Research on Tunnel Risk Control and Evaluation Index Based on Fuzzy Theory

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Abstract: In recent years, many large scaled tunnels, like the Kouksa Tunnel, with complicated construction have emerged in China. The multiple factors, including intricate topography and weather conditions, all make the potential risks highly uncontrollable during tunnel excavation. The researching group made comprehensive assessments to geological risks of the Kouksa Tunnel through the fuzzy theory, and drew the conclusion that its risk belonged to level three, as a medium one. By assessing geological risks, it will be helpful for the construction unit to take measures to prevent high-risk geological disasters and ensure the safety of tunnels.

1. Introduction

Tunnel engineering has always played an important role in the entire transportation industry. Nowadays, with the advancement of the social science and technology economy, the demand for tunnel construction is increasing. In recent years, related data have shown that the safety accidents have caused serious damage to the national property and constructors’ personal safety [1].

The Kouksa Tunnel is located in Akesai County, Gansu Province. There are many “V”-shaped erosion valleys with little vegetation around the tunnel, which ranges from the north bank of Dangjinshan to the right bank of Changcaogou. Its total length and maximum depth are 306m and 32m respectively. The geological structure with the extremely poor lithology is mainly composed of fault mud and fault breccia. The surface water is mainly composed of ice and snow melt water. Meanwhile, the mainly sources of groundwater recharge are atmospheric precipitation and surface runoff. In addition, the traffic is difficult because of the few pedestrian access roads at the entry and exit of the tunnel.

Some scholars have done a large quantity of thorough researches about the safety management and risk taking of shield tunneling. Einstein.HH (1994) considered the long-term and construction risk when comparing the construction schemes of the Adler Tunnel, and applied risk analysis method to give a lower cost scheme [2]; Kampmann (1998) proposed a concrete classification system for potential geological disasters in the Copenhagen Metro System, and finally raised 48 risk mitigation measures on risk assessment techniques [3]; Chinese scholar Ru Mao (2003) introduced the risk index into the tunnel engineering risk assessment, and now this method has been widely applied and recommended in the Chinese tunneling field [4]. However, the tunnel risk management still needs to be improved because the Chinese theoretical researches and practical experiences are quite scarce.

In order to quantitatively calculate potential geological disasters, this paper focuses on the evaluation of risky factors in the Kouksa Tunnel based on the fuzzy theory. The fuzzy relation matrix
is used to formulate emergency measures for the geological disasters with higher risk values, which can greatly reduce the economic loss and casualties of the tunnel during the construction process.

2. Fuzzy comprehensive evaluation theory
Fuzzy comprehensive evaluation is a method based on fuzzy mathematics [5]. This method transforms the qualitative evaluation into quantitative evaluation. And it can make an overall evaluation of objects that are restricted by various factors through the membership degree theory of fuzzy mathematics.

The risk assessment of tunnel construction is a difficult-quantify fuzzy problem. This method, with the characteristics of clear results and strong systematizations [6], is easy to comprehensively evaluate on the hydrogeology and geological structure of the tunnel. Thus, the risk level of the Kouksa Tunnel can be obtained.

2.1 Specific evaluation steps
1. Establish a factor set. Integrate the various factors $U_i (i = 1, 2, \ldots, n)$ to obtain a set of factors: $U = (u_1, u_2, \ldots, u_n)$.
2. Establish an evaluation set. Measure the evaluation indicators and obtain an evaluation set: $V = (v_1, v_2, \ldots, v_m)$.
3. Establish weight set. Collect elements and establish judgment matrix. Determine the weight of each index, and get the weight set: $W = (w_1, w_2, \ldots, w_n)$, and should satisfy: $\sum_{i=1}^{n} w_i = 1$.
4. Establish a single factor judgment matrix. The method of expert evaluation is used to obtain the judgment matrix. And the evaluation set is a single factor evaluation matrix composed of $n$ fuzzy subsets $R$.

2.2 First-level fuzzy comprehensive evaluation
1. This study adopts fuzzy comprehensive evaluation model is large size and small size, namely:

$$B = \{ b_j = \bigvee_{l=1}^{n} \left( w_{l A r_{ij}} \right) \} \quad (j = 1, 2, \ldots, m)$$

2. After obtaining $b_j$, the result $V_j$ of the judgment is determined according to the maximum membership degree rule.

2.3 Second-level fuzzy comprehensive evaluation
This article divides risks into two levels, since some factors are placed on one layer which causes small weight factors to be ignored easily. The single factor assessment of each stratum is the result of the next-level multi-factor induction, which is generally a comprehensive calculation from the lower strata to the higher strata.

3. Risk assessment system
During the tunnel construction process, many factors only can be judged by the experience of geological operators. As the Delphi Method is widely representative and reliable [7], it is used to conduct questionnaires to experts to score the tunnel geological risks. After contrasting the data and reflecting the opinions, the type of geological disasters can be determined.

3.1 Expert assessment process
1. Selects 10 experts with rich experience in construction to score the geological risks in the Kouksa Tunnel.
2. Design the questionnaire for the experts and collect the written replies.
3. Collect the first opinion of the expert group, and then use the mathematical tools to summarize the results, compare and convey the results to the experts.
4. Sort out the opinions and distribute them to the experts again. Four rounds are carried out until these opinions are no longer changed.
5. Analyze the opinions and get the final results.
After the above process, the potential risks of the tunnel are mainly four types of landslide, freezing, water inrush, and entry and exit of the tunnel risk. Finally, the comprehensive evaluation system is shown in Table 1.

| Index | Weights | Index | Weights |
|-------|---------|-------|---------|
| Landslide risk $u_1$ | $w_1=0.434$ | Geological structure $u_{11}$ | $w_{11}=0.454$ |
| | | Groundwater effect $u_{12}$ | $w_{12}=0.229$ |
| | | Crushing rocks risk $u_{13}$ | $w_{13}=0.229$ |
| | | Prevention measures $u_{14}$ | $w_{14}=0.044$ |
| | | Slope support risk $u_{15}$ | $w_{15}=0.044$ |
| | | Frost heaving $u_{21}$ | $w_{21}=0.894$ |
| Freezing risk $u_2$ | $w_2=0.166$ | Lining surface icing $u_{22}$ | $w_{22}=0.072$ |
| | | Snow water icing $u_{23}$ | $w_{23}=0.034$ |
| | | Groundwater movement $u_{31}$ | $w_{31}=0.244$ |
| Water inrush risk $u_3$ | $w_3=0.332$ | Pipeline buried $u_{32}$ | $w_{32}=0.248$ |
| | | Water layer distribution $u_{33}$ | $w_{33}=0.154$ |
| | | Seepage treatment $u_{34}$ | $w_{34}=0.229$ |
| | | Tunnel depth $u_{35}$ | $w_{35}=0.125$ |
| Entry and exit of the tunnel risk $u_4$ | $w_4=0.068$ | Structure character $u_{41}$ | $w_{41}=0.429$ |
| | | Stress change $u_{42}$ | $w_{42}=0.429$ |
| | | Supervision intensity $u_{43}$ | $w_{43}=0.142$ |

3.2 Establish a risk factor set

The set of factors based on Table 1 is as follows: $U = (u_1, u_2, u_3, u_4) = \text{(landslide risk, freezing risk, water inrush risk, entry and exit of the tunnel risk)}$.

| Index | Weights |
|-------|---------|
| Landslide risk | $W_1=0.434$ |
| Freezing risk | $W_2=0.166$ |
| Water inrush risk | $W_3=0.332$ |
| Entry and exit of the tunnel risk | $W_4=0.068$ |

By considering the degree of influence on the entire tunnel project, the comments will be divided into five levels, namely $V = (v_1, v_2, v_3, v_4, v_5) = \text{(first, second, third, fourth, fifth)}$. And the corresponding risk value is given $5 \sim 1$, indicating the risk value $S=(5, 4, 3, 2, 1)$.

3.3 Establish a fuzzy relationship matrix

1. The statistics of the questionnaire can get the risk level of the corresponding risk factors. Take $u_{11}$ as an example: the number of low risk grade is 0, the number of relatively low risk grade is 3, the number of medium risk grade is 4, the number of relatively high risk grade is 3, and the number of high risk grade is 0. Finally, the evaluation vector $R_{11} = (0.0 \ 0.3 \ 0.4 \ 0.3 \ 0.0)$ can be obtained.

2. Create an evaluation model for the geological risk and establish a fuzzy relation matrix $R_i$.

$$R_i = \begin{bmatrix} R_{11} & R_{12} & R_{13} & R_{14} & R_{15} \\ 0.0 & 0.3 & 0.4 & 0.3 & 0.0 \\ 0.0 & 0.2 & 0.3 & 0.3 & 0.2 \\ 0.2 & 0.2 & 0.1 & 0.4 & 0.1 \\ 0.1 & 0.4 & 0.1 & 0.4 & 0.0 \\ 0.0 & 0.1 & 0.5 & 0.4 & 0.0 \end{bmatrix}$$
The tunnel risk is relatively high. In account of the frequent seismic activity, there are a great impact on the tunneling and potential tunnel risk is relatively high. In line with the statistics of excavation, the risk of landslide and water rezing are generally average and is a four-level risk.

3. First-level fuzzy evaluation: Through the first-level fuzzy assessment of the disaster risk, the single-factor risk level can be obtained.

Total score for $u_1$:

$$ B_1 = W_1 \cdot R_1 = \begin{bmatrix} 0.454 \ 0.229 \\ 0.044 \end{bmatrix}^T \begin{bmatrix} 0.0 & 0.3 & 0.3 & 0.3 & 0.0 \\ 0.2 & 0.2 & 0.3 & 0.3 & 0.2 \\ 0.2 & 0.2 & 0.1 & 0.4 & 0.1 \\ 0.1 & 0.4 & 0.1 & 0.4 & 0.0 \\ 0.0 & 0.1 & 0.5 & 0.4 & 0.0 \end{bmatrix} = \begin{bmatrix} 0.050 \ 0.250 \ 0.300 \ 0.332 \ 0.069 \end{bmatrix} \cdot \begin{bmatrix} 5 & 4 & 3 & 2 & 1 \end{bmatrix} = 3.208 $$

K_1 = B_1 \times S^T = 3.208. The risk of landslides is more prominent and is a four-level risk.

Total score for $u_2$:

$$ B_2 = W_2 \cdot R_2 = \begin{bmatrix} 0.894 \\ 0.072 \\ 0.034 \end{bmatrix}^T \begin{bmatrix} 0.3 & 0.1 & 0.1 & 0.1 & 0.2 & 0.3 \\ 0.2 & 0.2 & 0.5 & 0.1 & 0.0 \end{bmatrix} = \begin{bmatrix} 0.296 \ 0.107 \ 0.132 \ 0.189 \ 0.275 \end{bmatrix} $$

K_2 = B_2 \times S^T = 2.960. The risk of freezing is generally average and is a three-level risk.

Total score for $u_3$:

$$ B_3 = W_3 \cdot R_3 = \begin{bmatrix} 0.429 \\ 0.229 \\ 0.125 \end{bmatrix}^T \begin{bmatrix} 0.3 & 0.4 & 0.3 & 0.0 \ 0.4 & 0.4 & 0.4 & 0.1 \ 0.1 & 0.5 & 0.4 & 0.0 \end{bmatrix} = \begin{bmatrix} 0.028 \ 0.314 \ 0.343 \ 0.186 \ 0.129 \end{bmatrix} $$

K_3 = B_3 \times S^T = 3.101. The risk of water inrush is more prominent which means a four-level risk.

Total score for $u_4$:

$$ B_4 = W_4 \cdot R_4 = \begin{bmatrix} 0.429 \\ 0.142 \end{bmatrix}^T \begin{bmatrix} 0.1 & 0.4 & 0.2 & 0.3 & 0.0 \\ 0.2 & 0.2 & 0.4 & 0.1 & 0.0 \end{bmatrix} = \begin{bmatrix} 0.092 \ 0.253 \ 0.287 \ 0.268 \ 0.100 \end{bmatrix} $$

K_4 = B_4 \times S^T = 2.971. After the overall risk assessment, it is concluded that the construction of the Kouksa Tunnel is “three-level” risk which is “medium” risk.

4. Second-level fuzzy evaluation. Through the second-level fuzzy assessment of the disaster risk, the overall risk level of the tunnel is obtained.

$$ B = W \cdot R = \begin{bmatrix} B_1 & B_2 & B_3 & B_4 \end{bmatrix}^T = \begin{bmatrix} 0.434 & 0.166 & 0.332 & 0.068 \\ 0.050 & 0.296 & 0.059 & 0.028 \\ 0.250 & 0.107 & 0.319 & 0.314 \\ 0.300 & 0.132 & 0.336 & 0.343 \\ 0.332 & 0.189 & 0.240 & 0.343 \\ 0.069 & 0.275 & 0.240 & 0.186 \\ 0.092 & 0.100 \end{bmatrix} $$

K = B \times S^T = 3.252. After the overall risk assessment, it is concluded that the construction of the Kouksa Tunnel is “three-level” risk which is “medium” risk.

3.4 Discussion

On account of the frequent seismic activity, there is a great impact on the tunneling and the potential tunnel risk is relatively high. In line with the statistics of excavation, the risk of landslide and water...
inrush in the range of DK191+197~DK191+331 and DK191+331~DK191+406 occurs frequently; the risk of freezing and entry and exit of the tunnel in the range of DK191+436~DK191+473 occurs regularly. In terms of the single factor risk rating, the risk level of landslide and water inrush is relatively high while the risk of freezing and entry and exit of the tunnel is relatively low. Through rating the overall risk, the risk value K=2.971 has been obtained, which indicates that the overall risk of the tunnel is three, as a medium one.

Analyzing the results obtained above, it is necessary to develop the special construction plans to deal with landslide and water inrush problems before actual construction, and strengthen the construction site safety education for constructors in the same way. As for the construction units, they should adopt and combine the geological method in the construction process, meanwhile strengthen supervision to reduce risks, which can ensure the smooth progress of project quality and construction.

4. Conclusion
This paper assesses the risk level of the Kouksa Tunnel based on the fuzzy theory method. According to the actual situation of the Kouksa Tunnel, a total of 4 first-level indicators and 16 second-level indicators are established. And then it will set up a risk assessment system by the analytic hierarchy process and fuzzy matrix. Finally, the tunnel construction risk value is 2.971 and the geological risk level is three, which is medium risk. Among them, the risk of landslide and water inrush is the most likely geological disaster and the corresponding evaluation grade is relatively high; while the freezing and entry and exit of the tunnel take second place, and the corresponding evaluation grade is medium.

In the research process, the superiority of the fuzzy level evaluation method gradually reflects. And it can be seen that this method, which is scientific and practical, adapts to the particularity of geological conditions to assess tunnel hazard risk. The supervision departments should take plans to handle the risks like landslide and water inrush before the tunnel construction, and that can effectively ensure the safety of the construction and utilize reasonable costs to achieve the scheduled goals.

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