Fuzzy Comprehensive Evaluation of Subway Shield Construction Risk Based on WSR and Combined Weighting

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Abstract. Aiming at the problem of risk evaluation of subway shield construction, a fuzzy comprehensive evaluation method based on WSR and combined weighting is proposed. Firstly, using the WSR methodology to analyze and select the risk indicators of the subway shield system from the three dimensions of “Wuli - Shili - Renli”, a risk assessment index system for subway shield construction was constructed. Then, fuzzy theory is introduced to establish a comprehensive evaluation model of subway shield construction based on combined weighting. Through the multiplication synthesis method, the weight values of the analytic hierarchy process and the entropy weight method are combined, and the principle of fuzzy relation synthesis is used to comprehensively evaluate the membership level. In the end, the shield tunnel in Qingdao Metro Line X is used as an example to calculate and demonstrate. The results show that the risk is at the “general” level, which is basically consistent with the actual situation. It shows the feasibility and applicability of the established evaluation method, which has guiding significance for reducing the risk of subway shield construction.

1. Introduction

With the acceleration of the urbanization process, the problem of traffic congestion is becoming increasingly serious. Since the introduction of the subway into China in the 1950s, the pressure on urban traffic has been greatly relieved. At present, many cities have entered the “subway era”, and the subway has gradually become the new and backbone force in urban transportation[1]. According to relevant statistics, by the end of 2018, among the national urban rail transit lines, subway operating lines were 4354.3 kilometers, accounting for 75.6 percent; subway lines under construction were 5315.6 kilometers, accounting for 83.4 percent[2]. The shield method is a large-scale comprehensive construction method with shield machine as the core. With the advantages of high mechanization and fast construction speed, it is widely used in subway construction projects in Beijing, Tianjin, Shanghai, Shenzhen and other cities. However, subway projects are generally built in busy urban areas, with heavy traffic and complicated surrounding environments. In addition, the hidden dangers behind the rapid development, such as the reduction of the level of safety management, have led to subway construction accidents in recent years, causing loss of property and lives. Yu H Y et al.[3] analyzed the methods of 113 subway construction accidents in 2002-2018 and found that the number of shield tunnel accidents was the largest, accounting for 50.44 percent. Therefore, it is urgent and necessary to study the risk of subway shield construction.

It is a hot topic in today’s research that scholars combine all kinds of mathematical models with risk assessment theory to establish a scientific and reasonable model to evaluate the risk of subway construction. In terms of foreign research, Hyun K C et al.[4] used a combination of fault tree analysis
(FTA) and analytic hierarchy process (AHP) to carry out risk assessment of shield construction methods, and used Seoul Metro as an example to verify the method reliability. Baradaran V et al.[5] established a GAHP model to evaluate the risk of Tehran subway by combining gray theory with AHP. Turn to domestic research, Huang Z et al.[6] proposed a comprehensive evaluation models using cloud theory in view of the ambiguity and randomness of the risk assessment process. Hu C C et al.[7] introduced the extension theory, established a shield risk evaluation model through the correlation function, and applied it to the shield interval of Ningbo Line 2. Gong P S et al.[8] used the ISM to establish a hierarchical structure of risk events and completed a risk assessment of subway construction.

In summary, the research on the risk assessment of subway construction by combining with mathematical models has achieved good results. But many theories still need to be tried and improved. This paper uses the WSR methodology to build a concise and reasonable risk evaluation index system for subway shields from a systematic perspective. Establishing comprehensive evaluation model by combining weighting and fuzzy theory, and take a shield tunnel section of Qingdao Metro Line X as an example for risk evaluation. It is hoped to provide a theoretical basis for controlling subway construction risks.

2. Construction of risk evaluation index system for subway shield construction based on WSR

2.1 WSR Methodology

WSR is the abbreviation of “Wuli - Shili - Renli” methodology. It was proposed by Chinese scholars in the 1990s, and a tool for solving complex system problems guided by the dialectical thought of Chinese philosophy. In this methodology, Wuli(W) is a study on “what it is”, which refers to people’s understanding of the laws of the objective world and the constitutive factors of the system’s objective existence, such as mathematical theorems, river distribution, etc. Shili(S) is a study on “how to do”, which refers to how to arrange and manage objective things to achieve the purpose, such as making plans, site supervision, etc. Renli(R) is a study on “What should be done”, which refers to the influence of various system factors on human behavior, such as human actions, religious beliefs, and health status. Among the three factors, Renli(R) is the core position, Wuli(W) is the basis of practice, and Shili(S) is the normative method.

2.2 Index system construction

The risk assessment of subway shield construction is a complex system with multiple levels and dimensions. Based on the existing literature [4-8], this paper applies and uses the ideas of the WSR methodology to construct a subway shield construction risk evaluation index system from three dimensions, as shown in Figure 1.

The risk of the Wuli dimension is mainly derived from the surrounding environment of the construction site and construction machinery and equipment. There are five indicators including the distribution of underground pipelines and the performance of shield machines.

The risk of the Shili dimension is based on a full understanding of the Wuli, which mainly comes from the management system, organizational plan, and operating specifications derived from the construction. There are 6 indicators including construction safety emergency plan.

The Renli dimension emphasizes that it is possible to complete the work as smoothly as possible by relying on the people in the organization, and the relationship between people. There are five indicators including workers’ technical level, teamwork level and information communication status.
3. Determination of index weights based on combination weighting

Because most of the relevant data of subway shield construction risk indicators come from personal judgment of experts. It is inevitable to have a personal subjective color, in order to consider both the expert judgment of the experience and the objective truth of the problem, and try to solve the weight deviation caused by subjective and objective empowerment as much as possible. In this paper, a combination of the AHP method and the entropy method is used to determine the index weight.

3.1 AHP determines subjective weights

Analytic Hierarchy Process (AHP) is a qualitative and quantitative analysis method proposed by famous American operations researcher Satty T L in the 1970s. It has a wide range of applications and sufficient theoretical support. The calculation process of its weight is mainly to simulate the thinking process of human beings. By introducing the principle of “1 ~ 9 scale method”, the pairwise importance comparison of factors at various levels is made, and it is rewritten into the form of a judgment matrix. Then use formula (1) to solve the maximum characteristic root ($\lambda_{max}$) of the judgment matrix $B$, and the corresponding characteristic vector ($\mu$) is the weight value of the factor. In order to ensure the rationality of the allocation weights, only the $CR < 0.1$ obtained according to formula (2) can be considered to pass the consistency check requirement. That is, the data is reasonable and can be used. In formula (2), $n$ is the number of factors. And $RI$ is the average random variable index, which can be obtained by checking the correlation table.

\[ B\mu = \lambda_{max}\mu \quad (1) \]

\[ CR = \frac{CI}{RI}, \quad CI = \frac{\lambda_{max} - n}{n-1} \quad (2) \]
3.2 Entropy weight method to determine objective weights

The entropy weight method uses the concept of “entropy” in information theory, and mainly determines the objective weight by the degree of index information variation. Generally speaking, the smaller the information entropy of an indicator, the more information it has, the greater the impact of the indicator and the greater its weight. Specific weighting steps are as follows:

First, normalize the original data to get the matrix

\[ R = \left( \begin{array}{c} \sum_{i=1}^{m} x_{ij} \end{array} \right) \]

Then, \( E_j \) is calculated for the information entropy of each index. If \( r_{ij} = 0 \), then defined

\[ \lim_{r_{ij} \to 0} r_{ij} \ln r_{ij} = 0 \]

Finally, the weight \( f \) of each index is calculated.

\[ f_j = \frac{1 - E_j}{\sum_{j=1}^{n}(1 - E_j)} \] (5)

3.3 Calculation of combination weights

Suppose \( U_i = (U_1, U_2, \ldots, U_n) \) is the weight value of AHP method, \( F_i = (F_1, F_2, \ldots, F_n) \) is the weight value calculated by entropy weight method, then the combined weight value \( W \) is as follows:

\[ W_i = \frac{U_i \cdot F_i}{\sum_{i=1}^{n}(U_i \cdot F_i)} \] (6)

4. Fuzzy comprehensive evaluation model of subway shield construction risk

Choosing a suitable comprehensive evaluation method is very important for judging the risk level of subway shield construction. From the perspective of risk level, it is a fuzzy problem in itself. We can not strictly distinguish between “high” and “low” risks. At the same time, we need to quantify the evaluation results to measure the degree of risk. Therefore, this paper introduces the fuzzy theory, selects the fuzzy comprehensive evaluation method which has excellent effect in solving complex problems to evaluate the risk of metro shield construction. The specific steps are as follows:

1. Determine the set of evaluation factors and evaluation levels. Suppose \( Y = (y_1, y_2, \ldots, y_m) \) is \( m \) indicators of a certain level in the system of Figure 1, and \( V = (v_1, v_2, \ldots, v_n) \) is \( n \) evaluation levels. With reference to the risk grading in 《Urban Rail Transit Underground Engineering Construction Risk Management Specifications》 GB50625-2011 and the engineering risk acceptance criteria shown in [6], this article divides the risk evaluation criteria into 5 levels:

\[ V = \text{(very low, low, general, serious, extreme)} = (1, 2, 3, 4, 5) \]

2. Determine the fuzzy evaluation matrix. According to the set risk level, experts are invited to judge each index in Figure 1 on the basis of actual engineering, as the initial data matrix for risk evaluation. In formula (7), \( x_{ij} \) is the proportion of experts who think that index \( i \) belongs to rank \( j \) in the total number of people.
5. Case analysis

A section of Qingdao Metro Line X is constructed with a composite earth pressure balance (EPB) shield machine. The working length is 849m, and the buried depth of the tunnel vault is 10.04-12.06m. This section is located in the city’s bustling area, surrounded by a large number of shops and houses, and the underground pipelines are more complicated. This article takes the project as an example, builds a subway construction risk evaluation index system based on WSR, and uses combined weighting and fuzzy theory to evaluate shield construction risk.

In this paper, with the help of the project manager, the data source is obtained by filling in the questionnaire by the expert group. The expert group consists of six people, including the project’s middle managers, security technicians and university researchers. Among them, AHP data are obtained by experts through consultation, and entropy weight data or fuzzy matrix are filled in by each expert respectively. Limited to space, this paper only takes “Wuli” dimension as an example to demonstrate the calculation. The weight data is shown in Table 1, and the fuzzy comprehensive evaluation data is shown in Table 2.

5.1 Weight calculation

### Table 1. Expert weight information

| Index | AHP data          | Normalized entropy weighted data |
|-------|-------------------|---------------------------------|
|       | $W_1$ $W_2$ $W_3$ $W_4$ $W_5$ | Expert1 Expert2 Expert3 Expert4 Expert5 Expert6 |
| $W_1$ | 1 4/5 1/2 3/5 1/2 | 0.1667 0.1765 0.1667 0.1569 0.1667 0.1667 |
| $W_2$ | 5/4 1 1/3 2/5 2  | 0.1724 0.1609 0.1724 0.1609 0.1609 0.1724 |
| $W_3$ | 2 2 1 1 3  | 0.1647 0.1529 0.1765 0.1647 0.1647 0.1765 |
| $W_4$ | 5/3 5/2 1 1 4/3 | 0.1683 0.1584 0.1782 0.1683 0.1683 0.1584 |
| $W_5$ | 2 1/2 1/3 3/4 1 | 0.1702 0.1596 0.1702 0.1596 0.1702 0.1702 |

First, according to formula (1), $\hat{\lambda}_{max}=5.2380$ and the corresponding subjective weight $U_1=(0.122, 0.166, 0.302, 0.263, 0.147)$. The next step is to calculate formula (2), $RI = 1.12, CI = 0.059$, then $CR = 0.0531 <0.1$, so the data is available after passing the consistency check. Then, the normalized entropy weight method data in Table 1 are obtained by formula (3). In formula (4), information entropy $E=(0.999767, 0.999624, 0.999337, 0.999493, 0.999748)$ is obtained, which is substituted into formula (5) to obtain objective weight $F=(0.115, 0.185, 0.326, 0.250, 0.124)$. Finally, using formula (6), we get the combined weight $W_1=(0.062, 0.135, 0.433, 0.290, 0.080)$.

Similarly, we can get the rest of the combined weights:

- $W_1= (0.242, 0.311, 0.447)$; $W_2= (0.125, 0.089, 0.155, 0.161, 0.208, 0.262)$;
- $W_3= (0.372, 0.225, 0.106, 0.208, 0.089)$
### 5.2 Fuzzy comprehensive evaluation

| Index | $V=1$ | $V=2$ | $V=3$ | $V=4$ | $V=5$ | Index | $V=1$ | $V=2$ | $V=3$ | $V=4$ | $V=5$
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $W_1$ | 0     | 2     | 4     | 0     | 0     | $W_2$ | 0     | 3     | 3     | 0     | 0     |
| $W_3$ | 0     | 0     | 1     | 4     | 1     | $W_4$ | 0     | 1     | 3     | 2     | 0     |
| $W_5$ | 0     | 1     | 2     | 3     | 0     |       |       |       |       |       |       |

According to formula (7), the fuzzy evaluation matrix $X_1$ is obtained, and then substitute it into formula (8) to synthesize the comprehensive evaluation vector $Z_1=(0.026, 0.307, 0.614, 0.062, 0)$, $Z_2=(0.030, 0.375, 0.578, 0.052, 0)$. Finally, the three-dimensional comprehensive vector $Z_i$ is resynthesized to obtain the comprehensive evaluation result of the project: $Z=(0.021, 0.299, 0.534, 0.145, 0.011)$.

Through the above results, it is found that the risk level of the project is determined to be “general” by using the principle of maximum membership, and the risk levels of the three dimensions are “serious”, “general” and “general”. To avoid information loss, further single valued processing is performed according to formula (9): $C=0.021\times1+0.299\times2+0.534\times3+0.145\times4+0.011\times5=2.856$. The “serious” risk level is not reached, and the result is consistent with the level of the maximum membership principle. Similarly, $C_1=3.419$, $C_2=2.73$, $C_3=2.722$. The findings of $C_1>C_3>C_2$ indicate that the risk control of the “Wuli” dimension should be emphasized in practice. That is to say, the environment of the project itself is complicated, and more consultation and management are needed to ensure smooth construction.

### 6. Conclusion

There are many risk factors in the shield construction of subway construction. Scientific mathematical models should be used to guide the construction of the index system, determination of weights, and final evaluation. This paper introduces the WSR methodology, combines the characteristics of subway shields with existing literature, and selects 16 indicators from the three dimensions of “Wuli - Shili - Renli” to build a risk assessment index system for subway shield construction. Considering the limitations of a single weighting method and the fuzziness of risk evaluation, a fuzzy evaluation model of subway shield construction risk based on combined weighting is proposed. Taking the Qingdao Metro Line X as an example, the rationality and applicability of the model are shown.

According to the results of the case, the risk level of the shield interval is “general”, but the physical dimension reaches “serious”. These results can play a guiding role in the actual construction and ensure the safety of metro shield construction. Of course, the model of introducing fuzzy theory into this paper is only a simple focus on practical research, and the programming calculation needs to be further improved when there are many risk factors affecting subway construction.

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