# Research on risk prediction of subway shield construction based on triangular fuzzy function-entropy weight method

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**Abstract.** Shield construction of subway tunnel is located in underground closed operation, and the frequent occurrence of safety accidents will lead to the loss of personnel safety and project benefits. This paper determines the quantitative index and weight based on the triangular fuzzy function-entropy weight method, and combines the potential failure mode and effects analysis (FMEA) method to identify and evaluate the shield construction risk from the perspective of the shield construction unit. Combined with the case, the model is verified to be operable and effective. The model constructed in this paper can be embedded in various subway tunnel shield construction, and provide risk warning support for on-site construction.

**Keywords:** The subway; Shield construction; Risk early warning; FMEA; Triangle fuzzy function-entropy method.

## 1 Introduction

In order to relieve the problem of urban traffic congestion, developing metro rail transit has become the focus of the development of underground space in large and medium-sized cities in China. Shield method is a safe and efficient construction method in subway construction. Shield method is suitable for soft water-bearing strata and difficult construction conditions. The surrounding construction environment of shield tunneling machine has the characteristics of variability and complexity, so with the advancement of shield tunneling construction, the probability of safety accidents will gradually increase[1]. The "14th Five-Year Plan" construction industry Development Plan clearly points out that in the construction of smart city rail transit projects by 2025, improve the safety responsibility and risk prevention and control system, and the risk prevention and control of shield construction needs to constantly improve risk prevention and control and key technical measures to strengthen major risk management and control. Therefore, this study determines quantitative indicators and weights based on triangular fuzzy function-entropy weight method from the perspective of shield construction units, and combines the potential failure mode and effects analysis (FMEA) method to



T. Yao et al. (eds.), *Proceedings of the 2024 3rd International Conference on Engineering Management and Information Science (EMIS 2024)*, Advances in Computer Science Research 111,
https://doi.org/10.2991/978-94-6463-447-1_4

identify and evaluate shield construction risks, so as to give early warning to the dynamic process of shield construction and eliminate risk factors from the root, which has important practical significance for risk control.

In recent years, scholars at home and abroad have studied the risk early warning of subway shield construction, mainly focusing on the risk factors of shield construction, the hazardous environment, monitoring and measurement, and the real-time data of shield construction process. Zhang and Liu built fault tree and Bayesian network model, found the correlation between risk factors and security alarm data, and determined key risk factors through reverse reasoning of the model, so as to prevent and control the occurrence of similar failure impact risks[2]. Wang and Xu built a shield tunnel risk early warning model based on the extension matter-element theory, studied the principle of maximum correlation degree of tunnel excavation face collapse risk, and divided the warning level according to it, putting forward a new idea for tunnel shield construction risk early warning[3]. Bu and Zhen calculated the probability of subway tunnel risk occurrence by using the improved Monte Carlo method, and took preventive measures for the factors in the unsafe state of the tunnel structure, which could effectively reduce each single factor risk and reduce the overall risk occurrence probability to the scope of compliance with the construction safety standards[4]. Huang and Zhang used a two-dimensional cloud model (TDCM) to quantify the risk level from two aspects of risk harmfulness and probability, improve the evaluation accuracy, and study the effectiveness and applicability of TDCM evaluation method in the subway shield phase[5]. Mostofi proposed the non-optimality of machine learning models and studied risk assessment based on multi-head attention networks, using sparse incident networks to embed security incident information to improve the reliability and accuracy of predictions[6]. Senthil introduced an improved historical simulation statistical method that uses a risk statistical model to process risk data and improve the accuracy of construction risk prediction[7].

On the whole, due to the complexity, correlation and concealment of the safety wind management of subway shield construction, the collection and analysis of the risk factor data on the construction site in the existing studies are not comprehensive enough, and the correlation analysis of shield machine construction operation parameters and alarm data is not taken into account, and the understanding of shield construction risk management and early warning is insufficient. In this paper, FMEA is applied to the risk management process of subway shield construction, and the risk severity of shield construction is comprehensively analyzed from three dimensions of undetectability, possibility and severity. By putting forward countermeasures to the potential failure consequences of risk indicators, the possible accidents can be controlled and continuously improved in advance.

## 2 Risk Warning Model Of Subway Shield Construction Based on Fmea

Risk management of subway shield construction aims at the safety, duration and quality of underground space construction process, minimizes the risk cost and maximizes the benefit, extracts the cause factors through accident statistical analysis, and reduces the probability of risk occurrence to the greatest extent through identification, assessment, early warning and response to risk factors. Establish the model to verify the validity and maximize the project benefits[8].In this paper, FMEA is applied to the risk management of subway shield construction process, and the characteristics of the two are combined, and the accident analysis method and shield machine fault alarm data are used as data sources, so as to further study the cause mechanism of important risk events.

The research on subway shield construction risk is mainly a process of pre-control and continuous improvement, which needs to grasp the timely fault alarm data support of the construction site and put forward effective countermeasures. According to the shield cloud platform of Z Company, the platform mainly uses the Internet big data analysis technology to realize the visualization of the real-time operation, fault alarm and energy loss data of the shield machine during the construction process. The alarm data is collected through the remote monitoring platform and timely countermeasures are adopted to ensure the normal operation and safe excavation of the shield machine on site. According to the data stored in the shield cloud platform and the project experience, the risk factors are classified to find out the key risk factors and analyze the potential failure consequences. Based on FMEA analysis, the shield construction risk is evaluated from three dimensions of difficulty detection, severity and possibility, and the risk is sorted, and the warning threshold is set according to the order value. In the whole process, the index exceeding the threshold value is continuously improved to realize the applicability of FMEA in the risk warning of subway shield construction. The early warning process of subway shield construction risk based on FMEA is shown in Figure 1.

The early warning process of shield construction risk includes preparation stage, actualization stage, driving stage and arrival stage, focusing on risk identification and risk analysis. In order to determine the difficulty of risk detection in the shield construction process according to the feedback data of the shield cloud platform and the self-established early warning threshold, the risk frequency is determined by the occurrence times of risk indicators, and then the adverse consequences caused by the occurrence of the risk indicators are analyzed. The risk early warning index system is created by better fitting the engineering practice of subway shield construction and combining with relevant standards and norms, such as "Subway Construction Safety Evaluation Standards", "Shield Tunnel construction and acceptance Code", "Metro Engineering monitoring and measurement Technical regulations" and related literature. The risk warning index and failure mode analysis of subway shield construction are shown in Table 1.

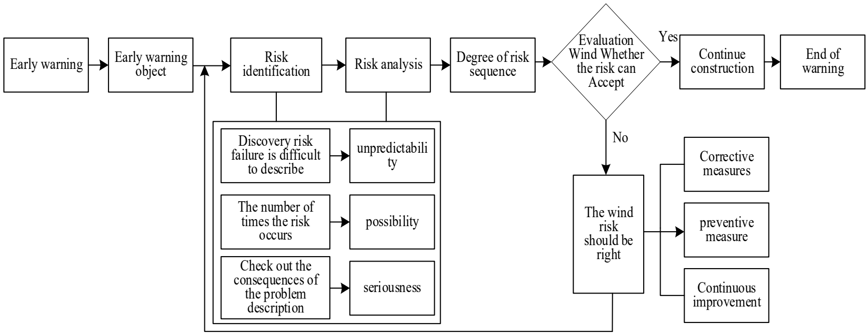


**Fig. 1.** Safety risk warning procedure of subway shield construction based on FMEA

**Table 1.** Subway shield construction risk warning indicators and failure mode analysis

| Risk type | Early warning index | Cause of failure | Primary failure consequence |
|---|---|---|---|
| Risk of subway shield construction process | Preparation | Geological investigation, shield machine type selection is wrong | Increase rework costs |
| | Assembly | Improper operation, lifting, rigging wear, personnel without a license to work | Object strike, height fall |
| | Shield launch | The end reinforcement quality is poor, the tunnel door sealing effect is poor | Collapsed |
| | Shield propulsion | Failure of support system, unreasonable construction technology | Collapse, settlement |
| | Segment engineering | Uneven joints, misalignment of concave and convex grooves, blockage of shield | Segment breakage, joint leakage |
| | Grouting | Cleaning is not timely, the quality of pipe segment is unqualified | The grouting pipe is blocked |
| | Muck transport | Slag removal system failure, poor slag performance, improper slag operation | The slag is not smooth |
| | Arrivals & departures | Improper operation, axis deviation, uneven loading of the base | Attitude change, base deformation, |
| Risk of subway shield construction | Cutter head system | Fatigue damage bearing seal failure, hydraulic system cleanliness is up to standard | Cutter head cannot start |
| | Screw system | Screw shaft, blade and cylinder wear too much, foreign matter, fatigue damage | Screw pump can not start |
| | Cylinder system | Blocking the filter, abnormal function of the propulsion valve group, cylinder leakage | The propulsion pump won't start |

| | | | |
|---|---|---|---|
| equip-ment | Belt conveyor | Mud solidification, the belt is scratched by hard foreign matter, conveyor roller falls | Belt conveyor can't start |
| | Shield tail sealing | Pipeline distribution control valve is abnormal, shield tail grease pipe is blocked | Shield tail seal failed |
| | Foam system | The foam flow regulation function is abnormal, the mixture is insufficient | The foam mixture pump won't start |
| | Bentonite injection | Bentonite hose pump wear, volumetric efficiency decrease, filter blockage | Bentonite mixer cannot start |
| | Grouting system | The grouting pressure is too large, the grouting lubricating oil is insufficient | Rotating machine fault |
| | Electrical control | Power compensation fault, shield machine power supply fault, PLC station fault | Electrical control fault |
| | Segment assembly | Abnormal operation of segment assembler, poor lubrication, abnormal propulsion | Segment mounting pump cannot start |
| | Water circulation | The air compressor high temperature alarm causes the air compressor to stop | Water circulation failure |
| | Pumping station | Oil quality is not qualified, hydraulic oil kinematic viscosity, cleanliness, water content is not up to standard | Hydraulic pump can not start |
| | Lubrication system | Lubrication system pressure, flow, EP2 pneumatic grease pump abnormal | Multipoint pump cannot start |
| Geologic environment risk | Geologic layer | Special strata such as bedrock bulge, soft soil and strong weathering | Collapse |
| | Obstacle | Shallow earth-covered, isolated obstacles | Mechanical failure |
| | Harmful gas | Carbon monoxide, methane, hydrogen sulfide exceeded the standard | Gas poisoning |

## 3 The Establishment of Risk Factor Evaluation Set and Triangular Fuzzy Function - Entropy Weight Model

FMEA is a qualitative risk analysis method widely used in construction, aerospace, automotive and other industries. This method multiplies the frequency (O), severity (S) and difficulty to detect (D) of risks to get the risk sequence number RPN[9]. According to relevant literature, a risk assessment set of difficulty, possibility and severity of subway shield construction is established, as shown in Table 2.

**Table 2.** FMEA-based Subway shield construction risk assessment set

| Lv. | Fuzzy number | Degree of undetect-ability | possibility | severity |
|---|---|---|---|---|
| VL | (0,0,2) | Almost certainly | Remote possibility | Almost harmless |
| L | (0,2,4) | Great opportunity | Less likely | Low hazard |
| M | (2,4,6) | Medium chance | probably | Moderate hazard |
| H | (4,6,8) | Less chance | More likely | Major hazard |
| VH | (6,8,8) | Little chance | Most likely | Particularly significant hazard |

Based on triangular fuzzy function and entropy method, the risk index value can be calculated, and the risk sequence degree can be calculated to determine the risk alarm value of shield construction. Fuzzy comprehensive evaluation method can determine the overall risk level of the construction section by combining the shield machine's own risk and the construction environment risk. Through the experience and knowledge of professionals, the uncertain factors can be effectively evaluated, and the overall risk can be effectively and targeted[10]. The triangular fuzzy function has the characteristics of simple construction and easy operation. Using the center of gravity method to defuzzify the evaluation value and the entropy weight method to calculate the weight can reduce the evaluation deviation caused by subjective evaluation [11].

### 3.1 The Triangular Fuzzy Function Method is Used to Calculate the Expert Evaluation Value

Construction coordinates (x, y, z) represent trigonometric fuzzy functions, where x is the upper bound, y is the median, and z is the lower bound.

$$\begin{cases}\tilde{A} = (x_1, y_1, z_1) \\ \tilde{B} = (x_2, y_2, z_2)\end{cases}, \quad a\tilde{A} + b\tilde{B} = (ax_1 + bx_2, ay_1 + by_2, az_1 + bz_2)$$

Membership degree $u_{\tilde{A}}(x)$ of $\tilde{A} = (x_1, y_1, z_1)$ is calculated by the following formula:

$$u_{\tilde{A}}(x) = \begin{cases}\frac{x-x_1}{y_1-x_1}, x \in [x_1, y_1] \\ \frac{z-x_1}{z_1-y_1}, x \in [y_1, z_1] \\ 0, x \notin [y_1, z_1]\end{cases} \tag{1}$$

The value $(\bar{x}_0(\tilde{A}))$ is obtained by deblurring it with the center of gravity method:

$$\bar{x}_0(\tilde{A}) = \frac{\int_{x_1}^{z_1} x u_{\tilde{A}}(x)dx}{\int_{x_1}^{z_1} u_{\tilde{A}}(x)dx} \tag{2}$$

### 3.2 The Entropy Weight Method is Used to Calculate the Weight of Expert Evaluation

In this paper, the risk evaluation of subway shield construction is carried out, and each index of shield construction risk index system must be quantitatively compared. According to the relevant data and literature of subway shield construction, the corresponding parameter values of each index are determined successively, which improves the operability of risk assessment.

The risk sequence degree $R_{ij}$ is calculated according to the weight value $\omega_i$ of expert $i$ and index $j$.

$$R_{ij} = E_{SR_{ij}} \times E_{OR_{ij}} \times E_{DR_{ij}} \tag{3}$$

$$R_{ij}{}' = \frac{R_{ij} - \min（R_j）}{\max（R_j）-\min（R_j）} \tag{4}$$

Where, $E_{SRij}$ is the evaluation value of $i$ experts on the severity of $j$ index after defuzzification by triangular fuzzy function; $E_{ORij}$ is the evaluation value of the probability of the $j$ index by the $i$ expert in the fuzzy function of the triangle; $E_{DRij}$ is the evaluation of the difficulty of the $j$ index by the $i$ expert in the fuzzy function of the triangle; $R_{ij}{}'$ is the risk order degree of the positive index logarithm.

The proportion $p_{ij}$ of expert $i$ under the evaluation of indicator $j$ for:

$$P_{ij} = R_{ij}{}' / \sum_{i=1}^{n} R_{ij}{}' \tag{5}$$

The entropy $e_i$ of expert $i$ 's score is calculated as:

$$e_i = -\mathrm{k} \sum_{j=1}^{\mathrm{n}} \mathrm{P}_{ij} \ln \mathrm{P}_{ij} \tag{6}$$

Among, $k = 1/ln\, n > 0$, and $e_i \geq 0$

Information entropy redundancy $d_i$ calculation: $d_i = 1 - e_i$

Expert $i$ 's rating weight $\omega_i$ compute:

$$\omega_i = d_i / \sum_{i=1}^{n} d_i \tag{7}$$

Indicator $j$ Integrated risk sequence $\mathrm{R}_j$ calculation:

$$\mathrm{R}_j = \sum_{i=1}^{\mathrm{n}} \omega_i \mathrm{R}_{ij} \tag{8}$$

## 4 Case Application

In this paper, Chaoyang Road station of Qingdao Metro Line X-Qiantangjiang Road station is located in Huangdao District of Qingdao City, with a total length of 5.23Km. In Qingdao, the shallow rock stratum is mainly granite, and more than 90% of subway lines need to pass through the granite stratum, and the excavation method of subway is mainly shallow buried and hidden. In the construction process of Qingdao subway, especially Line X, which is the main traffic road, will pass through rivers, crushing zones and important buildings, etc. In addition, the construction period is long, which is very prone to accidents. In order to prevent the occurrence of risk accidents, it is imperative to adopt reasonable methods to identify, evaluate and control risks. Check and record the construction site regularly every day. There are 11 risk indicators of shield construction, as shown in Table 3. Every week is an early warning cycle. Based on the 1-week work inspection records of the shield tunneling process, experienced safety management experts and supervisors on site conducted risk assessment on the risk indicators, and constructed a fuzzy scoring matrix according to the order of difficulty detection, possibility and severity, as shown in The matrix:

$$
\begin{array}{c} \textit{index} \\ X_{11} \\ X_{12} \\ X_{13} \\ X_{21} \\ X_{22} \\ X_{23} \\ X_{24} \\ X_{25} \\ X_{26} \\ X_{27} \\ X_{31} \end{array}
\begin{array}{c} \textit{Evaluationlevel} \\
\begin{bmatrix}
(M,VL,M) & (H,VL,M) & (M,VL,M) & (H,VL,M) & (M,VL.M) \\
(M,VL,VL) & (M,VL,VL) & (M,VL,VL) & (VH,VL,VL) & (L,VL,VL) \\
(H,VL,L) & (L,VL,L) & (H,VL,L) & (L,VL,L) & (H,VL,L) \\
(M,H,L) & (M,H,M) & (M,H,L) & (L,H,M) & (M,H,L) \\
(H,VL,M) & (M,VL,H) & (M,L,H) & (L,L,H) & (M,L,H) \\
(M,VL,L) & (L,VL,L) & (M,VL,L) & (L,VL,VH) & (L,VL,M) \\
(M,VH,VH) & (M,VH,VH) & (M,VH,H) & (L,VH,VH) & (L,VH,H) \\
(L,VH,L) & (H,VH,M) & (M,VH,M) & (L,VH,H) & (H,VH,L) \\
(H,H,M) & (H,M,M) & (H,H,M) & (L,H,L) & (M,M,M) \\
(M,VL,L) & (H,VL,VL) & (L,VL,L) & (L,VL,L) & (L,VL,L) \\
(M,H,M) & (L,H,M) & (L,VH,M) & (VL,H,L) & (L,M,L)
\end{bmatrix} \end{array}
$$

$$
\begin{array}{c} \text{index} \\ X_{11} \\ X_{12} \\ X_{13} \\ X_{21} \\ X_{22} \\ X_{23} \\ X_{24} \\ X_{25} \\ X_{26} \\ X_{27} \\ X_{31} \end{array}
\begin{array}{c} \text{Evaluation level} \\
\begin{bmatrix}
10.72 & 16.08 & 10.72 & 16.08 & 10.72 \\
1.80 & 1.80 & 1.80 & 3.29 & 0.89 \\
8.04 & 2.68 & 8.04 & 2.68 & 8.04 \\
48 & 96 & 48 & 48 & 64 \\
16.08 & 16.08 & 32 & 24 & 48 \\
5.36 & 2.68 & 5.36 & 9.82 & 5.36 \\
214.92 & 214.92 & 175.92 & 107.46 & 87.96 \\
29.32 & 175.92 & 117.28 & 107.46 & 87.96 \\
144 & 96 & 144 & 24 & 64 \\
5.36 & 2.70 & 2.68 & 2.68 & 2.68 \\
86 & 48 & 58.64 & 8.04 & 24
\end{bmatrix} \end{array}
$$

According to the defuzzification of the triangular fuzzy function, the above risk sequence degree matrix is obtained.

**Table 3.** FMEA analysis of metro shield construction risk

| Target layer | Criterion layer | Index level | Times | Check the description of the problem | Degree of risk sequence | Risk sequence |
|---|---|---|---|---|---|---|
| Subway shield construction | Subway shield construction Process risk $X_1$ | Assembly $X_{11}$ | 1 | Improper operation | 13.05 | 7 |
| | | Shield propulsion $X_{12}$ | 1 | Failure of support system | 1.98 | 11 |
| | | Grouting $X_{13}$ | 1 | Cleaning is not timely | 5.71 | 9 |

| | | | | | | |
|---|---|---|---|---|---|---|
| risk warn ing | Subway shield con-struction Equip-ment risk $X_2$ | Belt con-veyor $X_{21}$ | 8 | Mud solidification, the belt is scratched by hard foreign matter, conveyor roller falls | 58.65 | 4 |
| | | Screw conveyor $X_{22}$ | 2 | Screw shaft, blade and cyl-inder wear too much, for-eign matter, fatigue damage | 25.50 | 6 |
| | | Electrical control $X_{23}$ | 1 | PLC station fault | 5.71 | 8 |
| | | Cutter head $X_{24}$ | 26 | Fatigue damage bearing seal failure, hydraulic system cleanliness is up to standard | 165.9 6 | 1 |
| | | Cylinder $X_{25}$ | 13 | Blocking the filter, abnormal function of the propulsion valve group, cylinder leak-age | 99.85 | 2 |
| | | Shield tail seal-ing $X_{26}$ | 7 | Pipeline distribution control valve is abnormal, shield tail grease pipe is blocked | 96.11 | 3 |
| | | Segment assembly $X_{27}$ | 1 | Abnormal operation of seg-ment assembler, poor lubri-cation, abnormal propulsion | 3.29 | 10 |
| | Geologi-cal envi-ronment Risk $X_3$ | Obstacle $X_{31}$ | 11 | Shallow earth-covered, iso-lated obstacles | 48.90 | 5 |

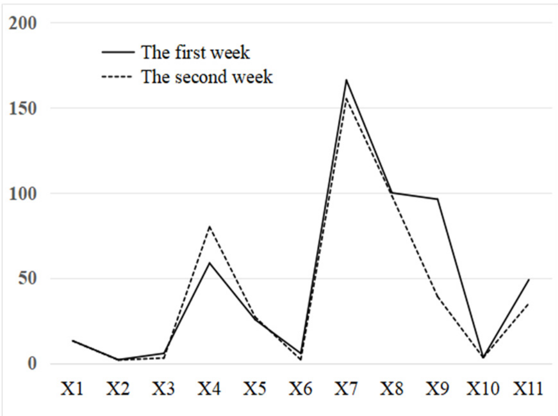


**Fig. 2.** Risk degree line chart in two adjacent weeks

Based on the entropy weight method, the score weights of experts are calculated to get 0.2264, 0.2220, 0.1925, 0.2121, 0.1465. The FMEA analysis of subway shield construction risk is shown in Table 3.

The record of the shield cloud platform and the score values of each dimension were calculated to compare the rationality of the actual score. According to the value of comprehensive risk sequence degree, it can be seen that the three indexes of cutter head system, cylinder system and shield tail sealing system have the largest risk sequence degree, which accords with the characteristics of shield construction risk research. According to the rich experience of project experts, the risk degree 2.68 of at least one of the three dimensions less than level L can be determined as the risk warning threshold. Construction site operation according to the calculated risk sequence degree of the pre-warning sequence: cutter head system, cylinder system, shield tail sealing system, belt conveyor system, underground obstacles, screw conveyor system, assembly and debugging, electrical control system, synchronous grouting, segment assembly system, shield propulsion. According to the ranking of the risk importance in the construction process of the construction section, continuous improvement is made to the construction technology and the tunneling anomaly of the shield machine.

The line chart of risk degree for the next two weeks is shown in Figure 2. The risk degrees of two consecutive weeks were recorded for comparative analysis, and the change and ranking of risk degrees were basically the same under the same index of shield construction process. Among them, the reason why the sequence degree of synchronous grouting changes the most is that the cleaning is timely, which reduces the probability of the grouting pipe clog risk, which conforms to the shield construction site, and verifies the effectiveness and feasibility of FMEA method in the risk early warning study of subway shield construction.

## 5 Conclusions

This study is based on FMEA for subway shield construction risk management. Through on-site monitoring and shield cloud platform alarm data, the risk index of subway shield construction can be comprehensively evaluated from three dimensions of difficulty detection, possibility and severity. Based on the analysis of the failure consequences of three risk indexes of subway shield construction process risk, equipment risk and geological environment risk, the early warning and prediction of subway shield construction risk are effective and forward-looking.

Based on the gravity center calculation of triangular fuzzy function and the weight value of entropy weight method, it can not only take the rich experience of experts into account, but also reduce the calculation deviation caused by subjectivity, and improve the effectiveness of the early warning value results.

Combined with the case of Qingdao Metro Line X, the validity and practicability of this model in the actual risk early warning study of subway shield construction are verified, which provides an effective method for the risk early warning study of subway shield construction that is easy to monitor and record data to obtain and forward-looking to prevent risks.

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