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To cite this article: Bo Wu *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **267** 042116

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Risk Assessment of Water Penetration for Shield Tunnel Construction in Coastal Area

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Abstract. In the process of assessing the risk of flooding during the construction of shield tunnel in coastal area, the basic probability of accidents is often difficult to be expressed by an exact numerical value due to the fact that the actual statistical data of accidents are too few or missing. In order to solve this problem, this paper, with the factors by combining the fuzzy Bayesian network inference advantages and the advantages of the fuzzy set theory to deal with fuzzy information, using a risk assessment method based on fuzzy Bayesian network method, established the waterfront subway shield tunnel construction risk decision model and predicted the subway shield tunnel flooded the area of probability; at the same time, the sensitivity of each basic event was calculated according to the fuzzy significance to identify the key risk factors, and the applicability and accuracy of this method were verified by combining with the regional engineering of Hujing station ~ Wanshou station of Fuzhou Metro Line 6.

1. Introduction

At present, under the background of global warming and advocating low-carbon environmental travel, taking the subway has become one of the important choices for people to travel in their lives. Under this influence, cities in various countries have vigorously developed metro rail transit in recent years. In the process of urban subway construction, there are corresponding construction methods for different geological conditions, and at the same time, there will be certain risks. Among them, in the shield construction of underground tunnels, water-rich and weak soil strata will lead to flooding accidents in the shield section, which has a huge negative impact on construction safety. For example, in September 2010, a flooding accident occurred on Beijing Metro Line 9 crossing Yuyuantan East Lake, which resulted in one death. In February 2018, a sudden flooding accident occurred between Green Island Lake and Huyong on Foshan Metro Line 2, which resulted in 8 deaths and 3 missing persons. From the above accident cases, we can see that these unexpected security incidents have caused heavy casualties and huge economic losses. Therefore, the process safety of shield tunneling during the construction of Metro has attracted much attention of researchers, among which the water permeability problem is the most important one. Metro construction in coastal areas also needs to consider this issue. Because the area is close to the coastline, there are similar water-rich soft strata in the planning route of shield tunnel tunneling, so it is particularly important to evaluate the water



permeability risk of shield tunnel in this area in the construction process of crossing water-rich soft strata.

At present, numerical simulation and fault tree analysis are the main methods to analyze the risk of flooding in shield tunnel construction. The former is analyzed by numerical simulation, such as WANG Huiwu and DAI Bing[1]. Finite difference model using software FLAC 3D established for the safety of the shield under wear HUANG Hejiang permeable formation was studied. The results show that the use of software for numerical simulation can comprehensively consider the situations of engineering, quantitative analysis, but the process of modeling based on a simplified, thus resulting in some errors; The latter through the establishment of the fault tree model of flood risk in subway construction, such as DE Hongzhou[2] combining expert survey ratings and fault tree analysis method in the process of subway construction in flood of each basic event is analyzed, but in this method, the probability of basic events needs to use the exact numerical said, and in the process of subway shield tunnel construction, with the lack of statistical data related to the accident, the probability of causing basic events is fuzzy, so using the method of shield tunnel flood risk research is likely to cause greater error.

Based on the theory of fuzzy mathematics and Bayesian network, this paper uses the risk analysis method of fuzzy Bayesian network to analyze the risk-causing mechanism in shield tunneling process, so as to accurately identify the main factors affecting the construction risk of shield tunneling through water-rich soft strata. In addition, aiming at the proposed influencing factors, this paper constructs the topological structure of the fuzzy Bayesian network model. At the same time, with the help of this topological structure model, the probability of water penetration accident is predicted, and the key influencing factors are found by sensitivity analysis. Subsequently, the forecasting method is verified by the actual project of Hujing Station to Wanshou Station of Fuzhou Metro Line 6, which proves that this method has high applicability for risk assessment of shield tunnel construction through water-rich soft stratum.

2. Construct fuzzy Bayesian network model

Fuzzy Bayesian network method is one of the commonly used methods in engineering analysis. It can deal with uncertainties and fuzziness in engineering. Many international scholars have studied this method and formed a theoretical basis. Cai B, Liu Y, Zhang Y and others[3] constructed the corresponding fuzzy Bayesian network model for the actual project. The model consists of four parts: analyzing the risk mechanism, constructing the model topology, fuzzifying the basic risk events and designing the conditional probability table of the model. The results greatly expand the application scope and applicability of the fuzzy Bayesian network method in practical engineering.

2.1 Risk mechanism analysis

In the constructive analysis of practical projects, the analysis of risk-causing mechanism is a key step, the main purpose of which is to identify the most basic causes leading to the top events. Therefore, this paper can establish fault tree model to analyze the risk mechanism of subway construction projects in coastal areas. The main way of fault tree analysis is to retreat from "top event" to "basic event" layer by layer until the most basic cause of the top event (namely basic event) is finally found. Through reading relevant articles and regulations and summarizing previous experience, it can be known that the water permeability risk in the construction process of shield tunnel in coastal area is the top event (T), and the main influencing factors can be divided into construction factor (M_1), natural factor (M_2) and other factors (M_3). To further refine these factors, we get the corresponding basic events include segment rupture (X_1), membrane rupture (X_2), shield tail seal failure of shield machine (X_3), shield tunneling has caused the construction segment displacement (X_4), brush the wall does not reach the designated position (X_5), tidal, lead to rising sea levels (X_6) ground water level rise, the rainy season (X_7), through the confined aquifer (X_8), the wear surface area (X_9), the tunnel uneven deformation (X_{10}), groundwater treatment method (X_{11}).

2.2 Construct the topology structure of fuzzy Bayesian network model

Based on the fault tree model established in this paper, the inherent logical relationship among risk factors, risk events and risk factors triggering risk events in engineering can be well described. At the same time, this paper can use the method of transforming fault tree model into Bayesian model to establish a reasonable fuzzy Bayesian network model. In addition, the establishment of fault tree model is a process of continuous improvement and gradual optimization. Its standard construction process is as follows: selecting the most unwanted risk event as the top event; analyzing the top event step by step from the top to the bottom, so as to find out the most direct causes of all events at all levels; then, using the corresponding logic symbols of fault tree to express the logical relationship between events at all levels until the bottom event is analyzed[4]. After the basic model of fault tree is constructed, the fault tree model is transformed into Bayesian network topology structure model by using relevant rules.

2.3 Ambiguity of basic events

In practical engineering construction projects, risk events always exist and the state is generally ambiguous and uncertain. In view of this situation, the traditional two-state state (safe state "0" and unsafe state "1") lacks accuracy and comprehensiveness in risk analysis. Therefore, researchers can usually use linguistic variables to describe vague factors. In this paper, "very dangerous, dangerous, safe" sets of linguistic values are used to describe the security state of each node. Correspondingly, the fuzzy numbers "1, 0.5, 0" are used to represent the above three states [5], and the sum of probability of occurrence of each event in three states is 1. Because the probability of occurrence of each node in practical engineering has certain fuzziness, and the probability of occurrence of root node in Bayesian network is generally accurate. In this paper, the fuzzy number in the theory of fuzzy sets is used to accurately describe the probability of occurrence of nodes. Normal Fuzzy Number, trapezoidal Fuzzy Number and triangular Fuzzy Number can be used to describe the fuzzy probability in practical engineering cases. Because of its clear mathematical meaning, easy for researchers to understand and simple mathematical calculation, triangular fuzzy number is selected to describe the occurrence probability of each node. The triangular fuzzy number is denoted as $A=(a, mb)$ (where a is the minimum possible probability value; m is the most likely probability; b is the maximum possible probability).

Due to the limitation of practical conditions, there is no exact statistical data in this paper, so the prior probability of root node will be obtained by expert scoring method. Firstly, the expert's judgment language is transformed into triangular fuzzy numbers by using three language variables of "very dangerous, dangerous and safe", and the expert's results are averaged to the probability of the X_i average (a_i and m_i , b_i). Thereafter, the mean area method obtained in the previous step is used to fuzzify the above average probability, and the exact probability $P(X_i, a_i)$ is obtained. See formula (1). Finally, in order to ensure that the sum of the probabilities of each root node in each state is 1, it is necessary to normalize the exact probabilities calculated in the next step and calculate the priori rate. The formula is shown in Formula (2).

$$P(X_{i,a_i})' = \frac{a_i + 2m_i + b_i}{4} \quad (1)$$

$$P(X_{i,a_i}) = \frac{P(X_{i,a_i})'}{\sum P(X_{i,a_i})'} \quad (2)$$

2.4 Design the conditional probability table of fuzzy Bayesian networks

The traditional Bayesian Network Conditional Probability Table (CPT) can be obtained by mapping the logic relations of the logic gates in the fault tree. However, the table is a fault tree logic gate reflecting the relationship between nodes, which can only represent the deterministic relationship. The uncertainties and probabilities of logical relationships among nodes can be obtained by changing the CPT values of the sub-nodes of Bayesian networks.

3. Risk assessment method based on fuzzy Bayesian network method

3.1 Predictive reasoning

The fuzzy Bayesian network method has an inference algorithm that can directly calculate the risk probability, so this method has its own advantages in the study of risk probability analysis [8]. After building the fuzzy Bayesian network model, it is assumed that the root node variable of the model is $X_i (i=1,2,3,\dots,n)$, the intermediate node variable is $M_i (i=1,2,3,\dots,m)$, and the leaf node variable is T . The fuzzy number X_{i,a_i} , M_{i,b_i} and T_q are used to represent the state of the corresponding node respectively. Where $a_j=0.1,\dots,k_i-1; b_j=0.1,\dots,l_i-1; q=0.1,\dots,r_i-1$ represents the number of corresponding node states. Given that the fuzzy probability of root node is $\tilde{P}(X_{1,a_1}), \tilde{P}(X_{2,a_2}), \tilde{P}(X_{3,a_3})$ in each state, the fuzzy probability of leaf node T in state T_q can be calculated by formula (3). When the root node X_i is in state X_{i,a_i} , the fuzzy probability of the leaf node T in state T_q is calculated by formula (4). Where L is the joint probability of root node X_i in state X_{i,a_i} and leaf node in state T_q .

$$\tilde{P}(T=T_q) = \sum_{X_1, X_2, \dots, X_n, M_1, M_2, \dots, M_m} \tilde{P}(X_1, X_2, \dots, X_n, M_1, M_2, \dots, M_m, T=T_q) = \sum_{\pi(T)} \tilde{P}(T=T_q | \pi(T)) \sum_{\pi(M)} \tilde{P}(M_1 | \pi(M_1)) \times \dots \times \tilde{P}(X_{1,a_1}) \times \dots \times \tilde{P}(X_{n,a_n}) \quad (3)$$

$$\tilde{P}(T=T_q | X_i = X_{i,a_i}) = \frac{\tilde{P}(X_i = X_{i,a_i}, T=T_q)}{\tilde{P}(X_i = X_{i,a_i})} \quad (4)$$

3.2 Risk factor sensitivity analysis

The definition of importance in this paper is the extent to which each basic event affects the event on the top of the system. Therefore, the sensitivity of risk factors is generally measured by importance [9]. Because each event in this paper is represented by triangular fuzzy numbers, the accuracy of fuzzy importance is higher than that of traditional importance [10]. Fuzzy significance represents the mathematical expectation of the difference between the fuzzy probability of the top event when the root node X_i is in different states and its state is "0" value. It can also be understood as the degree of influence of each root node on the leaf node. In this paper, the method to calculate the significance of root node is the barycenter value method. The fuzzy (F_n) significance of root node X_i to the T_q of leaf node T in state is calculated by formula (5):

$$I_{T_{F_n}, q}(X_i) = \frac{1}{k_i - 1} \sum_{a_i=1}^{k_i} E[\tilde{P}(T=T_q | X_i = X_{i,a_i}) - \tilde{P}(T=T_q | X_i = 0)] \quad (5)$$

Where, $\tilde{P}(T=T_q | X_i = 0)$ represents the fuzzy possibility of leaf node $T=T_q$ under the condition of root node $X_i = 0$. $\tilde{P}(T=T_q | X_i = X_{i,a_i}) - \tilde{P}(T=T_q | X_i = 0)$ represents the fuzzy significance degree of leaf node T caused by root node under the single condition $X_i = X_{i,a_i}$. $E[\tilde{P}(T=T_q | X_i = X_{i,a_i}) - \tilde{P}(T=T_q | X_i = 0)]$ represents the barycenter value of the fuzzy subset.

4. Case analysis

4.1 Engineering background

The project between Hujing station and Wanshou station area of Fuzhou Metro Line 6 is located in the planned area to be built in changle city. At the top of the area, farmland, ponds and residential buildings are the main ones. The length of the area between Hujing station and Wanshou station area (mileage CK30+026.519 ~ CK30+917.105) is 890.586m. Under this section, there are many irrigation ditches, small rivers and patches of ponds with water depths ranging from 1.00 to 2.00m. The tunnel structure mainly passes through the water-rich soft stratum which is rich in medium fine sand, fine sand and silty clay.

4.2 Construction of fuzzy Bayesian network model

Through the analysis of the risk mechanism mentioned above, we can easily get the main factors that influence the construction risk of shield tunnels when they pass through water-rich and weak strata. On this basis, the fuzzy Bayesian network topological structure model of shield tunnel construction risk through water-rich soft stratum can be established by combining the influencing factors with the fuzzy Bayesian network model, as shown in Figure 1. According to the above, all the influencing factors can be divided into three levels, and the numerical range of the corresponding evaluation indexes can also be obtained, as shown in Table 1.

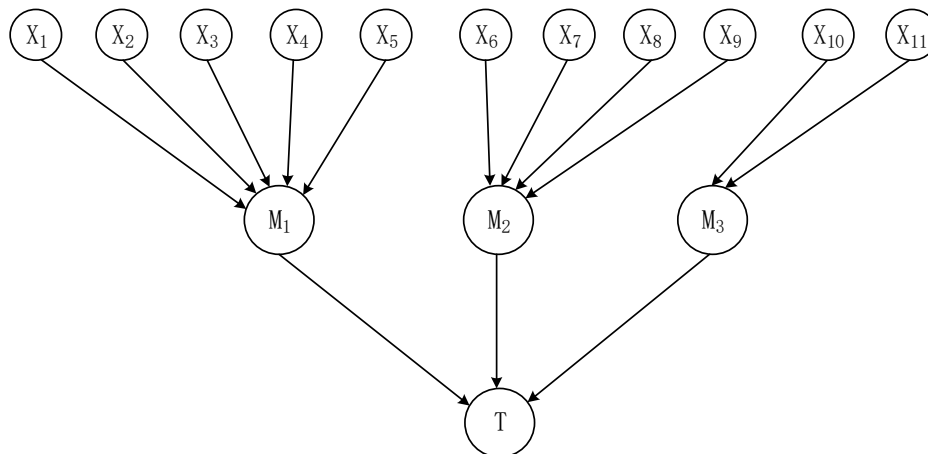


Figure 1. FBN topology model for shield tunnel crossing water-rich soft stratum construction risk.

Table 1. Classification and magnitude of risk factors for construction of shield tunnel crossing water-rich soft.

Intermediate nodes	Root node	Values for different security levels		
		security (0)	dangerous (0.5)	very dangerous (1)
Construction factors (M_1)	X_1 , Segment fracture /mm	[0, 0.2)	[0.2, 0.4)	[0.4, 0.6)
	X_2 , Waterproofing rupture /%	[0, 5)	[5, 10)	[10, 15)
	X_3 , Shield tail seal failure /%	[0, 10)	[10, 20)	[20, 30)
	X_4 , The shield tunneling machine caused the displacement of the pipe segment under construction /mm	[0, 6)	[6, 12)	[12, 18)
	X_5 , The brush wall is not in place / points	[80, 100)	(40, 80]	(0, 40)
Natural factors (M_2)	X_6 , Tides cause sea levels to rise /cm	(400, 600]	(200, 400]	(0, 200]
	X_7 , The water table rises during the rainy season /m	(0, 0.5)	[0.5, 1)	[1, 1.5)
	X_8 , Traversing confined aquifer / points	[80, 100)	(40, 80]	(0, 40)
	X_9 , Down through the surface water area / points	[80, 100)	(40, 80]	(0, 40)

Other factors (M_3)	X_{10} , The tunnel rises and deforms unevenly / points	[80, 100)	(40, 80]	(0, 40)
	X_{11} , Improper treatment of groundwater / points	[80, 100)	(40, 80]	(0, 40)

After the establishment of the fuzzy Bayesian network structure model, the expert scoring method is selected to obtain the prior probability of all root nodes, as shown in table 2. According to the logical relationship of bayesian network, expert opinions and engineering practice, the conditional probability table of intermediate node and leaf node is listed to obtain the probability of occurrence risk of leaf node. Taking table 3 as an example, the conditional probability table of construction factor (M_1) is listed below.

Table 2. Experts evaluate fuzzy prior probabilities of root nodes (part).

Root node	state	experts 1	experts 2	experts 3	experts 4	experts 5
X_1	0	(0.70,0.71,0.72)	(0.68,0.69,0.70)	(0.73,0.74,0.75)	(0.78,0.79,0.80)	(0.74,0.75,0.76)
	0.5	(0.24,0.25,0.26)	(0.23,0.24,0.25)	(0.23,0.24,0.25)	(0.17,0.18,0.19)	(0.22,0.23,0.24)
	1	(0.03,0.04,0.05)	(0.04,0.05,0.06)	(0.01,0.02,0.03)	(0.02,0.03,0.04)	(0.01,0.02,0.03)
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
X_{11}	0	(0.78,0.79,0.80)	(0.74,0.75,0.76)	(0.80,0.81,0.82)	(0.71,0.72,0.73)	(0.75,0.76,0.77)
	0.5	(0.18,0.19,0.20)	(0.21,0.22,0.23)	(0.16,0.17,0.18)	(0.23,0.24,0.25)	(0.20,0.21,0.22)
	1	(0.01,0.02,0.03)	(0.02,0.03,0.04)	(0.01,0.02,0.03)	(0.03,0.04,0.05)	(0.02,0.03,0.04)

Table 3. The conditional probability table of the intermediate node M_1 (part).

Segment fracture X_1	Waterproofing rupture X_2	Shield tail seal failure X_3	The shield tunneling machine caused the displacement of the pipe segment under construction X_4	The brush wall is not in place X_5	$P(M_1 = j X_1, X_2, X_3), j = 0, 0.5, 1$		
					$M_1 = 0$	$M_1 = 0.5$	$M_1 = 1$
0	0	0	0	0	1	0	0
0.5	0	0	0	0	0.8	0.1	0.1
1	0	0	0	0	0.7	0.2	0.1
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$			
0.5	0.5	0.5	0.5	0.5	0.1	0.2	0.7
0.5	1	1	1	1	0.1	0.1	0.8
1	1	1	1	1	0	0	1

4.3 Construction risk analysis of shield tunneling through water-rich and weak strata

4.3.1 Reasoning of risk prediction

According to the established fuzzy Bayesian network model, the following steps are used for risk inference prediction: fuzzy - normalization - risk probability prediction. In the process, you first need to calculate the fuzzy probability of the root node average, then according to the formula (3) and formula (4), respectively, for each of the root node fuzzy probability and fuzzy and normalized

processing, with the exact numerical value represents the probability of the root node, finally the probability can be used to calculate the probability of the leaf node is in a state of different, so as to achieve the goal of risk prediction. According to formula (4), the probability of occurrence of leaf node T in three states can be accurately calculated as: $P(T=1)=0.272$, $P(T=0.5)=0.383$, and $P(T=0)=0.358$, respectively. Obviously, $P(T=0.5) > P(T=0) > P(T=1)$, the probability of the safety risk of tunnel construction in this section being in a "dangerous" state is relatively high. The shield tunnel runs through a number of irrigation channels, small rivers, patches of ponds and other areas where surface water exists. During the rainy season, the ground water level rises and the tide causes sea level rise. All these factors have a great impact on the environmental safety of shield tunnel construction.

4.3.2 Calculation of root node significance

According to formula (5), the fuzzy significance of the root node can be obtained. According to the value of the root node's importance, the degree to which the leaf node is affected by the root node can be determined, and the influential factors with high significance should be focused on to reduce the probability of risk occurrence. The calculation results are summarized in table 4. According to table 4, when $T=0.5$ (the construction risk of shield tunnel crossing the water-rich and weak stratum is in a "dangerous" state), the order of fuzzy significance of root node is: $X_1 > X_3 > X_2 > X_6 > X_5 > X_4 > X_7 > X_{10} > X_8 > X_9 > X_{11}$, namely the influence factors of large effects on the safety of the X_1 (segment), the X_3 (shield tail seal failure of shield machine), X_2 (membrane rupture), therefore in the construction, when the shield tunnel construction flood risk in weak watery stratum "dangerous" state, to focus on and check in time the real-time situation of these factors. Similarly, when $T=1$ (of shield tunnel construction risk is in weak watery stratum "very dangerous" state), the size of the state of the root node importance order for $X_2 > X_3 > X_9 > X_1 > X_4 > X_7 > X_6 > X_{10} > X_8 > X_5 > X_{11}$, at this time of the influential factors with X_2 (membrane rupture), X_3 (shield tail seal failure of shield machine), X_9 (under wear surface area). In the actual construction of the project, when the construction risk of shield tunneling through the water-rich and weak stratum is "very dangerous", these factors should be paid special attention to.

Table 4. Fuzzy importance of root node.

root node	$I_{0.5,FU}(X_i)$	$I_{1,FU}(X_i)$
Segment fracture, X_1	0.080	0.055
Waterproofing rupture, X_2	0.072	0.081
Shield tail seal failure, X_3	0.077	0.079
The shield tunneling machine caused the displacement of the pipe segment under construction, X_4	0.053	0.053
The brush wall is not in place, X_5	0.059	0.025
Tides cause sea levels to rise, X_6	0.065	0.041
The water table rises during the rainy season, X_7	0.035	0.043
Traversing confined aquifer, X_8	0.019	0.028
Down through the surface water area, X_9	0.017	0.061
The tunnel rises and deforms unevenly, X_{10}	0.027	0.034
Improper treatment of groundwater, X_{11}	0.011	0.017

4.4 Conclusion

The continuous development of underground space promotes the continuous progress of Metro engineering, which leads to people's increasing attention to the safety risk of shield tunnel permeability in the process of Metro construction. In this paper, a construction risk model of shield

tunnel crossing water-rich soft strata based on the fuzzy Bayesian network method is established by combining the fuzzy set theory and Bayesian network. The main conclusions are as follows:

- Fuzzy Bayesian network method can solve the problems of lack of accident data and information ambiguity in the process of subway construction. At the same time, the model and method as well as the prior probability and fuzzy importance of each event in the construction risk of Shield Tunnel crossing water-rich soft stratum caused by Sun Chu have greater reliability and prediction breadth.
- From the importance of each basic event, it can be seen that segment rupture waterproof layer rupture and shield tail seal failure of shield tunnel have great influence on the construction risk of shield tunnel crossing water-rich soft stratum. Therefore, in the process of subway construction, we should strengthen the control of the above three factors and take preventive measures to ensure the quality of construction and avoid the safety accidents related to them to the greatest extent.
- Taking the construction section of Hujing Station to Wanshou Station of Fuzhou Metro Line 6 as an example, this paper uses the fuzzy Bayesian network method to predict the safety risk. The results show that the probability of accidents occurring in the construction process in this area is high, which is in line with the actual situation. The model method established in this paper has high reliability and practical significance. At the same time, this paper suggests that construction units should pay attention to and formulate relevant special plans to prevent accidents.

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