Study on vulnerability evaluation of rainstorm waterlogging disaster based on DEMATEL-AISM

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Abstract: In the hope of improving emergency management of underground rail transit in rainstorm waterlogging disasters, this study analysed the influencing factors of underground rail transit vulnerability in rainstorm waterlogging disasters. First, the influencing factors were identified from the three dimensions, namely, exposure, sensitivity and adaptive capacity, and an evaluation index system was established accordingly. The DEMATEL method was used to investigate the importance of each factor. Subsequently, the degree of influence was assessed with the AISM method. Ultimately, a hierarchical structure of the factors influencing the vulnerability of underground rail transit in rainstorm waterlogging disasters was established. The results show that S14 safety investment, S2 surrounding hazards, S3 topography of entrance and exit, S5 height of entrance and exit steps, and S6 weather conditions are the key influencing factors. According to these factors, rainstorm water logging risk can be reduced. The research results can also provide a theoretical basis for disaster prevention and mitigation and risk management in rainstorms and floods.

Keywords: Vulnerability; DEMATEL; AISM; Urban Waterlogging; Rail Transit

1 INTRODUCTION

In recent years, as global warming has made extreme weather and natural disasters more frequent, urban waterlogging disasters that used to occur in some coastal areas with relatively low terrain now often occur in inland cities. For example, from 20:00 on July 17, 2021 to 20:00 on July 20, 2021, Zhengzhou city in Henan province was hit by continuous large rainfall, whose total precipitation amounts to the total volume of 317 West Lakes. Consequently, this rainfall has imposed serious impacts on people's production and life, especially on the Jingguang Road tunnel and Metro Line 5. As an important part of people's daily life, underground rail transit is crucial to the functioning of the city, which is affected by many uncertain factors, such as many public emergencies. Given the vulnerability of underground rail transit, how to ensure its safety has once again become a common concern.

Since vulnerability has received widespread attention in many fields, from the natural sciences to social sciences, such as economics, psychology, and management, its concept has been constantly revised and redefined. In 1995, scholars gradually recognized the vulnerability of transportation systems. For instance, Taylor proposed many ways to measure road network vulnerability[12]. AVCI presented many procedures to evaluate the vulnerability of metro stations[1].

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Many scholars have investigated the influencing factors of vulnerability. Wang assessed vulnerability from three dimensions: exposure, sensitivity and adaptive capacity[15]. Xu Liqun analyzed influencing factors of road network vulnerability and divided them into two categories: internal and external ones[18]. Lin Qing divided the three factors of the human-machine ring into three dimensions: exposure, susceptibility and fitness, and utilized the ESAR model to study vulnerability[8]. Liu Min, Zhu Haiyan and Song Liangliang studied the vulnerability of underground rail transit from two perspectives, namely, sensitivity and disaster response capability[9]. Wang Junwu divided vulnerability into three aspects: the sensitivity of the disaster-bearing body, the risk of the disaster-inducing factor, and the adaptive capacity of the disaster-bearing body[14]. He Yabo conducted a vulnerability assessment of flood disasters in various provinces in China including four aspects: risk, exposure, disaster relief and resilience, and accumulated losses[6].

Considering existing research results, this study made a vulnerability assessment from the following three dimensions: exposure, sensitivity and adaptive capacity. Since underground rail transit is a complex network system, the DEMATEL-AISM model was adopted, which combined the advantages of the two models. Specifically, the DEMATEL model is capable of analyzing the causality and centrality of the impact factors and the AISM model can further determine the key influencing factors with a hierarchical structure. This study can therefore provide a reference for disaster prevention and mitigation and risk management of underground rail transit in Zhengzhou in public emergencies.

2 IDENTIFICATION OF INFLUENCING FACTORS OF UNDERGROUND RAIL TRANSIT RAINSTORM AND WATERLOGGING DISASTERS

A total of 41 articles published in the past 10 years were retrieved from core journals such as *China Safety Science Journal*, *Catastrophology*, *Journal of Natural Disasters*, *Modern Urban Rail Transit* and *Statistics and Decision*. After that, the literature highly related to this study was preliminarily screened out through reading and labelling and then systematically sorted and classified. Ultimately, 15 factors affecting the vulnerability of underground rail transit were extracted and classified according to three dimensions, and then coded as S1, S2, ..., S14, and S15, as shown in Table 1.

Table 1 vulnerability influencing factor system of underground rail transit under rainstorm and waterlogging disaster

Level I indicators	Level II indicators	Description
Exposure	Gender and age ratio of passengers	Self-rescue abilities vary with gender and age.
	Surrounding hazards	Whether the surrounding parking lot is high or low, the external water-blocking capacity will exacerbate the disaster
	Topography of entrance and exit	The topography of the entrance and exit of the subway and tunnel
	Types of entrance and exit	Metro entrance: open, closed, hidden
	Height of entrance and	The height of the steps at the entrance

	exit steps	
	Weather conditions	Uncontrollable factors increase the occurrence of disasters.
	Personal unsafe behavior	When a disaster occurs, unsafe behaviors such as failing to abandon the car and flee the scene in time should be avoided.
Sensitivity	Flood control emergency equipment qualification rate	Whether the emergency equipment meets the standards matters.
	Personal professional skills	The level of professional skills determines people’s cognitive and thinking abilities, which directly affect people's safety awareness, safety behaviors and safety habits.
	Emergency management capability	Emergency management plays a significant role in reducing losses.
	Completeness of emergency facilities	Whether the emergency equipment is complete is important.
	On-site emergency plan	A scientific emergency management plan can improve response efficiency and reduce the sensitivity of the subway system to the emergency.
Adaptive capacity	Water blocking capacity	The anti-retaining plate, waterproof groove, and civil enclosure at the entrance and exit
	Safety investment	Sufficient safety investment guarantees the operation of the subway.
	Emergency response efficiency	The more efficient the emergency response, the earlier effective measures are taken, and the less serious consequences of the accident.

3 CONSTRUCTION OF VULNERABILITY ASSESSMENT MODEL FOR STORM WATERLOGGING DISASTER OF UNDERGROUND RAIL TRANSIT

3.1 DEMATEL Method

(1) 30 experts and scholars in the field of management were invited to evaluate the relationships between the factors affecting the vulnerability of underground rail transit in the special case of rainstorm waterlogging disaster (Table 2). Then, the initial direct impact matrix O was obtained, including the degree of influence, the degree of centrality, and the degree of cause.

Table 2 Semantic scale of expert evaluation

Semantic variables	no impact	Minor impact	General impact	Strong impact	Stronger impact
scale	0	1	2	3	4

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(2) The initial matrix O is normalized to obtain the normalized direct relationship matrix N, as shown in Eq. (1).

$$N = O / \max\left(\sum_{j=1}^{n} o_{ij}\right) \tag{1}$$

(3) Considering the direct and indirect impacts between the influencing factors, the combined impact matrix T is calculated by summing. The formula is as follows:

$$T = \left(N + N^2 + N^3 + \cdots + N^k\right) = \sum_{k=1}^{\infty} N^k = N(I-N)^{-1} \tag{2}$$

(4) According to the combined impact matrix T, the value of the degree can be calculated as follows:

$$D_i = \sum_{j=1}^{n} t_{ij}, (i = 1, 2, 3, \cdots, n) \tag{3}$$

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$$M_i = D_i + C_i \tag{4}$$

$$R_i = D_i - C_i \tag{5}$$

3.2 AISM Method

(5) In order to simplify the system structure and facilitate the calculation of the overall relationship matrix, the threshold value λ (λ ∈ [0,1]) is introduced and the relationship matrix B based on the combined impact matrix T is calculated according to Eq. (7):

$$\begin{cases} b_{ij} = 1, t_{ij} \geq \lambda & (7) \\ b_{ij} = 0, t_{ij} \leq \lambda & (8) \end{cases}$$

(6) Further, considering the influence of the factor itself, the overall relationship matrix Z is calculated according to Eq. (8):

$$Z = B + I \tag{9}$$

(7) Based on Eq. (9), the formula to compute the reachable matrix K is as follows:

$$K = Z^{k+1} = Z^{k} \neq Z^{k-1} \quad (10)$$

(8) According to Eq. (10) and the reachability matrix K, the reachability set, antecedent set and intersection set of each factor Fi are identified, and then the adversarial hierarchy is divided according to results and causes.

(9) The skeleton matrix F is calculated. According to Eq. (10), the confrontation level of each factor is determined, as shown in Table 3. The reachable matrix K is indented to obtain the skeleton matrix F.

(10) According to Table 3 and the skeleton matrix F, based on the combination of causality and centrality degree, research results are classified and hierarchical structures are constructed.

4 EMPIRICAL ANALYSIS

4.1 Overview of Zhengzhou City

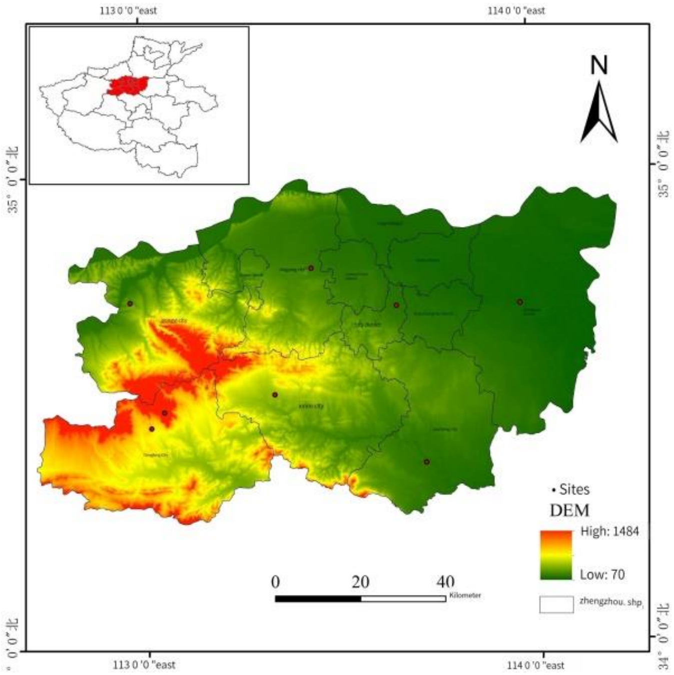

Fig.1. Topographic map of Zhengzhou

As displayed in Fig.1, Zhengzhou has a complex terrain, high in the southwest and low in the northeast. The Jingguang Road Tunnel is located at 113.66 east longitude and 34.72 north latitude in Zhengzhou’s 27th district. Metro Line 5 is a circular line on the outer edge of the city's core area, and functions as the backbone line, both of which have relatively low altitudes.

4.2 Model construction results

(1) We normalize the matrix O according to Eq. (1), and then calculate the combined impact matrix T through Eq. (2), as shown in Fig.2.

$$O=\begin{pmatrix}
0 & 1 & 1 & 1 & 1 & 0 & 3 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1\\
1 & 0 & 1 & 3 & 3 & 1 & 2 & 2 & 0 & 3 & 3 & 3 & 2 & 2 & 3\\
1 & 3 & 0 & 4 & 4 & 1 & 1 & 1 & 0 & 2 & 1 & 1 & 3 & 1 & 1\\
1 & 3 & 1 & 0 & 3 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 2 & 1 & 0\\
0 & 3 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0\\
2 & 2 & 1 & 2 & 1 & 0 & 1 & 1 & 0 & 2 & 1 & 4 & 2 & 2 & 2\\
1 & 3 & 0 & 2 & 1 & 2 & 0 & 2 & 2 & 0 & 1 & 2 & 1 & 1 & 0\\
1 & 3 & 1 & 1 & 1 & 3 & 2 & 0 & 0 & 3 & 3 & 2 & 2 & 1 & 2\\
1 & 1 & 1 & 1 & 1 & 1 & 3 & 1 & 0 & 0 & 1 & 2 & 0 & 0 & 0\\
1 & 2 & 1 & 1 & 1 & 1 & 2 & 1 & 2 & 0 & 0 & 0 & 2 & 1 & 4\\
0 & 2 & 1 & 1 & 1 & 1 & 2 & 1 & 1 & 4 & 0 & 3 & 4 & 2 & 3\\
1 & 3 & 3 & 2 & 2 & 3 & 2 & 3 & 0 & 2 & 1 & 0 & 1 & 2 & 2\\
1 & 2 & 3 & 3 & 3 & 1 & 3 & 3 & 0 & 0 & 0 & 1 & 0 & 3 & 2\\
1 & 3 & 2 & 3 & 3 & 1 & 3 & 4 & 1 & 2 & 3 & 4 & 4 & 0 & 3\\
1 & 3 & 1 & 1 & 1 & 1 & 3 & 1 & 2 & 2 & 0 & 3 & 1 & 1 & 0
\end{pmatrix}$$

$$T=\begin{pmatrix}
0.02 & 0.081 & 0.052 & 0.068 & 0.067 & 0.03 & 0.119 & 0.035 & 0.043 & 0.057 & 0.053 & 0.066 & 0.039 & 0.056 & 0.06\\
0.071 & 0.125 & 0.092 & 0.168 & 0.17 & 0.094 & 0.145 & 0.13 & 0.034 & 0.153 & 0.137 & 0.164 & 0.143 & 0.123 & 0.162\\
0.062 & 0.175 & 0.053 & 0.178 & 0.183 & 0.077 & 0.097 & 0.087 & 0.022 & 0.107 & 0.076 & 0.09 & 0.149 & 0.085 & 0.091\\
0.048 & 0.137 & 0.059 & 0.049 & 0.128 & 0.057 & 0.047 & 0.064 & 0.012 & 0.039 & 0.061 & 0.045 & 0.098 & 0.064 & 0.043\\
0.018 & 0.123 & 0.051 & 0.066 & 0.04 & 0.05 & 0.061 & 0.032 & 0.01 & 0.031 & 0.053 & 0.038 & 0.064 & 0.055 & 0.034\\
0.091 & 0.153 & 0.084 & 0.13 & 0.106 & 0.056 & 0.105 & 0.094 & 0.026 & 0.115 & 0.077 & 0.175 & 0.125 & 0.112 & 0.123\\
0.057 & 0.152 & 0.043 & 0.111 & 0.087 & 0.096 & 0.059 & 0.102 & 0.068 & 0.05 & 0.071 & 0.112 & 0.082 & 0.072 & 0.053\\
0.068 & 0.184 & 0.084 & 0.11 & 0.109 & 0.136 & 0.136 & 0.07 & 0.031 & 0.149 & 0.131 & 0.136 & 0.134 & 0.093 & 0.133\\
0.047 & 0.081 & 0.053 & 0.068 & 0.067 & 0.058 & 0.116 & 0.06 & 0.013 & 0.033 & 0.055 & 0.091 & 0.038 & 0.031 & 0.033\\
0.057 & 0.129 & 0.066 & 0.086 & 0.086 & 0.068 & 0.116 & 0.076 & 0.075 & 0.045 & 0.039 & 0.061 & 0.104 & 0.07 & 0.152\\
0.045 & 0.166 & 0.091 & 0.115 & 0.115 & 0.09 & 0.143 & 0.105 & 0.059 & 0.17 & 0.054 & 0.16 & 0.185 & 0.12 & 0.16\\
0.072 & 0.195 & 0.137 & 0.144 & 0.144 & 0.141 & 0.138 & 0.15 & 0.029 & 0.127 & 0.089 & 0.088 & 0.115 & 0.119 & 0.133\\
0.066 & 0.163 & 0.132 & 0.162 & 0.164 & 0.086 & 0.155 & 0.146 & 0.025 & 0.064 & 0.06 & 0.104 & 0.08 & 0.137 & 0.118\\
0.084 & 0.235 & 0.137 & 0.197 & 0.199 & 0.116 & 0.197 & 0.204 & 0.065 & 0.149 & 0.157 & 0.214 & 0.216 & 0.093 & 0.183\\
0.061 & 0.165 & 0.073 & 0.096 & 0.095 & 0.077 & 0.146 & 0.085 & 0.076 & 0.104 & 0.047 & 0.142 & 0.087 & 0.077 & 0.059
\end{pmatrix}$$

(2) According to matrix T, the centrality and the cause degree of each influencing factor are obtained. We take the centrality degree as the horizontal coordinate and the cause degree as the vertical coordinate, as shown in Fig. 2.

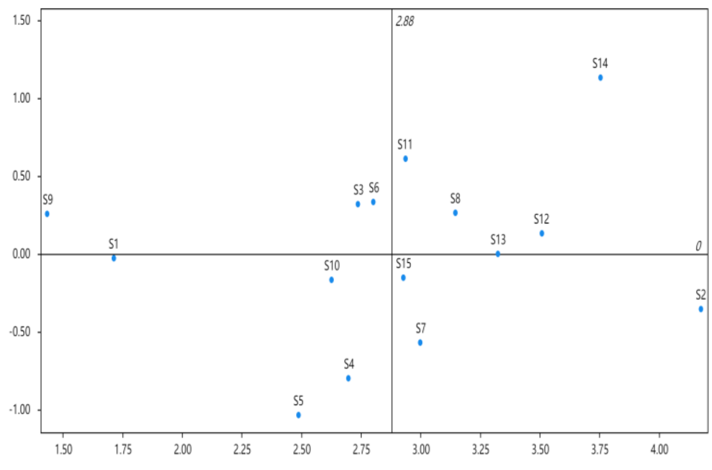

Fig.2. Centrality-cause diagram

(3) The hierarchical distribution of pair elements is obtained by the adversarial extraction of

the matrix K, as shown in Table 3.

Table 3 Final hierarchical division results

Level	UP (Results-oriented)	DOWN (Cause-oriented)
L1	S1 S4 S5 S9	S4 S5
L2	S2,S7,S8,S10,S12,S15	S2,S7,S8,S10,S12,S15
L3	S6 S13	S13
L4	S3 S11	S11
L5	S14	S1 S3 S6 S9 S14

(4) Then, according to Table 3 and the skeleton matrix F, hierarchical structures are constructed, as shown in Fig. 3.

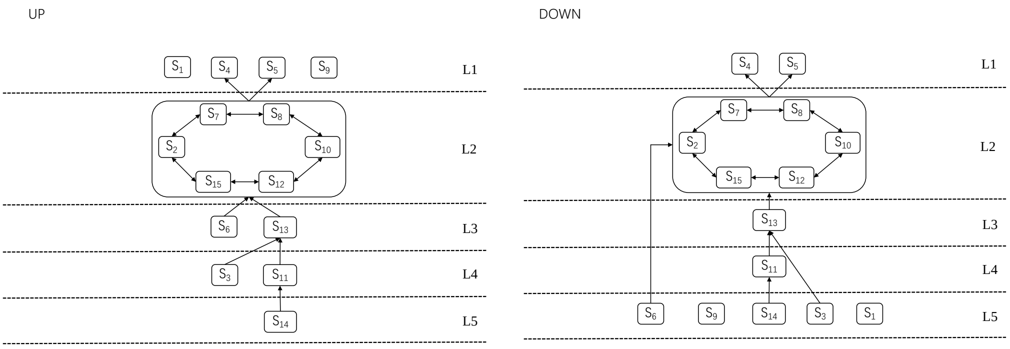

Fig.3. Hierarchical structures of the factors influencing the vulnerability of underground rail transit in rainstorm waterlogging disasters based on the DEMATEL-AISM model

4.3 Analysis of model results

It can be seen from Fig. 3 that the influencing factors form a directional hierarchical structure of 5 levels and it is divided into 3 layers. The bottom layer includes influencing factors in the L5, namely, S6 weather conditions, S3 topography of entrance and exit, and S14 safety investment. Since they are located at the bottom of the system, like the foundation of buildings, they have significant impacts on reducing the vulnerability of underground rail transit. The influencing factors in the middle layer include S2 surrounding hazards, S6 weather conditions, S7 personnel unsafe behavior, S8 flood control emergency equipment qualification rate, S10 emergency management capability, S12 on-site emergency management plan, and S15 emergency response efficiency. These 7 types of factors are the key to reducing the vulnerability of underground rail transit. They can directly affect the factors on the top level, and be influenced by the factors on the bottom level at the same time, as the connection between the bottom and top levels. There exists a cycle in the hierarchical structure of influencing factors, namely, S2 surrounding hazards, S7 personnel unsafe behavior, S8 flood control emergency equipment qualification rate, S10 emergency management capability, S12 on-site emergency management plan, and S15 emergency response efficiency. It is indicated that these factors are closely related and mutually dependent. The top layer includes S1 gender and age ratio of passengers, S4 types of entrance and exit, S5 height of entrance steps, and S9 personal professional skill, which directly affect emergency management. The effects of other factors need to be carried out through the top layer.

Considering the factors with the highest centrality and causality obtained by the DEMEL model and the bottom factors obtained by the AISM model, the most fundamental factors are determined as follows: S14 safety investment, S2 surrounding hazards, S3 topography of entrance and exit, S5 height of entrance and exit steps, S6 weather conditions.

5 CONCLUSION

In this study, the vulnerability of underground rail transit in heavy rainstorm waterlogging disasters was analysed from three dimensions: exposure, adaptive capacity and sensitivity. And 15 influencing factors were identified, and an index system was established accordingly. Based on the relationship between 15 factors and the combination of the factors with the highest centrality and causality obtained through the DEMATEL method and the bottom factors obtained by the AISM method, the 5 most fundamental factors were determined. The DEMATEL-AISM model was established to determine the vulnerability factors of underground rail transit vulnerability in rainstorm waterlogging disasters, which divided all factors into three layers: bottom layer, middle layer and top layer. In addition, the hierarchical structures of the influencing factors of underground rail transit vulnerability were established, and the relationships between various influencing factors were displayed. The research results provide a theoretical basis for disaster prevention and mitigation and risk management and control of heavy rainstorms and flood disasters.

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