# Study on the dynamic evolution of safety risks with activities in the construction of metro shield method

Na Xu, Chaoran Guo*, Xueqing Zhou

**Abstract:** The complex construction process of the metro shield method often leads to metro construction safety accidents, resulting in significant casualties and property damage. The various construction stages of metro shield construction comprise different construction activities and are accompanied by different safety risk factors. Therefore, the safety risk factors of metro shield construction have the characteristic of dynamic evolution with the activities. However, the traditional risk assessment often evaluates the risk factors as a whole before the shield construction but does not evaluate the risk factors dynamically by construction stages and by construction activities. To fill this gap, this paper aims to construct a dynamic bayesian-based safety risk assessment model for metro shield construction from the perspective of changing construction stages and activities. First, safety risk factors were identified using the WBS-RBS method. Then, a three-stage dynamic assessment model of safety risks was constructed to depict the shield launch, shield tunnel, and shield reach. Safety risk factors in each stage changed with the activities and the time. Besides, the risk factors in the former stage may affect the factors in the following stage. Dynamic bayesian network (DBN) was improved to address the model with the triangular fuzzy number and the leaky noisy-or-gate extension model. Finally, a case study was conducted. The model proposed in this paper enables to reveal the dynamic evolution of safety risks triggered by different construction activities. It offers a new simulated model for the prevention of safety accidents in the construction of metro shield method.
**Keywords:** Risk assessment and analysis; Construction safety; Metro shield construction; Dynamic Bayesian Network.

## 1 Introduction

The construction industry is well known as a highly risk prone industry (Renault et al., 2016)[1]. Within the construction industry, metro construction is especially dangerous (Zhou et al., 2022)[2]. The metro project is a complex system project, featuring a large construction scale, many construction participants, complex construction techniques and a changing operating environment (Li et al., 2022, Liu et al., 2018, Li et al., 2018)[3-5]. Shield construction technology has become a popular construction method for urban metro construction due to its high degree of mechanization, low environmental impact during construction and the adaptability of the shield to the strata. The characteristics of metro shield construction determine to a certain extent the risks of construction.

The safety risks of metro shield construction are inseparable from the construction activities. Different construction activities can give rise to different risk factors. Risk analysis should be divided into different construction phases according to the guidelines or criteria for engineering risks (Eskesen et al., 2004, Mohurd China, 2012)[6-7]. Risk factors are dynamic in nature, evolving from inception to extinction. However, traditional risk management usually treats construction activities as static variables (Enshassi et al., 2020)[8]. Lack of research on risk changes from the perspective of construction activities. Commonly practiced static risk analysis approaches fail to fit with the dynamic nature of the construction project process. To a certain extent, this has led to the occurrence of safety risk accidents in the construction of the metro shield method. This makes it extremely difficult for metro construction safety risk managers to manage.

This paper mainly contributes to:

(1) Proposing safety risks in metro shield construction safety risks have dynamic and time-series evolutionary characteristics. Dynamicity is reflected in the dynamic change of risk along with construction activities. The chronological nature is reflected in the fact that the development of the risk itself changes continuously over time.

(2) The shield construction is divided into three stages: shield launch, shield tunnel and shield reach. Based on DBNs, a "three-stage" safety dynamic risk assessment model is proposed. The model can reveal the dynamic evolution of the relationship between the construction activities and safety risk factors of the shield method of the metro.

In the next sections, the current state of research on the identification and assessment of safety risks in the construction of metro shields is first reviewed. Then, a dynamic risk assessment model is proposed. This is followed by step-by-step experiments using case study and an analysis of the results. Finally, conclusions are drawn to inform the reader of opportunities for future research.

## 2 literature review

The safety risks of metro construction projects are related to many influencing factors. Such as the construction form of the station or tunnel, construction technology, hydrogeological conditions and the surrounding environment (Ding et al., 2012)[9]. Zhang (2019)[10] through statistical analysis of data from 200 metro tunnel construction accidents, the metro construction safety risk factors are classified into four categories: geological risk factors, construction technology risk factors, environmental risk factors and management risk factors. Wu (2020)[11] summarized the risk factors into hydrogeological factors, riverine factors, tunnel design factors, external environmental factors and construction management factors, based on statistics on the causes of safety accidents in underwater shield tunnel construction and the environment faced by the actual project. Li (2018)[12] used SPSS20.0 software to conduct cluster analysis on China's metro construction accident data and classified safety risk knowledge sources into three categories: technical risk, geological risk and environmental risk. In summary, metro construction safety risk factors usually contain four types of risk: mechanical risk factors, personnel operation risk factors, management risk factors and environmental risk factors. The above research has laid the foundation for this paper on the identification of safety risks in metro shield construction.

The risk identification study focuses on metro shield construction as a whole. On the identification of safety risks in the construction of the metro shield method. Zhang (2016)[13] proposed a BIM-based risk identification expert system (B-RIES) to address the shortcomings of the traditional safety risk identification process in metro construction. Liu (2018)[14] used exploratory factor analysis (EFA) and structural equation model (SEM) to identify nine common safety risk factors during shield machine tunneling construction. Pan (2019)[15] identified risk factors in terms of mechanical damage, ground collapse, gushing water and mud, and gas leakage and explosion based on fuzzy entropy theory. Xing (2019)[16] developed a domain ontology (SRI-Onto) to formalize knowledge of safety risks in metro construction to support safety risk identification. However, the above-mentioned studies generally regard the construction of metro shield method as a static construction stage. The identification of safety risk factors in shield construction from a dynamic perspective is lacking. Zhou (2021)[17] proposed a building information model (BIM)-based risk identification method for metros, which improves the efficiency of safety risk-specific design.

Risk assessment for identified risk factors, a tool for building proactive safety strategies (Labib and Read, 2013)[18]. In terms of research on the safety risk assessment of metro shield method construction, Hamidi (2010)[19] used event trees to construct a risk assessment model to quantitatively evaluate the construction risk of the underwater shield method in the Han River. Luo (2019)[20] established a new safety risk assessment model for subway close-attached undercrossing construction using Analytic Hierarchy Process (AHP) and Fuzzy Matter Element Method (FMEM). Lyu (2020)[21] addressed the difficulty of establishing a consistent judgment matrix in the fuzzy analytical hierarchy process (FAHP), and the method was applied to the risk assessment process for the Jinan metro tunnel construction. Wang (2017)[22] used a fuzzy integrated Bayesian Network (FCBN) to assess the safety risk of an underground construction project under uncertainty. Zhao (2018)[23] proposed an assessment of risk factors for tunnel excavation based on a database of incident reports. Zhou (2020)[24] assessed risks during construction by coupling a risk management system and a quality management system in the Xiamen Metro Line 3 project. Gong (2020)[25] provided a wealth of knowledge for the safety risk assessment of deep foundation construction solutions through a machine learning approach.

The above literature reveals that research has mainly focused on static risk assessment, ignoring the impact of risk interactions (Xue et al., 2020)[26]. Currently, scholars are gradually beginning to conduct research from the perspective of dynamic risk. Safety risk factors are constantly changing and interacting with each other during the long-term construction process. Dynamically changing safety risk factors make it difficult for managers to predict their security status (Xu et al., 2020)[27]. Zhou (2013)[28] developed a 4D model by integrating safety risks with the construction management process. It achieved that the safety status of relevant components can be continuously visualized in the system as safety risks evolve. Zhang (2013)[29] Used BN for security control in dynamic and complex project environments. This provides a new systematic decision support model for the construction of shield tunnels in the Yangtze underground in Wuhan. Wu (2015)[30] used a systematic approach of BN for underground tunnel construction for dynamic risk analysis. BN is powerful in dealing with uncertain information and can use conditional probabilities to calculate the probability of unknown parameters. However, it is limited in its ability to handle dynamic time series information. BN generally does not take into account the relevance of information before and after time and does not allow for dynamic assessment (Qian et al., 2020)[31]. DBNs, on the other hand, have great advantages in handling time series information and have been used in dynamic risk assessment studies (Wu et al., 2016)[32]. Liu (2018)[33] used DBNs to model the risk management process of complex systems, overcoming the difficulties of modelling dynamic large-scale systems. Liu (2020)[34] developed a dynamic Bayesian

Copula model to reflect the time-varying effects of the environment adjacent to the construction of the metro shield method. This method allows an accurate assessment of the structural reliability of the tunnel. Zhang (2022)[35] proposed a complex interaction between risk factors that cause accidents by analyzing the dynamic change characteristics of accident causation. However, the above studies lacked consideration of changes in safety risk factors triggered by changes in construction activities. It is difficult to reflect the dynamic evolution pattern of safety risk factors at each stage of metro shield launch, shield tunnel and shield reach.

## 3 Dynamic evolution Characteristics of safety risks with activities

Metro shield construction safety risks are dynamic and sequential in nature (Zhou et al., 2020)[36]. The dynamic nature is reflected in the fact that risk factors change dynamically with construction activities. The metro shield is divided into three construction stages: shield launch, shield tunnel and shield reach. The different construction stages contain different construction activities and generate different safety risks. Some of the safety risk factors emerge and disappear with the construction activities. These factors are referred to in this paper as direct risk factors and typically include technical factors, human factors, and environmental factors. Some safety risk factors are present throughout the construction of the shield and do not change with the construction activities. These are referred to in this paper as indirect risk factors and usually include management factors. Indirect safety risk factors often lead to safety incidents through direct safety risk factors.

The temporal characteristics are reflected in two aspects: firstly, the probability of occurrence of risk factors varies at different times. When several construction activities are carried out simultaneously, the probability of risk factors occurring is higher. As the construction activities are completed, the probability of the risk factors occurring decreases. Secondly, the impact between risk factors can change over time. If managers manage different construction activities in different construction sections, the impact of the level of management on construction activities will change. Therefore, the safety risks of metro shield method construction have a time-series character.

Fig_1 illustrates the evolution of safety risk factors with activity in the shield method of metro construction. $W_1$ indicates the shield launching stage, $W_2$ the shield tunneling stage and $W_3$ the shield reaching stage. A second digit is added under each construction stage to indicate the specific construction activity. The metro shield construction safety risk factors are classified into mechanical risk factors ($RM_1$), personnel operational risk factors ($RH_2$), management risk factors ($RA_3$) and environmental risk factors ($RE_4$). $R_1$ is used to represent the launching stage safety risk, $R_2$ the tunneling stage safety risk and $R_3$ the reaching stage safety risk.

The shield launching stage, the shield tunneling stage and the shield reaching stage are interlinked as a dynamic construction whole. The initial network of the shield tunnel BN is the end state of the completion of construction activities in the shield launching stage. The initial network of the shield reaching stage BN is the end state when the construction activities of the shield tunneling construction stage are completed. This results in three successive 'time steps' of metro shield construction risk evolution. Each end of construction activity in the diagram corresponds to a T moment, and the three stages of construction activity unfold in sequence. As shown in Fig_1, moments 0-$T_0$ represent the duration of the shield launching stage, moments $T_0$-$T_1$ represent the duration of the shield tunneling stage and moments $T_1$-$T_2$ represent the duration of the shield reaching stage. The solid arrow line represents the causal relationship between the construction activity and the direct safety risk factor, e.g., $R_1M_1$ has a direct effect on the construction activity $W_{11}$. The dotted arrows represent the causal relationship between indirect safety risk factors and direct safety risk factors, e.g., $R_1A_3$ has an effect on $R_1H_2$ and thus acts on $W_{12}$. The environmental and management risk factors at the end of the shield start stage affect the construction activities at the beginning of the shield tunnel, e.g., $R_1E_4$ affects $R_2M_1$ and thus $W_{21}$ and $W_{22}$. The management and environmental risk factors at the end of the shield tunneling stage affect the construction activities at the beginning of the shield reaching stage, e.g., $R_2A_3$ affects $R_3H_2$ and thus $W_{32}$.

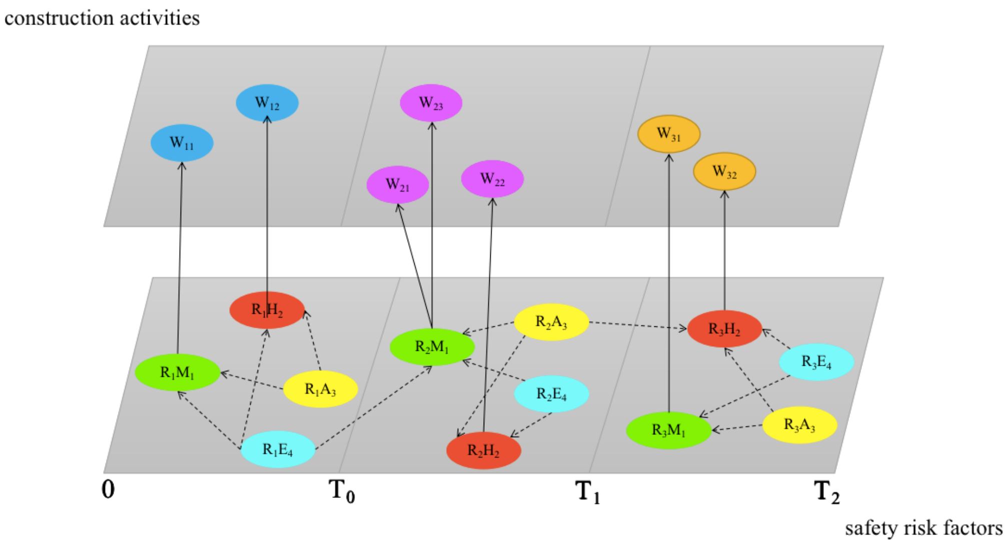



**Figure 1 Dynamic change diagram of construction activities and safety risk factors**

## 4 Dynamic evolution model based on improved DBN

According to the dynamic and time-series characteristics of the safety risks of metro shield construction, the use of DBNs is proposed to construct a risk assessment model. Reduce the computation of conditional probabilities by adding auxiliary nodes to the Bayesian network. Dynamic Bayesian networks are established by identifying dynamic nodes based on construction activities. In this case, the prior probabilities of the safety risk factor nodes and the transfer probabilities of the dynamic nodes are calculated using triangular fuzzy numbers. The conditional probabilities of the child nodes are obtained using the Leaky Noisy-or Gate model.

DBN is an extension of the static BN in the time-series space, adding the influence of the time factor on the model to the BN. DBNs link the temporal relationships of adjacent time steps to the causal relationships of individual time steps. It is effective in dealing with uncertainty, temporal and dynamic problems.

### 4.1 Bayesian Network topology construction and optimization

Bayesian Networks are probabilistic graphical models that represent relationships between variables by pointing arrows (H.-J. Lenz, 2011)[37], As shown in Fig_2(a). The nodes represent safety risk factors and Ri is the parent of the child node R. The arrow line indicates the causal relationship between the safety risk factors. The strength of association between nodes is expressed using conditional probabilities (Nordgård and Sand, 2010)[38].

Let risk factor $R_1, R_2, \cdots R_n$ influence risk factor R, the variables are mutually exclusive and $P(R_i) > 0$. Assuming that there is a risk factor R and that the occurrence of the risk factor R occurs at the same moment as the other risk factors $R_1, R_2, \cdots R_n$, the Bayesian formula is expressed as follows:

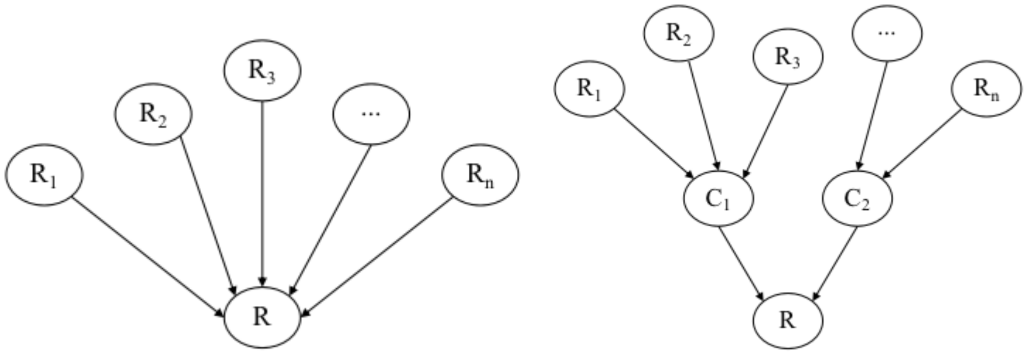
$$P\left(R_i \middle| R\right) = \frac{P\left(R_i\right)\ P\left(R \middle| R_i\right)}{\sum_{j=1}^{n} P\left(R_i\right)\ P\left(R \middle| R_i\right)} \tag{1}$$

$P(R_i)$in the formula denotes the probability of $R_i$ occurring and is the prior probability of node $R_i$, which can be obtained using expert knowledge or experience (Namazian and Yakhchali, 2018. Zhang et al., 2016)[39-40]. $P(R_i|R)$ denotes the probability of $R_i$ occurring given the conditions under which R occurs and is the posterior probability of $R_i$. In a BN, the posterior probabilities are obtained by updating the prior probabilities (Neapolitan 2007)[41]. $P(R|R_i)$ is then the conditional probability of the child nodes in the BN.

In this study, the nodes in a BN are considered as binary variables, i.e. each node corresponds to only two risk states. The safety risk factor is denoted by F when it occurs and by T when it does not occur. If poor shield selection adaptability = F, indicating that poor shield selection adaptability occurs; Poor shield selection adaptability = T, indicating that poor shield selection adaptability does not occur. So when the child node *R* has multiple parents $R_1$, $R_2$, $R_3$, …, $R_n$, the conditional probability $P(R|R_1, R_2, \ldots, R_n)$ is as in Eq.(2), a total of $2^n$ parameters need to be calculated. As the number of parent nodes increases, the number of parameters to be calculated by the child nodes grows significantly. And by adding the auxiliary node $C_i$, the conditional probability calculation of the BN can be reduced (As shown in Fig_2b).

$$P\left(R\middle|R_p\right) = 1 - \prod_{i:R_i \in R_n}\left(1 - P_i\right) \tag{2}$$

where $R_p$ denotes the other terms of the conditional probability table of node R.




**(a)** **(b)**

**Figure 2 (a) BN before optimization; (b) Optimized BN**

### 4.2 Dynamic Bayesian Network building

On the basis of the static BN topology, a safety risk state transfer network is identified to construct a DBN. State transfer networks are networks that implement the transition from static BNs to DBNs (Li et al., 2019)[42]. Firstly, the trends in the direct safety risk factors associated with construction activities and the impact of indirect safety risk factors on construction activities are identified as they unfold. Next, dynamic nodes are set up using this influence relationship. Finally, a state transfer network is created based on the influence of indirect safety risk factors on direct safety risk factors.

Fig_3 shows a schematic diagram of the state transfer network, in which node $R_t^i$ represents the value of the i-th safety risk factor taken at moment t. The arrow line indicates the causal relationship between the dynamic node at moment t and the dynamic node at moment t+1. Cause at moment t, effect at moment t+1.

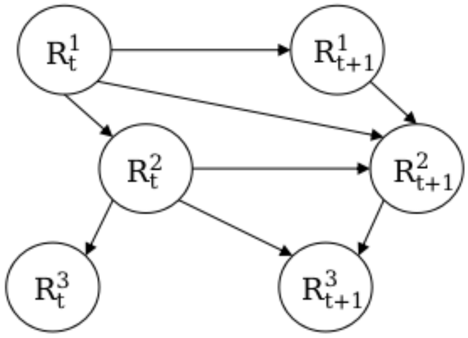



**Figure 3 State transfer network**

The Markov hypothesis considers that the probability of a node at time t+1 is only influenced by moment t and is independent of the time segment before moment t (Xiao, 2007)[43]. The conditional probability process at adjacent times is smooth, i.e., the conditional probability table for each node at each moment and the transfer probabilities between moments do not change over time (F. Bartolucci,2006. P.-A. Brameret et al.,2015)[44-45]. Based on these two assumptions, DBN can be represented by $(B_0, B_\rightarrow)$. $B_0$ is the initial network BN and $B_\rightarrow$ denotes the state transfer network between two adjacent time steps (Xiang and Zhou, 2020)[46]. The conditional probability distribution between two adjacent time steps can be expressed as:

$$P\left(R_{t+1}\middle|R_t\right) = \prod_{i=1}^{n} P\left(R^i_{t+1}\middle|P_a\left(R^i_{t+1}\right)\right) \tag{3}$$

where $P_a\left(R_{t+1}^i\right)$ denotes the parent node of $R_{t+1}^i$.

### 4.3 A priori probability determination based on triangular fuzzy numbers

BN nodes have multi-state characteristics and the exact probabilities of multi-state events are difficult to obtain. Therefore, this study uses a triangular fuzzy number approach to calculate the probability of occurrence of safety risk factor nodes in BNs. Triangular fuzzy numbers are denoted by $\tilde{A} = (a, b, c)$ , $a \le b \le c$, where *a, b* and *c* are real numbers and denote the minimum possible value, the possible value and the maximum possible value respectively.

In order to ensure the objectivity of the domain experts' judging results, natural language variables are introduced to represent the triangular fuzzy numbers. The natural language variables for the degree of risk impact are expressed in seven levels of natural language: very low, fairly low, low, medium, high, fairly high, very high, etc. (Wickens, 2021)[47]. The correspondence is shown in Table 1.

**Table 1 Triangular fuzzy numbers corresponding to natural language variables.**

| natural language variables | triangular fuzzy numbers |
|---|---|
| Very Low (VL) | 0.0, 0.0, 0.1 |
| Low(L) | 0.0, 0.1, 0.3 |
| Fairly Low (FL) | 0.1, 0.3, 0.5 |
| Medium (M) | 0.3, 0.5, 0.7 |
| Fairly High (FH) | 0.5, 0.7, 0.9 |
| High (H) | 0.7, 0.9, 1.0 |
| Very High (VH) | 0.9, 1.0, 1.0 |

The area-mean method (Lan and Fan, 2010)[48] is used to transform the fuzzy mean probabilities into probability values that best represent that fuzzy set. The formula for fuzzy number averaging is expressed as follows：

$$P_{ij,\ A} = \frac{a_{ij} + 2b_{ij} + c_{ij}}{4} \tag{4}$$

Eq. (4) is used to transform the triangular fuzzy number into a fixed value based on the experts' judgement. Use this value as the a priori probability of the safety risk factor.

### 4.4 Determination of state transfer probabilities

In a DBN topology, the transfer probabilities of dynamic nodes at moments t greater than 1 need to be calculated. This is used to determine the probability values of dynamic nodes over time. P ($R_t$=F,$R_{t+1}$=T) denotes the probability that if node R occurs at moment t, it will not occur at moment t+1. There are four combinations of transfer probabilities for dynamic nodes R, P($R_t$=F, $R_{t+1}$=T)、P($R_t$=F, $R_{t+1}$=F)、P($R_t$=T, $R_{t+1}$=F)、P($R_t$=T, $R_{t+1}$=T).

The transfer probabilities of dynamic nodes are found by converting the assessment results of domain experts into triangular fuzzy numbers. The specific algorithm is calculated in the same way as the a priori probability of the safety risk factor.

### 4.5 Conditional probabilistic inference algorithms

Each variable in the Noisy-or-gate model (Feng et al., 2020)[49] is regarded as a binary variable, corresponding to two different states, true value 1 and false value 0, respectively. Each variable is sufficient to cause R to occur when the other variables are false. However, the occurrence of child nodes in BNs is not necessarily caused by the occurrence of parent nodes but may be caused by other unknown factors. So, by fusing the unknown factors into one factor $R_x$ according to the Leaky Noisy-or Gate model (Henrion,1989)[50], the probability of connection $P_i$ between parent and child nodes can be solved.

$$P_i = \frac{P\left(R \middle| R_i\right) - P\left(R \middle| \overline{R_i}\right)}{1 - P\left(R \middle| \overline{R_i}\right)} \tag{5}$$

The connection probabilities $P_1, P_2, \ldots, P_i, \ldots, P_n$ between node R and its parent node can be calculated according to Eq. (5). The conditional probability of node R can be obtained by combining the probability of connection $P_x$ with the unknown factor $R_x$.

## 5 Case study

### 5.1 Project Overview

Taking the first phase of a city metro line 6 project (Project X) as the research object, the shield tunneling interval F from station C to station D was selected for the assessment of the safety dynamic risk of the metro shield method construction. The shield interval from Station C to Station D starts at ZDK7+810.710~ZDK8+336.482, with a left line length of 525.772m. The starting mileage is YDK7+810.70~ YDK8+334.512, the right line is 523.802m long. Maximum longitudinal slope of the zone 13‰, minimum longitudinal slope 5.077‰. Minimum depth of burial approximately 10.2m, maximum depth of burial approximately 12.8m. The shield tunneling interval has a small topographic relief with an overall high northeast and low southwest. The geological background of the substrate is stable and there are no other adverse or special geological effects affecting the stability of the site. The groundwater type is mainly bedrock fissure diving. The upper part of the shield tunneling interval is mainly woodland and agricultural land. The shield equipment is an earth pressure balanced shield machine, ZTE 6250, manufactured by China Railway Construction Heavy Industry Group Co. This section of the interval line is scheduled to be excavated from 1 June 2022 and the shield tunneling will be completed on 1 October 2022.

### 5.2 Questionnaire Survey Design

The data to be collected for this experiment was obtained using questionnaires and expert interviews. The data obtained from (1) are used to construct a theoretical model for the evolution of safety risks in the construction of the metro shield method. Then a case study of project X is carried out through (2) and (3).

(1) Questionnaire A: correspondence relationship of work and risk. Research units include metro shield construction units, supervisory units, units in charge of construction, design units and a small number of universities and research institutes. The target group was experts with at least 3 years' experience in metro shield construction (Table 2). A total of 48 questionnaires were distributed and 43 questionnaires were returned, with a return rate of 89.6%.

(2) Questionnaire B: Project X safety risk factors occurrence probability and transfer probability data collection. Interviews were conducted with five managers from the construction units, supervisory units, units in charge of construction and design units working on X projects.

(3) Questionnaire C: Project X conditional probability data collection. Survey respondents and recoveries are as in (2).

The survey data all passed the reliability and validity tests.

**Table 2 Basic information of respondent**

| Survey Respondent Information | Category | Number of samples | Percentage of total |
|---|---|---|---|
| Working Unit | Construction Unit | 4 | 9.3% |
| | Supervisory Unit | 5 | 11.6% |
| | Unit in charge of construction | 27 | 62.8% |
| | Design Unit | 5 | 11.6% |
| | Universities & Research Institutes | 2 | 4.7% |
| Title | Technical staff | 1 | 2.4% |
| | Assistant level | 5 | 11.6% |
| | Engineers | 24 | 55.8% |
| | Associate Senior | 12 | 27.8% |
| | Full Senior | 1 | 2.4% |
| Years of experience | 3-5 years | 14 | 32.6% |
| | 5-10 years | 16 | 37.2% |
| | 10-15 years | 7 | 16.2% |
| | 15-20 years | 3 | 7.0% |
| | 20 years and above | 3 | 7.0% |

### 5.3 Identification of work-based safety risk factors

Based on the literature research related to the safety risks of metro shield construction, *Code for construction and acceptance of shield tunneling method* (GB50446-2017)[51] and *Standard for construction safety assessment of metro engineering* (GB50715-2011)[52] and other information, establish the WBS-RBS (Work Breakdown Structure-Risk Breakdown Structure) of metro shield construction (Siami-Irdemoosa, 2015, Wang, 2020)[53-54].

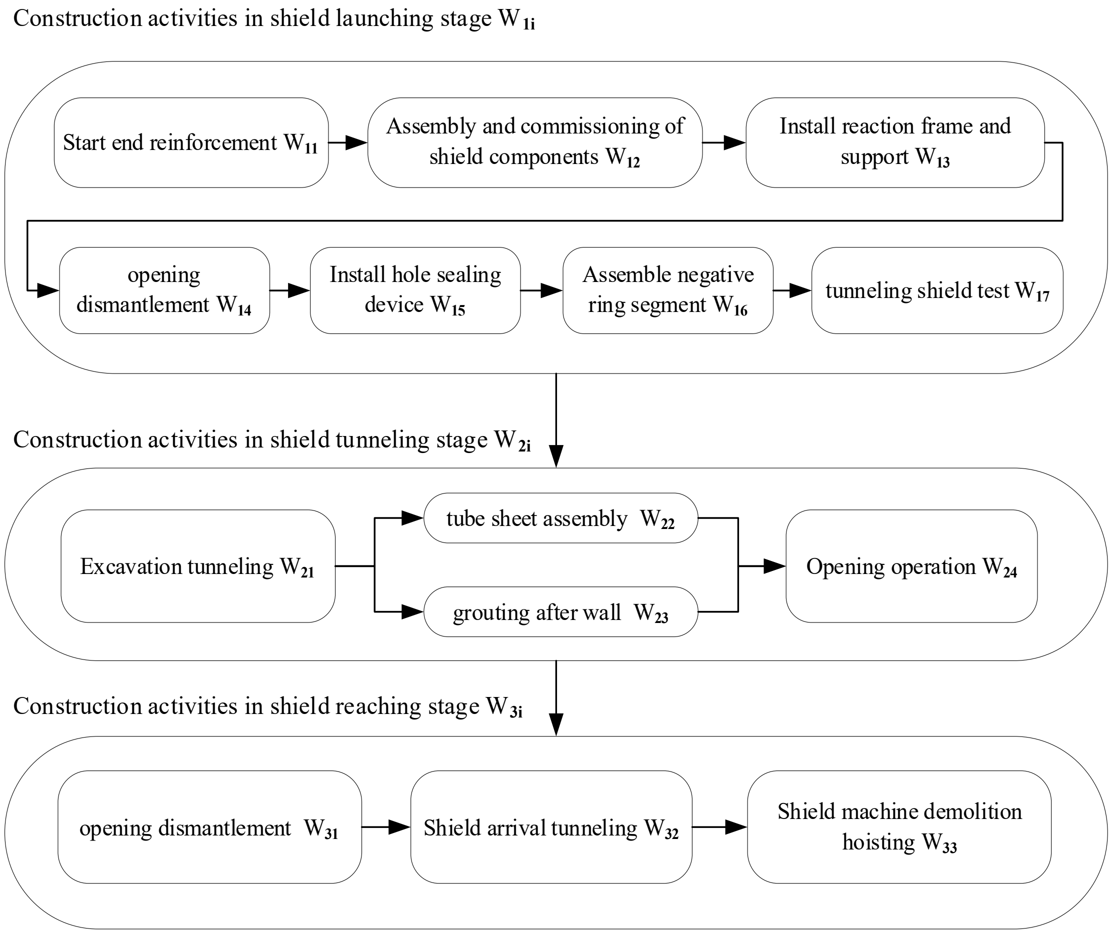



**Figure 4 Metro Shield Construction WBS**

From mechanical risk factors, personnel operation risk factors, management risk factors and environmental risk factors, the safety risks of shield launch, shield tunnel and shield reaching stages are broken down respectively. (Fig_5)

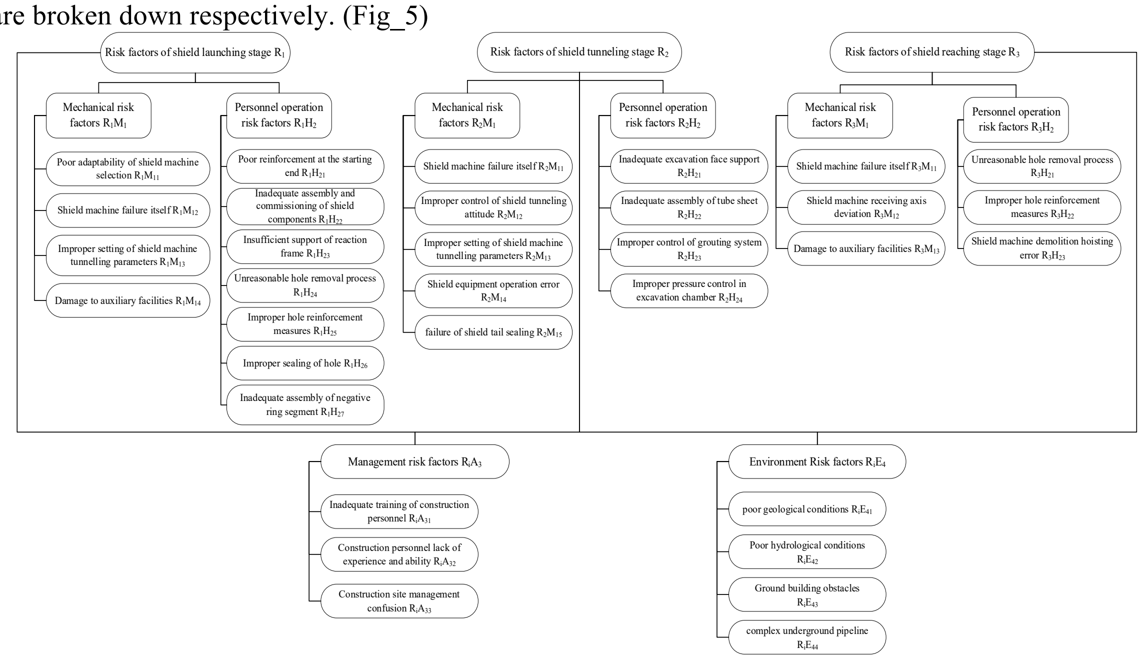



**Figure 5. Metro Shield Construction RBS**

Based on Questionnaire A, collect the WBS-RBS mapping relationships. If half or more of the experts believe that a construction activity corresponds to a safety risk factor, the mapping relationship is considered to exist, otherwise it is considered not to exist. Finally, a list of safety risk factors for the construction of the shield method is shown in Table 3.

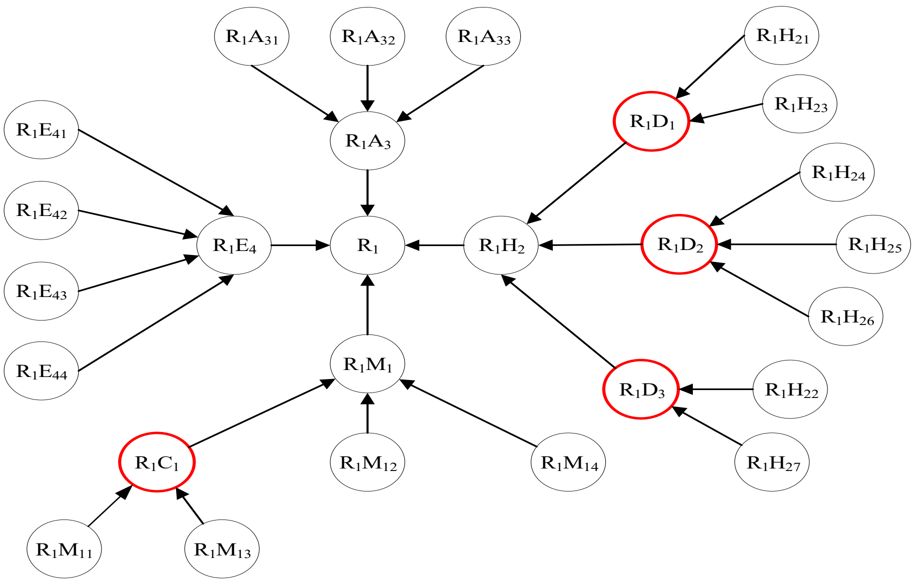
**Table 3 work-based safety risk factors**

| Construction activities | Safety risk factors |
|---|---|
| Start end reinforcement $W_{11}$ | Poor reinforcement at the starting end $R_1H_{21}$ |
| Assembly and commissioning of shield components $W_{12}$ | Inadequate assembly and commissioning of shield components $R_1H_{22}$ |
| Install reaction frame and support $W_{13}$ | Insufficient support of reaction frame $R_1H_{23}$ |
| opening dismantlement $W_{14}$ | Unreasonable hole removal process $R_1H_{24}$<br>Improper hole reinforcement measures $R_1H_{25}$ |
| Install hole sealing device $W_{15}$ | Improper hole reinforcement measures $R_1H_{25}$<br>Improper sealing of hole $R_1H_{26}$ |
| Assemble negative ring segment $W_{16}$ | Inadequate assembly of negative ring segment $R_1H_{27}$ |
| tunneling shield test $W_{17}$ | Poor adaptability of shield machine selection $R_1M_{11}$<br>Shield machine failure itself $R_1M_{12}$<br>Improper setting of shield machine tunnelling parameters $R_1M_{13}$<br>Damage to auxiliary facilities $R_1M_{14}$ |
| Excavation tunneling $W_{21}$ | Shield machine failure itself $R_2M_{11}$<br>Improper control of shield tunneling attitude $R_2M_{12}$<br>Improper setting of shield machine tunnelling parameters $R_2M_{13}$<br>Inadequate excavation face support $R_2H_{21}$ |
| tube sheet assembly $W_{22}$ | Inadequate assembly of tube sheet $R_2H_{22}$ |
| grouting after wall $W_{23}$ | failure of shield tail sealing $R_2M_{15}$<br>Improper control of grouting system $R_2H_{23}$ |
| Opening operation $W_{24}$ | Shield equipment operation error $R_2M_{14}$<br>Improper pressure control in excavation chamber $R_2H_{24}$ |
| opening dismantlement $W_{31}$ | Unreasonable hole removal process $R_3H_{21}$<br>Improper hole reinforcement measures $R_3H_{22}$ |
| Shield arrival tunneling $W_{32}$ | Shield machine failure itself $R_3M_{11}$<br>Shield machine receiving axis deviation $R_3M_{12}$<br>Damage to auxiliary facilities $R_3M_{13}$ |
| Shield machine demolition hoisting $W_{33}$ | Shield machine demolition hoisting error $R_3H_{23}$ |
| Whole Process of Shield Construction W | Inadequate training of construction personnel $RA_{31}$<br>Construction personnel lack of experience and ability $RA_{32}$<br>Construction site management confusion $RA_{33}$<br>poor geological conditions $RE_{41}$<br>Poor hydrological conditions $RE_{42}$<br>Ground building obstacles $RE_{43}$<br>complex underground pipeline $RE_{44}$ |

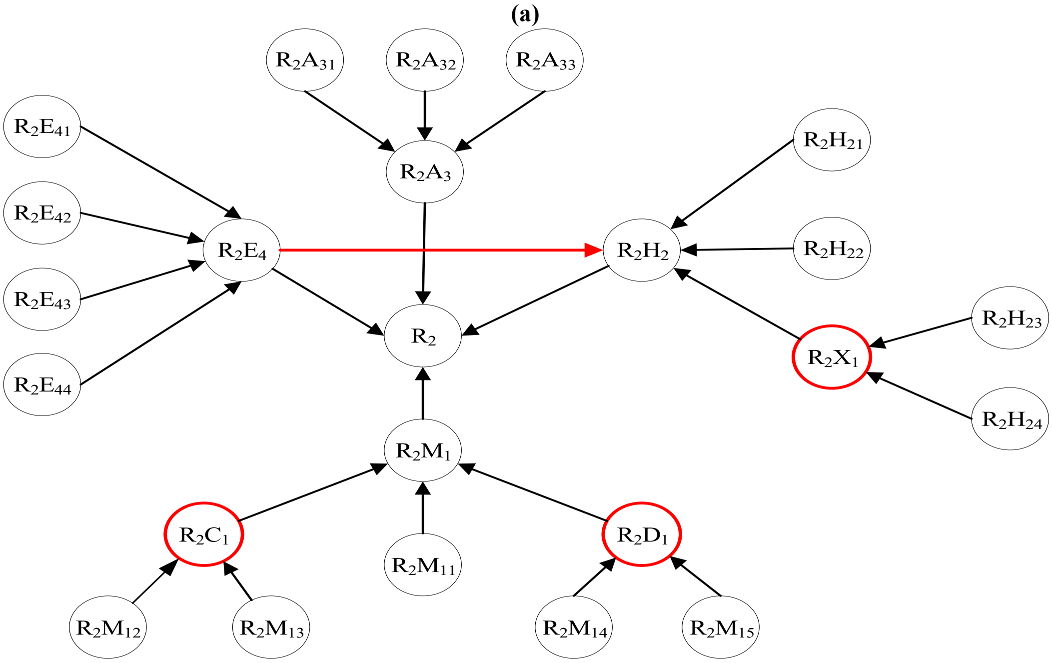
## 5.4 Bayesian Network topology

A BN topology based on a hierarchy of safety risk factors. In the shield launching stage BN, four auxiliary nodes are added: shield machine parameter setting problem $R_1C_1$, end reinforcement problem $R_1D_1$, Tunnel portal chiseling and sealing problem $R_1D_2$, and shield machine assembly and tube piece assembly fault $R_1D_3$. In the shield tunneling stage BN structure, three auxiliary nodes are added to the shield machine parameter setting problem $R_2C_1$, shield equipment problem $R_2D_1$ and system control failure $R_2X_1$.The constructed BNs for the shield launching stage, shield tunneling stage and shield reaching stage are shown in Fig_6a-c.

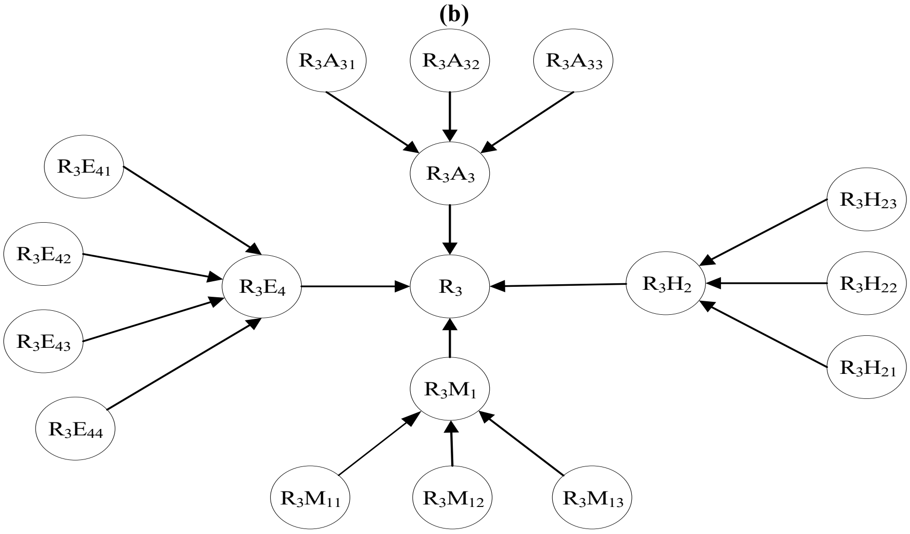
The environmental risk factors indirectly influence the operational risk factors of personnel and thus the risk of the shield tunneling system. In the shield tunnel process, the interval lines are longer compared to the shield launching stage and the shield tunneling stage. Therefore, the duration of the impact of environmental risk factors on personnel operational risk factors during construction is longer than during the shield launching and reaching stages of construction activities. Therefore, the causal relationship between environmental risk factors and personnel operational risk factors is increased in the BN topology for the shield tunneling stage.




**(a)**




**(b)**

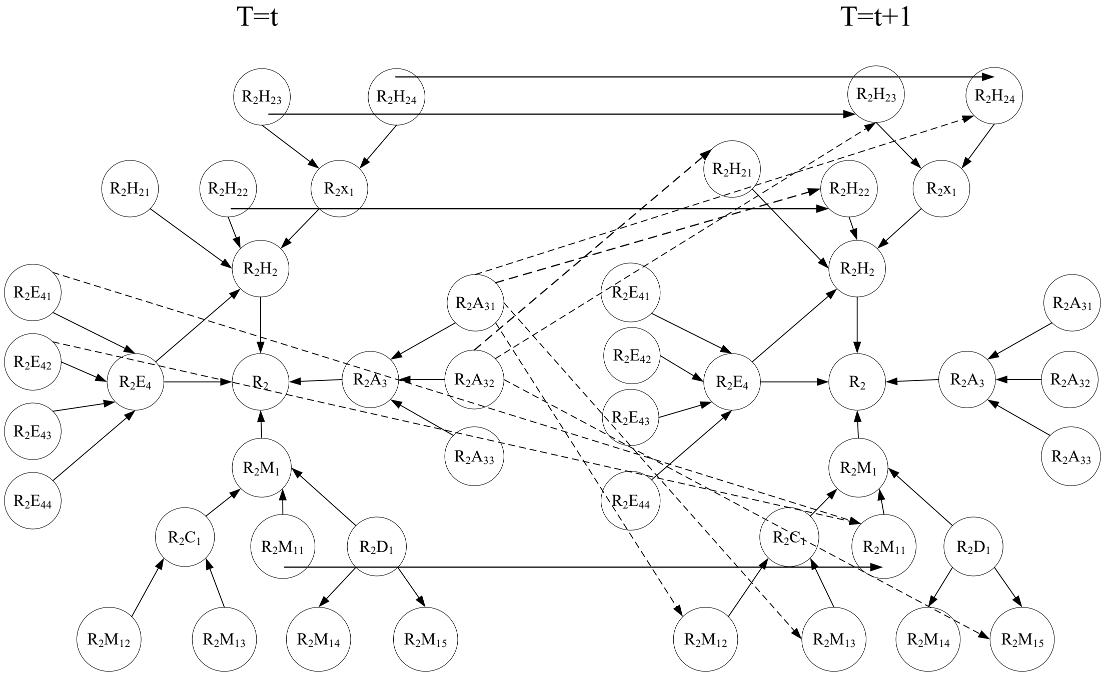



**(c)**

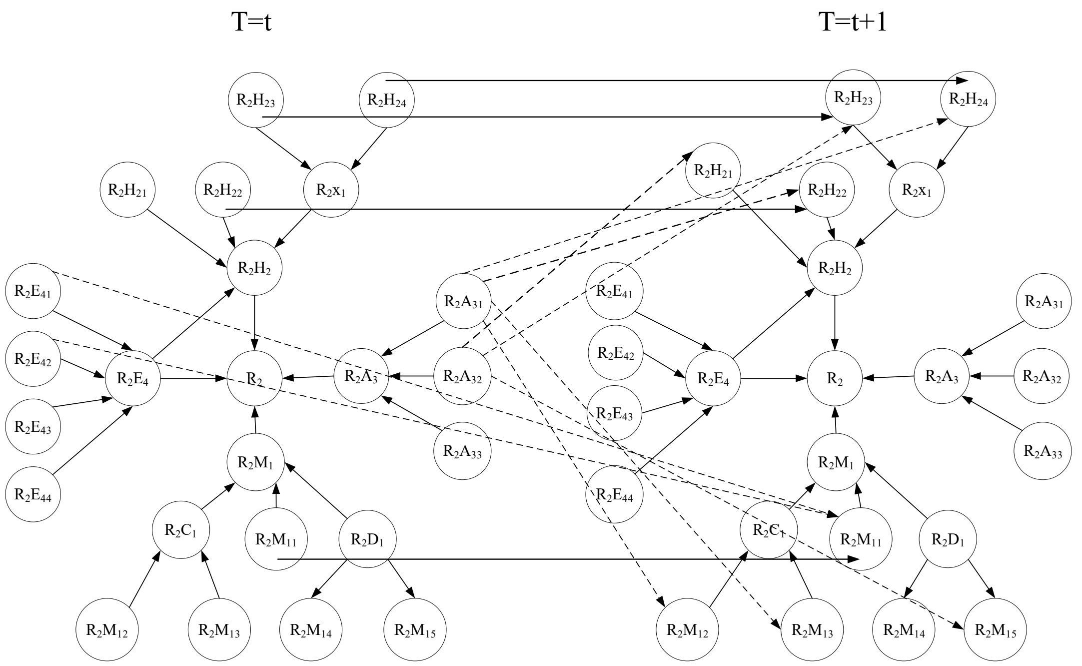
**Figure 6 (a) BN topology in shield launching stage; (b) BN topology in shield tunneling stage; (c) BN topology in shield reaching stage**

## 5.5 Safety Risk State Transfer Network

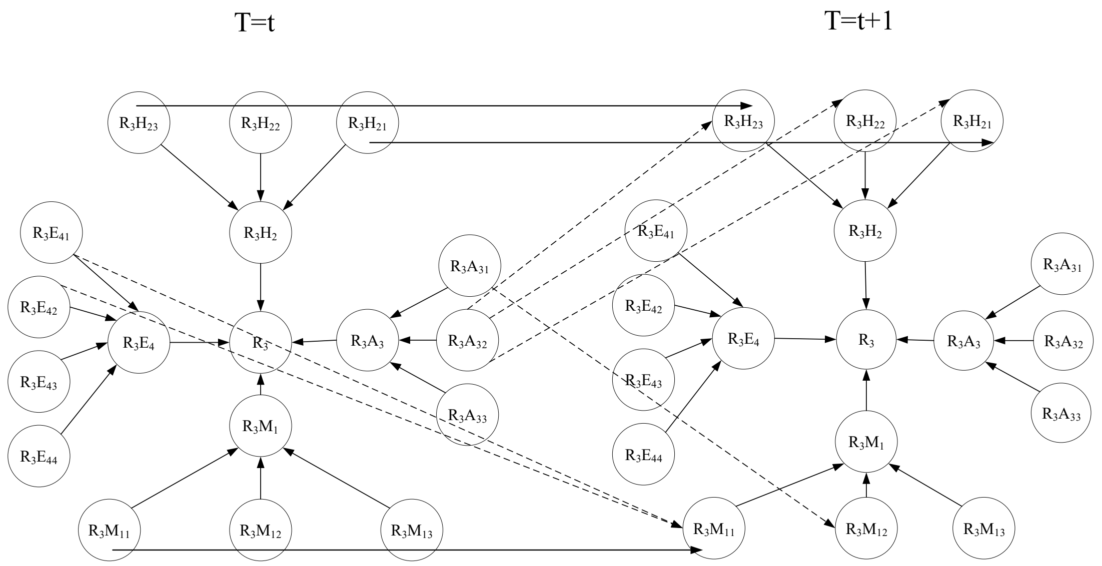
During the shield launching stage, the start end reinforcement $W_{11}$(T=t+1) will be directly influenced by the poor reinforcement at the starting end $R_1H_{21}$(T=t) at the previous moment. Then there is the real arrow line pointing from the dynamic node $R_1H_{21}$(T=t) to $R_1H_{21}$(T=t+1). Construction personnel lack of experience and ability $R_1A_{32}$(T=t) will result in insufficient support of reaction frame $R_1H_{23}$(T=t+1), thus indirectly affecting the Install reaction frame and support $W_{13}$(T=t+1). Then there is an imaginary arrow line pointing from node $R_1A_{32}$ (T=t) to $R_1H_{23}$ (T=t+1). The dynamic nodes enable the trend of the direct safety risk factors associated with construction activities to be clarified as well as the impact of indirect safety risk factors on construction activities. The state transfer network for the three stages of shield construction is shown in Fig_7a-c. Moments t to t+1 represent the influence of the static BN at the previous moment on the static BN at the next moment.




**(a)**




**(b)**

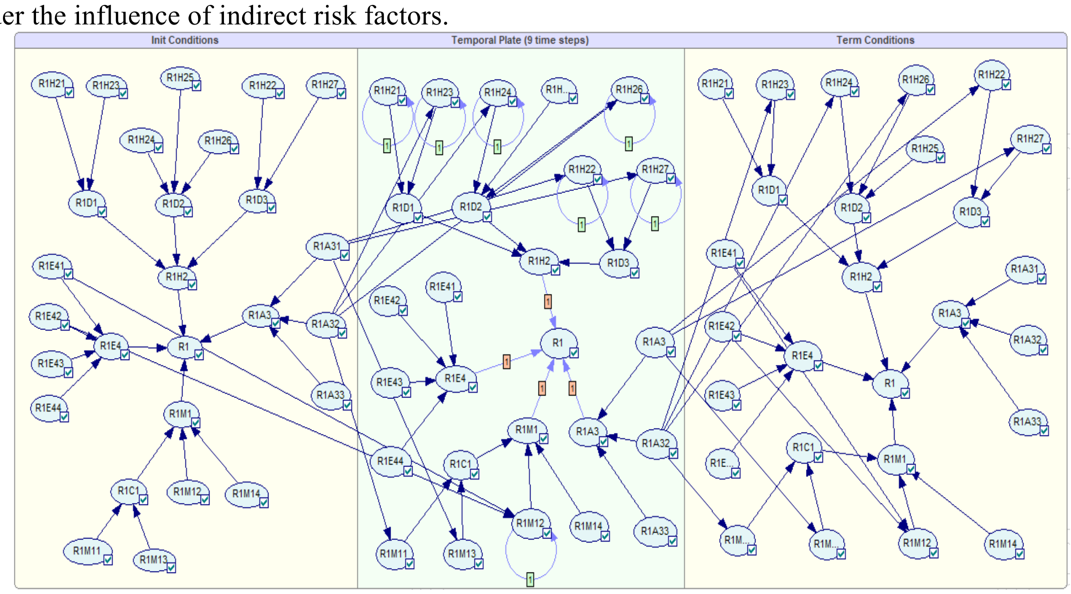



**(c)**

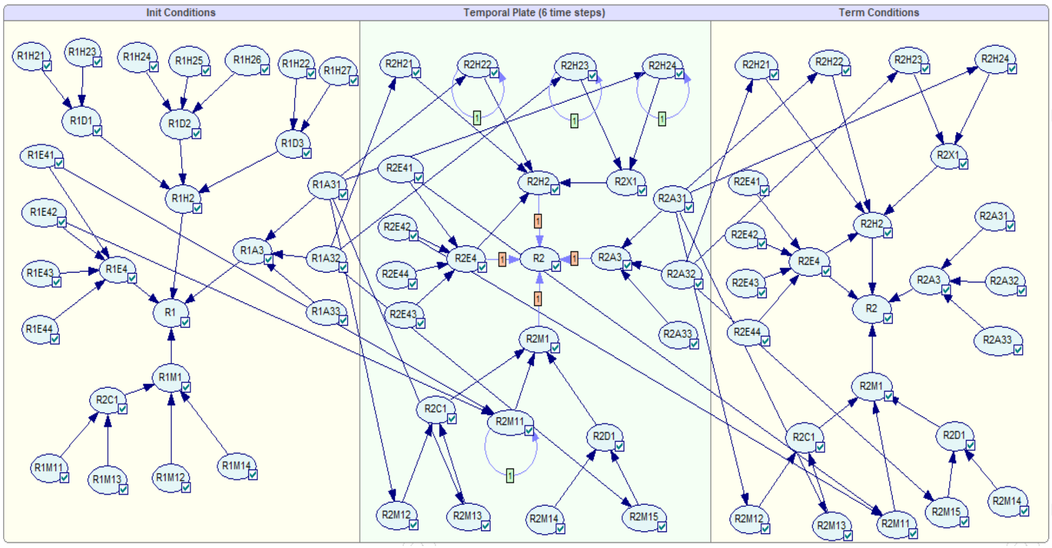
**Figure 7 (a) Shield launching stage state transfer network; (b) Shield tunneling stage state transfer network; (c) Shield reaching stage state transfer network**

### 5.6 Three-stage dynamic assessment model construction

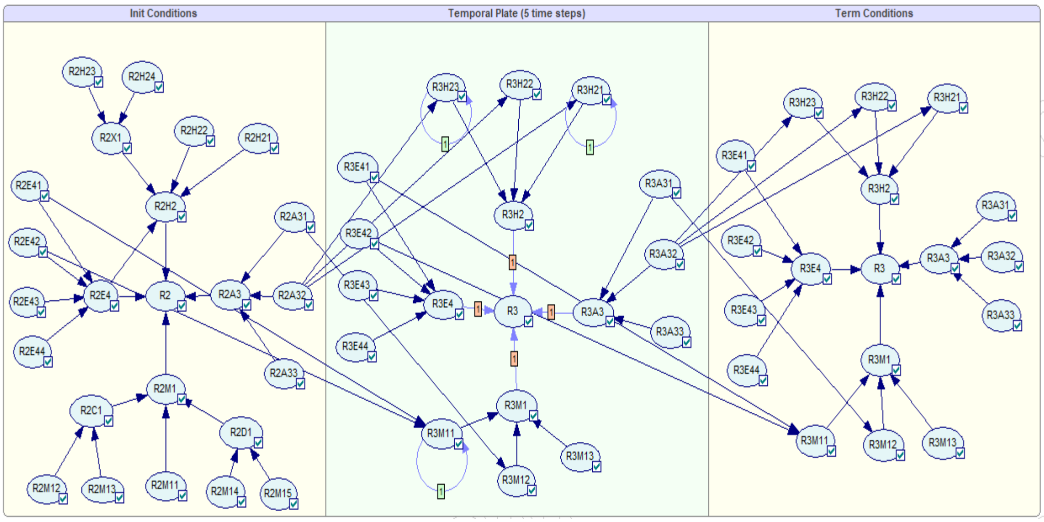
According to the results of the decomposition of the construction activities of the metro shield method, there are 7 construction activities in the shield launching stage, 4 construction activities in the shield tunneling stage and 3 construction activities in the shield reaching stage. Therefore, the shield launching stage is assumed to be a 9-time step, with moment 0 corresponding to the shield launching stage static BN, moments 1-7 corresponding to the shield launch construction stage and moment 8 corresponding to the shield launching stage completion moment. The shield tunneling stage is a 6-time step, where 0 corresponds to the end of the shield launching stage, 1-4 corresponds to the shield tunnel construction stage and 5 corresponds to the shield tunnel construction completion stage. The shield reaching stage is a 5-time step, with 0 corresponding to the completion of the shield tunneling stage, 1-3 to the shield reaching stage and 4 to the completion of the shield reaching stage. With this idea, a DBN topology is constructed for each stage of the construction of the metro shield method, Fig_8a-c. In each stage of the DBN, the nodes represent safety risk factors. Init Conditions represents the static BN topology for each stage of the shield construction, corresponding to moment 0. The Temporal Plate represents the area of dynamic change in each stage of shield construction, where the nodes with a circle "1" are dynamic nodes and the transfer probability of dynamic nodes in the transfer process is only related to the construction activity at the previous moment. Term Condition represents a static BN under the influence of indirect risk factors.




**(a)**




**(b)**




**(c)**

**Figure 8 (a) DBN topology at shield launching stage; (b) DBN topology at shield tunneling stage; (c) DBN topology in shield reaching stage**

## 5.7 Dynamic Bayesian Network node probabilities

Due to space limitations, the following case study is based on the shield tunneling stage. Based on the data results of Questionnaire B, combined with the triangular fuzzy number averaging Eq. (4), the prior probability of the safety risk factors of Project X and the transfer probability of the dynamic nodes can be obtained. As shown in Table 4-5.

**Table 4 Probability of safety risk factors**

| Risk factors | Code | prior probability |
|---|---|---|
| Shield machine failure itself | $R_2M_{11}$ | 0.54 |
| Improper control of shield tunneling attitude | $R_2M_{12}$ | 0.55 |
| Improper setting of shield machine tunnelling parameters | $R_2M_{13}$ | 0.52 |
| Shield equipment operation error | $R_2M_{14}$ | 0.55 |
| failure of shield tail sealing | $R_2M_{15}$ | 0.59 |
| Inadequate excavation face support | $R_2H_{21}$ | 0.60 |
| Inadequate assembly of tube sheet | $R_2H_{22}$ | 0.50 |
| Improper control of grouting system | $R_2H_{23}$ | 0.54 |
| Improper pressure control in excavation chamber | $R_2H_{24}$ | 0.65 |
| Inadequate training of construction personnel | $R_2A_{31}$ | 0.45 |
| Construction personnel lack of experience and ability | $R_2A_{32}$ | 0.58 |
| Construction site management confusion | $R_2A_{33}$ | 0.43 |
| Gushing sand and water | $R_2E_{41}$ | 0.74 |
| Ground building obstacles | $R_2E_{42}$ | 0.17 |

**Table 5 Dynamic node transition probability**

| Node | $R_2H_{22}(t)$ | F | T | Node | $R_2H_{23}(t)$ | F | T |
|---|---|---|---|---|---|---|---|
| $R_2H_{22}(t+1)$ | T | 0.44 | 0.75 | $R_2H_{23}(t+1)$ | T | 0.49 | 0.70 |
| | F | 0.56 | 0.25 | | F | 0.51 | 0.30 |
| $R_2H_{24}(t+1)$ | $R_2H_{24}(t)$ | F | T | $R_2M_{11}(t+1)$ | $R_2M_{11}(t)$ | F | T |
| | T | 0.46 | 0.73 | | T | 0.41 | 0.63 |
| | F | 0.54 | 0.27 | | F | 0.59 | 0.37 |

Based on the results of Questionnaire C, combined with the connection probability Eq. (5), the connection probability of the parent node and the child node is calculated., As shown in Table 6. Using the conditional probability Eq. (6), the conditional probability of the node can be found.

**Table 6 Connection probability between parent node and child node**

| | | | | |
|---|---|---|---|---|
| Parent Node | $R_2E_{41}$ | $R_2E_{42}$ | | |
| Child Node $R_2E_4$ | $P$=0.58 | $P$=0.20 | | |
| Parent Node | $R_2M_{12}$ | $R_2M_{13}$ | | |
| Child Node $R_2C_1$ | $P$=0.42 | $P$=0.40 | | |
| Parent Node | $R_2M_{14}$ | $R_2M_{15}$ | | |
| Child Node $R_2D_1$ | $P$=0.40 | $P$=0.35 | | |
| Parent Node | $R_2H_{23}$ | $R_2H_{24}$ | | |
| Child Node $R_2X_1$ | $P$=0.36 | $P$=0.44 | | |
| Parent Node | $R_2M_{11}$ | $R_2C_1$ | $R_2D_1$ | |
| Child Node $R_2M_1$ | $P$=0.44 | $P$=0.38 | $P$=0.41 | |
| Parent Node | $R_2H_{21}$ | $R_2H_{22}$ | $R_2X_1$ | |
| Child Node $R_2H_2$ | $P$=0.40 | $P$=0.43 | $P$=0.32 | |
| Parent Node | $R_2A_{31}$ | $R_2A_{32}$ | $R_2A_{33}$ | |
| Child Node $R_2A_3$ | 0.50 | 0.48 | 0.50 | |
| Parent Node | $R_2E_4$ | $R_2A_3$ | $R_2H_2$ | $R_2M_1$ |
| Child Node $R_2$ | $P$=0.38 | $P$=0.35 | $P$=0.35 | $P$=0.38 |

The prior probability, transfer probability and conditional probability of each node are input into the shield boring DBN for automatic node updating. The updated DBN is shown in Fig_9.

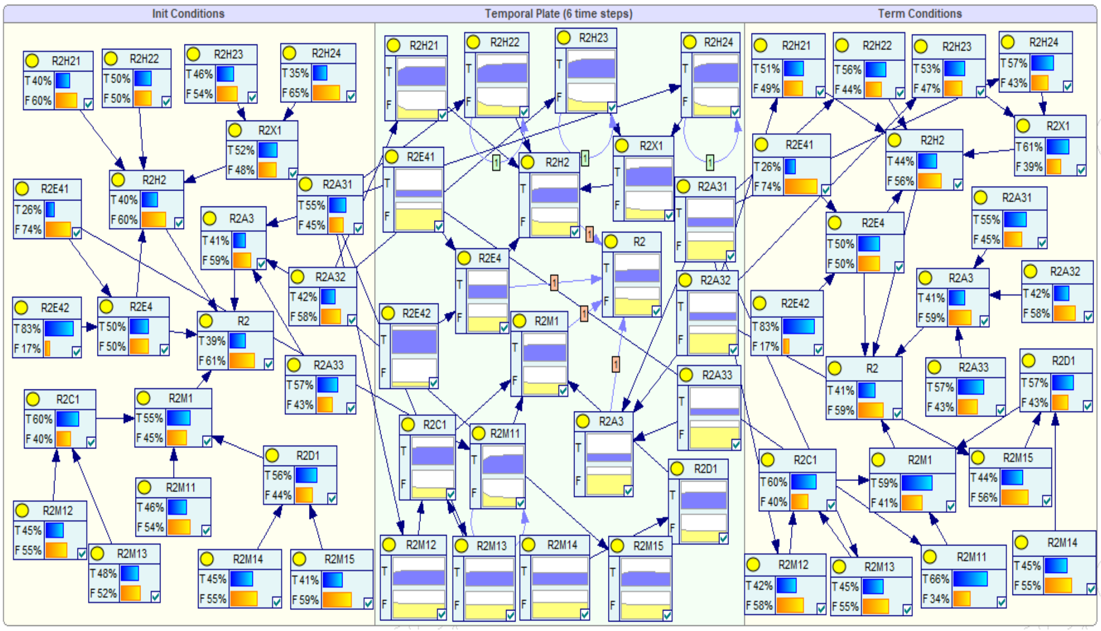



**Figure 9 Pie chart of DBN in tunneling section of Project X**

The initial network shows a static network of safety risk factors at each node when construction activities are carried out simultaneously without the influence of indirect risk factors. The nodes are causally related based on the safety risk factor hierarchy only. The node probability is the value of the probability of the node occurring throughout the construction activities. However, in the actual construction process, mechanical and operational risk factors are influenced by management risk factors and environmental risk factors. The terminal network is the probability of the node occurring under the influence of the management risk factors and environmental risk factors. According to the updated DBN node posterior probability diagram, it can be seen that the biggest safety hazard during the construction process of this project is the hydrological condition.

The systematic risk $R_2$ for the shield tunneling stage is reduced compared to the initial network probability value. The reason for this is that as construction activities are carried out, some of the safety risk factors change and no longer affect construction activities. Therefore, at the end of the construction activities, the systemic risk is reduced relative to the superimposed effect of all construction activities.

### 5.8 Construction safety risk status assessment

According to the UN Intergovernmental Panel on Climate Change (IPCC) classification of risk levels and Code for risk management of underground works in urban rail transit (GB50652-2011) for the classification of risk acceptance criteria. This paper classifies the safety risk level and risk acceptance criteria for the construction of metro shield method as follows. As shown in Table 7.

**Table 7 Safety risk level and risk acceptance criteria for Metro Shield Construction**

| Probability of risk factors | Risk levels | Acceptance guidelines | Disposal principles |
|---|---|---|---|
| 0 < P≤33% | Ⅳ | Ignorable | Risk management can be implemented |
| 33% < P≤66% | Ⅲ | Acceptable | Risk management should be implemented |
| 66% < P≤99% | Ⅱ | Reluctance | Risk management should be implemented to reduce risk |
| 99% < P≤100% | Ⅰ | Unacceptable | Risk control measures must be put in place to reduce risk |

Based on the experimental results, it can be seen that the overall risk level of this shield tunneling interval is at level III. Construction safety risk management should be carried out in accordance with the requirements for construction safety in metro construction projects, and the risk status is at an acceptable level. The assessment results are consistent with the risk rating of Project X. Among the safety risk factors, sand and water surges are Level II risks and the remaining risk factors are Level III risks. This indicates the need to strengthen the monitoring of hydrological conditions during the construction of the shield tunneling interval.

### 5.9 Analysis of construction activities and dynamic changes in safety risk factors

The dynamic node 0 moment corresponds to the initial static network and from moment 1 the nodes start to shift under the influence of indirect safety risk factors. moments 1-4 represent the digging construction process and moment 5 tends to a steady state. The excavation tunneling activities correspond to the risk factor of Shield machine failure itself, the tube sheet assembly activities correspond to the risk factor of inadequate tube sheet assembly, the grouting after wall activities correspond to the risk factor of improper control of the grouting system, and the opening and tool change activities correspond to the risk factor of improper control of the improper pressure control in excavation chamber. Gives the trend of dynamic node probabilities based on the posterior probabilities of nodes in the shield tunneling stage, As shown in Fig_10.

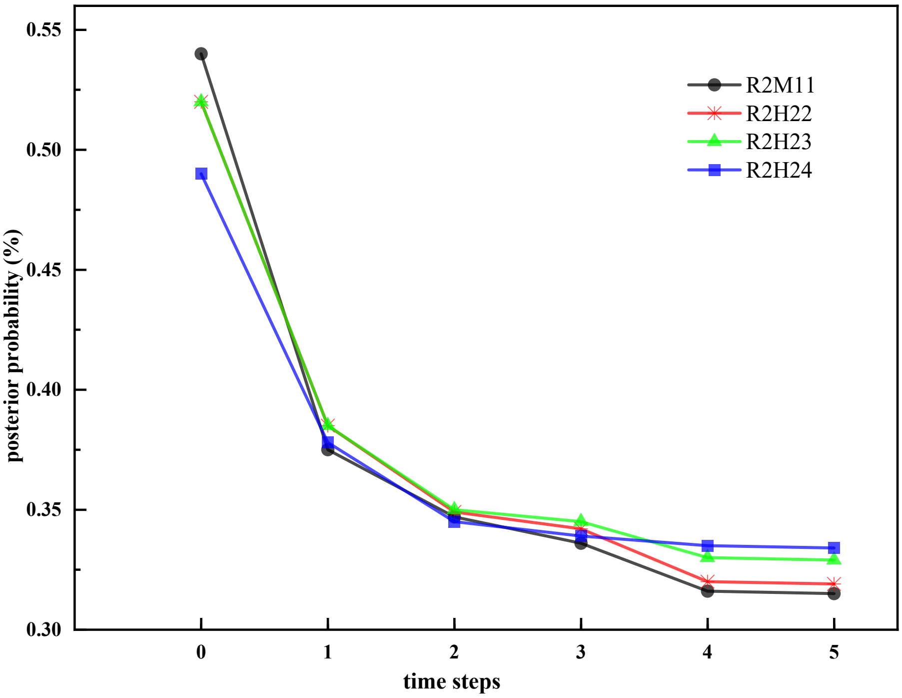



**Figure 10 Posterior probability of dynamic nodes in shield tunneling section**

Based on the trend of dynamic nodal probability changes during the shield tunneling stage, the construction activities and safety risk factors during the shield tunneling stage were analyzed as follows：

1) Due to the objective geological and hydrological conditions during the shield tunnel tunneling construction activities, the safety risk factor of gushing sand and water $R_2E_{41}$ is always present. Under the influence of indirect safety risk factors, the shield machine failure itself risk $R_2M_{11}$ occurs simultaneously and reaches its maximum static BN risk probability at moment 0. With the completion of the shield tunneling construction activities, the risk of shield machine failure itself begins to diminish. The shield machine completes its excavation tunneling construction activities at 4 moments. The shield machine failure itself disappears, but the indirect risk of sand and water surges will persist until the shield reaching stage.

2) Tube sheet assembly activities continue until the completion of the formed tunnel. Under the influence of inadequate training of construction personnel $R_2A_{31}$, the construction activities were affected by the presence of safety risk factors due to the inadequate assembly of tube sheet $R_2H_{22}$. With the end of construction activities at 4 moments, the risk factor of inadequate assembly of tube sheet $R_2H_{22}$ safety disappeared.

3) The grouting after wall activities is carried out when the tube sheet is assembled. Construction personnel lack of experience and ability $R_2A_{32}$ led to improper control of the grouting system $R_2H_{23}$ occurred. Grouting after wall ends at 4 moments, the Improper control of grouting system $R_2H_{23}$ disappears, and the management risk factor persists.

4) Inadequate training of construction personnel $R_2A_{31}$ led to Improper pressure control in excavation chamber $R_2H_{24}$ risk factors occurring during the opening and tool change activities. The opening and tool change activities ends at 5 moments. Improper pressure control in excavation chamber $R_2H_{24}$ disappears, while probabilistic stabilization exists to manage the risk.

## 6 Discussion

The dynamic risk assessment model proposed in this paper realizes a systematic and dynamic assessment of the safety risk status in the three stages of shield launch, shield tunnel and shield reach. Compared with the traditional safety risk assessment model for the shield method, the model not only takes into account the different risk factors arising from changes in construction activities during the risk identification stage but also takes into account the transferability between risk factors and risk states during the risk assessment process. It can more accurately describe the evolution of safety risks with changes in construction stages and activities.

The analysis of the results shows that the construction stages of the metro shield method are interlinked and the safety risk factors are transmitted in a dynamic chain. In the risk system of construction activities, environmental and management risk factors are always objectively present in each construction stage and have an indirect impact on construction activities. Operational and mechanical risk factors emerge with the construction activities and disappear at the end of the construction activities and have a direct impact on the construction activities. During construction activities such as shield tunnel, pipe assembly, post-wall grouting and bunker changing, attention should be paid not only to the direct safety risk factors arising from construction operations, but also to the management of indirect safety risk factors.

Trends in systemic risk suggest that safety risk factors do not lead to accidents immediately after they are observed to occur, but may have an impact at the next point in time. Managing risk therefore requires not only controlling risk at the moment of occurrence, but also assessing the state of risk after occurrence to avoid affecting other construction activities. In contrast, considering safety risk factors as dynamic variables and studying the risk evolution paths of dynamic variables leading to safety risk incidents in metro shield construction can enable real-time risk analysis of the metro shield construction process and provide a new perspective on risk response.

## 7 Conclusions

Safety risks in the construction activities of metro shield method are uncertain and complex. Based on risk transfer and dynamic risk management theory, this paper reveals the dynamic and time-series characteristics of safety risk factors for construction activities. Using the WBS-RBS analysis method, the expert survey method and the Bayesian method, a dynamic risk assessment model for the construction safety of the metro shield method is constructed, which includes three "time steps": shield launch, shield tunnel and shield launch. This is an improvement from the previous static model. By adding time to the model, the state of each factor changes with construction activity and affects the risk assessment. This is more in line with the actual situation of a construction site. The proposed DBN-based analysis method provides methodological support for the dynamic risk analysis of the safety of metro shield construction.

In addition, this paper analyses the dynamic evolution process of the safety risk state and safety risk factors with the construction activities of the metro shield method from multiple perspectives. It reveals the dynamic evolution of the relationship between the construction activities and safety risk factors of the metro shield method, and provides a new perspective for risk response. In summary, the risk assessment model proposed in this study provides a new framework for the dynamic assessment of safety risks in the construction of metro shield methods.

Some limitations need to be considered in related research. In this paper, the scope of shield construction activities is defined in the three stages of shield launch, shield tunnel and shield launch, without considering the construction activities in the shield preparation stage, which lacks safety risk identification for the whole process of shield construction. With the development of artificial intelligence technology, it is recommended that subsequent research be conducted to extract accident information based on metro shield construction accident cases and to more comprehensively establish a safety risk network for the whole process of metro shield construction. At the same time, machine learning-based methods can be used in the future to learn from metro shield method construction accident cases in order to obtain more objective probabilities of occurrence of safety risk factors.

## Reference


[1] Renault, B. Y. & Agumba J. N. Risk management in the construction industry: a new literature review. Proceedings of the 4th International Building Control Conference (IBCC); Kuala Lumpur, MALAYSIA, F 2016 Mar 07-08. https://doi.org/10.1051/matecconf/20166600008.

[2] Zhou, Z., Goh, Y. M., Shi, Q., Qi, H. & Liu, S. Data-driven determination of collapse accident patterns for the mitigation of safety risks at metro construction sites [J]. Tunnelling and Underground Space Technology, 2022, 127. https://doi.org/10.1016/j.tust.2022.104616.

[3] Li, X., Liao, F., Wang, C. and Alashwal, A. Managing Safety Hazards in Metro Subway Projects under Complex Environmental Conditions [J]. Asce-Asme Journal of Risk and Uncertainty in Engineering Systems Part a-Civil Engineering, 2022, 8(1). https://doi.org/10.1061/ajrua6.0001212.

[4] Liu, P., Li, Q., Bian,J., Song, L. & X. Xiahou. Using interpretative structural modeling to identify critical success factors for safety management in subway construction: A China study [J]. International journal of environmental research and public health, 2018, 15(7): 1359. https://doi.org/10.3390/ijerph15071359.

[5] Li, M., Yu, H. & Liu, P. An automated safety risk recognition mechanism for underground construction at the pre-construction stage based on BIM [J]. Automation in Construction, 2018, 91: 284-292. https://doi.org/10.1016/j.autcon.2018.03.013.

[6] Eskesen, S. D., Tengborg, P., Kampmann, J. & Veicherts, T. H. Guidelines for tunnelling risk management: international tunnelling association, working group No. 2 [J]. Tunnelling and Underground Space Technology, 2004, 19(3): 217-237. https://doi.org/10.1016/j.tust.2004.01.001.

[7] Mohurd China. Code for Risk Management of Underground Works in Urban Rail Transit, Standard of the People's Republic of China, GB 50652-2011, Mohurd China, Beijing, China, in Chinese 2012.

[8] Enshassi, M. S. A., Walbridge, S., West, J. S. and Haas, C. T. Dynamic and Proactive Risk-Based Methodology for Managing Excessive Geometric Variability Issues in Modular Construction Projects Using Bayesian Theory [J]. Journal of Construction Engineering and Management, 2020, 146(2). https://doi.org/10.1061/(asce)co.1943-7862.0001747.

[9] Ding, L. Y., Yu, H. L., Li, H., Zhou, C., Wu, X. G. and Yu, M. H. Safety risk identification system for metro construction on the basis of construction drawings [J]. Automation in Construction, 2012, 27: 120-137. https://doi.org/10.1016/j.autcon.2012.05.010.

[10] Zhang, S., Shang, C., Wang C., Song, R. & Wang, X. Real-Time Safety Risk Identification Model during Metro Construction Adjacent to Buildings [J]. Journal of Construction Engineering and Management, 2019, 145(6). https://doi.org/10.1061/(asce)co.1943-7862.0001657.

[11] Wu, Z. & Zou, S. A static risk assessment model for underwater shield tunnel construction [J]. Sadhana-Academy Proceedings in Engineering Sciences, 2020, 45(1). https://doi.org/10.1007/s12046-020-01370-w.

[12] Li, M., Yu, H., Jin, H. & Liu, P. Methodologies of safety risk control for China's metro construction based on BIM [J]. Safety Science, 2018, 110: 418-426. https://doi.org/10.1016/j.ssci.2018.03.026.

[13] Zhang, L., Wu, X., Ding, L., Skibniewski, M. J. & Y. Lu. BIM-BASED RISK IDENTIFICATION SYSTEM IN TUNNEL CONSTRUCTION [J]. Journal of Civil Engineering and Management, 2016, 22(4): 529-539. https://doi.org/10.3846/13923730.2015.1023348
[14] Liu, W., Zhao, T., Zhou, W. and J. Tang.Safety risk factors of metro tunnel construction in China: An integrated study with EFA and SEM [J]. Safety Science, 2018, 105: 98-113. https://doi.org/10.1016/j.ssci.2018.01.009.
[15] Pan, H., Gou, J., Wan, Z., Ren, C., Chen, M., Gou, T., Luo, Z. Research on Coupling Degree Model of Safety Risk System for Tunnel Construction in Subway Shield Zone. Mathematical Problems in Engineering 2019. https://doi.org/10.1155/2019/5783938.
[16] Xing, X., Zhong, B., Luo, H., Li, H. & Wu, H. Ontology for safety risk identification in metro construction [J]. Computers in Industry, 2019, 109: 14-30 https://doi.org/10.1016/j.compind.2019.04.001.
[17] Zhou, M., Tang, Y., Jin, H., Zhang, B. & Sang, X. A BIM-BASED IDENTIFICATION AND CLASSIFICATION METHOD OF ENVIRONMENTAL RISKS IN THE DESIGN OF BEIJING SUBWAY [J]. Journal of Civil Engineering and Management, 2021, 27(7): 500-514. https://doi.org/10.3846/jcem.2021.15602.
[18] Labib, A. & Read, M. Not just rearranging the deckchairs on the Titanic: Learning from failures through Risk and Reliability Analysis [J]. Safety science, 2013, 51(1): 397-413. https://doi.org/10.1016/j.ssci.2012.08.014.
[19] Hamidi, J. K., Shahriar, K., Rezai, B., Rostami, J. & Bejari, H. Risk assessment based selection of rock TBM for adverse geological conditions using Fuzzy-AHP [J]. Bulletin of Engineering Geology and the Environment, 2010, 69(4): 523-532. https://doi.org/10.1007/s10064-009-0260-8.
[20] Luo Z., Zeng, L., Pan, H., Hu, Q., Liang, B. & Han, J. Research on Construction Safety Risk Assessment of New Subway Station Close-Attached Undercrossing the Existing Operating Station. Mathematical Problems in Engineering 2019. https://doi.org/10.1155/2019/3215219.
[21] Lyu, H.-M., Sun, W.-J., Shen, S.-L. & Zhou, A.-N. Risk Assessment Using a New Consulting Process in Fuzzy AHP [J]. Journal of Construction Engineering and Management, 2020, 146(3). https://doi.org/10.1061/(asce)co.1943-7862.0001757.
[22] Wang, Z. Z. & Chen, C. Fuzzy comprehensive Bayesian network-based safety risk assessment for metro construction projects [J]. Tunnelling and Underground Space Technology, 2017, 70: 330-342. https://doi.org/10.1016/j.tust.2017.09.012.
[23] Zhao, T.; Liu, W., Zhang, L. and Zhou, W. Cluster Analysis of Risk Factors from Near-Miss and Accident Reports in Tunneling Excavation [J]. Journal of Construction Engineering and Management, 2018, 144(6). https://doi.org/10.1061/(asce)co.1943-7862.0001493.
[24] Zhou H., Zhao, Y., Shen, Q., Yang, L. & Cai, H. Risk assessment and management via multi-source information fusion for undersea tunnel construction [J]. Automation in Construction, 2020, 111. https://doi.org/10.1016/j.autcon.2019.103050.
[25] Gong, P., Guo, H., Huang, Y. & Guo, S. SAFETY RISK EVALUATIONS OF DEEP FOUNDATION CONSTRUCTION SCHEMES BASED ON IMBALANCED DATA SETS [J]. Journal of Civil Engineering and Management, 2020, 26(4): 380-395. https://doi.org/10.3846/jcem.2020.12321.
[26] Xue, Y., Xiang, P., Jia, F. & Liu, Z. Risk Assessment of High-Speed Rail Projects: A Risk Coupling Model Based on System Dynamics [J]. International Journal of Environmental Research and Public Health, 2020, 17(15). https://doi.org/ 10.3390/ijerph17155307.
[27] Xu, N., Liu, Q., Ma, L., Deng, Y., Chang, H., Ni, G., Zhou, Z. A Hybrid Approach for Dynamic Simulation of Safety Risks in Mega Construction Projects [J]. Advances in Civil Engineering, 2020. https://doi.org/10.1155/2020/9603401.
[28] Zhou, Y., Ding, L. Y. & Chen, L. J. Application of 4D visualization technology for safety management in metro construction [J]. Automation in Construction, 2013, 34: 25-36. https://doi.org/10.1016/j.autcon.2012.10.011.
[29] Zhang, L.; Wu, X., Ding, L., Skibniewski, M. J. & Yan, Y. Decision support analysis for safety control in complex project environments based on Bayesian Networks [J]. Expert Systems with Applications, 2013, 40(11): 4273-4282. https://doi.org/10.1016/j.eswa.2012.11.022.
[30] Wu, X., Jiang, Z., Zhang, L.; Skibniewski, M. J. & Zhong, J. Dynamic risk analysis for adjacent buildings in tunneling environments: a Bayesian network based approach [J]. Stochastic Environmental Research and Risk Assessment, 2015, 29(5): 1447-1461. https://doi.org/10.1007/s00477-015-1045-1.

[31] Qian H., Zhang, R. & Zhang, Y.-j. Dynamic risk assessment of natural environment based on Dynamic Bayesian Network for key nodes of the arctic Northwest Passage [J]. Ocean Engineering, 2020, 203. https://doi.org/10.1016/j.oceaneng.2020.107205.
[32] Wu, S.; Zhang, Zheng, L. W., Liu, Y. & Lundteigen, M. A. A DBN-based risk assessment model for prediction and diagnosis of offshore drilling incidents. Journal of Natural Gas Science and Engineering 2016, 34: 139-158. https://doi.org/10.1016/j.jngse.2016.06.054.
[33] Liu, Q., Tchangani, A., Peres, F. & Gonzalez-Prida, V. Object-oriented Bayesian network for complex system risk assessment [J]. Proceedings of the Institution of Mechanical Engineers Part O-Journal of Risk and Reliability, 2018, 232(4): 340-351. https://doi.org/10.1177/1748006x17753026.
[34] Liu, W., Cai, L., J. Chen; Wang, Y. & Wu, H. Reliability Analysis of Operational Metro Tunnel Based on a Dynamic Bayesian Copula Model [J]. Journal of Computing in Civil Engineering, 2020, 34(3). https://doi.org/10.1061/(asce)cp.1943-5487.0000886.
[35] Zhang, Y., Xing, X., Antwi-Afari, M. F. & Wu, M. Safety Risk Estimation of Construction Project Based on Energy Transfer Model and System Dynamics: A Case Study of Collapse Accident in China. International Journal of Environmental Research and Public Health 2022, 19(21). https://doi.org/ 10.3390/ijerph192114386.
[36] Zhou, C., Kong, T., Jiang, S., Chen, S., Zhou, Y. & Ding, L. Quantifying the evolution of settlement risk for surrounding environments in underground construction via complex network analysis [J]. Tunnelling and Underground Space Technology, 2020, 103. https://doi.org/10.1016/j.tust.2020.103490.
[37] Lenz, H.-J. Finn V. Jensen; Thomas D. Nielsen (2007): Bayesian Networks and Decision Graphs: Springer, New York [J]. Statistical Papers, 2011, 52(1).
[38] Nordgård, D. E. & Sand, K. Application of Bayesian networks for risk analysis of MV air insulated switch operation [J]. Reliability Engineering and System Safety, 2010, 95(12). https://doi.org/10.1016/j.ress.2010.06.012.
[39] Namazian, A. & Yakhchali, S. H. Modified Bayesian Network–Based Risk Analysis of Construction Projects: Case Study of South Pars Gas Field Development Projects [J]. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 2018, 4(4). https://doi.org/10.1061/AJRUA6.0000997.
[40] Zhang, J., Teixeira, A. P., Guedes Soares, C., Yan, X. & Liu, K. Maritime Transportation Risk Assessment of Tianjin Port with Bayesian Belief Networks [J]. Risk analysis : an official publication of the Society for Risk Analysis, 2016, 36(6): 1171-1187. https://doi.org/10.1111/risa.12519.
[41] Neapolitan, R. E. Learning Bayesian networks. Knowledge discovery and data mining 2007.
[42] Li, Z., Wang, T., Ge, W., Wei, D. & Li, H. Risk Analysis of Earth-Rock Dam Breach Based on Dynamic Bayesian Network [J]. Water, 2019, 11(11). https://doi.org/10.3390/w11112305.
[43] Xiao, Q. Dynamic Bayesian Network Inference Learning Theory and Application. Beijing: National Defence Industry Press, 2007.
[44] Bartolucci, F. Likelihood inference for a class of latent Markov models under linear hypotheses on the transition probabilities [J]. Journal of the Royal Statistical Society: Series B (Statistical Methodology), 2006, 68(2): 155-178. https://doi.org/10.1111/j.1467-9868.2006.00538.x.
[45] Brameret, P.-A., Rauzy, A. & Roussel, J.-M. Automated generation of partial Markov chain from high level descriptions [J]. Reliability Engineering and System Safety, 2015, 139. https://doi.org/10.1016/j.ress.2015.02.009.
[46] Xiang, W. & Zhou, W. Integrated pipeline corrosion growth modeling and reliability analysis using dynamic Bayesian network and parameter learning technique [J]. Structure and Infrastructure Engineering, 2020, 16(8): 1161-1176. https://doi.org/10.1080/15732479.2019.1692363.
[47] Wickens, C. D. Engineering psychology and human performance. 2nd ed. New York: Harper Collins Publishers Inc, 1992, 211-257.
[48] Lan, R. & Fan, J. Complete metric on triangular fuzzy numbers and its application to decision-making [J]. Journal of Systems Engineering, 2010, 25(3): 313-319. https://doi.org/10.3724/SP.J.1087.2010.02828.
[49] Feng, X., Jiang, J.-c. & Wang, W.-f. Gas pipeline failure evaluation method based on a Noisy-OR gate bayesian network [J]. Journal of Loss Prevention in the Process Industries, 2020, 66: 104175. https://doi.org/10.1016/j.jlp.2020.104175.
[50] Henrion, M. Some practical issues in constructing belief network. Amsterdam: Uncertainty in Artificial Intelligence: 1989.

[51] Mohurd China. Code for construction and acceptance of shield tunneling method, GB50446-2017, Mohurd China, Beijing, China, in Chinese 2017.
[52] Mohurd China. Standard for construction safety assessment of metro engineering, GB 50715-2011, Mohurd China, Beijing, China, in Chinese 2012.
[53] Siami-Irdemoosa, E., Dindarloo, S. R. & Sharifzadeh, M. Work breakdown structure (WBS) development for underground construction [J]. Automation in Construction, 2015, 58: 85-94. https://doi.org/10.1016/j.autcon.2015.07.016.
[54] Wang, J. Construction of Risk Evaluation Index System for Power Grid Engineering Cost by Applying WBS-RBS and Membership Degree Methods. Mathematical Problems in Engineering 2020. https://doi.org/10.1155/2020/6217872.