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Original citation & hyperlink:
Guo, Q, Amin, S, Hao, Q & Haas, O 2020, 'Resilience Assessment of Safety System at Subway Construction Sites Applying Analytic Network Process and Extension Cloud Models', Reliability Engineering and System Safety, vol. 201, 106956.
https://dx.doi.org/10.1016/j.ress.2020.106956

DOI 10.1016/j.ress.2020.106956
ISSN 0951-8320

Publisher: Elsevier

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DOI: 10.1016/j.ress.2020.106956

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Resilience Assessment of Safety System at Subway Construction Sites Applying Analytic Network Process and Extension Cloud Models

Abstract

This paper applies resilience theory in safety management to three subway construction sites: the Shuangzhai, the Sports Centre and the Sanyizhuang stations on the Xi'an Metro Line 14. It analyses the resilience connotation and evaluates the system resilience using the resilience index. The Delphi method determined the resilience indices. The ANP extension cloud synthesis was constructed combining the cloud and matter-element extension theories to address the randomness and ambiguity of the resilience assessment process for subway construction sites. This study reveals that the resilience level was consistent with actual engineering project assessment at all stations. The resilience assessment of the Shuangzhai Station project ranks first followed by that of Sanyizhuang and then the Sports Centre station. The findings of this study argue for strengthening the resilience management, taking measures to optimise and improve the security system, enhancing the defence ability and anti-risk mechanism at the construction sites of the sports centre and the Sanyizhuang stations.

Key Words: subway construction; safety system; resilience; ANP; extension cloud model

1. Introduction

Safety management at subway construction sites is challenging in China due to the large scale of subway construction projects and the frequent accidents at the construction sites [1-3]. The accidents at subway construction sites are characterised by frequent occurrence, strong derivative and occurrence of collateral disasters that degenerate the safety situation. The resilience of subway construction sites can be improved by increasing the anti-interference ability and redundancy of the construction sites. This would help to shorten the accident recovery time, avoid the occurrence of secondary disasters, and reduce the occurrence of accidents. Resilience science emphasises the system's response to the pre-process and post-process performance of risk events. The resilience-based safety management emphasises the ability of a system to respond to risks and adverse events as well as its ability to cope, adapt, be resilient and achieve a new state of security through a series of performances of system. Chen [4] argued that robustness and recoverability were two aspects to assess the resilience of a system. Chen [5] defined the resilience of subway engineering system as a system performance to resist and cope with risk disasters during the subway construction process.

There are qualitative and quantitative methods to analyse the risk and safety at underground construction sites. The qualitative methods include Fault Tree Analysis (FTA), Comprehensive Fuzzy Evaluation Method (CFEM) and Safety Check List (SCL). The quantitative methods are influence diagrams, Artificial Neural Network (ANN), Support Vector Machine (SVM), Bayesian network (BN) and decision trees [6-12]. The FTA can be ambiguous when all failure modes are required to be implemented and probabilities are required to be updated. This may lead to FTA being unable to identify the common cause of failures [13]. The FTA requires high level of expertise to work on the combination of events to accurately estimate the human errors in investigating complex man-made systems. Chen [5] applied the Bayesian network to evaluate the factors affecting the resilience of subway engineering systems. The BN analysis considers the occurrence probability of root nodes as a crisp value; however, the exact value of the probability is difficult to obtain due to insufficient data [14,15]. The BN analysis is also sensitive to prior probabilities and parameters leading to computation approximation. Wu et al. [6] applied dynamic Bayesian network (DBN) to address the potential uncertainty and randomness underlying the safety management in tunnel construction. The DBN model requires significant manpower to collect large quantities of monitored data that may be subject to human errors. The DBN analysis can lead to an incorrect estimation of risk because the identified hazards are often overlapping and are not identified with the same level of details and the relations amongst them are not described [16].

CFEM converts continuous value to single category value endangering the loss of important information [17]. CFEM is arbitrary to process large and small values and has problems related to the maximum membership degree principle and fluctuations in assessment results [18,19]. ANNs require large data sets. Davidson [20] developed a post-disaster resilience assessment framework for power systems and simulated the probability and process of discrete events based on actual measurable data to improve the effectiveness of quantitative assessments. Li [21] formulated a resilience index incorporating the robustness, redundancy, intelligence and rapidity of a system. Huang [22] constructed a resilience assessment model and analysed the performance process for safety resilience curve. Chen [4] used functional-dependent network analysis (FDNA) to assess the resilience level of architecture and discussed the maximum recoverability of the system combining the dependency constraints in FDNA.

These approaches are confined to static control management and could suffer from modelling uncertainties to accurately present the dynamic environment at the subway construction sites [1-3]. The analytic network process (ANP) can deal with all kinds of dependence systematically to select the constructive resilience strategies in subway construction sites. The traditional ANP model cannot effectively reflect the dependencies and feedback relationships among the influential resilience factors of subway construction systems. The drawbacks of traditional ANP models was overwhelmed by integrating the Cloud extension model because Cloud model has great advantages in the fuzziness and randomness of boundary partition. ANP is selected to calculate the weight of each index in the resilience evaluation system. Cloud computing and cloud transformation are accomplished by using digital features such expectation, entropy and hyper-entropy. The membership degree is obtained by calculating the number of cloud droplets, and the transformation function from qualitative to quantitative is established.

The previous studies [4-20] assessed the risk at the subway construction sites focusing on planning and reducing vulnerabilities. The resilience assessment can enhance the ability to anticipate the risk, prepare for and adapt to change conditions and withstand, respond to, and recover rapidly from accident at the subway construction sites.

This paper develops the resilience index to assesses the resilience of subway construction sites by analysing the resilience connotation applicability to the safety system of subway construction sites for three stations in China. The paper is organised as follows. Section 2 presents the concept of safety resilience at subway construction sites. Sections 3-6 discuss the methodology, case application, analysis and discussion and conclusions, respectively.

2. Safety Resilience at Subway Construction Sites

The safety resilience at subway construction sites refers to the maintenance, absorption, response and recovery process of the entire system when the subway faces the unknown risk impact or disturbance during the construction process. The Safety resilience can restore the system to the prior level. For instance, the safety resilience in the event of a risk shock or disturbance is expressed as impact or disturbance absorption, avoidance of next risk or accident, and enhancement of adaptive ability towards uncertain events through accident retrospection and learning to achieve system optimisation. Figure 1 shows the concept curve of safety resilience at subway construction sites. The t_0~t_1 phase illustrates the presence of risk impact or disturbance with the system at its initial safe state (Figure 1). The risk impact and disturbance are encountered at time t_1 when the system's withstand capability exceeds the threshold. The system is constantly subjected to risk shocks and disturbances during t_1~t_2 phase and its ability to absorb the risk is gradually reduced causing accidents, damage to system and eventually failure of the system (Figure 1). The security of the system can be restored by taking the necessary emergency measures counter to risk shocks or disturbances at t_2~t_4 phase where t_3~t_4 phase denotes the recovery phase (Figure 1). The system can be restored to the pre-existing security state (X_0) through the recovery phase (t_4~t_5 phase). It can also improve its security and resilience by establishing a better security state (X_1) than the initial state (X_0). Poor management and learning ability may result in system's inability to restore at the initial security state (X_2) (Figure 1).

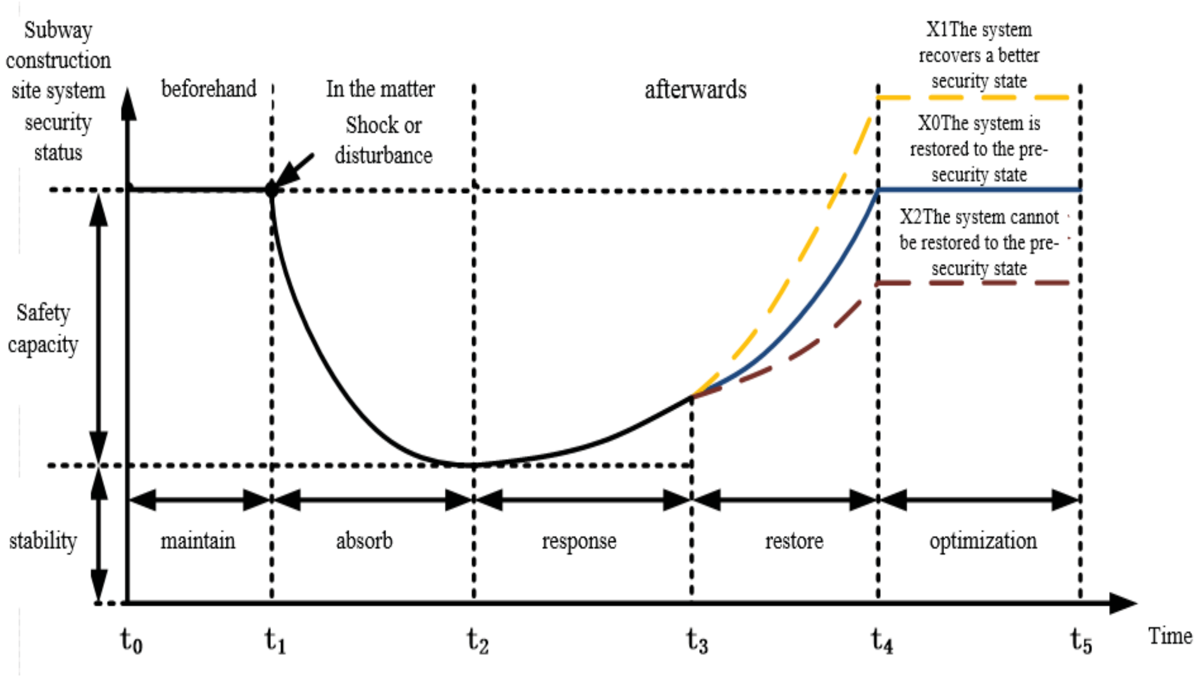


Figure 1: The resilience concept curve of the safety system of subway construction site

The safety system of the subway construction sites is divided into four subsystems such as organisation members, material technology, management and environment (Figure 2). The resilience performance process of the safety system is completed, and the regularity model of the resilience characteristics is formed through the interaction between four subsystems of the subway construction sites (Figure 3). The resilience performance is characterised by stability, redundancy, efficiency and fitness of the system. The stability is the inherent property of the system to resist the external risk shocks and disturbances, and to maintain the system's safety status at the maximum extent during the risk events and accidents. Redundancy degree can be used as a backup device to keep the system running normally after the system suffers huge losses or the original equipment and machinery are damaged. Efficiency determines the response time of the system to adverse events and the degree of loss reduction. The fitness is the system’s ability to absorb the accidents and overcome for the deficiencies.

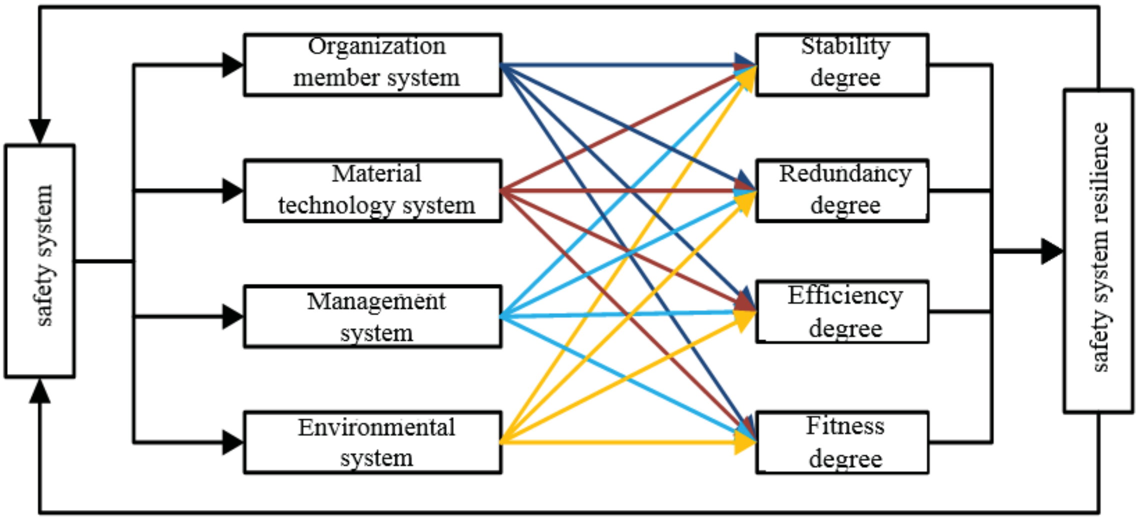


Figure 2: Conceptual model of resilience of safety system in subway construction site

The initial system maintains a safe and stable state. Under the impact or disturbance of risk, the stability degree, redundancy degree, efficiency degree and fitness degree of resilience are used to describe its state. In the process of gradually reducing its ability to absorb risks until exceeding the maximum limit, the organization member system, material technology system, management system and environmental system coordinate with each other and take necessary emergency measures to restore the safety of the system. Through recovery, the system may be restored to a prior safe state, a better safe state than the initial state Alternatively, the system may be damaged and lost due to various factors, which is the unsafe state of the system.

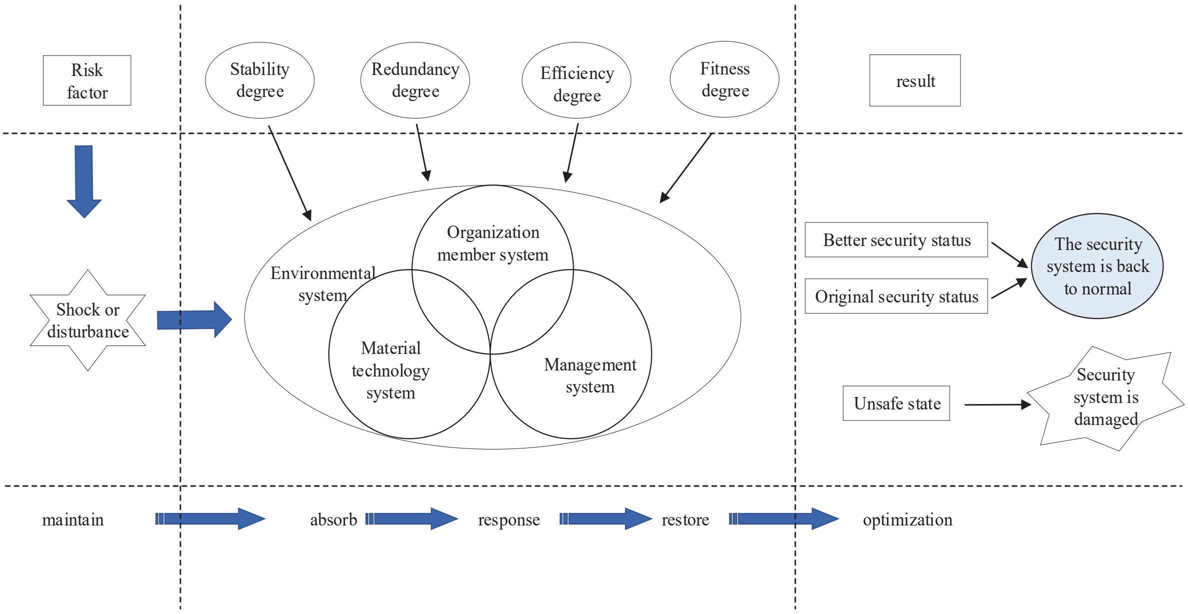


Figure 3: The regularity model of safety features of the subway construction site

3. Methodology

The assessment index is a key for evaluating the safety resilience of subway construction sites. This study applied the bibliometric method to screen the resilience indices in the search interface of the China Knowledge Network (CNKI) full-text database. The 224 out of 742 articles published during the period of 2000-2019 articles were screened based on the application of resilience indices in those studies. The Delphi method was used to collect data from experts through questionnaire survey. This study invited ten experts of this subway construction project to score the indicators for safety resilience of the sites such as, three senior engineers of the construction unit, three senior managers of the construction unit and two senior engineers of the supervision unit and two professors in the field of subway safety management. The most representative indicators were identified from collected data using statistical techniques and indicators with low common value or significant deviations of their factor correspondence were eliminated. The identified resilience indicators for subway construction sites are summarised in Table 1.

The resulting reports were summarised, and the predictability of these evaluation indicators were discussed, then organised by experts. The facilitator then gave feedback to the expert, and the process is repeated until a consensus be obtained.

Table 1: Assessment index system for safety resilience of subway construction site

Target layer	**Primary indicators**	**Secondary indicators**
Subway construction site safety system resilience A	Stability degree B_1	Adjacent building protection measures C_1; Construction safety management mechanism C_2; Risk source assessment and response C_3; Safety management of geological hazards C_4; Safety awareness of personnel C_5; Professional skill level of personnel C_6; Physical and mental state of personnel C_7; Mechanical equipment status and performance C_8; Stability of power supply system C_9; Safety measures C_{10}
	Redundancy degree B_2	Redundancy of power supply system C_{11}; Redundancy of water supply system C_{12}; Redundancy of emergency material reserve C_{13}; Redundancy of emergency communication command system C_{14}; Redundancy of emergency medical rescue system C_{15}
	Efficiency degree B_3	Emergency survival ability of personnel C_{16}; Emergency management system C_{17}; Emergency response plan C_{18}; Special contingency plan for emergencies C_{19}; Common accident

	prevention and treatment measures C_{20}; Emergency access and shelter C_{21}
Fitness degree B_4	Emergency rescue knowledge education and drill C_{22}; Emergency command organisation operation management C_{23}; Work safety education and training C_{24}; Risk monitoring and intelligent warning technology C_{25}; Accident prevention popularisation and intelligence C_{26}; Safety input C_{27}

The Analytic Network Process (ANP) extension cloud synthesis was constructed combining cloud and matter-element extension theories to address the randomness and ambiguity of the resilience assessment process at subway construction sites (Figure 4). The ANP is a multi-criteria decision-making structure with dependence and feedback relationships among the factors from the safety resilience assessment system. The ANP structure has two layers: the control and the network layers. The relationships between the selected indicators (Table 1) in the safety resilience index at subway construction sites are outlined in the ANP structure model. B_i (i=1,2,3,4) are the first-level indicators and C_i (i=1, 2...,27) are the second-level indicators (Figure 5). The level of resilience evaluation index is divided into target level, first level index and second level index. The matter element of the corresponding level can be obtained based on the valueof the evaluation index. The fuzzy and random characteristics of the cloud model are used to fuzzify the evaluation level. The value of each interval is converted into the cloud representation. The corresponding cloud parameters are determined by the index approximation method. The index correlation is then obtained from the resilience evaluation index system through the two-dimensional form of expert questionnaire survey. The correlation is exploited to identify the four first level influencing factors and 27 second level affected factors. The questionnaire of the first level index system and the second level index correlation of the safety system resilience index system of the subway construction site is then obtained. Based on the ANP model in the super decision software, the relationship between indexes under different criteria is established. According to the constructed 30 index judgment matrix, the matrix input is completed by comparing the matrix input model between two groups. The judgment matrix of the resilience index system of the field safety system is input into the super decision-making software, and its consistency is tested. The unweighted super matrix, weighted super matrix and limit matrix are obtained. In the limit matrix, the column vector is the ultimate absolute ranking of all indexes. It is the final weight ranking of all indexes of security system resilience. The second level index calculates the cloud membership degree between the actual score value of each index and the normal cloud of the resilience evaluation grade standard through the formula $\mathrm{y} = \exp\left[\frac{-(x-Ex)^2}{2(E_n^{'})^2}\right]$. MATLAB is used to calculate the membership degree of the index to the grade, and then obtain the comprehensive membership degree matrix *K*. The membership degree of the first level index to the grade can be obtained by weighting the membership degree of the second level index to the grade. The membership degree of the target layer to each resilience level can be obtained by weighting the membership degree of the first level index to the second level. According to the principle of maximum membership, if $\mathrm{k_j}(N) = \max_{\mathrm{j}\{1,2,...,m\}} \mathrm{k_j}(N)$, the resilience grade of the object *n* to be evaluated is referred to as grade *J*.

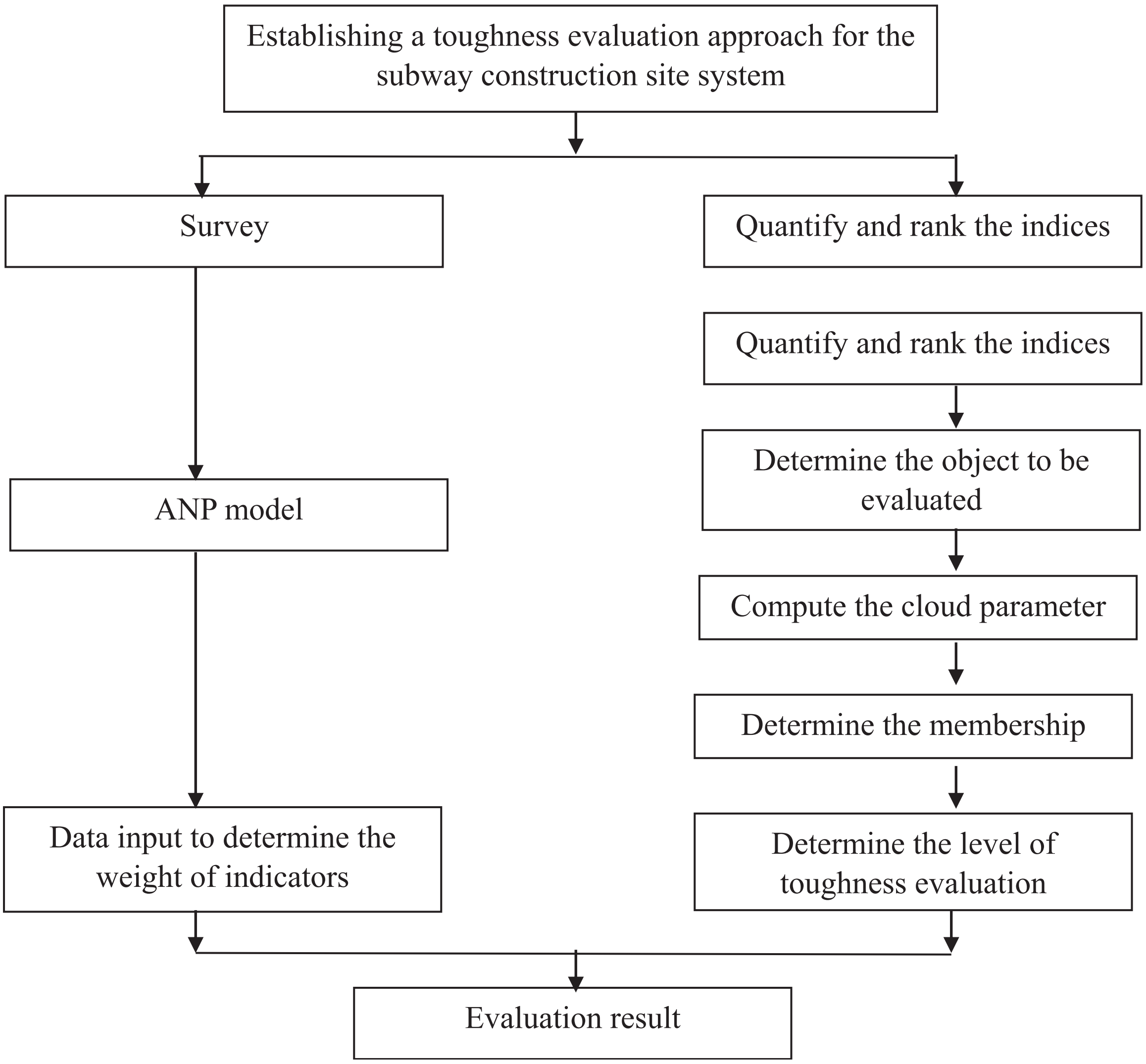


Figure 4: Flow chart of the resilience assessment at a subway construction site

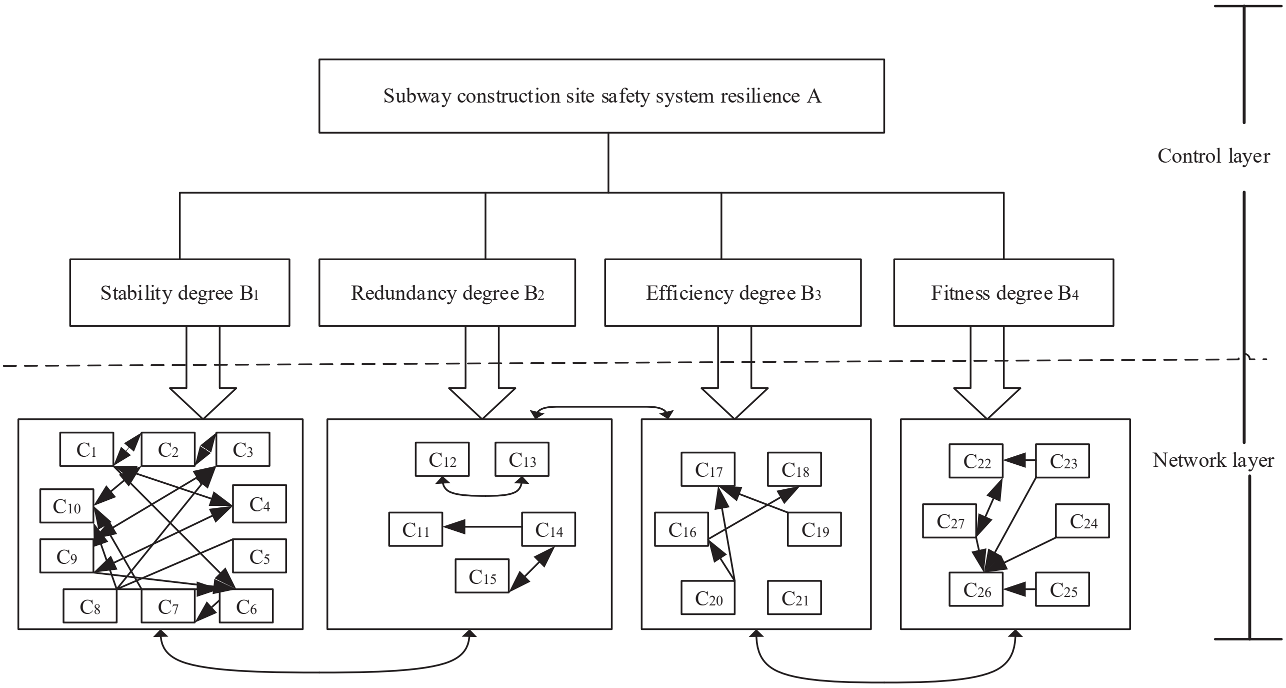


Figure 5: **ANP structure model for the resilience index system at subway construction site**

The core of the ANP is the solution supermatrix that is calculated by means of Super Decisions. The resilience index, that is the input to the judgement matrix, was constructed with a super-decision-making (Super Decisions) software developed by Rozann Satty and William Adams based on the theory of ANP to programme the calculation procedure of ANP (Figure 6) [23-24]. The resulting weighted supermatrix, limit supermatrix and index weights are given in Table 2.

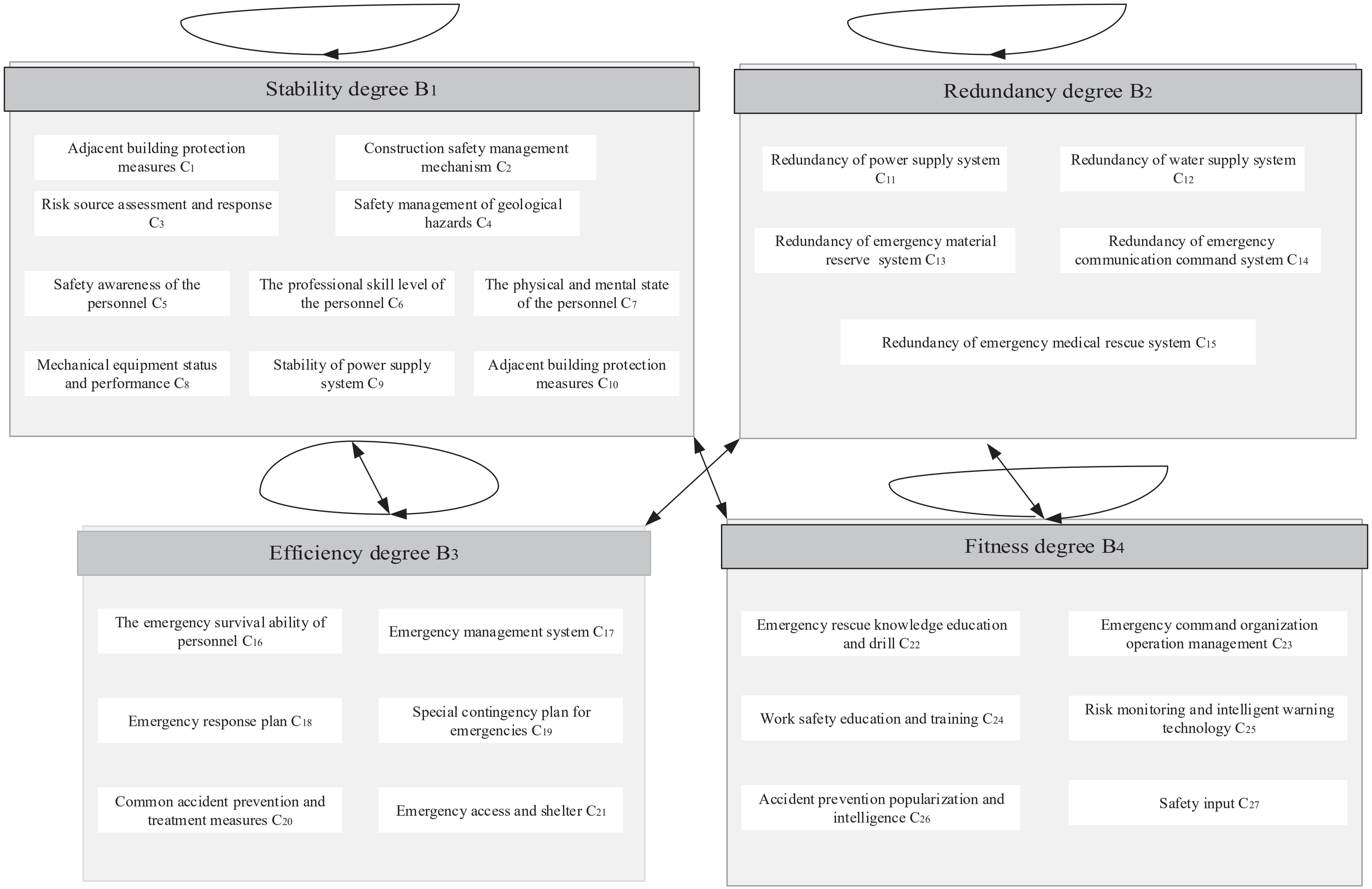


Figure 6: Modelling diagram of the resilience index system of the safety system of the subway construction site

Table 2: Weight of safety resilience assessment index for subway construction sites

Stability degree B_1	0.3857	Adjacent building protection measures (C_1)	0.0118
		Construction safety management mechanism (C_2)	0.0693
		Risk source assessment and response (C_3)	0.0299
		Safety management of geological hazards (C_4)	0.0255
		Safety awareness of personnel (C_5)	0.0737
		Professional skill level of personnel (C_6)	0.0134
		Physical and mental state of personnel (C_7)	0.0198
		Mechanical equipment status and performance (C_8)	0.0802
		Stability of power supply system (C_9)	0.0391
		Safety measures (C_{10})	0.0482
Redundancy degree B_2	0.11409	Redundancy of power supply system (C_{11})	0.0082
		Redundancy of water supply system (C_{12})	0.0102
		Redundancy of emergency material reserve (C_{13})	0.0415
		Redundancy of emergency communication command system (C_{14})	0.0362
		Redundancy of emergency medical rescue system (C_{15})	0.0224
Efficiency degree B_3	0.1821	Emergency survival ability of personnel (C_{16})	0.0523
		Emergency management system (C_{17})	0.0157
		Emergency response plan (C_{18})	0.0486
		Special contingency plan for emergencies (C_{19})	0.0227
		Common accident prevention and treatment measures (C_{20})	0.0466
		Emergency access and shelter (C_{21})	0.0064

Fitness degree B_4	0.3181	Emergency rescue knowledge education and drill (C_{22})	0.0355
		Emergency command organisation operation management (C_{23})	0.1098
		Work safety education and training (C_{24})	0.0331
		Risk monitoring and intelligent warning technology (C_{25})	0.0837
		Accident prevention popularisation and intelligence (C_{26})	0.0056
		Safety input (C_{27})	0.0108

The assessment method, developed by the extension cloud model, is a multi-index assessment method combining the cloud model with matter-element extension theory. Matter-element describes problems forming an ordered triple $R=\left(N,C,V\right)$, where N is the name of the described problems, C is the feature of problems, and V is the feature value of problems. Through extension changes, the classical and node domains were determined for the problems to be evaluated, and the correlation function and correlation degree were calculated to carry out the quantitative and qualitative assessment processes.

The fuzzy and stochastic characteristics of cloud model were used to fuzzify the boundary of assessment grades in the extended cloud model, and the values of each grade interval were converted into cloud representations. Cloud model has digital features such as expectation (E_x), entropy (E_n) and hyper-entropy (H_e). Ex reflects the point value of concept for safety resilience corresponding to grade limit, En is a measure of uncertainty that is the randomness of data collection and fuzziness of data boundaries in the process of safety resilience grade assessment and He states the degree of data dispersion of safety resilience grade assessment and the correlation between the randomness and fuzziness in assessment. The normal cloud model (Ex, En, He) replaced the fixed value of thing eigenvalue *V*, realising the mathematical description of randomness and fuzziness in the assessment process. Equation 1 represents the matter element (R_i) where *n* is the assessment object, namely the safety system resilience, $C = \{C_1, C_2, \ldots, C_n\}$ is the index set and *n* is the index quantity.

$$R_i = \begin{bmatrix} N & C_1 & (Ex_1, En_1, He_1) \\ & C_2 & (Ex_2, En_2, He_2) \\ & \vdots & \vdots \\ & C_p & (Ex_p, En_p, He_p) \end{bmatrix} == \begin{bmatrix} N & C_1 & V_1 \\ & C_2 & V_2 \\ & \vdots & \vdots \\ & C_p & V_p \end{bmatrix} \tag{1}$$

The grade intervals were artificially divided following the actual engineering conditions to form double constraint intervals $[C\,min, C\,max]$ that were used to calculate the cloud parameters (Equations 2-4).

$$Ex = \frac{C\min + C\max}{2} \tag{2}$$

$$En = \frac{C\max - C\min}{6} \tag{3}$$

$$He = \sigma; \tag{4}$$

where $He = 0.1$ in the situation.

The membership degree between the matter element to be evaluated and the matter element represented by the cloud model was determined by the cloud certainty degree of corresponding value. If the secondary index value is regarded as a cloud drop, the problem can be transformed into finding the membership degree of the cloud drop representing the cloud. The calculation of correlation function in the extension assessment method was converted into membership calculation based on the cloud model. The calculation steps are: (1) estimate the cloud parameters (Ex, En, He) using Equations 2, 3 and 4; (2) generate normal random numbers En with expectation Ex and standard deviation He; (3) calculate the membership degree of each grade corresponding to cloud droplets, $y = \exp\left[\frac{-(x-Ex)^2}{2(E_n')^2}\right]$; (4) repeat the above steps *n* times ($n = 2{,}000$) with the median of all results as the final membership value.

The comprehensive membership matrix *k* was obtained using Equation 5 where $k_m(c_p)$ is the cloud membership and *P* is the number of assessment indices. The membership degree of the first-level index to the grade was obtained by weighting the membership degree of the second-level index to the grade (Equation 6). The degree of membership of the target layer to each level of resilience was weighted by the degree of membership by the first level indicator (Equation 7). The rating was estimated following the principle of maximum membership (Equations 8 and 9).

$$K = \begin{bmatrix} k_1(c_1) & k_2(c_1) & \cdots k_m(c_1) \\ k_1(c_2) & k_2(c_2) & \cdots k_m(c_2) \\ \vdots & \vdots & \vdots \\ k_1(c_p) & k_2(c_p) & \cdots k_m(c_p) \end{bmatrix} \tag{5}$$

$$\mathrm{K}(\mathrm{b_i}) = \{\mathrm{w}_{c1}', \mathrm{w}_{c2}', \ldots, \mathrm{w}_{cn}\} \bullet \begin{bmatrix} \mathrm{k}_1(c_1) & \mathrm{k}_2(c_1) & \cdots & \mathrm{k_m}(c_1) \\ \mathrm{k}_1(c_2) & \mathrm{k}_2(c_2) & \cdots & \mathrm{k_m}(c_2) \\ \vdots & \vdots & & \vdots \\ \mathrm{k}_1(c_n) & \mathrm{k}_2(c_n) & \cdots & \mathrm{k_m}(c_n) \end{bmatrix} \tag{6}$$

$$\mathrm{K}(\mathrm{a_i}) = \{\mathrm{w}_{b1}', \mathrm{w}_{b2}', \ldots, \mathrm{w}_{b\varphi}\} \bullet \begin{bmatrix} \mathrm{k}_1(\mathrm{b}_1) & \mathrm{k}_2(\mathrm{b}_1) & \ldots & \mathrm{k}_m(\mathrm{b}_1) \\ \mathrm{k}_1(\mathrm{b}_2) & \mathrm{k}_2(\mathrm{b}_2) & \ldots & \mathrm{k}_m(\mathrm{b}_2) \\ \vdots & \vdots & & \vdots \\ \mathrm{k}_1(\mathrm{b}_\varphi) & \mathrm{k}_2(\mathrm{b}_\varphi) & \ldots & \mathrm{k}_m(\mathrm{b}_\varphi) \end{bmatrix} \tag{7}$$

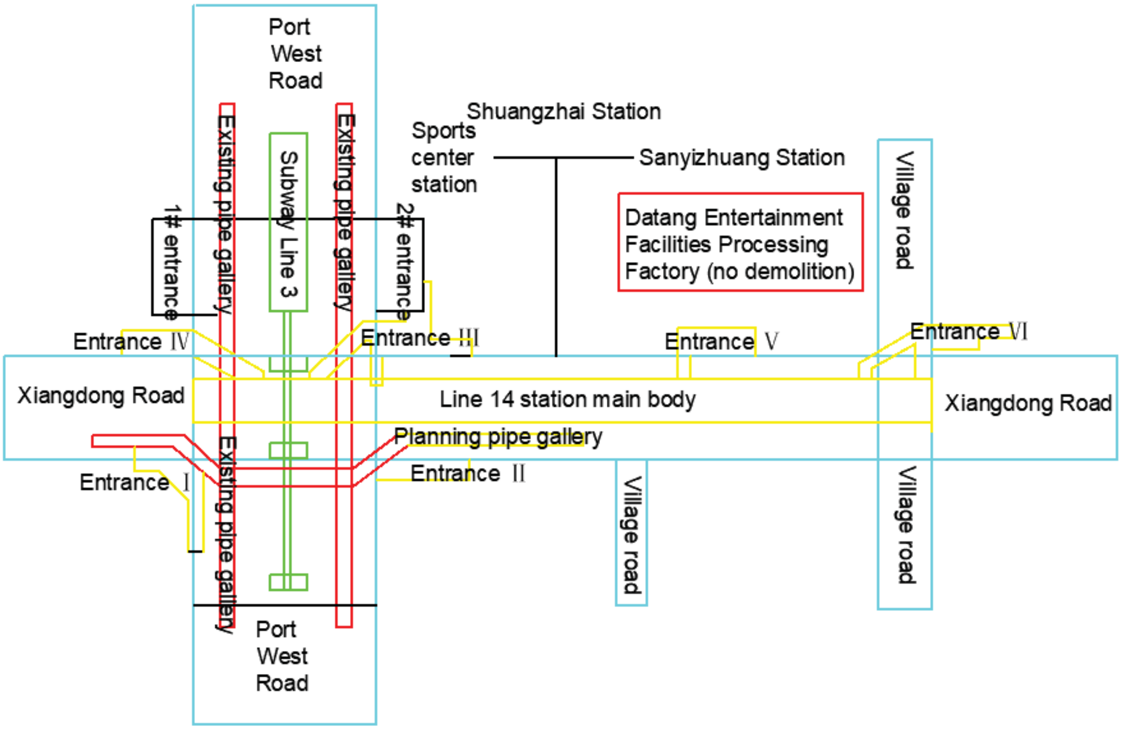
$$\overline{\mathrm{K}}_\mathrm{j}(\mathrm{N}) = \frac{\mathrm{K_j}(N) - \min_\mathrm{j}\mathrm{K_j}(N)}{\max_\mathrm{j}\mathrm{K_j}(N) - \min_\mathrm{j}\mathrm{K_j}(N)} \tag{8}$$

$$\mathrm{j}^* = \frac{\sum_{\mathrm{j=1}}^{\mathrm{m}} \mathrm{j} \bullet \overline{\mathrm{K}}_\mathrm{j}(N)}{\sum_{\mathrm{j=1}}^{\mathrm{m}} \overline{\mathrm{K}}_\mathrm{j}(N)} \tag{9}$$

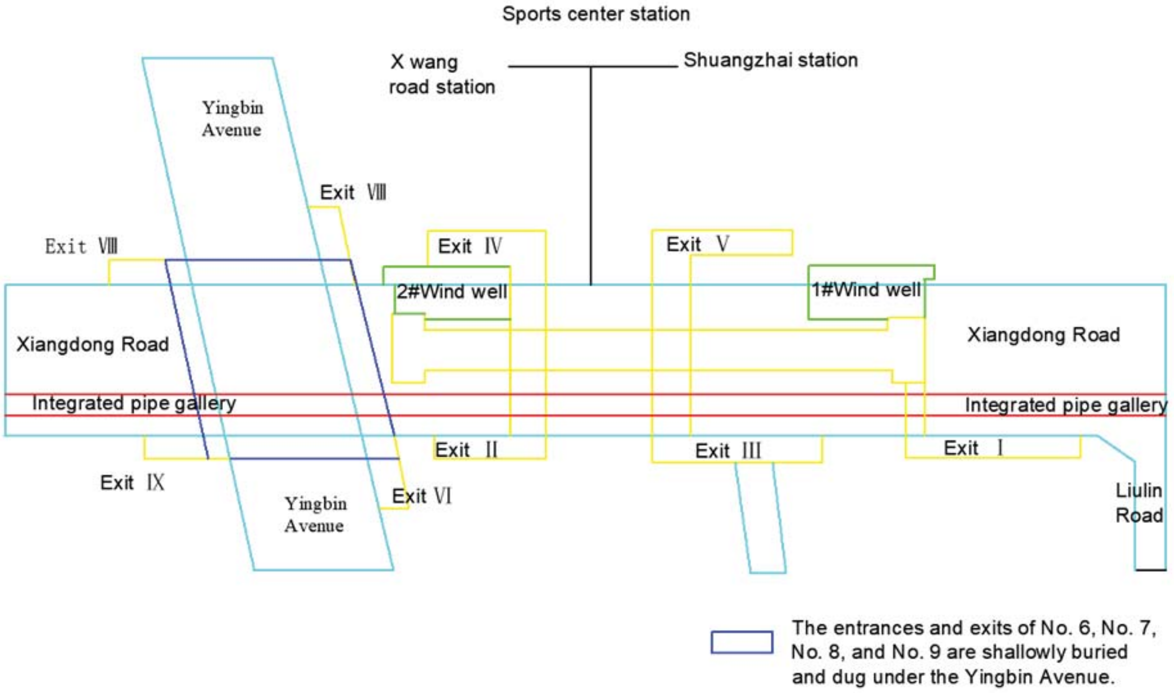
where, $K(ci)$ is the comprehensive membership matrix of second-order index to resilience grade; w_{ci} is the weight vector of secondary index; $K(bi)$ is the comprehensive membership matrix of first-level indicator to resilience level; w_{bi} is the weight vector of first-level indicator; and j^* is the characteristic value of safety resilience for subway construction sites.

4. Case application

The Xi'an Metro Line 14 project connects Weiyang District, Chanba district and international port area. The project starts from the open excavation section (not included) of the distribution line behind the North Station of airport line and is constructed along the avenue between the Xuefu road and Xiangdong road. The total length of the project is 13.8 km comprising of eight stations and three sections. The case study considered in this paper is the Section 2 of the general contracting of the first phase of the Xi'an Metro Line 14 (North Railway Station ~ Heyi Village). The Section 2 is 6.552 km long from Xinwang Road Station (excluding) to Gangwu Avenue Station (excluding) and comprises 3 stations such as Shuangzhai, Sports Centre and Sanyizhuang Stations. The resilience of the safety system is assessed for Shuangzhai, Sports Centre and Sanyizhuang Stations (Figure 7).

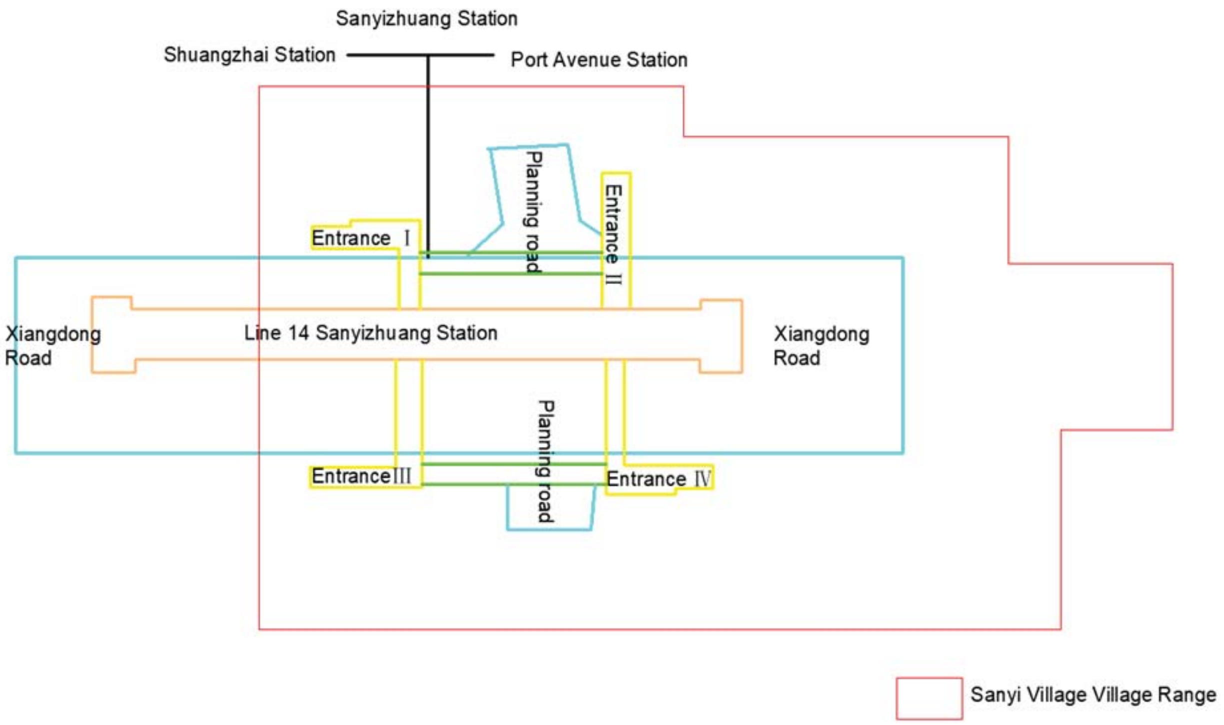


(a) Shuangzhai Station



The entrances and exits of No. 6, No. 7, No. 8, and No. 9 are shallowly buried and dug under the Yingbin Avenue.

(b) Sports centre station



(c) Sanyizhuang Station

Figure 7: Situation plan of selected stations

The safety resilience at subway construction sites was divided into three resilience levels: high (level 1), moderate (level 2) and low (level 3) (Table 3). The resilience levels were assigned to the assessment indicators of the safety system at subway construction sites by combining the expert opinions in construction industries (Table 4).

The standard normal cloud model of each assessment index was obtained by using Equations 2-4 that is the resilience level limit of each assessment index (Table 4). MATLAB programming was used to draw the indicator level cloud map combining the extension cloud model generation algorithm and the indicators data in Table 4. Figure 8 shows the resilience rating assessment standard cloud map for the C_1 and C_2 indicators. The cloud parameters and membership matrix of the safety system for each station were calculated. Table 5 shows the resilience secondary assessment indicators and membership degree of safety system at the construction site of Shuangzhai Station. The membership degrees of the first level indicators and the target layer were estimated using Equations 5-7 (Table 6). The principle of maximum membership states the resilience level of the safety system (*N*) that belongs to level *j* as $k_j(N) = max_{j\ =\ \{1,2,\ldots,m\}} k_j(N)$. The resilience level of the safety system at the construction site of Shuangzhai Station in Xi'an Metro Line 14 is Grade 1 (high resilience) considering $\max_{j = \{1,2,3\}} \mathrm{K}_j(N) = \mathrm{K}_1(N)$. A resilience eigenvalue ($j^*=1.47$) was obtained using Equations 8 and 9 for the construction site of Shuangzhai Station. The resilience assessment results for the other two stations (Sports Centre and Sanyizhuang) were obtained following the same procedure (Table 7).

Table 3: Resilience rating of safety system at subway construction site

Resilience	level	Level description
Level 1	High	The system has good resilience, coping ability and ability to withstand risk or accident. It can quickly take effective emergency rescue activities in the aftermath of the event. In addition, the system has good recovery and adaptability and can restore the system at a safe state within a short period.
Level 2	Moderate	The system has resilience, coping ability and emergency rescue capability towards risk or accident, but the affordability is low. In addition, the system has good recovery and adaptability and can restore the system at a safe state within a certain period.
Level 3	Low	The system has poor resilience, coping ability, emergency rescue capability and affordability towards risk or accident. It can quickly take effective emergency rescue activities in the aftermath of the event. The system has insufficient recovery and adaptability and requires a long period to be restored to a safe state.

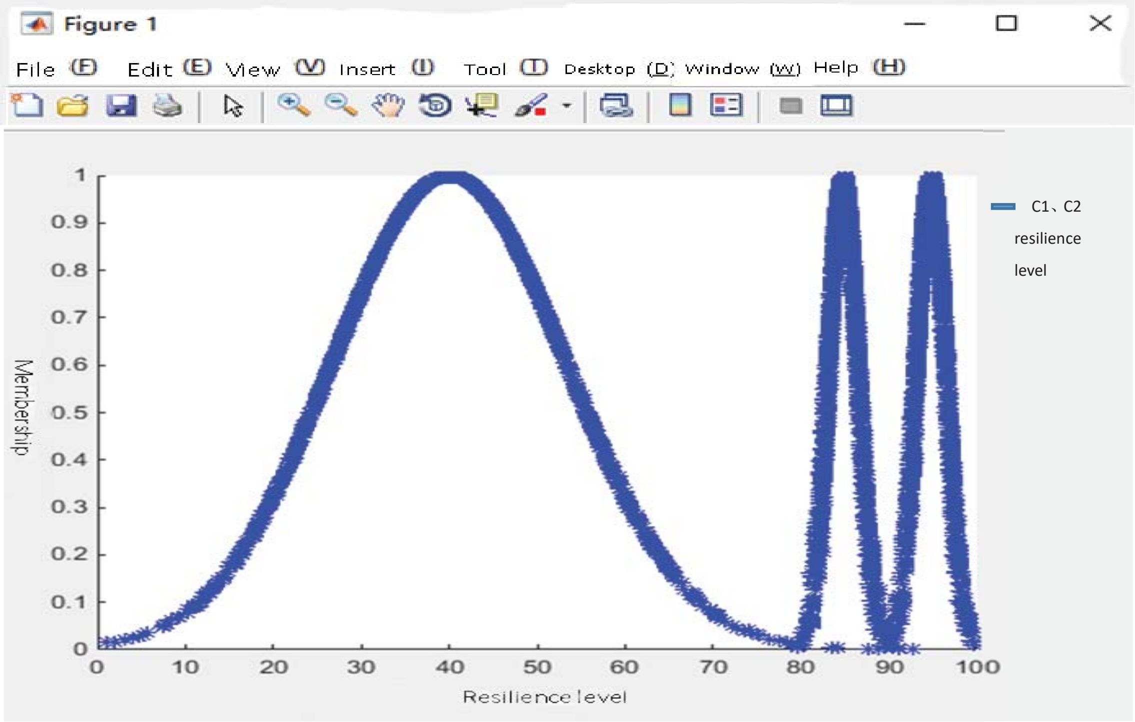


Figure 8: Resilience rating assessment standard cloud map for C_1 and C_2 indicators

Table 4: Level limits of resilience assessment index and assessment index level boundary cloud model for the safety system of subway construction site

Grade boundary cloud model	Level limits of resilience assessment index			Assessment index level boundary cloud model		
	High	Moderate	Low	Cloud1 (High)	Cloud2 (Moderate)	Cloud3
Adjacent building protection measures C_1	(100,90]	(90,80]	(80,0)	（95，1.67，0.1）	（85，1.67，0.1）	（40，13.3，0.1）
Construction safety management mechanism C_2	(100,90]	(90,80]	(80,0)	（95，1.67，0.1）	（85，1.67，0.1）	（40，13.3，0.1）
Risk source assessment and response C_3	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）
Safety management of geological hazards C_4	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）
Safety awareness of personnel C_5	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）
Professional skill level of personnel C_6	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）
Physical and mental state of personnel C_7	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）
Mechanical equipment status and performance C_8	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）

Stability of power supply system C_9	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）
Safety measures C_{10}	(100,90]	(90,80]	(80,0)	（95，1.67，0.1）	（85，1.67，0.1）	（40，13.3，0.1）
Redundancy of power supply system C_{11}	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）
Redundancy of water supply system C_{12}	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）
Redundancy of emergency material reserve C_{13}	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）
Redundancy of emergency communication command system C_{14}	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）
Redundancy of emergency medical rescue system C_{15}	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）
Emergency survival ability of personnel C_{16}	(100,90]	(90,80]	(80,0)	（95，1.67，0.1）	（85，1.67，0.1）	（40，13.3，0.1）
Emergency management system C_{17}	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）
Emergency response plan C_{18}	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）
Special contingency plan for emergencies C_{19}	(100,85]	(85,75]	(75,0)	（92.5，2.5，0.1）	（80，1.67，0.1）	（37.5，12.5，0.1）

Table 5: Resilience secondary assessment indicators and membership degree of safety system at the construction site of Shuangzhai Station

Secondary indicators	Score value	Weights	High resilience	Moderate resilience	Low resilience
Adjacent building protection measures C_1	90	0.01183	0.0113	0.0115	0
Construction safety management mechanism C_2	78	0.06925	0	0	0.0169
Risk source assessment and response C_3	78	0.02986	0	0.4882	0.0053
Safety management of geological hazards C_4	90	0.02545	0.6065	0	0
Safety awareness of personnel C_5	78	0.07365	0	0.4882	0.0053
Professional skill level of personnel C_6	96	0.01335	0.3753	0	0
Physical and mental state of personnel C_7	90	0.01980	0.6065	0	0
Mechanical equipment status and performance C_8	80	0.08022	0	0	0.0306
Stability of power supply system C_9	86	0.03905	0.0340	0.0016	0
Safety measures C_{10}	86	0.04820	0.0340	0.8370	0.0025
Redundancy of power supply system C_{11}	88	0.00818	0.1979	0	0
Redundancy of water supply system C_{12}	87	0.01021	0.0889	0	0

Redundancy of emergency material reserve C_{13}	77	0.04145	0	0.1992	0.0068
Redundancy of emergency communication command system C_{14}	86	0.03623	0.0340	0.0016	0
Redundancy of emergency medical rescue system C_{15}	82	0.02240	0	0.4882	0.0018
Emergency survival ability of personnel C_{16}	80	0.05233	0	0.0109	0.0108
Emergency management system C_{17}	86	0.01568	0.0340	0.0016	0

Table 6: The first-level assessment indicators of the resilience of the safety system at the construction site of the Shuangzhai Station and the calculation of the membership degree of the target layer

First-level indicators	Weights	High resilience	Moderate resilience	Low resilience	Level
Stability degree B_1	0.385690	0.035554559	0.091075507	0.00429416	2
Redundancy degree B_2	0.114087	0.003758311	0.019250488	0.00032218	2
Efficiency degree B_3	0.182099	0.056073261	0.000595485	0.000565164	1
Fitness degree B_4	0.318124	0.054855665	0.002907224	0.004651704	1
Target layer		0.041803601	0.038356438	0.003275706	1

Table 7: Summary of the resilience level and actual project assessment of the safety system on the construction site of Xi'an Metro Station.

Station	Resilience level	Resilience level eigenvalue	Level description	Xi'an Metro Line 14 Phase I Project Engineering Assessment Score
Shuangzhai Station	Level 1	1.47	High resilience	85.3
Sports center station	Level 2	1.76	Moderate resilience	62.5
Sanyizhuang Station	Level 2	1.77	Moderate resilience	65.5

5. Analysis and Discussion

A comparison between the characteristic values of the resilience grade and the Engineering Assessment Score is shown in Figure 9. The assessment of the first phase of the Xi'an Metro Line 14 is a comprehensive assessment score for the safety, quality, schedule and environmental protection of the construction site. The engineering assessment score reflects the safety status, resilience assessment result and actual engineering assessment score at the construction sites. The rationality and effectiveness of the resilience assessment can be verified and the relationship between the safety resilience and safety state can be reflected by this comparison. Figure 9 shows that the level of resilience is consistent with the actual engineering project assessment justifying the effectiveness of the resilience assessment. The assessment value of the construction site at the Shuangzhai Station ranks first amongst the three stations followed by construction sites at Sanyizhuang and Sports Centre stations. The findings of Figure 9 argue for strengthening the resilience management, initiating necessary measures to optimise and improve the resilience of the safety system, and to enhance the defence ability and anti-risk level at the construction sites of Sanyizhuang and Sports Centre stations.

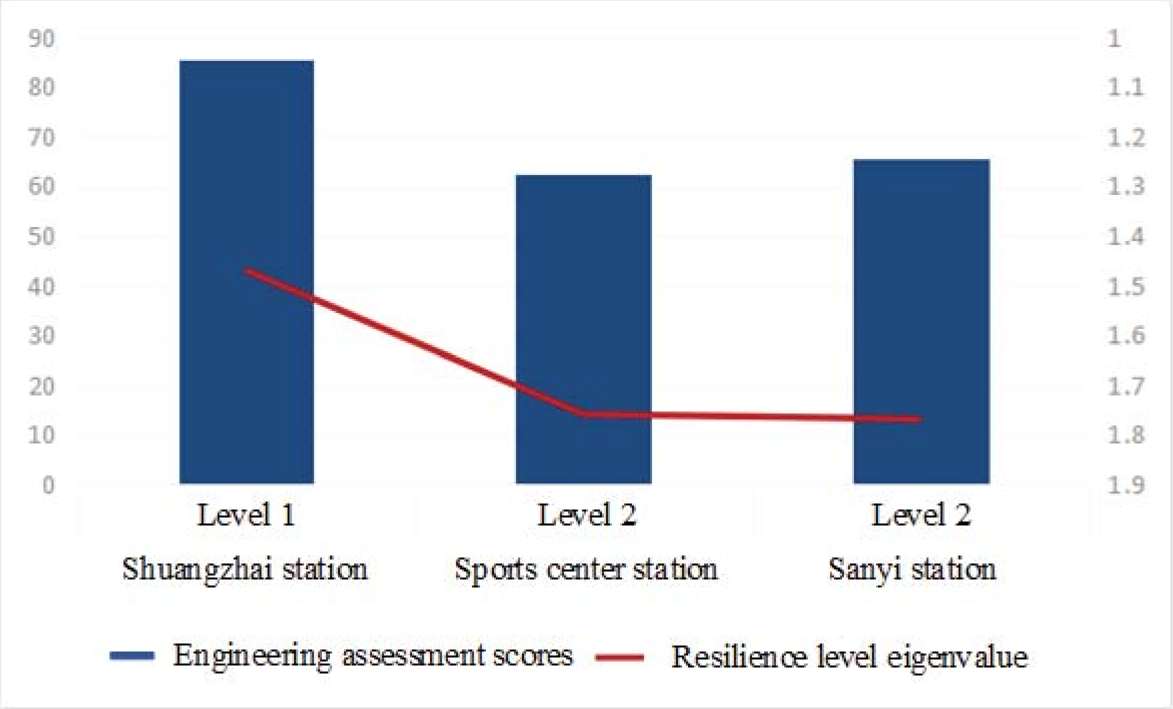


Figure 9: Comparison of the resilience level eigenvalue and engineering assessment

scores of the safety system of the construction site of Xi'an Metro Stations

This paper proposes to optimise the resilience and improve strategies addressing three aspects of resilience, namely information technology assurance, organisational security and mechanism assurance. This approach should improve the system's self-repair and adaptive capacity together with the system's recovery and rapid response capacity (Figure 10). The information technology assurance provides decision support system (DSS) for decision makers by integrating, analysing and processing the actual data, knowledge and model. It improves the efficiency and quality of DSS by providing scientific decisions applicable to the construction environment at the subway construction sites. The five main modules included in the DSS of the subway construction sites are:

(1) *User management and help module*: the DSS is an intelligent decision-making platform for subway project managers and decision makers. It suggests necessary pre-control measures and emergency strategies when risks, accidents, disasters or adverse events occur. The user management of the decision support platform can improve the efficiency of the project management and ensure the orderly progress of decision management.

(2) *Risk monitoring and early warning module*: Risk monitoring is a crucial step in subway construction engineering. It is necessary to identify, monitor and warn the risk of the construction sites to ensure that the system remains in a safe state. The decision-making platform for the subway construction sites stores and analyses the risk monitoring data obtained from various information sources and information transmission equipment. It then gives early warning to the risk monitoring system in the presence of an early warning level.

(3) *Emergency plan and rescue module*: This module was developed to analyse the causes of emergency, the successful treatment of the emergency response plan and the rescue measures. The hidden danger and accident risks are explored. Then the emergency plan and rescue

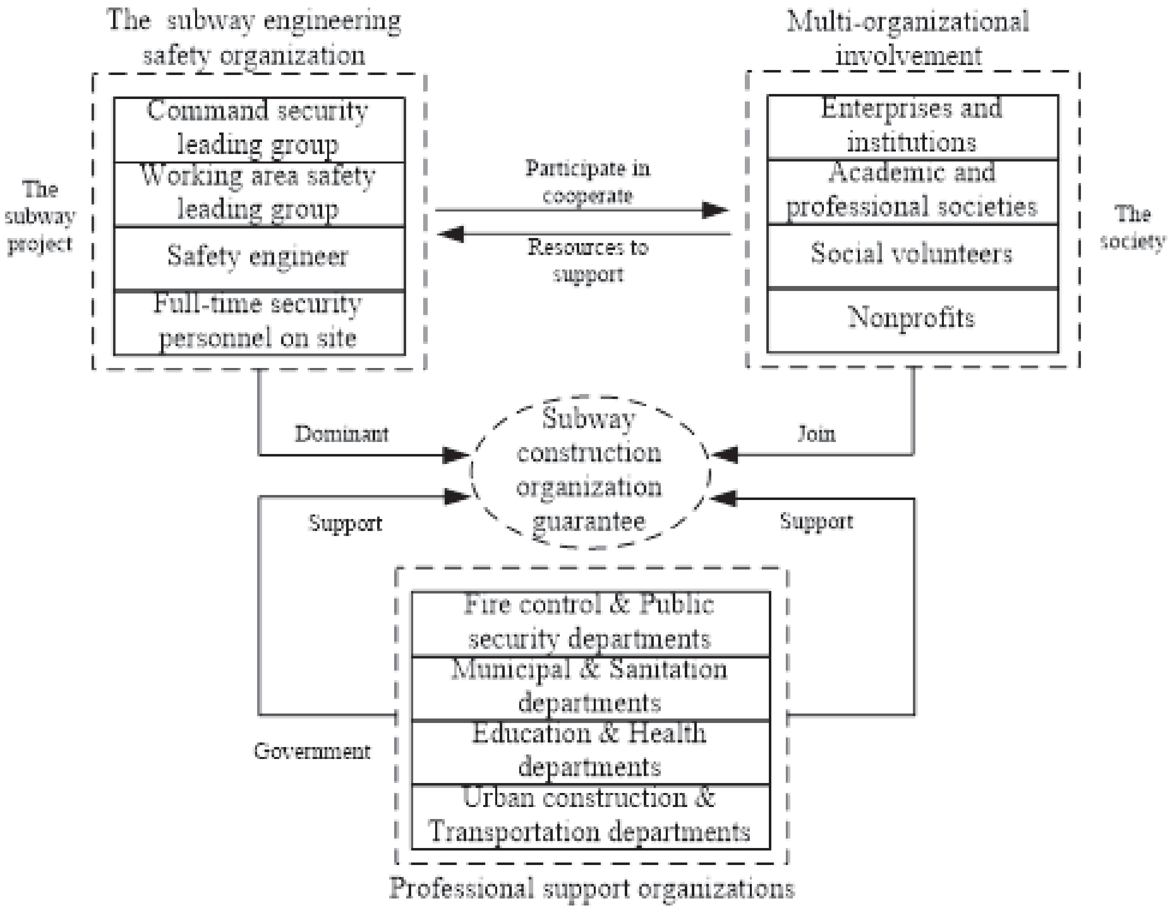
operations are referred in association with mining rules based on the knowledge of accidents and emergency cases.

(4) *Decision support module*: This module is based on various information bases in the database system. It plays two roles. First, it provides data support for risk monitoring, early warning module, emergency plan and rescue module. Second, it provides data information for decision support module based on knowledge reasoning. The decision support module deals with the problems associated with early warning and rescue decision, supported by multi-directional resources.

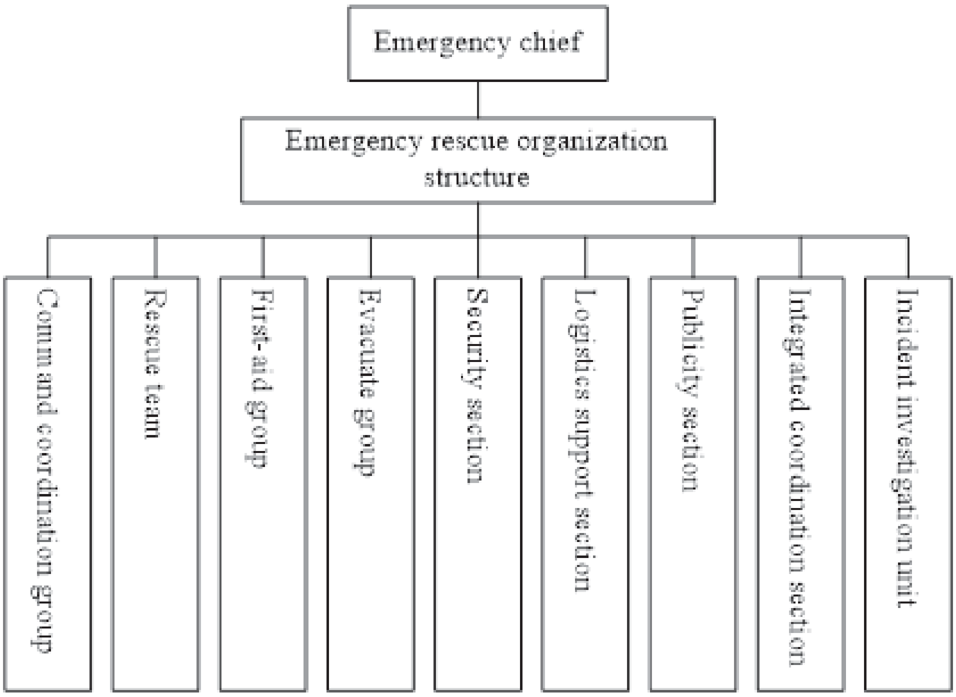
(5) *Integrated query module*: This module provides the integrated query and retrieval functions. It calculates the values of early risk warning and compatibility of emergency plan, selects the optimal solution and provides the visualisation of comprehensive counter measure query function.

Figure 10: Composition of safety resilience optimisation and promotion strategy at subway construction sites

The safety resilience of subway construction sites focuses on the prevention ability as well as the response and recovery during and in the aftermath of the event. However, the organisational internal coordination and external cooperation with multiple stakeholders play a pivotal role in the improvement of safety resilience (Figure 11). The organizational guarantee strategy for the optimisation and the improvement of the safety resilience includes the external and the internal organisational structures at the subway construction sites. The external organisational structure involves multi-attribute and multi-participant society, and a tripartite organisation including subway engineers, society and government. The three parties will form an interconnected strategic structure of subway engineering organisation through participation, appropriate resource support and lead support (Figure 11a). The organisation at the subway construction site coordinates efficiently the expanding relief activities at the construction sites, reduces the recovery time of the system, and operates the emergency rescue operations. In summary, the safety resilience system at the subway construction sites emphasises the principle of disaster prevention and evacuation by risk identification, preventive measures, early warning, evacuation principles through the emergency management ability of managers and staff. The construction organisations should promote the subway engineering management mechanism and build the resilience mechanism for optimisation and security policy (Figure 12).



(a) Strategic structure for external organisation



(b) Strategic structure for internal organisation

Figure 11: Organisational guarantee strategy for subway construction site

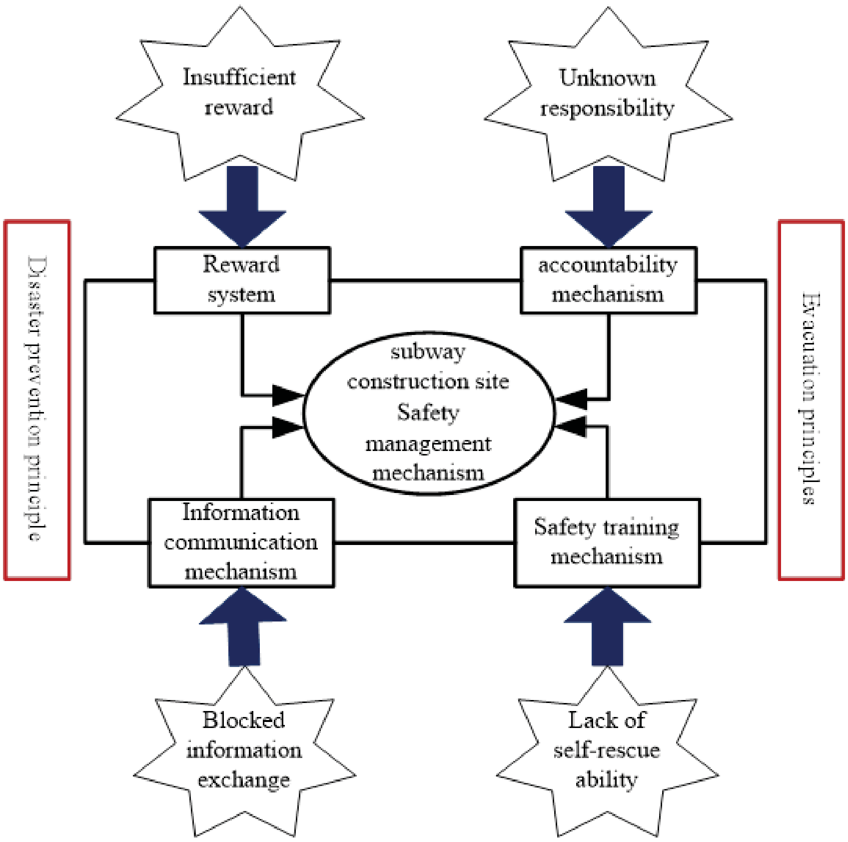


Figure 12: Function diagram for the safety management mechanism for a subway construction site

6. Conclusions

Frequent accidents occur in subway construction sites in China. The resilience of the safety system, at subway construction sites, refers to the maintenance, absorption, response or recovery process of the entire system when the subway faces unknown risk impacts or disturbances during the construction process. Safety resilience can enhance the coping ability and adaptability and reduce the accident occurrences and recovery times. This paper applied resilience theory to the safety management of subway construction engineering. It analysed the resilience connotation applicable to the safety system and evaluated the system resilience in terms of resilience indices. The method was applied to the Shuangzhai, Sports Centre and Sanyizhuang Stations at Section 2 of Xi'an Metro Line 14 (North Railway Station ~ Heyi Village) .

The Delphi method determined the resilience indicators and the ANP extension cloud synthesis was constructed combining cloud and matter-element extension models to address the randomness and ambiguity of the resilience assessment process at the subway construction sites. The comparison of the resilience characteristics and the engineering assessment of the construction sites at the three stations revealed that the resilience level is reliable and consistent with actual engineering project assessment. The assessment value of the Shuangzhai Station project ranks first followed by that of the Sanyizhuang and the Sports Centre stations. The findings of this study argue for strengthening the resilience management, taking measures to optimise and improve the security system, enhancing the defence ability and anti-risk mechanisms at the construction sites of the sports centre and the Sanyizhuang stations.

This paper introduces the resilience theory integrating cloud and matter-element extension models in the safety assessment of subway construction projects. This is a new perspective for safety management. The traditional risk management approach was transformed into a resilience management perspective that provides a theoretical basis for future research in the field of subway construction engineering and reference for the safety management of subway engineering. In addition, the ability of safety management and comprehensive emergency response at subway construction sites were improved and optimised through three aspects of guarantee strategies.

This study was carried out based on the risk impact and disturbance faced by subway engineers. There are no clear limits on a specific accident, disaster or adverse event that may be suffered. This work can be exploited by future studies to evaluate the performance process and regularity of the safety resilience at subway construction sites in the context of specific accidents or disasters. The resilience assessment index requires to integrate interdisciplinary connotation and practical engineering research characteristics. The resilience assessment indices are elaborated and evaluated qualitatively urging for quantifiable indicators to increase the operability of the assessment process.

Data availability statement

All data, models, and code generated or used during the study appear in the submitted article.

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