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Fuzzy Mathematical Method Based Comprehensive Security Evaluation Model of the Railway Operating Tunnel

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Abstract: The railway operating tunnel security evaluation is the chief problem in the tunnel operation and management. There are many factors affect the railway tunnel security. And there are great harms in the safety incidents. So the heart of ensuring operational safety is to establish effective security risk evaluation model in the security monitoring. The fuzzy mathematical method was used in this study to estimate the railway operating tunnel security evaluation index and construct the evaluation index system. On the basis of the main factors that affect the railway operating tunnel security, this study classified the main parameters according to the corresponding indexes. Furthermore, it proposed the railway operating tunnel security evaluation model and method which combined the qualitative and quantitative analysis together. The study considered the security evaluation indexes weight by the expert evolution method. Then it gave the security level standard for the evaluation result. Compared with the existing railway security evaluation method, this fuzzy comprehensive evaluation model can better reflect the actual situation to the railway tunnel. And the model has high reliability and accuracy.

Key words: Fuzzy mathematical method, railway tunnel, security evaluation, expert evaluation method

INTRODUCTION

By the end of 2009, there were 7573 railway tunnels in operation in the whole railway lines in China. The overall length of the railway tunnels was approximately 5148 km. And the length of the total tunnels with the length longer than 5 km was about 18% of the overall length. There were 18 tunnels longer than 10 km. The tunnels longer than 20 km are the Wushaoling Tunnel in Lan-Xin Railway, the Taihangshan Tunnel in Shi-Tai Railway, etc. (Zhang, 2012). There were 3739 disqualified tunnels because of the disease. They were 49.4% of the total operating railway tunnel in China. Some of them had serious disease which had been endangered the traffic safety (Yang and He, 2008). The railway department should do security evaluation systematically on the railway in time. The aim is to make it clear the security situation of the operating tunnels and the tunnel disease and deficient in its operation. Furthermore, the tunnel security levels are evaluated to provide basis for the railway safety operation (Diamantidis *et al*., 2000).

The railway operating tunnel security evaluation is the safety assessment for the overall security of the operating railway tunnels. The researches on the railway tunnel security evaluation at home and abroad are mainly concentrated on the tunnel construction period. The researchers did most work on the safety design of the tunnel structure, the security evaluation on the tunnel construction safety and construction methods, etc. Only a few researches were the security evaluation of tunnel operation. And the contents were limited to a single aspect. So it is necessary to establish the railway operating tunnel security comprehensive evaluation system for the railway tunnel operation state (Yang, 2000). The fuzzy mathematical method was used in this study to estimate the railway operating tunnel security evaluation index and construct the evaluation index system. On the basis of the main factors that affect the railway operating tunnel security, this study classified the main parameters according to the corresponding indexes. Furthermore, it proposed the railway operating tunnel security evaluation model and method which combined the qualitative and quantitative analysis together. It provides theoretical guidance for the railway tunnel security.

COMPREHENSIVE EVALUATION OF THE RAILWAY OPERATING TUNNEL SECURITY

The definition of the railway tunnel security: The railway tunnel security evaluation is one of the important contents of the railway security system project. The aim is to realize the overall railway safety. It uses the systems

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engineering method to do comprehensive evaluation and forecast for the risks existing in the railway tunnels. According to the risk size in the railway tunnel, corresponding safety measures are adopted to achieve system safety. The railway tunnel security evaluation is the important part of the modern high-speed railway safety production. It actively promotes the modernization and scientific of the security management (Zhang, 2007).

Different from the railway tunnel routine security management and the railway tunnel security supervision and inspection, the railway tunnel security evaluation is on the basis of the negative effect taken by the technology. It analyzes, demonstrates and evaluates the feasibility, incidence, severity and the adopted countermeasures of the loss and damage. Its significance lies in that it is helpful to improve the enterprise security management level.

At present, it is mainly dependent on the investigation and on-site inspection by the experienced technical staff. Then it develops the treatment programs by experience and checking the original design. The diagnosis for the railway tunnel security is stochastic and subjective. So it is important and imperative to develop qualitative and quantitative method to do comprehensive evaluation on the railway operating tunnel security. This study adopted the fuzzy mathematical method to do the comprehensive railway operating tunnel security. The flow chart of the railway operating tunnel security comprehensive evaluation is shown as the Fig. 1.

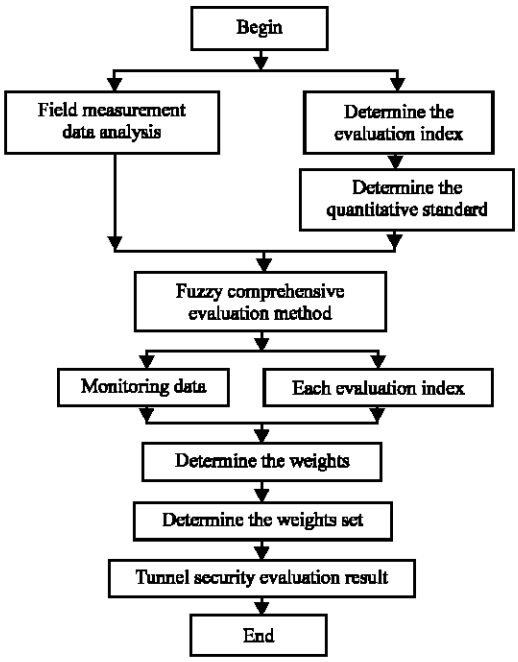

Fig. 1: Comprehensive evaluation flowchart of the railway operating tunnel security

The tunnel security evaluation index system: The key point of the entire evaluation system is the definition the evaluation index. It is also the premise to obtain the real objective results. There are many factors that infect the railway operating tunnel security. According to the principles of the conciseness, scientificity, hierarchy, independence and maneuverability, the selection of the evaluation index must be on the basis of correct analysis on the railway tunnel structure security. The selected index should maximum reflect the influence of various factors and fully reflect the railway tunnel security. So this study analyzed railway tunnel security related disciplines. It also considered ⟨⟨Railway Operating Tunnel Lining Safety Rating Interim Provisions⟩⟩ and ⟨⟨Railway Tunnel Equipment Deterioration Evaluation Standard--Tunnel⟩⟩ in China. The tunnel is the structural system composed by the interacted surrounding rock and the supporting structure. The tunnel security is not only related to the defects and lining cracks formed in the tunnel construction process, the original engineering geology and hydrogeology, structural design and construction technology and etc, but also the surrounding rock deterioration, lining crack caused by the load variation, lining material deterioration by the percolation water and frost heaving, space deficiency caused by fast lining deformation and distortion and maintenance. So this study divided the tunnel security according to the lining diseases, lining defects, rock classification, groundwater conditions, equipment failure and etc. Then it established the comprehensive evaluation index system of the railway tunnel security state. The system is shown in Table 1 (Wu *et al*., 2003).

Where, the Target is the railway operating tunnel security state U. In the criteria layer, the factors set U_i = {Lining Defects U_1, Lining Diseases U_2, Surrounding Rock Classification U_3, Groundwater Conditions U_4, Equipment Failure U_5}. The effect of Lining Defects U_1 and Lining Diseases U_2 on the railway tunnel security is obvious. So the weights of them are larger. The weights of Lining Defects U_1 and Lining Diseases U_2 were set 0.36 and 0.33, respectively. The Surrounding Rock Classification U_3 is the factor that checks the surrounding rock classification weather is match with the design in the construction process. It could adjust the support parameters in terms of the surrounding rock classification. The surrounding rock has no swell ability in this case. The main consideration of Groundwater Conditions U_4 is that the groundwater is non-corrosion or weak corrosion. The

Table 1: Comprehensive evaluation index system of the railway operating tunnel security

Target layer	Criteria layer	Weights	Index layer	Weights
Railway tunnel security	Lining defects U_1	0.36	Lining thickness (U_{11})	0.40
			Lining concrete strength (U_{12})	0.60
	Lining diseases U_2	0.33	Cavity behind the lining (U_{21})	0.15
			Backfill not dense(U_{22})	0.13
			Base not dense (U_{23})	0.05
			Lining leaking (U_{24})	0.06
			Lining cracks (U_{25})	0.09
			Lining displacement or deformation (U_{26})	0.07
			Clearance inadequate (U_{27})	0.08
			Lining crushing or flaking (U_{28})	0.09
			Lining corrosion (U_{29})	0.10
			Overall track bed damage (U_{210})	0.08
			Invert or backplane breakage (U_{211})	0.09
			Base bed softening, frothing (U_{212})	0.10
	Surrounding rock classification U_3	0.12	Levels U_{31}	1.00
	Groundwater conditions U_4	0.08	Development U_{41}	1.00
	Equipment failure U_5	0.11	Illumination U_{51}	0.35
			Ventilation U_{52}	0.15
			Firefighting U_{53}	0.50

equipment failure U_5 denotes the development situation of the unsafe factors and its influence on the traffic safety.

In the index layer, the factors set is $U_{in} = \{U_{i1}, U_{i2}, L, U_{in}\}$, i = 1, 2, L, 5. Where, U_{in} is the number n factors of the number i sub-factor set. For instance, the Lining Diseases index layer factor set is $U_{2n} = (U_{i1}, U_{i2}, L, U_{in})$, i = 1, 2, L, 12. There are 12 factors in it. This study made detailed study on the railway operation materials, disease investigation and observation materials, lining state detection and etc. Then it chose the weights for the main parameters affected the railway tunnel security.

The foundation of the tunnel security fuzzy evaluation factors set and the comment set: Fuzzy evaluation is the theory that realizing fuzzy information quantitative by the membership in the fuzzy mathematics. It chooses factors domain values and uses traditional mathematical methods to do quantitative evaluation on these factors. Then the evaluation conclusion is calculated. The foundation of the tunnel security fuzzy evaluation factors set and evaluation set is shown as follows:

- Assume the evaluation factors set is $U = \{u_1, u_2, \ldots, u_m\}$, the comment set is $V = \{v_1, v_2, \ldots, v_m\}$. Where, U denotes the set composed by the comprehensive evaluation factors. V denotes the set composed by the comments. Firstly, the evaluation factors u_i were evaluated to get the membership r_{ij} of evaluation grade v_j. In this way, the single factor evaluation set of the number i factor u_i was $r_i = (r_{i1}, r_{i2}, r_{i3})$. The evaluation matrix R was constructed by m evaluation factors. Accordingly, the railway operating tunnel security fuzzy comprehensive evaluation was the following fuzzy transformation B = A.R. Where, A is the fuzzy subset of u (Gong and Liu, 2007; Hu, 2004):

$$R = \begin{vmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{vmatrix}$$

- There are many factors affecting the railway operating tunnel operational safety. So the 2-layer fuzzy comprehensive evaluation model was chosen. According the constituted evaluation factor system, the factors set was $U = \{U_1, U_2, U_3, U_4, U_5\}$. Where, U_i was the number i factor of first layer. It could be decided by n elements on the second layer. That was $U_i = \{U_{i1}, U_{i2}, \ldots, U_{in}\}$, i = 1, 2, 3, 4, 5

The evaluation set is the set composed by the evaluation results according to the evaluated object. In order to reflect the railway tunnel risk occurrence probability, 5 grades are assumed. That is (level I, level II, level III, level IV, level V) = (Safe, Slightly severe, More severe, Severe, Extremely severe). It is shown in Fig. 2.

The weights of the operating tunnel security evaluation structure: There are 3 commonly used methods to determine the weights. They are the expert evaluation method, the relatively comparison method and the analytic hierarchy process. Whether the weights determined process scientific or not directly decides the correctness of the evaluation result. This study adopted the expert evaluation method to determine weights. The participating persons are experts in various aspects. They gave the weights according to their personal experience

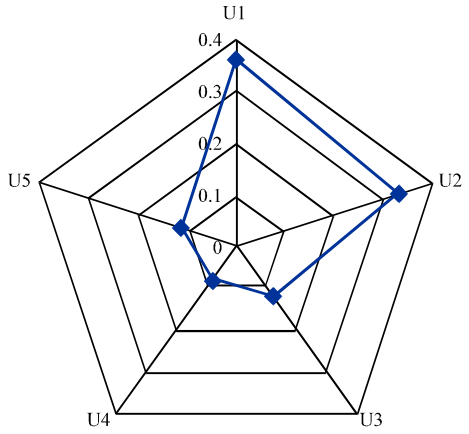

Fig. 2: The analysis on the comprehensive indexes weight of the railway tunnel security evaluation

and the specific circumstances of the construction site. This method avoids the partiality caused by the lack of experience or the personnel structure insufficiency. The tunnel security factor evaluation set (membership) was determined by the judge scoring method. 16 experts were chosen as judges from the design, construction, supervision, supervision management units to compose safety expert group. They evaluated 19 single factors on the criteria layer by the system evaluation set. The results were the evaluation set and weights. They are shown in Table 1. There are certain uncertainties of the evaluation results by the fuzzy maximum membership principle. In order to get the acceptable evaluation results, the evaluation results grade adopts the hundred mark system. The railway tunnel security grade standards are shown in Fig. 2 (Asakura and Kojima, 2003).

THE APPLICATION OF THE EVALUATION MODEL

Project description: The fuzzy evaluation model in this study was used to do comprehensive security evaluation on one railway operating tunnel in the Shanghai-Han-Rong passenger corridor. This railway tunnel is located in the junction of the central and western regions in China. It is west from Chongqing City and east end at the Lichuan City in Hubei Province.

Single factor membership matrix and the 1-lever fuzzy comprehensive evaluation: The fuzzy evaluation is realized by the single factor evaluation model, that is $B_i = WI \bullet R_i = \{b_{i1}, b_{i2}, \ldots\ldots, b_{in}\}$. Where, W is the fuzzy subset that estimates the importance degree of the evaluation set U_i. R_i is the total evaluation matrix of the k_i factors in R_i. 19 2-level factors in the 5 1-level factors are estimated by the single factor primary comprehensive evaluation. The 5 1-level factors are the lining defects, disease lining, rock classification, groundwater conditions and Equipment failure. 16 experts in the design, construction, supervision, supervision management units were invited to compose judges group. They scored the 19 2-level evaluation factors according to the security evaluation grade. The scores were normalized after the weighted average process. The result was the 1-level evaluation factors importance degree fuzzy subset.

It is shown as follow:

$$W = (0.36, 0.33, 0.12, 0.08, 011)$$

2-level fuzzy comprehensive evaluation: The sub-factors W_i of each evaluation factors and the weight distribution are shown as follows:

$$W_1 = (W_{11} \quad W_{12}) = (0.4, 06)$$

$$W_2 = (W_{21} \quad W_{22} \quad W_{23} \quad W_{24} \quad W_{25} \quad W_{26} \quad W_{27} \quad W_{28} \quad W_{29} \quad W_{210} \quad W_{211} \quad W_{212}) = (0.15, 0.13, 0.05, 0.06, 0.09, 0.07, 0.08, 0.09, 0.10, 0.08, 0.09, 0.10)$$

$$W_3 = (W_{31}) = 1.0$$

$$W_4 = (W_{41}) = 1.0$$

$$W_5 = (W_{51} \quad W_{52} \quad W_{53}) = (0.35, 0.15, 0.5)$$

The 1-level evaluation factors importance degree fuzzy subset could be got by the fuzzy comprehensive evaluation set mentioned above. By combining it with the single factor 1-level evaluation result, the 2-level evaluation matrix R was got. It is shown as follow:

$$R = \begin{vmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{vmatrix} = \begin{vmatrix} 0.29, 0.38, 0.23, 0.10, 0.00 \\ 0.22, 0.35, 0.22, 0.13, 0.08 \\ 0.25, 0.40, 0.17, 0.09, 0.09 \\ 0.27, 0.36, 0.18, 0.10, 0.09 \\ 0.25, 0.42, 0.25, 0.08, 0.00 \end{vmatrix}$$

The analysis of the evaluation results: The system was comprehensively evaluated by the 2-level fuzzy comprehensive evaluation model $B = W \bullet R$. The evaluation result was got by the maximum membership principle. It is shown as follow:

$$B = W \bullet R = (0.25, 0.26, 0.26, 0.25, 0.10)$$

It was normalized and the result was B = (0.22, 0.23, 0.23, 0.22, 0.10). According to the mean of the security grade scores in Table 2, the total score of the system evaluation was calculated. It is shown as follow:

$$B = 0.22 \times 95 + 0.23 \times 85 + 0.23 \times 75 + 0.22 \times 65 + 0.10 \times 30 = 75$$

The result was 75. So this tunnel was belonged to the security evaluation level II. The driving conditions over

Table 2: The evaluation standard of the railway tunnel security state

Scores	Technical grade	Security situation
85-100	Level I	Safe
70-85	Level II	Slightly severe
55-70	Level III	More severe
40-55	Level IV	Severe
0-40	Level V	Extremely severe

the years denoted that this tunnel was in the slightly severe state. It need be repaired and maintained in time. So the fuzzy evaluation was accordance with the actual case.

This evaluation method adopted the qualitative and quantitative combined multiple indexes to evaluate the railway operating tunnel security. It more focused on the railway lining material deterioration and added many quantitative indexes. Compared with the Chinese existing railway security evaluation method (Zhang *et al*., 2009a,b; Luo *et al*., 2006; Liu, 2006; Hui *et al*., 2008), the method in this study can better reflect the actual situation of the railway operating tunnel. It has high reliability and accuracy.

Comparison with other evaluation method: Analytic Hierarchy Process (AHP) was also used on the tunnel security evaluation. Analytic hierarchy process is a quantitative and qualitative combined method. It represents the subjective judgment by number form. This method can reduce the losses caused by subjective opinions and make the evaluation result reasonable. The existed 1-9 scale has some shortcomings in the practical applications. The maximum deviation and mean square deviation of the 10/10~18/2 scale are the smallest. So, it has the highest level of rationality. The tunnel was evaluated by the Analytic Hierarchy Process. This method founded new evaluation set to assess the tunnel security level. The result was that this tunnel was in the slightly safe state. This result approximately agreed with the result got by the fuzzy evaluation method. So the Analytic Hierarchy Process evaluation method is feasible.

For the fuzzy evaluation method, it should be noted that detailed analysis should be done on the collected railway construction and operation materials, disease investigation and observation materials, lining state detection and etc. And it need carefully choose the main parameters affected the railway security. On this basis, the evaluation model can be used to evaluate the railway safety grade. In the actual evaluation, the procedure and method of the railway examination and diagnosis, the non-destructive testing technology on the tunnel diseases, the diagnosis expert system of diseased tunnel all should be fully used to make the evaluation more objective and perfect.

CONCLUSION

The fuzzy comprehensive evaluation method has good operability and ease to use. It can get qualitative and quantitative results to do fuzzy comprehensive evaluation on the operating safety factors of the railway tunnel. The quantitative results are correspond the relevant qualitative results. The results are intuitive, scientific, reasonable and reliable.

The main factors that affect tunnel operating security could be got by the correlation analysis. Figure 2 shows that the indexes that greatly impact the operating railway tunnel security comprehensive factors weights are the lining diseases, lining defects and etc. So it should improve the tunnel construction protection level and the tunnel security level.

The regularly safety inspection and evaluation should be done on the entire tunnel operating process. The results should be feedback in time. It can provide a reference of the security problems in the tunnel operating process for the field operations managers. It can exclude the security risks in the construction process timely and effectively. The management model in the operating process can change from passive to active and preventive.

In short, this study applied the fuzzy mathematical method on the evaluation model and the 5 indexes which affected the railway tunnel operating security. This model was applied on the Shanghai-Han-Rong passenger corridor and the results accorded with the actual situation. It shows that this evaluation method and the security evaluation model have good reliability and accuracy. The evaluation method and the security evaluation model have high promotion value.

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