden works of anchors, small steel pipes and steel arch frames. The quality of geological exploration and design should be improved to ensure tunnel construction safety.

Safety management significantly affects materials ($\beta = 0.30$), technical ($\beta = 0.34$), and human factors ($\beta = 0.17$), with the most significant effect on the materials factors. The selection, maintenance, and preservation of mechanical equipment, safety materials and construction materials at construction sites are inseparable from safety management. Another primary task of safety management is the management of people. Human behavior is trained and guided by the management unit, and personnel's working conditions and working ability directly affect the completion of construction technology and construction quality [38]. Therefore, management units and related personnel, materials and site management should coordinate and play a joint role. Specific management programs should be provided for materials and people, such as procurement and maintenance for materials, machinery and other equipment, safety education and training programs, etc.

There are also some limitations of this study. First, although we consider different identities of tunnel practitioners, not all types of identities in tunnel construction are included. Second, since the questionnaire is subjective, the respondents may be influenced by social expectations, and in turn may not honestly report the risk factors in tunnel construction [39]. Therefore, in the future, the scope

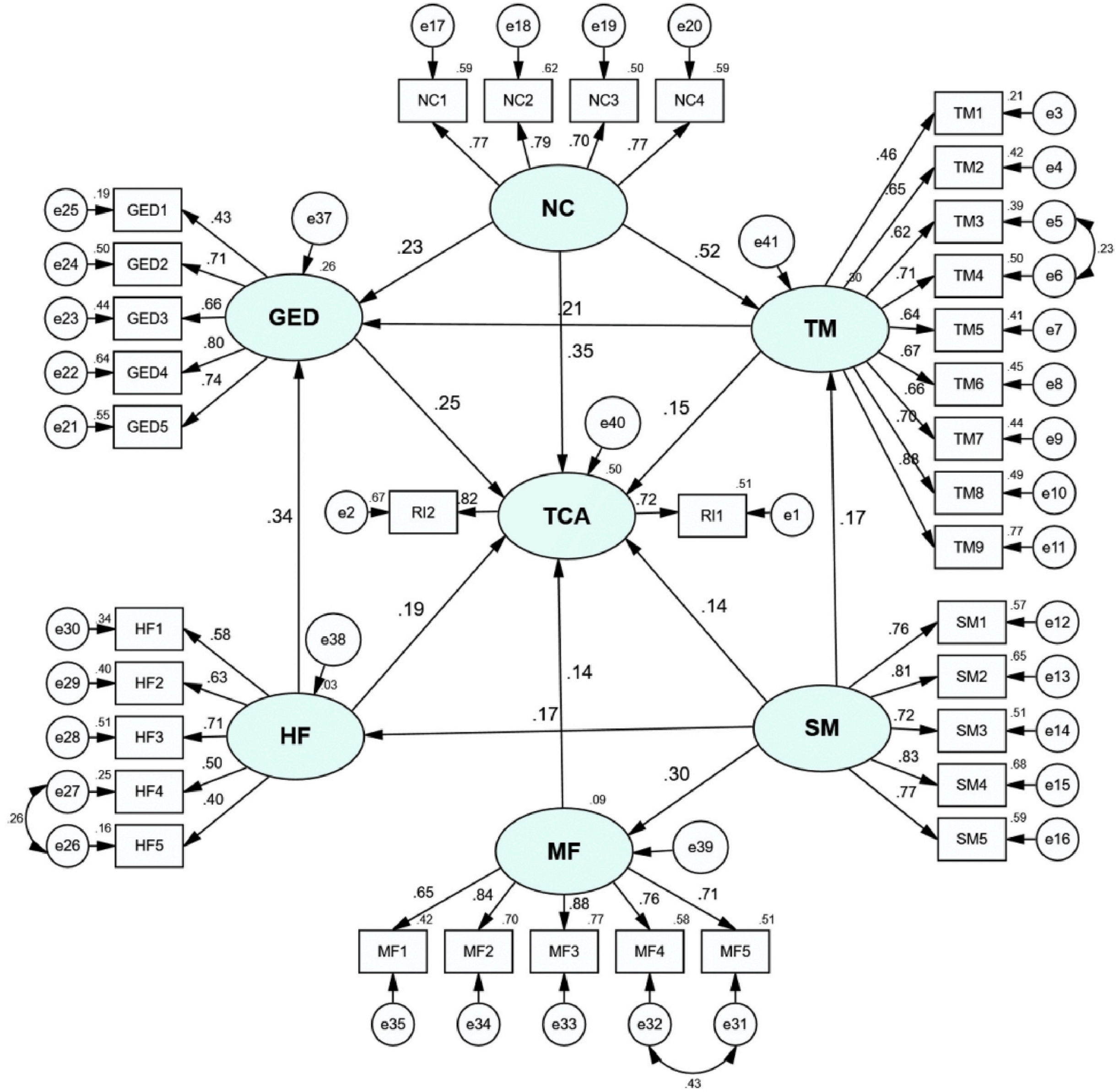

Fig. 4. Risk factors path relationship.

Table 8
Standardized direct, indirect and total effects of latent variables on tunnel construction accidents.

Latent variables	Direct effect	Indirect effect	Total Effect
Human Factors	0.191	0.086	0.277
Materialss Factors	0.139	0.000	0.139
Geological Exploration Design	0.254	0.000	0.254
Technical Management	0.151	0.053	0.204
Safety Management	0.137	0.123	0.260
Natural Conditions	0.352	0.164	0.516

and number of respondents can be expanded to reduce the adverse impact on the experimental results. In addition, with the development of tunnel construction technologies, the influencing factors of tunnel construction accidents can be explored from more dimensions.

6. Concluding remarks

This study reviewed the related literature on tunnel construction characteristics and tunnel accidents. Combined with practical engineering experience, a variable system of the influencing factors of tunnel construction accidents is established, and the interaction mechanism between variables is analyzed using the structural equation model.Based on the research results, the following conclusions are made.

1. The structural equation model effectively describes the internal logic relations of the factors affecting tunnel construction accidents. Furthermore, the existing research conclusions are enriched because the tunnelling tests were conducted about the influence relationships among the variables and all 13 failures.
2. The tunnel construction accidents are mainly affected by 6 factors, in descending order, natural conditions, human factors, safety management, geological exploration design, technical management, and materials factors.
3. Tunnel construction accidents are easily affected by natural conditions and human factors, so we should pay special attention to cutting off the link between them. Risks in the natural environment are identified through survey and design, and it is necessary to develop a long-term practical training and education system to improve tunnel construction practitioners' safety awareness and professional skills, thereby effectively reducing construction accidents.

Author contribution statement

Yanqun Yang: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Yu Wang: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Said M. Easa: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Xiaobo Yan: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data will be made available on request.

References

[1] X. Feng, S. Qui, Tunnelling and Underground Construction in China-Challenges and Progress, in: Paper Presented at the ISRM International Symposium-8th Asian Rock Mechanics Symposium, 2014.
[2] E. Martynova, S.G. West, Y. Liu, Review of principles and practice of structural equation modeling, Struct. Equ. Model.: A Multidiscip. J. 25 (2) (2018) 325–329.
[3] B. Xiong, M. Skitmore, B. Xia, A critical review of structural equation modeling applications in construction research, Autom. ConStruct. 49 (2015) 59–70.
[4] V. Arumugam, G. Kannabiran, S. Vinodh, Impact of technical and social lean practices on SMEs' performance in automobile industry: a structural equation modelling (SEM) analysis, Total Qual. Manag. Bus. Excel. 33 (1–2) (2022) 28–54.
[5] J.K. Harter, F.L. Schmidt, S. Agrawal, S.K. Plowman, A.T. Blue, Increased business value for positive job attitudes during economic recessions: a meta-analysis and SEM analysis, Hum. Perform. 33 (4) (2020) 307–330.
[6] T.-s. Zhao, W. Liu, Y.-J. Zhang, Research on construction process based theory for safety management, Ch. Saf. Sci. J. Beijing 26 (2016) 122–127.
[7] G.C. Homans, Social behavior as exchange, Am. J. Sociol. 63 (6) (1958) 597–606.
[8] F.E. Bird, H. Matthysen, Management guide to Loss Control, National Occupational Safety Association, with the Permission of the Institute Press, Atlanta, Georgia, USA, 1984.
[9] Z.E. Zhou, L.L. Meier, P.E. Spector, The role of personality and job stressors in predicting counterproductive work behavior: a three-way interaction, Int. J. Sel. Assess. 22 (3) (2014) 286–296.
[10] A. Qazi, A. Daghfous, M.S. Khan, Impact of risk attitude on risk, opportunity, and performance assessment of construction projects, Proj. Manag. J. 52 (2) (2021) 192–209.
[11] K.A. Brown, P.G. Willis, G.E. Prussia, Predicting safe employee behavior in the steel industry: development and test of a sociotechnical model, J. Oper. Manag. 18 (4) (2000) 445–465.
[12] A.S.J. Holt, Principles of Construction Safety, John Wiley & Sons, 2008.
[13] D.C. Russell, The consulting engineer in the 21st century, Appita: Technol. Innov. Manuf. Environ. 57 (6) (2004) 436–439.
[14] D. Langford, S. Rowlinson, E. Sawacha, Safety Behaviour and Safety Management: its Influence on the Attitudes of Workers in the UK Construction Industry, Engineering, Construction and Architectural Management, 2000.
[15] R.A. Haslam, S.A. Hide, A.G. Gibb, D.E. Gyi, T. Pavitt, S. Atkinson, A.R. Duff, Contributing factors in construction accidents, Appl. Ergon. 36 (4) (2005) 401–415.
[16] S. Antomarioni, M.M. Bellinello, M. Bevilacqua, F.E. Ciarapica, R.F. da Silva, G.F.M. de Souza, A data-driven approach to extend failure analysis: a framework development and a case study on a hydroelectric power plant, Energies 13 (23) (2020) 6400.
[17] A. Kumar Mishra, P. Aithal, Job safety analysis during tunnel construction, Int. J. Appl. Eng. Manag. Lett. (IJAEML) 5 (1) (2021) 80–96.
[18] D. Fang, X. Huang, J. Hinze, Benchmarking studies on construction safety management in China, J. Construct. Eng. Manag. 130 (3) (2004) 424–432.
[19] S. Mohamed, Safety climate in construction site environments, J. Construct. Eng. Manag. 128 (5) (2002) 375–384.
[20] J. Cao, R. Zhao, L. Hu, Q. Liang, Z. Tang, Application of Internet of things based on wireless sensor in tunnel construction monitoring, J. Sens. (2022).
[21] Z. Fang, Z. Zhu, P. Wu, R. Wang, C. Ma, Z. Wang, Excavation and support method of tunnel with high ground stress and weak surrounding rock based on GIS, Arabian J. Geosci. 14 (7) (2021) 1–13.
[22] A. Riella, M. Vendramini, A. Eusebio, L. Soldo, The design geological and geotechnical model (DGGM) for long and deep tunnels, in: Engineering Geology for Society and Territory 6, 2015, pp. 991–994.

[23] L. Ding, L. Zhang, X. Wu, M.J. Skibniewski, Y. Qunzhou, Safety management in tunnel construction: case study of Wuhan metro construction in China, Saf. Sci. 62 (2014) 8–15.
[24] A. Aalianvari, H. Katibeh, M. Sharifzadeh, Application of fuzzy Delphi AHP method for the estimation and classification of Ghomrud tunnel from groundwater flow hazard, Arabian J. Geosci. 5 (2) (2012) 275–284.
[25] E.-S. Hong, I.-M. Lee, H.-S. Shin, S.-W. Nam, J.-S. Kong, Quantitative risk evaluation based on event tree analysis technique: Application to the design of shield TBM, Tunn. Undergr. Space Technol. 24 (3) (2009) 269–277.
[26] V. Komolvilas, W. Tanapalungkorn, P. Latcharote, S. Likitlersuang, Failure analysis on a heavy rainfall-induced landslide in Huay Khab mountain in Northern Thailand, J. Mt. Sci. 18 (10) (2021) 2580–2596.
[27] Z. Xu, W. Wang, P. Lin, L. Nie, J. Wu, Z. Li, Hard-rock TBM jamming subject to adverse geological conditions: influencing factor, hazard mode and a case study of Gaoligongshan Tunnel, Tunn. Undergr. Space Technol. 108 (2021), 103683.
[28] J.-s. Wang, L. Wang, Y. Li, Y.-x. Zhang, Z.-g. Cao, C.-l. Li, Tectonic evolution and the analysis of unfavorable geology in a tunnel, J. Coal Sci. Eng. 15 (4) (2009) 374–381.
[29] L. Soldo, M. Vendramini, A. Eusebio, Tunnels design and geological studies, Tunn. Undergr. Space Technol. 84 (2019) 82–98.
[30] H.W. Heinrich, Industrial Accident Prevention. A Scientific Approach, in: Industrial Accident Prevention. A Scientific Approach, second ed., 1941.
[31] P.M. Bentler, C.-P. Chou, Practical issues in structural modeling, Socio. Methods Res. 16 (1) (1987) 78–117.
[32] R.C. MacCallum, M. Roznowski, C.M. Mar, J.V. Reith, Alternative strategies for cross-validation of covariance structure models, Multivariate Behav. Res. 29 (1) (1994) 1–32.
[33] M.S. Bartlett, The effect of standardization on a χ 2 approximation in factor analysis, Biometrika 38 (3/4) (1951) 337–344.
[34] H.F. Kaiser, An index of factorial simplicity, Psychometrika 39 (1) (1974) 31–36.
[35] F.J. Al-Mahameed, X. Qin, R.J. Schneider, M.R.R. Shaon, Analyzing pedestrian and bicyclist crashes at the corridor level: structural equation modeling approach, Transport. Res. Rec. 2673 (7) (2019) 308–318.
[36] S.-C. Li, S.-C. Li, Q.-S. Zhang, Y. Xue, W. Ding, S. Zhong, Y. Lin, Forecast of karst-fractured groundwater and defective geological conditions, Chin. J. Rock Mech. Eng. 26 (2) (2007) 217–225.
[37] D.-x. Liang, Z.-q. Jiang, S.-y. Zhu, Q. Sun, Z.-w. Qian, Experimental research on water inrush in tunnel construction, Nat. Hazards 81 (1) (2016) 467–480.
[38] T.S. Abdelhamid, J.G. Everett, Identifying root causes of construction accidents, J. Construct. Eng. Manag. 126 (1) (2000) 52–60.
[39] D.G. Fischer, C. Fick, Measuring social desirability: Short forms of the Marlowe-Crowne social desirability scale, Educ. Psychol. Meas. 53 (2) (1993) 417–424.