Research on the Stratification and Mechanism of Factors Influencing Fire Resilience of Subway Stations

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Abstract. To explore the hierarchical relationship and mechanism of the influencing factors of fire resistance resilience in subway stations, based on resilience theory, this study analyzes and identifies the influencing factors of fire resistance resilience from four aspects: technology, organization, society, and economy. The decision laboratory analysis method (DEMATEL) and interpretive structural model (ISM) are combined to study the correlation and hierarchical relationship between the influencing factors. On the basis of the hierarchical relationship, the cross influence matrix multiplication method (MICMAC) is used to analyze the mechanism of the influencing factors. The results showed that by comprehensively considering the influence degree, affected degree, centrality, causal degree, and centrality weight of 31 influencing factors, 11 key influencing factors were identified, including monitoring and control systems, resource allocation, and emergency response; Based on the impact on the fire resistance of subway stations, the 31 influencing factors are divided into a 3-layer and 7-step ladder structure, and the dependency relationship between the influencing factors at each level is obtained. This study can provide theoretical reference for effectively improving the level of subway fire safety management.

Keywords: subway station fire; Security resilience; Influencing factors; Decision experimental analysis method; Explain the structural model; the cross influence matrix multiplication method

1 Introduction

Due to the diversity of triggering factors and the severity of consequences, subway station fires pose a direct risk to public property and passenger safety [1]. Studying the interrelationships between factors affecting the fire resistance of subway stations, identifying the key factors of subway fire resistance, and clarifying the hierarchical relationship between influencing factors are of great significance for improving subway fire resistance and reducing the consequences of subway fire accidents.

At present, domestic and foreign scholars have conducted research on subway fires from different perspectives. Nie C [2] and Wang Q [3] studied the disaster causing factors of subway station fires; Liu J [4] and Huang Y [5] conducted a qualitative and quantitative

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risk assessment of subway station fires; Liu J [6], Liu W [7], and Wang C [8] studied the emergency management of subway station fires, the preparation and evaluation of emergency plans, and optimized the operability of emergency plans from the perspective of shortening emergency response time; Xiahou W [9] studied the fire resistance design of subways; Chen Y [10] studied the simulation of emergency evacuation in subway stations. The above research on subway fires is analyzed from the perspective of risk prevention or emergency management.

Due to the diversity of triggering factors for subway station fire accidents, the analysis from the perspective of risk pre control or emergency management is not comprehensive enough. The research on subway fire risk should comprehensively coordinate disaster response preparation, risk and hidden danger prevention and response, and emergency rescue capacity construction to achieve disaster prevention and reduction and enhance the ability to respond to disaster environments. The introduction of resilience theory into the field of disaster risk management [11,12] provides a new perspective for the study of subway fire disasters. Resilience is the ability of a system to maintain its own structure and function, take timely measures to repair and adapt to changes when facing internal and external disturbances [13]. In the existing research on subway fire resilience, Huang Y, et al. [14] evaluated the safety resilience of subway fires based on the AHP-PSO fuzzy combination weighting method, and identified that the automatic fire alarm system has the greatest impact on overall resilience. Liu J, et al. [15] constructed a resilience risk assessment model for subway under fire disturbance based on the two-dimensional cloud model method to identify important influencing factors and conduct risk warning analysis for subway fire disasters. Bi W [16] constructed a Bayesian network for fire resistance resilience of subway station systems, obtaining the maximum fire resistance resilience value and the causal chain of failure, respectively. The above studies have all focused on resilience risk assessment and identification of key factors, without a clear study on the hierarchical relationship between factors affecting subway fire resistance resilience.

To further study the fire resistance of subway stations, it is necessary to first clarify the hierarchical relationship and mechanism of the influencing factors. By using the decision laboratory method, the impact of fire resilience related factors on subway station systems can be analyzed, key influencing factors can be identified, and combined with explanatory structural models, a hierarchical relationship model of fire resilience related factors can be constructed to stratify the influencing factors. On the basis of the hierarchical relationship model, combined with the cross influence matrix multiplication method, further clarify the mechanism of the influencing factors. Therefore, integrating the above three methods, analyzing the hierarchical relationship and mechanism of the factors affecting the resilience of subway fires, provides theoretical guidance for the safety guarantee of subway systems. Compare and analyze the research results with the references to verify the reliability of the results.

2 Research Method

The decision laboratory analysis method (DEMATEL) [17] can characterize the correlation between influencing factors, but cannot explain the complex logical relationship between influencing factors, and cannot represent the strength of the relationship between influencing factors. Interpreting Structural Modeling (ISM) [18] intuitively understands the causal hierarchical structure of system factors, but cannot quantify the correlation between influencing factors. The cross influence matrix multiplication method (MICMAC) [19] applies the principle of matrix multiplication to analyze the mechanism of interaction between influencing factors at a deeper level based on hierarchical relationships.

Based on these three methods, analyze the influencing factors and combine them to achieve complementary advantages, enhancing the scientific decision-making and quantitative analysis of the system, as shown in Figure 1.

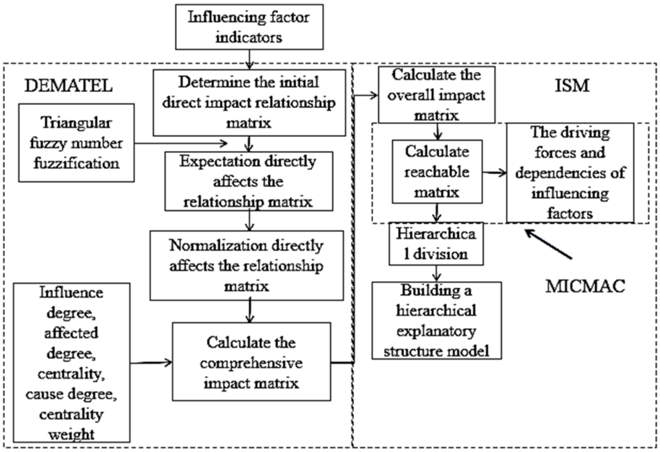

Fig. 1. FDEMATEL-ISM-MICMAC modeling process

3 Research Process

3.1 Selection of Factors Influencing Fire Resilience of Subway Stations

Based on the case of subway station fire accidents, citing literature such as Huang Y, et al. [14], Liu J, et al. [15], and Bi W [16], as well as the standard specification GB51298-2018 "Code for Fire Protection Design of Subways", based on resilience theory, combined with the "TOSE" method proposed by the American Center for Interdisciplinary Research in Earthquake Engineering [20], comprehensively identify the factors affecting the fire resistance of subway station systems from four aspects: technical (T) organization (O), social (S), and economic (E). Using a questionnaire survey method, nearly 20 personnel and safety experts engaged in subway station work were surveyed. The impact intensity of each factor was rated on a scale of 1-5, and the influencing factors with an average value of no less than 4 were selected. Referring to the screening results of fire influencing factors by Bi W [16], the dissenting influencing factors were further surveyed to determine the main influencing factors of fire resistance resilience in subway stations. The influencing factors were marked as A_1, A_2, A_3, A_{31}, as shown in Table 1.

3.2 Construction of a Joint Model Based on FDEMATEL-ISM-MICMAC

Determine the Correlation of Influencing Factors.

In the study of the relationship between group size and decision-making [21], it was pointed out that the focus is on quality consistency, with 5-10 people being the most suitable. Therefore, four safety experts and two subway station managers were invited to rate the strength of the impact factors in Table 1 using five relationships: no impact (0), very weak impact (1), weak impact (2), strong impact (3), and very strong impact (4), and obtain six initial direct impact relationship matrices A.

Table 1. Factors affecting the fire resistance toughness of subway stations

Identifying dimensions	Absorption capacity	Resistance ability	Recovery capability	Adaptability
T(technology)	Passenger entry security CheckA_1	Fire alarmA_{10}		
	Smoke suppressorA_2	Emergency facilities and EquipmentA_{11}		
		Evacuation design of subway StationsA_{12}		
		Subway fire prevention DesignA_{13}		
		Fire extinguishing EquipmentA_{14}		
		Ventilation and smoke Exhaust systemA_{15}		
O(organization)	Power supply equipment inspectionA_3	Station personnel inspectionA_{16}	Emergency repair and rescueA_{25}	Cause investigationA_{28}
	Safety trainingA_4	Fire emergency planA_{17}	Recovery actionsA_{26}	Summarize experienceA_{29}
	Security checkA_5	Emergency organizational		Implement rectification

	Hot work safetyA_6 Auxiliary equipment inspectionA_7	StructureA_{18} Quality of emergency PersonnelA_{19} ResponseA_{20} Fire exits are unobstructedA_{21}		measuresA_{30}
S(society)	Passenger safety awarenessA_8	Passenger evacuation skillsA_{22} Fire IoT systemA_{23}		
E(economy)	Prevention investmentA_9	Resistance investmentA_{24}	Restore investmentA_{27}	Rectification investmentA_{31}

Use Table 2 to fuzzify the initial direct impact matrix and use formula (1) to obtain the expected direct impact matrix *Z*.

$$E(\overline{\omega}) = \frac{l + 2m + n}{4} \tag{1}$$

In the formula, $E(\overline{\omega})$ Represents the average expected value of each factor, l and n represent the left and right endpoints of the triangular fuzzy number, and m represents the peak value of the triangular fuzzy number.

Table 2. Semantic Transformation Table

Language operator	Triangular Fuzzy Number(TFN)
No effect (0)	(0，0，1)
Very weak impact (1)	(0，1，2)
Weak impact (2)	(1，2，3)
Strong influence (3)	(2，3，4)
Very strong impact (4)	(3，4，4)

Normalize the expected direct impact matrix *Z* using formula (2) and calculate the normative expected direct impact matrix *N*.

$$N = \frac{z_{ij}}{\max\limits_{1 \le i \le n}\left(\sum_{j=1}^{n} z_{ij}\right)} \tag{2}$$

In the formula, $\max\limits_{1 \le i \le n}\left(\sum_{j=1}^{n} z_{ij}\right)$ is the maximum sum of rows in matrix *Z*.

Use formula (3) to calculate the comprehensive impact matrix *T*.

$$T = \sum_{k=1}^{\infty} N^{k} = N(I - N)^{-1} \tag{3}$$

In the formula, I represents the identity matrix.

Using the comprehensive impact matrix T, calculate the degree of influence (D_i), degree of influence (C_i), centrality (M_i), degree of cause (R_i), and centrality weight (W_i) of the influencing factors, as shown in Table 3.

$$D_i = \sum_{j=1}^{n} t_{ij}, (i = 1, 2, \cdots, n) \tag{4}$$

$$C_i = \sum_{j=1}^{n} t_{ji}, (i = 1, 2, \cdots, n) \tag{5}$$

$$M_i = D_i + C_i \tag{6}$$

$$R_i = D_i - C_i \tag{7}$$

$$W_i = \frac{M_i}{\sum_{i=1}^{n} M_i} (i = 1, 2, \cdots n) \tag{8}$$

In the formula, t_{ij} represents the elements in the comprehensive impact matrix T.

Draw a scatter plot of "centrality causality" based on the centrality and causality values of the influencing factors in Table 3. Divide the scatter plot into four quadrants based on the average of centrality and causality, as shown in Figure 2.

Table 3. D_i, C_i, M_i, R_i, W_i Calculation Results

	D_i	C_i	M_i	R_i	W_i
A_1	0.3040	**0.6523**	0.9563	-0.3482	0.0296
A_2	0.3040	0.4569	0.7609	-0.1529	0.0235
A_3	0.4770	0.4526	0.9297	0.0244	0.0288
A_4	**1.0263**	0.5969	**1.6231**	0.4294	**0.0502**
A_5	0.3040	0.4517	0.7558	-0.1477	0.0234
A_6	0.3040	0.5128	0.8169	-0.2088	0.0253
A_7	**0.9258**	0.4526	**1.3784**	**0.4731**	**0.0426**
A_8	0.4243	0.4745	0.8988	-0.0503	0.0278
A_9	**0.9522**	0.3040	**1.2562**	**0.6481**	**0.0389**
A_{10}	0.4243	**0.7013**	1.1255	-0.2770	0.0348
A_{11}	0.3699	**0.6821**	1.0520	-0.3122	0.0325
A_{12}	0.3040	0.5447	0.8487	-0.2406	0.0263
A_{13}	0.3040	0.5447	0.8487	-0.2406	0.0263
A_{14}	0.3942	**0.6582**	1.0524	-0.2640	0.0326
A_{15}	0.3355	0.6128	0.9484	-0.2773	0.0293
A_{16}	0.4913	0.5264	1.0177	-0.0351	0.0315
A_{17}	**1.4380**	0.4453	**1.8833**	**0.9927**	**0.0583**
A_{18}	0.5195	0.4325	0.9521	0.0870	0.0294
A_{19}	0.3642	0.5541	0.9183	-0.1900	0.0284
A_{20}	0.3040	**1.4534**	**1.7574**	**-1.1493**	**0.0544**
A_{21}	0.4200	0.4142	0.8342	0.0058	0.0258

A_{22}	0.3040	0.4958	0.7998	-0.1918	0.0247
A_{23}	0.3985	0.3896	0.7881	0.0090	0.0244
A_{24}	**0.8501**	0.3040	1.1541	**0.5460**	0.0357
A_{25}	0.4243	**0.6292**	1.0535	-0.2049	0.0326
A_{26}	0.3241	0.6047	0.9287	-0.2806	0.0287
A_{27}	0.5574	0.3040	0.8615	0.2534	0.0266
A_{28}	0.4164	0.4200	0.8364	-0.0035	0.0259
A_{29}	**0.8321**	0.3699	**1.2019**	**0.4622**	**0.0372**
A_{30}	0.6946	0.4200	1.1146	0.2746	0.0345
A_{31}	0.6731	0.3040	0.9772	0.3691	0.0302

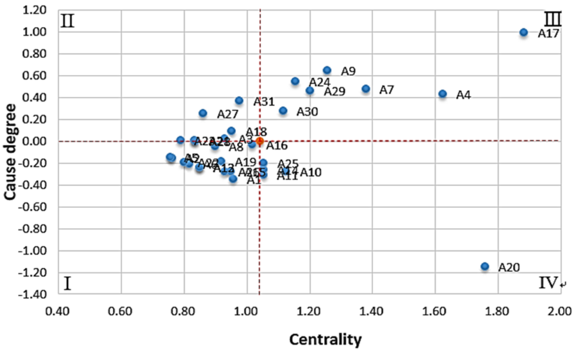

Fig. 2. Centrality - Causality (Scatter plot)

Stratification of Influencing Factor.

According to formula (9), convert the comprehensive impact matrix T into the overall impact matrix H.

$$H = I + T \tag{9}$$

In the formula, I represents the identity matrix.

Systems with multiple factors require setting thresholds λ To eliminate some relationships with less impact, in order to simplify the system hierarchy and facilitate structural division. Based on threshold λ Set rules: threshold λ It can be calculated through mathematical methods [22] $\lambda=\alpha+\beta$ (Among them α, β Set the mean and standard deviation of the elements in matrix T, as well as the values in the comprehensive impact matrix H. Set the threshold through the above two methods $\lambda=\alpha+\beta= 0.2$, $\lambda= 0.1$, 0.05, 0.02, calculate reachable matrices. Following the principle of similar ranking between node degree and centrality [23], select $\lambda= 0.02$; Following the principle of moderate node degree [23], further refinement $\lambda= 0.022$, 0.024, 0.026, 0.028, after multiple verifications and combined with actual situations, threshold values were selected $\lambda= 0.022$. According to formula (10), convert the overall influence matrix H to the reachable matrix K.

$$\begin{cases} K_{ij} = 1, h_{ij} \geq \lambda, (i, j = 1, 2, \cdots, n) \\ K_{ij} = 0, h_{ij} < \lambda, (i, j = 1, 2, \cdots, n) \end{cases} \tag{10}$$

In the formula: K_{ij} is the constituent element of the reachable matrix K; h_{ij} is the constituent element of the overall impact matrix H; λ is the threshold.

$$K = \begin{Bmatrix}
1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
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\end{Bmatrix}$$

According to the reachable matrix K, perform inter level decomposition. Based on the reachable matrix K, obtain the reachable set O (A_i) and the antecedent set P (A_i), and divide the system into different levels according to formula (11), as shown in Table 4.

$$O(A_i) = O(A_i) \cap P(A_i), i = 1, 2, ..., n \quad (11)$$

In the formula, A_i is the set of factors.

Table 4. Hierarchy Classification Results of Factors Influencing Fire Resilience of Subway Station Systems

level	Hierarchical division results
0	A_1, A_2, A_5, A_6, A_{12}, A_{13}, A_{20}, A_{22}
1	A_8, A_{10}, A_{11}, A_{14}, A_{15}, A_{19}, A_{21}, A_{23}, A_{25}, A_{26}
2	A_3, A_7, A_{16}, A_{18}, A_{24}, A_{27}
3	A_4
4	A_{17}, A_9
5	A_{28}, A_{29}, A_{30}
6	A_{31}

According to Table 4, a directed graph of the ISM hierarchy of influencing factors can be drawn, as shown in Figure 3.

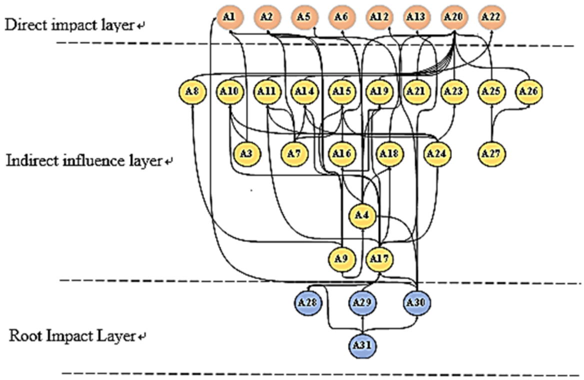

Fig. 3. ISM hierarchy diagram of factors affecting fire resilience of subway station systems

Clarify the Mechanism of Action of Influencing Factors.

According to the reachability matrix *K*, calculate the driving force and dependency of the influencing factors using formulas (12) - (13), with the average value of the driving force and dependency as the dividing line, and finally divide into four quadrants to clarify the position and role of the influencing factors, as shown in Figure 4.

$$U_i = \sum_{j=1}^{n} a_{ij}^{k}, (i = 1, 2, \cdots, n) \tag{12}$$

$$V_j = \sum_{i=1}^{n} a_{ij}^{k}, (j = 1, 2, \cdots, n) \tag{13}$$

In the formula, a_{ij} is the factor in the reachable matrix *K* that has an impact on j with i, and a_{ji} is the factor in the reachable matrix *K* that has an impact on j with i.

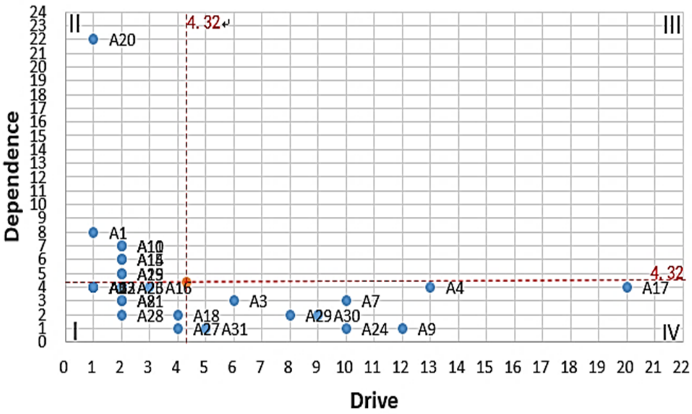

Fig. 4. Driver Dependency (Scatter plot)

4 Result Analysis and Suggestions

4.1 Analysis of Key Influencing Factors

According to Table 3, there are 13 causal factors and 18 outcome factors affecting the fire resistance of subway stations. The biggest causal factor is the level of completeness of fire emergency plans, and the biggest outcome factor is emergency response actions. Based on the 28 principles, select the top 20% of the influencing factors with the highest weight among the influencing degree, being affected degree, centrality, causal degree, and centrality, and identify the key influencing factors of fire resistance in subway stations through union analysis: A_1, A_4, A_7, A_9, A_{10}, A_{11}, A_{14}, A_{17}, A_{20}, A_{24}, and A_{29}. These 11 key influencing factors mostly exist in the dimensions of absorption and resistance, including monitoring and control systems (A_1, A_{10}) and emergency plans (A_{17}) Factors such as emergency response (A_{20}) are related to the emergency response mechanism, and emphasis should be placed on improving the emergency response mechanism in terms of enhancing fire resilience.

As shown in Figure 2, the 11 influencing factors in the third and fourth quadrants have high centrality, and the degree of influence of these factors is positively correlated with centrality. Therefore, the influencing factors of the third and fourth quadrants should be given special attention in improving fire resistance.

4.2 Analysis of the Hierarchical Structure of Influencing Factors

The 7 levels in Table 4 of the hierarchical division results of the fire resistance resilience factors of the subway station system are divided into direct impact layer (layer 0), indirect impact layer (layer 1-4), and root impact layer (layer 5-6), as shown in Figure 3. The factors that directly affect the layer directly affect the fire resistance of subway stations; The factors that indirectly affect the layer are not only influenced by the factors that fundamentally affect the layer, but also by the factors that directly affect the layer, playing a transitional role in the system; The fundamental influence layer ultimately affects the fire resistance of subway stations and plays a leading role in the system.

4.3 Analysis of the Mechanism of Influencing Factors

According to Figure 4, the factors located in the second quadrant have the characteristics of high dependence and low driving force, including 8 factors such as security inspection system (A_1), fire alarm system (A_{10}), and emergency facilities (A_{11}). They are located in the transition layer of the ISM level and need to be resolved by solving other factors. The factors located in the fourth quadrant have the characteristics of high driving force and low dependence, including 9 factors such as equipment safety inspection (A_3, A_7), safety training (A_4), and passenger safety awareness (A_8). They are located at the bottom level of the ISM level and belong to deep-seated influencing factors. The resolution of other influencing factors depends on these influencing factors. The relationship between the 14 influencing factors located in the I quadrant and other influencing factors is relatively weak and can be addressed separately.

4.4 Result Verification

This article analyzes and identifies the key influencing factors of subway fire resistance resilience, and the role and status of these factors are highly consistent with the important influencing factors in the research conclusions of Liu J, et al. [16] and Bi W [17]. They mostly exist in the dimensions of absorption and resistance. When improving subway fire resistance resilience, the focus is on monitoring and monitoring systems, improving emergency plans, and emergency response. The validity of the research results in this article was verified, and the hierarchical relationship and mechanism of the influencing factors were presented intuitively.

5 Conclusion

1) From the perspective of resilience, 31 factors affecting the resilience of subway stations against fire were identified from four dimensions: technology, organization, society, and economy. *A* comprehensive analysis was conducted on the relationship between the four influencing factors of pre disaster prevention, resistance during disasters, post disaster rescue and recovery learning, providing theoretical guidance for the prevention of subway fire accidents.

2) Integrate fuzzy DEMATEL, ISM, and MICMAC methods to analyze the relationship between factors affecting fire resilience in subway stations. Intuitively present the hierarchical relationship and mechanism of factors affecting fire resilience in subway stations, not only identifying the key factors of fire resilience in subway stations, but also the most important 11 key influencing factors such as monitoring and control systems, resource allocation, and emergency response, *A* hierarchical division was also conducted on the 31 related factors of fire resistance resilience in subway stations, and all influencing factors can be divided into direct influencing factors, indirect influencing factors, and fundamental influencing factors based on their roles. Long term monitoring of indirect influencing factors, emphasizing fundamental influencing factors, and targeted adjustment of direct influencing factors are effective ways to enhance the fire resistance resilience of subway stations, providing suggestions for safety management of subway fires, and laying the foundation for the evaluation of subway fire resistance resilience.

3) In the process of screening influencing factors and confirming the relationship between influencing factors, although methods such as triangular fuzzy numbers and DEMATEL are used to correct the reachability relationship of influencing factors and improve the scientificity of hierarchical division, the subjectivity of experts cannot be completely eliminated. Therefore, in the future, further exploration can be made on the construction of network models and measurement methods for resilience curves, and their application in the study of factors affecting subway disaster resilience.

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