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Min Han
Geotechnical and Structural Engineering Research Center, Shandong University
Teng Xia
School of Civil Engineering, Shandong University
Maoxin Su (sumaoxin2019@163.com)
Geotechnical and Structural Engineering Research Center, Shandong University https://orcid.org/0000-0002-4718-4295
Yiguo Xue
Geotechnical and Structural Engineering Research Center, Shandong University

Research Article

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Posted Date: January 12th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1212772/v1

Risk analysis of tunnel water and mud inrush using interpretive structural modeling and fault tree

Min Han[1], Teng Xia[2], Maoxin Su[1]*, Yiguo Xue[1]

[1]Geotechnical and Structural Engineering Research Center, Shandong University, Jinan, Shandong 250061, China

[2]School of Civil Engineering, Shandong University, Jinan, Shandong 250061, China

M, Han[1]

Email: 202035011@mail.sdu.edu.cn

T, Xia[2]

Email: Tengxiasdu@163.com

M, Su[1]*

* Corresponding author.

Email: sumaoxin2019@163.com

ORCID: 0000-0002-4718-4295

Y, Xue[1]

Email: xieagle@sdu.edu.cn

Abstract: Water and mud inrush is a common geological hazard in tunnel construction. Risk analysis of tunnel water and mud inrush has always been an important subject. In order to avoid the geological hazard, this paper presents a risk analysis model of tunnel water and mud inrush. The model combines the interpretive structural modeling method (ISM) and fault tree analysis (FTA). Relying on the Qinyu tunnel in the Weiwu expressway project, water and mud inrush risk factors are obtained by using ISM. Fundamental risk factors include formation lithology, attitude of stratum, strata combination, topography and geomorphology, geological structure and weather. ISM core risk factors are used as FTA basic events. Fuzzy importance of FTA basic events is obtained by using fuzzy interval calculation. The results show that geological structure is the primary risk factor causing Qinyu tunnel water and mud inrush. The model achieves qualitative and quantitative analysis of tunnel water and mud inrush. It accurately determines the main factors affecting the tunnel water and mud inrush, which is conducive to accident prevention.

Keywords: Tunnel water and mud inrush, Risk analysis model, Interpretive structural modeling method, Fault tree analysis

Acknowledgements: Much of the work presented in this paper was supported by the Shandong Provincial Natural Science Foundation (Grant number ZR2014EEM028, Grant number 2019GSF111028), National Natural Science Foundations of China (Grant number 41877239). The authors would like to express appreciation to the reviewers for their valuable comments and suggestions that helped improve the quality of our paper.

Author contribution:

All authors contributed to the study conception and design. Data collection and analysis were performed by MH, TX, MXS and YGX. The first draft of the manuscript was written by MH and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

1. Instruction

In the process of tunnel construction, water and mud inrush disasters often occur, which seriously threaten the safety of the constructor (Yuan et al. 2019). At present, there are many risk analysis methods of tunnel water and mud inrush, such as coupling model (Zhu et al. 2014; Liu et al. 2017), normal cloud theory (Wang et al. 2016), gray theory (Zhu et al. 2018), normal grey cloud clustering method (Li and Yang 2018), mathematical model (Wang et al. 2019), attribute interval recognition theory (Wang et al. 2020), and AHP-Cloud theory (Peng et al. 2020),etc. Interpretive structural modeling method (ISM) can fully consider all influencing factors (Govindan et al. 2012), and it can realise qualitative risk analysis of tunnel water and mud inrush. Fault tree analysis (FTA) can achieve the impact level of risk factors, and it can realise quantitative risk analysis (Tanaka et al. 2009). Due to the comprehensiveness of combining ISM and FTA, a risk analysis model of tunnel water and mud inrush is significant for accident prevention.

There are many influencing factors of tunnel water and mud inrush. According to various factors, scholars have proposed many risk analysis methods. For example, Li et al. (2011) developed a water inrush forecasting system relying on the submarine tunnel. Chiu and Chia (2012) proposed a hydrogeological conceptual model and analysed the influence of groundwater. Based on the nonlinear grey Bernoulli model, Ma and Bai (2015) predicted the groundwater inflow and inrush risk. Shi et al. (2016)

established a stability analysis model by considering the effect of groundwater seepage force. Li et al. (2017) expatiated the water and mud inrush under the water-bearing and mud-filling structure. Shi et al. (2018) established a potential model based on attribute mathematics. In addition to groundwater, other engineering geological conditions such as geological structure, topography and geomorphology are the influencing factors of water and mud inrush. However, there are few studies on risk analysis models that combine all engineering geological conditions.

Proper and efficient tunnel construction methods, such as grouting (Li et al. 2016; Yuan et al. 2019), forward geological prediction (Zhang et al. 2010; Fan et al. 2018) and monitoring measurement (Sun et al. 2018). These can reduce the probability of water and mud inrush accidents. Zhao et al. (2013) classified water and mud inrush in view of the surrounding rocks and weather. They chose geological prediction and drainage methods according to risk degrees of different sections in the tunnel. Therefore, construction techniques are also the factors influencing tunnel water and mud inrush. However, most water and mud inrush risk models do not consider construction technologies factors. Water and mud inrush has the characteristics of randomness, suddenness and complexity. An accurate assessment of the tunnel’s risk requires a comprehensive analysis based on the tunnel’s engineering geology and construction techniques.

In view of the above problems, this study proposes a risk analysis model combining ISM and FTA for the first time. The research relies on the Qinyu tunnel in the Weiwu expressway project. ISM identifies the relationship between risk factors, determines the fundamental cause of the accident, and completes the qualitative analysis of tunnel water and mud inrush. Based on the qualitative analysis results, a fault tree is established. Fuzzy importance and probability are obtained by using fuzzy interval calculation. The results show that geological structure is the primary factor causing Qinyu tunnel water and mud inrush. Therefore, the risk analysis is conducive to preventing water and mud inrush in the tunnel.

2. Risk factors of tunnel water and mud inrush

Based on the engineering geological conditions of the site and the experience of constructor, the study identifies the potential risk factors of Qinyu tunnel water and mud inrush.

2.1 Engineering background

Qinyu tunnel belongs to the deep buried and long-mile tunnel under Weiwu expressway in Gansu Province, China (Figs. 1 and 2). The geological description and risk analysis of Qinyu tunnel are shown in Table 1. The tunnel is constructed by step method. The study referred to the mining construction criterion. The key technologies and common problems in tunnel construction are shown in Table 2.

Fig. 1 Geographical location map of the Qinyu tunnel in China mainland. The red square shows the location of the tunnel. The Qinyu tunnel located in Dangchang County, Gansu Province, China

Fig. 2 Plane graphs and vertical section of the tunnel. (a) The topography and geomorphology of the Qinyu tunnel. The Qinyu tunnel goes through a high mountainous area. The tunnel mileage is YK345+035~YK348+059 and the river in tunnel area is Min River. (b) The vertical section of the tunnel. Overlaying soil is Quaternary Holocene landslide accumulation horizon (Q_4^{del}). Underlying bedrock are Triassic slate (T_L^{Ls}), Lower Permian limestone, dolomitic limestone, marl (CP_{dg}^{Ls}), and Middle Devonian slate (D_g^{sb}). The maximum buried depth of the tunnel is 705 m. It passes through three faults

Table 1 Geological description and risk analysis of the Qinyu tunnel in Weiwu expressway project

Table 2 Key technologies and common problems in tunnel construction

Tunnel water and mud inrush cause heavy casualties and economic losses. The accident is the dynamic instability of groundwater migration systems or storage conditions disrupted by external forces (Li et al. 2018). The factors affecting water and mud inrush are numerous and complicated. Karst is present in part of the Qinyu tunnel, and the tunnel axis crosses three faults. Therefore, the tunnel has the potential risk of water and mud inrush.

2.2 Risk factors

Relying on the Qinyu tunnel, this research analysed the potential risk factors and divided them into natural and artificial factors. Natural risk factors have four aspects, including engineering geological conditions, hydrogeological condition, weather and tunnel characteristics. Specifically, engineering geological conditions include formation lithology, attitude of stratum, topography and geomorphology, strata combination and geological structure. Hydrogeological condition refers to groundwater in this study. Tunnel characteristics include surrounding rock grade and tunnel depth. The natural risk factors are shown in Table 3. Artificial risk factors refer to construction conditions, as shown in Table 4.

Table 3 Natural risk factors for tunnel water and mud inrush

Table 4 Artificial risk factors for tunnel water and mud inrush

According to the potential factors in Tables 3 and 4, this study combined the tunnel design description, construction experience and references to determine the relationship between the factors (Basarir 2006; He 2014). In Fig. 3, C indicates that the column elements directly affect the row elements; conversely, R indicates that the row elements directly affect the column elements.

Fig. 3 The relationship between each risk factor of the Qinyu tunnel water and mud inrush. C indicates that the column elements directly affect the row elements. R indicates that the row elements directly affect the column elements

3. Interpretive structural modeling method

ISM is a qualitative analysis method that divides the whole system into subsystems. In addition, ISM can make the system clear by establishing an interpretive structural model. It is convenient to get the relationship between each subsystem and the whole system. Currently, ISM has been applied in many fields, including energy (Ansari et al. 2013) and marine engineering (Wu et al. 2015). However, there are few studies on tunnel water and mud inrush.

3.1 Theory of ISM

There are 20 potential risk factors of the Qinyu tunnel water and mud inrush (Tables 3 and 4). Adjacency matrix A (a_{ij}) is established according to Fig. 3. A (a_{ij}) reflects the relationship between each risk factor:

$$a_{ij} = \begin{cases} 0, & N_i \ and \ N_j \ are \ not \ directly \ related \\ 1, & N_i \ and \ N_j \ are \ directly \ related \end{cases} . \quad (1)$$

Here, $i = j = 20$ in this study.

This research used Boolean algebra method (1+1=1, 1+0=1, 0+1=1, 0+0=0) to calculate Eq. 1, so that the adjacency matrix A (a_{ij}) satisfies the following equation:

$$A_i = \left(A + I\right)^i, 1 \le i \le n-1 , \quad (2)$$

where I $(i = j)$ is the identity matrix, n is the adjacency matrix A order.

When $A_1 \neq A_2 \neq A_3 \neq \cdots \neq A_{r-1} \neq A_r = A_{r+1}$, the reachability matrix M can be obtained as follows:

$$M = \left(A + I\right)^r. \tag{3}$$

In Eq. 3, A is the adjacency matrix, I ($i = j$) is the identity matrix, r is the reachability matrix M order. We decomposed the reachability matrix M, i.e., filtered out the rows with all zero elements (except the diagonal elements). The corresponding elements of these rows are the first level risk factors. We named the reachability matrix M after decomposition as M_1. Then we used the same method to decompose M_1 and got the second level risk factors. Finally, the ISM grading results was got, as shown in Table 5.

Table 5 ISM grading results

3.2 Qualitative analysis

According to Table 5, ISM model of the Qinyu tunnel water and mud inrush is established, as shown in Fig. 4. ISM model realises the qualitative analysis of the water and mud inrush. It clearly reflects the sorting of all risk factors. Engineering geological conditions directly affect the groundwater seepage. Engineering geological conditions and hydrogeological condition determine the depth of tunnel. The classification of tunnel surrounding rock grade should fully consider the engineering geological conditions, hydrogeological conditions and tunnel depth. Surrounding rock grade and bench length directly affect the cyclical footage length.

Fig. 4 ISM model of the Qinyu tunnel water and mud inrush. The first level factors represent the direct reasons for water and mud inrush, and the sixth level factors represent the fundamental reasons. We defined risk factors in levels 3 to 6 as the ISM core risk factors, the ISM core risk factors are $N_1, N_2, N_3, N_4, N_5, N_6, N_7, N_8, N_9, N_{10}$ and N_{16}

In addition, the first level factors represent the direct reasons for water and mud inrush, and the sixth level factors represent the fundamental reasons. The first level risk factors are all artificial factors, including protracted support, unreasonable support method, insufficient advanced support, exceeding closing cycle limitation, unreasonable blasting method and inadequate grouting or drainage. Incorrect and inefficient construction techniques may directly cause accidents. The sixth level risk factors are all natural factors, including formation lithology, attitude of stratum, strata combination, topography and geomorphology, geological structure and weather.

The risk factors in levels 3 to 6 are in the middle or bottom part of the whole model. These factors play a leading role in the ISM model, and they have an impact on the factors in levels 1 to 2 of the top layer. Therefore, these factors are defined as the ISM core risk factors. In this study, the ISM core risk factors are $N_1, N_2, N_3, N_4, N_5, N_6$, N_7, N_8, N_9, N_{10} and N_{16}.

4. Fault tree analysis method

FTA is an essential tool for quantitative system reliability and safety analysis, which can connect the top event (TE) and basic events (BE) through logic gates and intermediate events. At present, FTA has been applied to the risk analysis of tunnels, such as Shield Tunnel (Hyun 2015) and highway tunnel (Ný́vlta 2012) etc. ISM realises the qualitative analysis of Qinyu tunnel water and mud inrush. In order to quantify the risk factors of the accident, ISM and FTA are combined in this study.

There are many types of fuzzy numbers in FTA. The operation of trapezoidal fuzzy number is simple, high precision, and it can perform reliable quantitative analysis on the target system (Verma et al. 2012). Therefore, this study uses trapezoidal fuzzy number to give the occurrence probability of BEs.

4.1 Theory of trapezoidal fuzzy number

Zadeh (1965) presented fuzzy number to deal with vagueness or imprecision in the judgement of human decisions. The fuzzy sets are considered as an extension of conventional sets of numbers. In practice, the linguistic variables are utilised to convert decision opinion into reasonable knowledge (Chen 2017).

FTA is applied for the situation that lack or incompleteness of data. This method can quantify the judgements from experts. Trapezoidal fuzzy number membership function is given by (Zadeh 1965)

$$\mu_{\tilde{A}_1}(x)=\begin{cases}\dfrac{x-a}{b-a} & a\le x\le b\\ 1 & b\le x\le c\\ \dfrac{d-x}{d-c} & c\le x\le d\\ 0 & \text{otherwise}\end{cases}, \tag{4}$$

where $\tilde{A}_1=(a,b,c,d)$ is the trapezoidal fuzzy number. The membership function image of trapezoidal fuzzy number is shown in Fig. 5. ISM core risk factors are used as FTA basic events (Table 6), and an OR gate FTA model is established based on the ISM model (Fig. 6).

Fig. 5 The membership function image of trapezoidal fuzzy number $\tilde{A}_1=(a,b,c,d)$. a and b are the lower and upper confidence limits

Fig. 6 FTA model of the Qinyu tunnel water and mud inrush. ISM core risk factors are used as FTA basic events. It includes 11 basic events, i.e. A_1: fifth grade surrounding rock, A_2: large depth, B_1: active groundwater movement, C_1: soluble rock formation, C_2: changeable strata, C_3: the existence of the impermeable stratum, C_4: the existence of karst and strong permeability formation, C_5: water-bearing fault, D_1: heavy precipitation, E_1: non-standard forward geological prediction and E_2: unreasonable bench length

Table 6 Correspondence between the ISM core risk factors and the FTA basic events

4.2 Calculating possibility from expert judgement

Firstly, the experts give their opinions about each basic event. The basic events in the whole chain have played a vital role. Due to the experts having different levels of experiences, education and intellectual accumulation of knowledge, etc. In order to improve the accuracy of the evaluation and avoid the research question, the tunnel experts judgment used the weighted score method. Then, it can calculate each basic event possibility through the expert's academic language converted into a practical probability means. Hsu and Chen (1996) proposed SAM (Similar Aggregation Method). The basic steps for translating linguistic terms into the corresponding fuzzy numbers SAM method are described as follows.

4.2.1 Aggregating the possibilities obtained

Each expert has different personal experiences and expertise in the field. The weighting factor for each expert is determined according to Tables. 7 and 8. Table 7 is the information of the experts. In this step, each expert $E_k (k = 1, 2, \ldots, M)$ presents their opinions by comparing specific attributes with specific contexts using a set of predefined language variables. Then, the linguistic terms of experts are converted to corresponding fuzzy numbers. The common evaluation fuzzy language variables are very high, high, medium high, medium, medium low, low, and very low. The expert evaluations of the fuzzy language variables are transferred into trapezoidal fuzzy numbers, as shown in Fig. 5. The fuzzy numbers conversion scale is shown in Table 9.

Since each expert has different opinions, it is necessary to aggregate the expert opinions to reach a consensus. The detail of equations is explained as follows (Lavasani et al. 2015, Senol et al. 2015).

Table 7 Details of tunnel experts

Table 8 Weighting scores of experts

Table 9 Linguistic terms and their corresponding trapezoidal fuzzy number

1. Calculating the degree of agreement:

In this step, E_{u} and E_{v} defines each pair of experts, $S_{\mathrm{u\,v}}(\tilde{R}_{u},\tilde{R}_{v})$ gives views of experts where $S_{\mathrm{u\,v}}(\tilde{R}_{u},\tilde{R}_{v})\in[0,1]$. In this context, $\tilde{A}=(\mathrm{a}_1,\mathrm{a}_2,\mathrm{a}_3,\mathrm{a}_4)$ and $\tilde{B}=(b_1,b_2,b_3,b_4)$ are two trapezoidal fuzzy numbers. Eq. 5 is used to calculate the degree of similarity between two fuzzy numbers by adopting the similarity function of *S*. which is defined as

$$S_{uv}(\tilde{A},\tilde{B})=1-1/4\sum_{i=1}^{4}\left|a_i-b_i\right|. \tag{5}$$

Here, $S_{uv}(\tilde{A},\tilde{B})\in[0,1]$. The larger value of $S_{uv}(\tilde{A},\tilde{B})$ the greater similarity between two fuzzy numbers $\tilde{A}$ and $\tilde{B}$.

2. Calculate average agreement (AA) degree $AA(E_{\mathrm{u}})$ of the experts:

Eq. 6 is used to calculate the average agreement degree of the tunnel experts.

$$AA(E_u)=\frac{1}{M-1}\sum_{u\neq v}^{M}S_{\mathrm{u\,v}}(\tilde{R}_{u},\tilde{R}_{v}) \tag{6}$$

Here, M is the number of experts.

3. Calculate the relative agreement (RA) degree, $RA(E_{\mathrm{u}})$ of the experts:

Eq. 7 is used to determine the average agreement degree of experts

$$E_u (u = 1, 2, \ldots, M) \text{ as } RAs(E_u) = \frac{AA(E_u)}{\sum_{\mathrm{u}=1}^{M} AA(E_u)} \tag{7}$$

4. Estimate the consensus coefficient (CC) degree, $CC(E_{\mathrm{u}})$ of the experts:

Eq. 8 is used to predict the degree of the consensus coefficient of experts.

$$CC(E_u) = \beta \cdot \omega(E_u) + (1-\beta) \cdot RA(E_u) \tag{8}$$

Here, β is a relaxation factor in the method. It determines the importance of $\omega(E_u)$ compared with $RA(E_u)$. When $\beta=0$, no significance is attached to the weight of an expert. When $\beta=1$, the consensus degree of an expert is equal to its weight of importance. The consensus degree coefficient for each expert provides a good measure for evaluating the relative importance of each expert's opinion. In this study, we set $\beta=0.5$

5. The aggregated result of the expert judgments:

The aggregated result of the expert judgments $\tilde{R}_{AG}$ can be obtained as follows:

$$\tilde{R}_{AG} = CC(E_1) \times \tilde{R}_1 + CC(E_2) \times \tilde{R}_2 + \cdots + CC(E_M) \times \tilde{R}_M, \tag{9}$$

where $\tilde{R}_{AG}$ is an aggregate fuzzy number of basic events, and R_i is the fuzzy probability given by an expert.

4.2.2 Defuzzifying of aggregated expert judgment

This step involves converting trapezoidal fuzzy numbers into crisp numbers, suitable for analysis and decision making in the fuzzy environment. Sugeno (1999) employed Centre of Gravity (COG) or Centre of Area (COA) as a defuzzification technique. It is expressed by Eq. 10:

$$X^{*}=\frac{\int u_i(x)x\,\mathrm{dx}}{\int u_i(x)}, \tag{10}$$

where X^{*} is fuzzy possibility. $u_i(x)$ defines aggregated membership function and X is the output variable. In this context, $X^{*}=\frac{1}{3}\cdot\frac{(a_4+a_3)^2-a_4a_3-(a_1+a_2)^2+a_1a_2}{a_4+a_3-a_1-a_2}$

4.2.3 Converting possibilities to probabilities

Onisawa (1988) has proposed a function, which can be used for converting fuzzy failure possibility (FPs) to fuzzy failure probability (FPr). (Lin and Wang 1998). The following equation is used (Eq. 11).

$$FPr=\begin{cases}\frac{1}{10^k}, & FPs\neq 0\\ 0, & FPs=0\end{cases} \tag{11}$$

$$K=\left(\frac{1-FPs}{FPs}\right)^{\frac{1}{3}}\times 2.301, \tag{12}$$

FPr can be calculated from the FPs and K which is defined as a constant number (Corlett 1981). K represents the safety criterion based on the lowest bound of the error rate and error rates of a routine. It can be calculated by Eq. 12.

4.2.3 Computing total failure probability of TE

The probability of TE can be illustrated with the following Eq. 13.

$$P_{TE}=1-\prod_{i=1}^{n}\left(1-P_i\right) \tag{13}$$

In Eq. 13, P_i are the occurrence probabilities for each basic event, and P_{TE} is the probability for the occurrence of the top event.

4.3 Application

Karst is extremely developed in southwest China. With the construction of major infrastructure projects for transportation, water conservancy and hydropower, underground projects in karst areas are increasing. During the construction of the tunnel, karst fissure water disasters are often encountered. This will lead to the occurrence of underground karst water and mud inrush, surrounding rock Collapse, deformation and cracking of supporting structure (Li et al. 2010). Water and mud inrush is a severe geological disaster restricting tunnel construction. Accidents of water inrush and mud inrush occurred many times in the Qiyaoshan tunnel, the Lingjiao tunnel, the Yiwan railroad, the Qiyueshan tunnel and others. Such accidents result in huge economic losses, casualties, and delays. Therefore, the risk assessment and control of water inrush and mud inrush have gradually become key technical problems in karst tunnel construction. This study took the Qinyu tunnel as an example, analysed the application of FTA in tunnel water and mud inrush risk research. This article focused on calculating the probabilities of accident and the importance of each basic event. The quantitative analysis of tunnel water and mud inrush can be achieved.

This article calculated the probability based on the data collected by experts with extensive experience. The experts include tunnel engineering project manager, Chief engineer, Supervisor, Minister of engineering department and professor. Them for tunnel construction has extensive knowledge and experience. In view of this, table 7 lists the details of the experts who participated in this survey.

In this research, the probability is used to predict risks. The first step in the quantitative analysis is to establish a fault tree model based on BEs and TE (Table 6). Due to the lack of probabilistic data of BEs, it is a practical method to use the tunnel expert judgment to calculate the possibility of BEs and convert the language used by experts into probability. Table 8 shows the weighting scores of experts. Table 9 shows the linguistic terms and their corresponding trapezoidal fuzzy number, which convert the language expressions of tunnel experts into fuzzy numbers.

Due to the tunnel experts are non-homogeneous, they may have different views on a particular attribute. Therefore, it is essential to introduce the dominant factors. According to their profiles, Table 10 shows the weights of the tunnel experts who participated in the survey. Based on the experience of the tunnel experts, Table 11 lists their linguistic judgements for basic event possibilities.

Table 10 Weights of tunnel experts participated to survey

Table 11 Linguistic judgements of tunnel experts for basic event possibilities

According to the method described above, the basic event A1 for water and mud inrush accident is aggregated. To calculate the comprehensive opinion of experts, Eq. 5 is adopted. Therefore, the similarity function and similarity value of basic event A1 are given in Table 12. By Eqs. 6-8, Table 13 shows the average agreement (AA), relative agreement (RA) and consensus coefficient (CC) of tunnel experts. In the calculation, β is nominated as 0.5 since six tunnel experts are considered as identical. In order to aggregate expert judgments, Eq. 9 is used. After obtaining the aggregate results, the fuzzy numbers are converted into clear values by the defuzzification process.

Table 12 Similarity function and similarity value for basic event A1

Table 13 *AA, RA* and *CC* values of marine experts for basic event A1

Using the same method, we calculated the average agreement, relative agreement and consensus coefficient of other basic events. Table 14 shows the probability of failure (FPr) and the probability value derived from the comprehensive experts judgments (R_{AG}) and defuzzification（FPs）for each of the BEs by Eqs. 9-12. Order the severity according to the probability of the BEs in Table 15. Then the probability of TE is derived from Eq.13. After calculation, the probability of TE is 0.45242. The results show that water and mud inrush probability is 45.24%. This accident probability is very high. The relevant departments should pay great attention to this issue and take corresponding measures to avoid it effectively. According to the rankings of probability for all BEs, the severity is $S_{C5} > S_{B1} > S_{C2} > S_{C4} > S_{A2} > S_{C1} > S_{C3} > S_{A1} > S_{E1} > S_{E2} > S_{D1}$. The primary risk factor of Qinyu tunnel water and mud inrush is geological structure. Faults have a significant impact on tunnel safety. The fuzzy importance rankings are geological structure, groundwater, attitude of stratum, topography and geomorphology, tunnel depth, formation lithology, strata combination, surrounding rock grade, forward geological prediction, bench length and weather. During the construction of the Qinyu tunnel, the water-bearing state of faults should be closely monitored. In addition, factors such as rock formation and burial depth cannot be neglected. Construction and forward geological prediction are carried out in accordance with the specifications. To prevent the water inrush from the tunnel, it is necessary to investigate the geological conditions at the tunnel site, and formulate corresponding construction measures according to the hydrogeological conditions and engineering geological conditions.

Table 14 Converting failure possibility into failure probability

Table 15 Probabilities and severity of FTA basic events

5. Discussion

Tunnel water and mud inrush have the characteristics of randomness, suddenness and complexity. Engineering geological conditions and hydrogeological conditions determine the possibility of tunnel water and mud inrush. Proper and efficient tunnel construction methods can reduce the probability of accidents. Therefore, accurately assessing the tunnel's risk requires a comprehensive analysis based on engineering geology and construction techniques. In order to analyse the risk of tunnel water and mud inrush comprehensively, this study proposes a risk analysis model combining ISM and FTA for the first time; it achieves qualitative and quantitative analysis of water and mud inrush. The research relies on the Qinyu tunnel in the Weiwu expressway project; hence, all risk factors in ISM and FTA are based on this tunnel. However, in the risk analysis of other tunnels, the corresponding risk factors can be modified according to the field conditions of different tunnels. The risk analysis method combining ISM and FTA has universal applicability.

Taking the risk analysis of the Qinyu tunnel as an example, an ISM model of water and mud inrush is established. ISM model indicates the relationship of various risk factors, and its core risk factors are used as FTA basic events. We get the primary risk factor of water and mud inrush, and realise the quantitative analysis of the accident through FTA model. The core risk elements in ISM, basic events in FTA and probabilities in Tab 14 of other tunnels may be different. Different tunnels need to be adjusted according to actual conditions.

6. Conclusion

The risk analysis model of tunnel water and mud inrush achieves qualitative and quantitative analysis of water and mud inrush. It is conducive to the prevention of tunnel water inrush. The following conclusions are drawn:

(1) Relying on the Qinyu tunnel, this study identifies the potential risk factors of water and mud inrush. We divide them into natural and artificial factors. Natural risk factors include engineering geological conditions, hydrogeological condition, weather and tunnel characteristics. Artificial risk factors refer to construction conditions. These risk factors are used to establish the ISM model.

(2) ISM model of tunnel water and mud inrush is established. It realises the qualitative analysis of accidents and reflects the sorting of all risk factors. The sixth level factors represent the fundamental reasons, including formation lithology, attitude of stratum, strata combination, topography and geomorphology, geological structure and weather. The risk factors in levels 3 to 6 are defined as the ISM core risk factors. These core risk factors are used as FTA basic events.

(3) FTA model of tunnel water and mud inrush is established. It realises the quantitative analysis of accidents and clearly reflects the ranking of fuzzy importance. The probability of water and mud inrush is 0.452415. The primary risk factor of the Qinyu tunnel water and mud inrush is geological structure. Therefore, the

water-bearing state of faults should be closely monitored during the construction of the Qinyu tunnel.

(4) The risk analysis model of tunnel water and mud inrush combines ISM and FTA. It realises a comprehensive analysis based on the engineering geology and construction techniques of the tunnel. The model is conducive to accident prevention.

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Declarations

Funding: This research was supported by the Shandong Provincial Natural Science Foundation (Grant number ZR2014EEM028, Grant number 2019GSF111028), National Natural Science Foundations of China (Grant number 41877239).

Competing Interests:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution:

All authors contributed to the study conception and design. Data collection and analysis were performed by MH, TX, MXS and YGX. The first draft of the manuscript was written by MH and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Figures

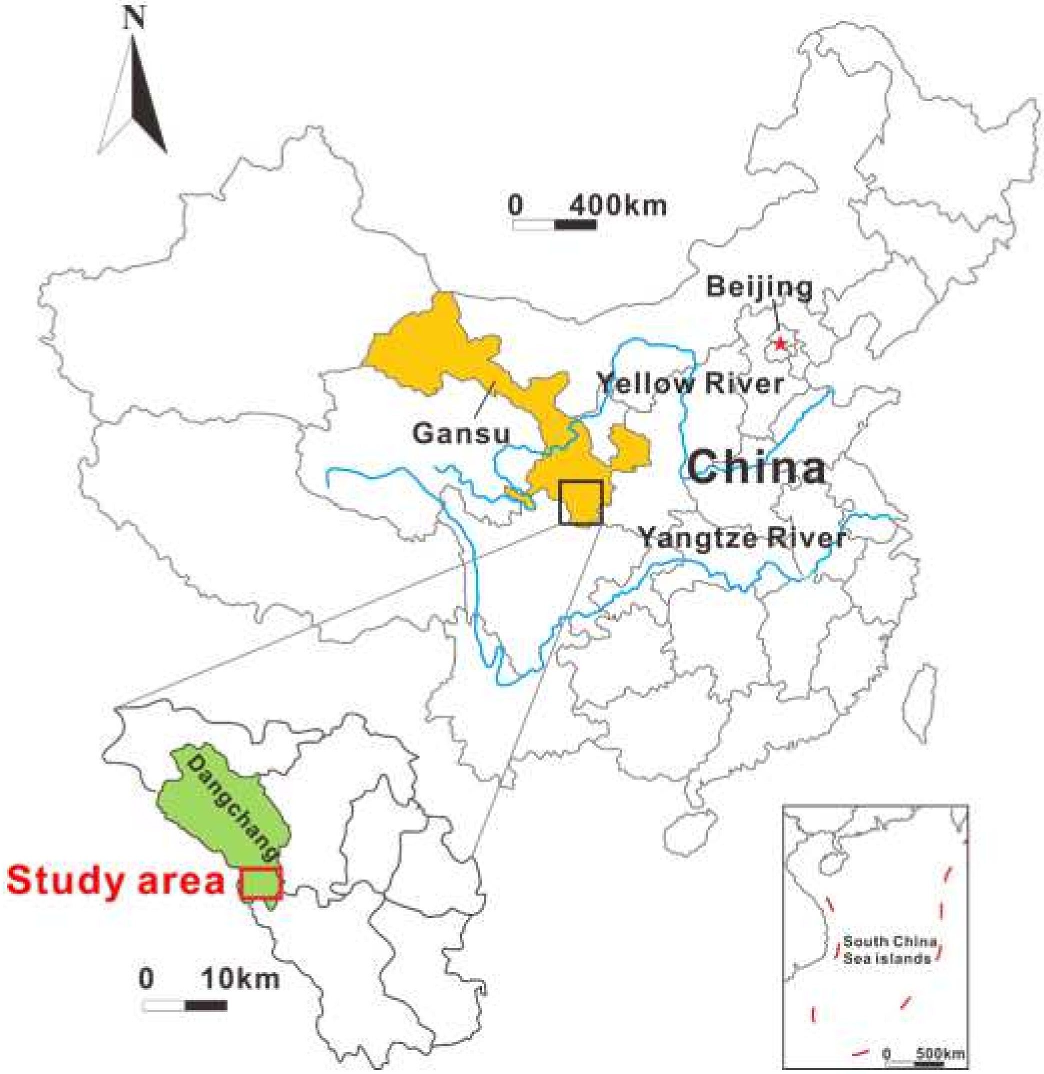

Figure 1

Geographical location map of the Qinyu tunnel in China mainland. The red square shows the location of the tunnel. The Qinyu tunnel located in Dangchang County, Gansu Province, China

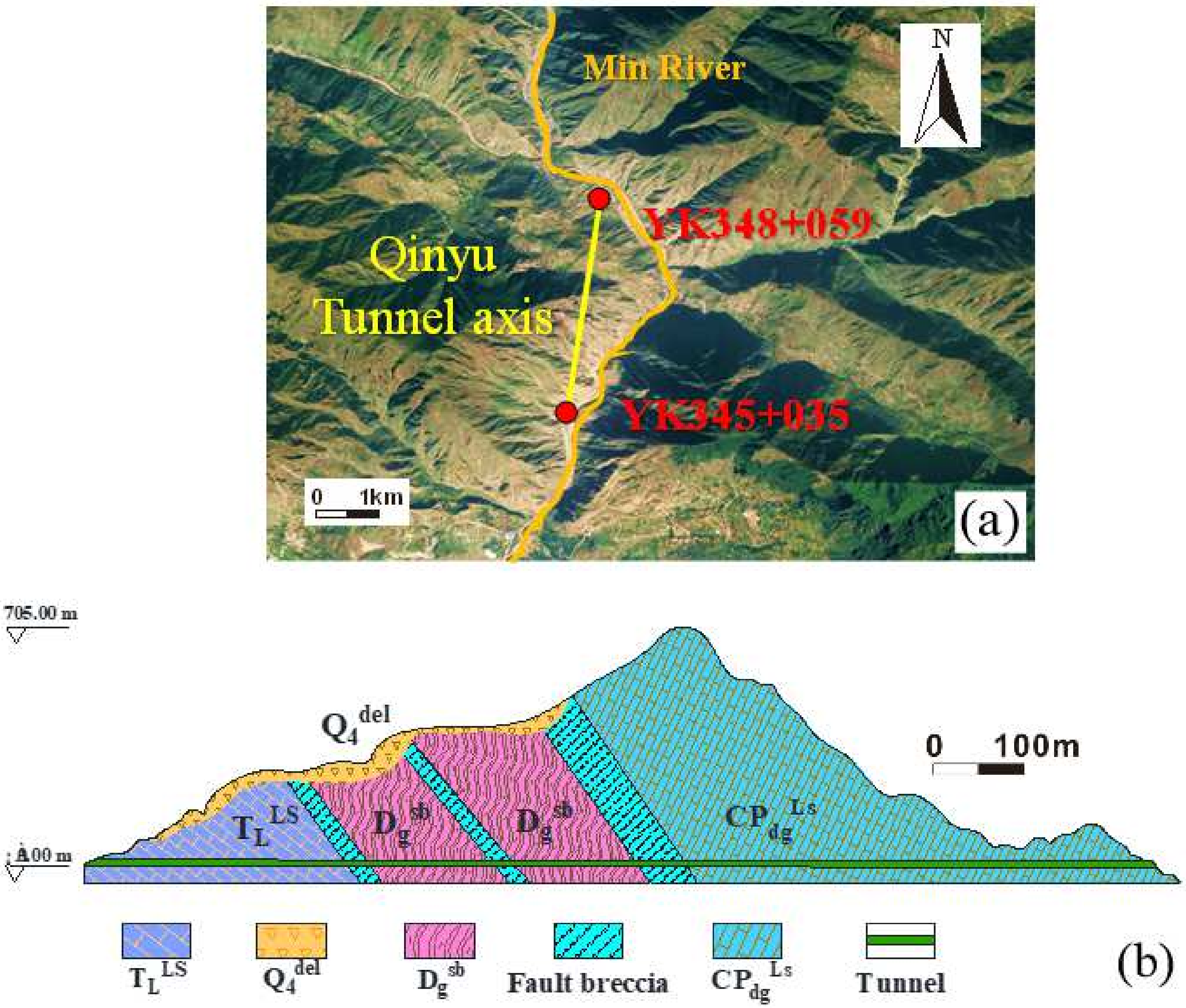

Figure 2

Plane graphs and vertical section of the tunnel. (a) The topography and geomorphology of the Qinyu tunnel. The Qinyu tunnel goes through a high mountainous area. The tunnel mileage is YK345+035~YK348+059 and the river in tunnel area is Min River. (b) The vertical section of the tunnel. Overlaying soil is Quaternary Holocene landslide accumulation horizon (Q_4^{del}). Underlying bedrock are Triassic slate (T_L^{Ls}), Lower Permian limestone, dolomitic limestone, marl (CP_{dg}^{Ls}), and Middle Devonian slate (D_g^{sb}). The maximum buried depth of the tunnel is 705 m. It passes through three faults

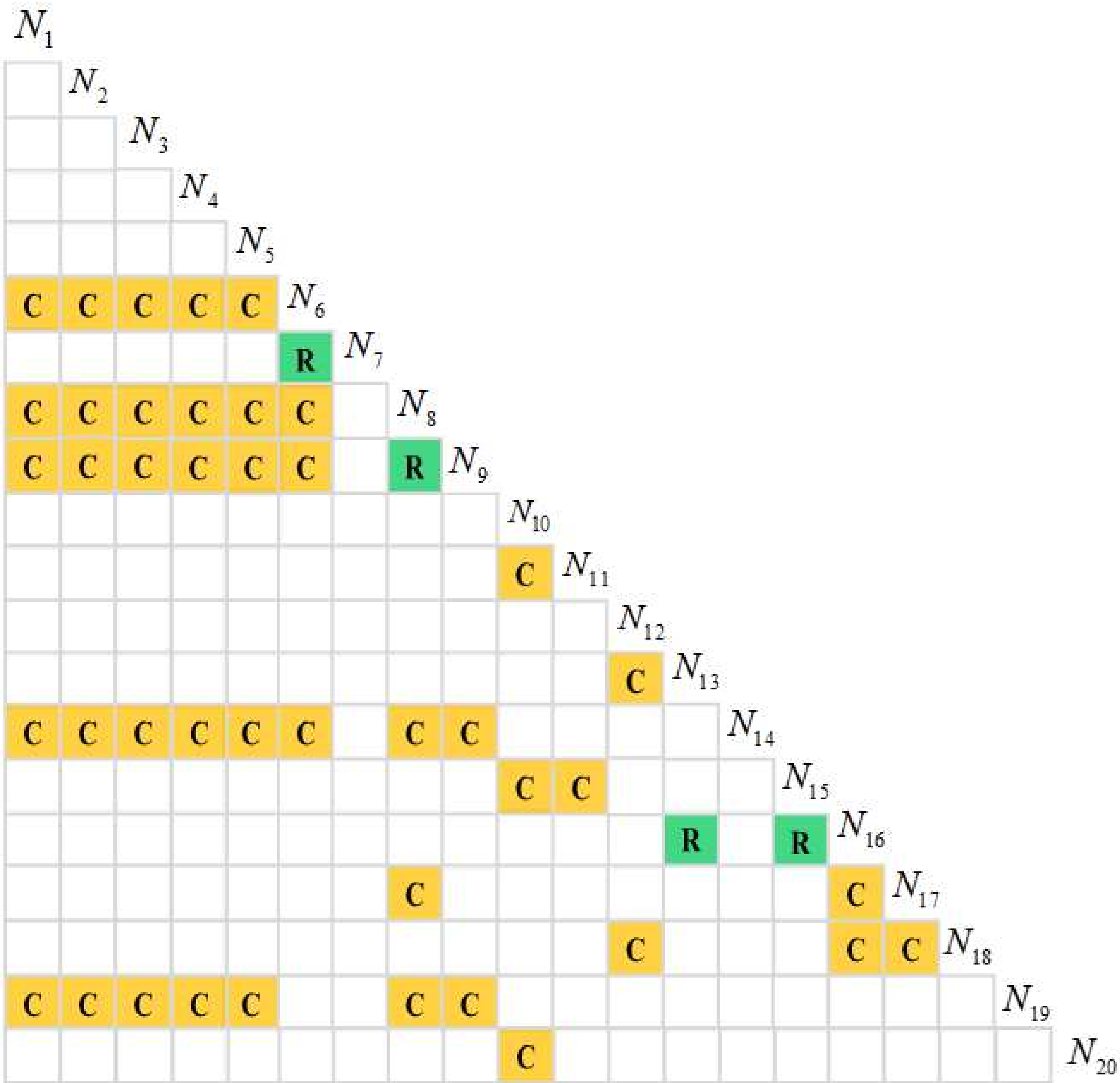

Figure 3

The relationship between each risk factor of the Qinyu tunnel water and mud inrush. C indicates that the column elements directly affect the row elements. R indicates that the row elements directly affect the column elements

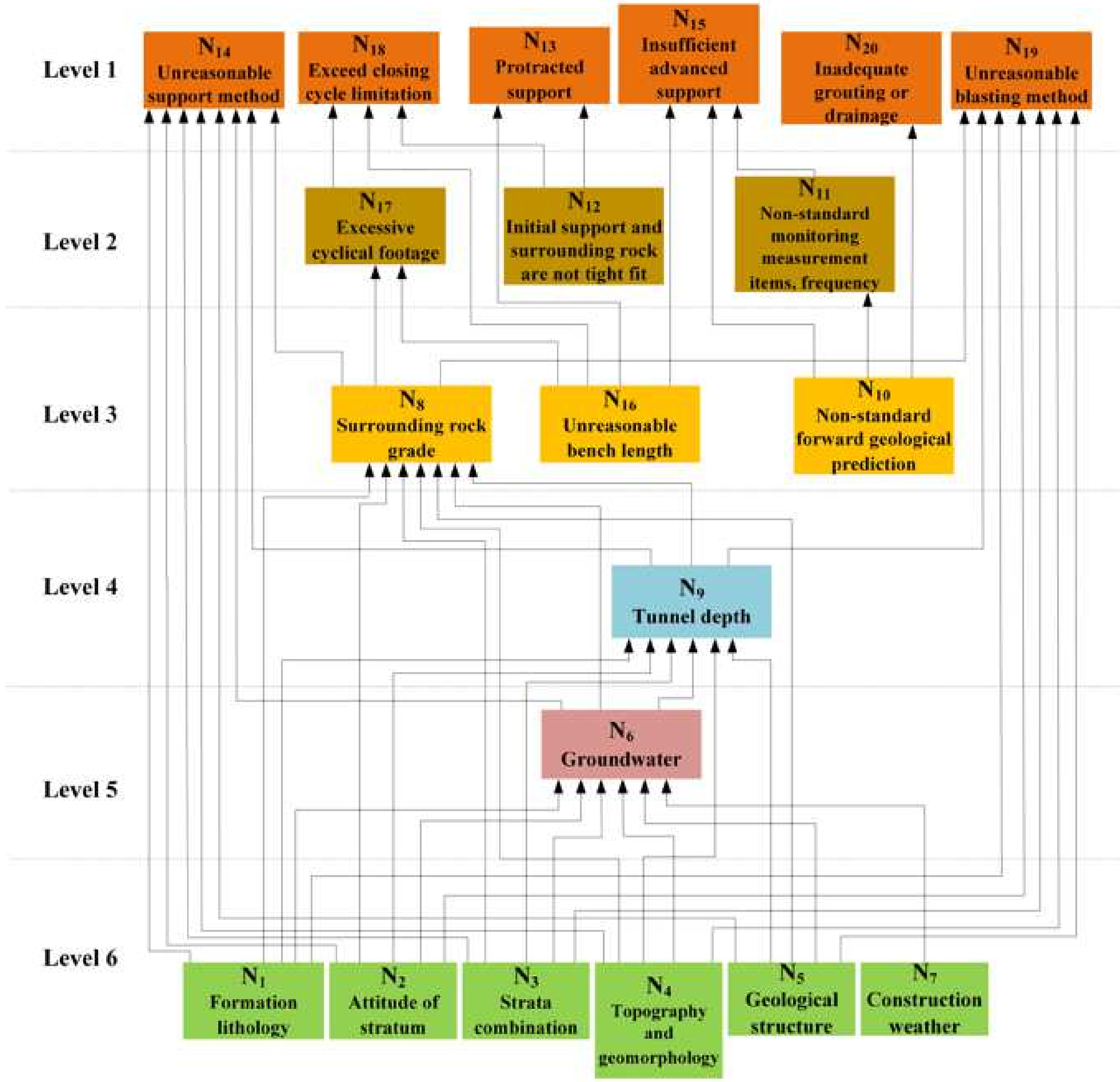

Figure 4

ISM model of the Qinyu tunnel water and mud inrush. The first level factors represent the direct reasons for water and mud inrush, and the sixth level factors represent the fundamental reasons. We defined risk factors in levels 3 to 6 as the ISM core risk factors, the ISM core risk factors are *N1, N2, N3, N4, N5, N6, N7, N8, N9, N10 and N16.*

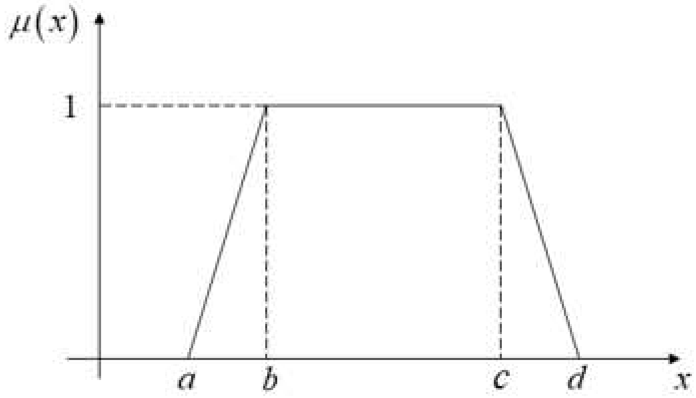

Figure 5

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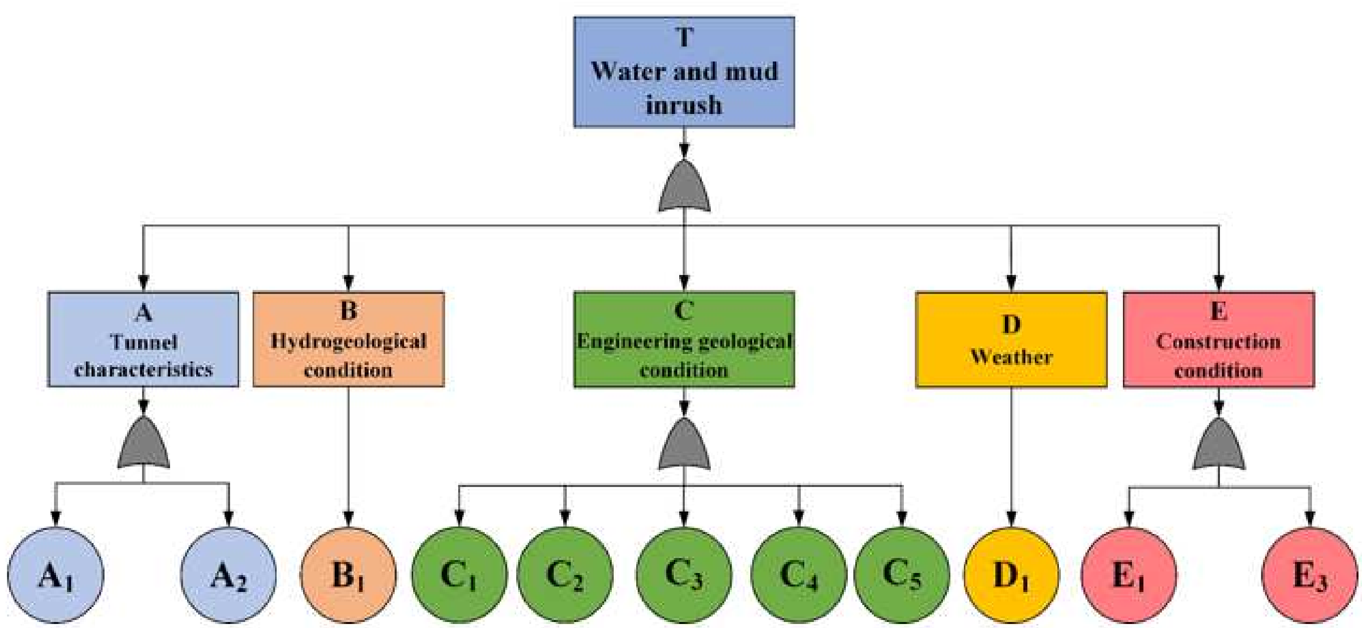

Figure 6

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