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Researches on a Novel Railway Tunnel Security Evaluation System and Method

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Abstract: To ensure the safety in the high-speed railway tunnel whole process, from planning, design, construction, operating to abandon, this study constructed the railway tunnel security evaluation system and method. The existing evaluation systems simply evaluate one certain phase of the railway tunnel life, without the whole process of the railway tunnel security. This paper considered the railway tunnel full life cycle security. It evaluated the security from the planning phase, design phase, construction phase, operating phase to abandon phase. The aim is to ensuring the whole process security, which are the designing security, construction security and operating security. This study adopted the Fuzzy Evaluation Method to establish the Railway Full Life Cycle Security system. The evaluation system has 31-layer factors, 192-layer factors, 683-layer factors. Applying the mathematical modelon the practical engineering, the results matched with the actual situation. The research provides a theoretical basis on the railway tunnel whole process safety.

Key words: Railway tunnel, security evaluation system, evaluation method

INTRODUCTION

With the development of the Chinese high-speed rail, China has the world's first high-speed railway mileage in nowadays. The high-speed rail train speed is increasing. The high-speed rail lines with the speed of above 200 or 300 km h^{-1} increase steadily. The high-speed rail is different from the ordinary railway. In order to satisfy the high-speed operation of the train, it must ensure a larger bend radius than the ordinary railway. During the high-speed rail construction, especially in the mountains or foothills regions, more bridges and tunnels are needed in order to lower slope and bend radius. There are many tunnels in this kind of region. Adjacent two tunnels are in two maintains. Most of the middle sections between them are valleys. In order to connect the two tunnels, the bridges are needed. Finally the bridge and tunnel connected tunnel group in the mountainous area is formed.

By the increasing of the railway tunnel projects number, many different security problems are gradually revealed. There are several links in a railway tunnel project, such as the design phase, site construction, operations and etc. In these links, any problem or in consideration would cause great losses and negative social effects. Many different factors affect the railway tunnel security system. Meanwhile, the relationships between these factors are complicated. So the data interferences greatly affect the evaluation system. The railway tunnel security is really a complex system.

During the tunnel construction process, the fatal accident rate is above 50% of the total tunnel safety accident rate. Much work has been reported in the tunnel construction process security evaluation. Little research has been conducted in the railway tunnel full life cycle security evaluation system. The system needs the evaluation of every links from plan, design, construction, to running in the whole railway tunnel life (Hong and Liu, 2011).

In the first time, this study proposed the concept of Railway Tunnel Full Life Cycle Security (RTFLCS). It is on the research of full life cycle theory. Based on the multi-level and multi-objective fuzzy optimization model, it established the railway tunnel full life cycle security mathematical model and the railway tunnel full life cycle security evaluation system. This evaluation system was used in engineering. The results were matched with actual security conditions. The evaluation system has guiding significance for the railway full life cycle safety management.

DEFINITION OF RAILWAY TUNNEL FULL LIFE CYCLE SECURITY

In 1966, the American economist Raymond Vernon proposed the product cycle theory. At first, the product cycle theory was mentioned in the International investment and international trade in the product cycle. It analyzed the product cycle and its impact on trade pattern on the basis of the production technological change.

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Raymond Vernon considered that like the living things, the products also had life cycle, which usually evolves through five different phases from origin, growth, maturity, standardization to decline (Dong, 2003).

At home and abroad, hardly any research on the full life cycle security. Most engineering evaluation of the full life cycle theory focused on the project cost. Meanwhile, the security evaluation was only the evaluation on one certain phase of the railway tunnel life. There was little material about the whole process of the railway tunnel security. The railway tunnel full life cycle security evaluation is the whole process security evaluation. It is the whole process from plan, design, construction, running, conservation management to scrap. The aim of this study is to evaluate the whole process security including design phase security, construction phase security to running phase security. According to the fuzzy evaluation theory and method, this study established the railway tunnel full life cycle security evaluation index system or model. It could supply the theoretical base for the railway tunnel whole process security.

This study improved the concept of Railway Tunnel Full Life Cycle Security (RTFLCS) in the first time. The RTFLCS is the railway tunnel whole life cycle (plan-design-construction-running-conservation management-scrap/collapse). It is shown in Fig. 1. In a word, the RTFLCS is the theory which seeks the security method in every links from plan, design, construction, running, conservation management until scrap to satisfy the optimal overall security performance in the whole railway tunnel life. The major problems of the tunnel security are the design security, construction security and running security, which are also theemphasesofthisstudy.

FUZZY COMPREHENSIVE EVALUATION MODEL

The evaluation factor set (Factors set): Evaluation factor U is the set of the comprehensive evaluation factors

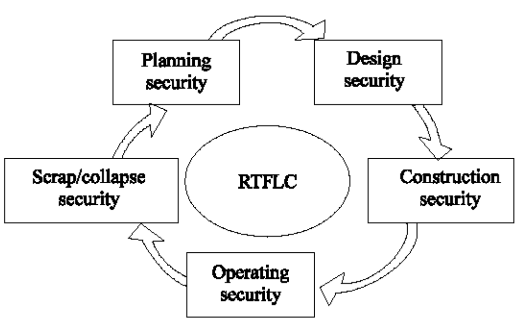

Fig. 1: Safety phases in the Railway Tunnel Full Life Cycle Security (RTFLC)

(Liu *et al*., 2007; Hu, 2004; Gong and Liu, 2007). It has the hierarchy feature. It's 1-level factors are shown as follows:

$$U = \{U_1, U_2, U_3,...U_n\}$$

The 2-level factors are:

$$U_i = \{U_{i1}, U_{i2}, U_{i3},...U_{ij}\}$$

where, U_{ij} is the number j factors in the number i criteria layer.

The remark set: The remark set is the set for the possible outcomes of all the factors. It can be graded by the experts. For the evaluation purpose, the remark set is founded as follows:

$$V = \{V_1, V_2, V_3, V_4, V_5\}\{\text{Safety, Respectively safe, Basically Safe, Less Safe, Unsafe}\}$$

Weight set: The weight set of 1-level factor is:

$$W = \{W_1, W_2...W_i\}$$

The weight set of 2-level factor is:

$$W_{ij} = \{W_{i1}, W_{i2}...W_{ij}\}$$

ESTABLISHMENT OF THE RAILWAY TUNNEL SECURITY EVALUATION INDEX SYSTEM

The core of the entire evaluation system is the definition the evaluation index, which is also the premise to obtain the real objective results. There are many factors affecting the railway tunnel security. By the principles of the conciseness, scientificity, hierarchy, independence and maneuverability, the selection of the evaluation index based on the correct analysis for whole process of the railway tunnel structure security. The selected index should fully reflect the impact degree of various factors and maximally reflect the railway tunnel security. Meanwhile, this study comprehensively considered Railway Tunnel Design Specifications, Railway Tunnel Construction Technology Guidance, Railway Tunnel Equipment Deterioration Evaluation Standard-Tunnel and Interim Provisions of the Risk Assessment and Management of Railway Tunnels in China. On the basis, the tunnel security was divided to the design security, construction security and running security. Accordingly, the classification values of the RTFLCS comprehensive evaluation index were established. Table 1 shows the design security. Table 2 shows the construction security. Table 3 shows the running security (Wu *et al*., 2003 ; Tan and Xiang, 2013; Zhang *et al*., 2009; Liu, 2006).

Table 1: Railway Tunnel Full Life Cycle Security (RTFLCS) comprehensive evaluation index (Design phase)

Target layer	System layer	Weight No.	Index layer	Weight No.	Target layer	Criteria layer
Railway tunnel full life cycle security	Design security	0.35	Terrain	0.11	Bias	1.00
					Lithology and weathering degree	0.41
			Geology	0.20	Structure (Monocline, syncline, anticline fault)	0.36
					Groundwater	0.23
					Bedding	0.27
			Adverse geology	0.21	Karst	0.35
					Coalbed and mineral goaf	0.15
					Extrusion formation	0.33
			Special rock	0.09	Swelling rock, soil, frozen soil, soft soil	1.00
			Design situation	0.16	Conventional design	0.33
					Special design	0.46
					Monitoring and measurement design	0.21
			Tunnel	0.17	Section	0.28
					Length	0.38
					buried depth	0.34
			Others	0.06	Service tunnel	1.00

Table 2: Railway Tunnel FullLifeCycle Security (RTFLCS) comprehensive evaluation index (Construction phase)

Target layer	System layer	Weight No.	Index layer	Weight No.	Target layer	Criteria layer
Railway tunnel full life cycle security	Construction security	0.4	Collapse	0.24	Excavation	0.22
					Blasting	0.25
					Supporting and lining	0.34
					Monitoring and measurement	0.19
			Water inrush	0.17	Excavation	0.17
					Blasting operation and blasting equipment	0.19
					Construction period waterproofing and drainage	0.21
					Supporting and lining	0.21
					Protection	0.12
					Monitoring and measurement	0.10
			Gas	0.12	Blasting operation and blasting equipment	0.08
					Excavation	0.09
					Uncovering coal, outburst prevention	0.19
					Ventilation	0.17
					Fire control measure	0.17
					Supporting and lining	0.09
					Protection	0.08
					Electrical equipment and working machine	0.08
					Monitoring and measurement	0.05
			Large deformation	0.18	Excavation	0.19
					Construction equipment and facility	0.21
					Blasting operation and blasting equipment	0.23
					Supporting and lining	0.24
					Monitoring and measurement	0.13
			Rockburst	0.16	Blasting operation and blasting equipment	0.21
					Excavation	0.30
					Supporting and lining	0.34
					Monitoring and measurement	0.25
			High ground temperature	0.08	Excavation	0.25
					Ventilation	0.27
					Supporting and lining	0.28
					Monitoring and measurement	0.20
			Others	0.05	Security management	1.00

Table 1 shows the Railway Tunnel Full Life Cycle Security (RTFLCS) index in the design phase. This evaluation system comprehensively considered the aspects of terrain, geology, adverse geology, special rock, design situation, tunnel and service gallery in the design process. The geological conditions decide the difficulty degree of design. So the weights of the geology, adverse geology are large. They are 0.20 and 0.21 in the table.

Table 2 shows the Railway Tunnel Full Life Cycle Security (RTFLCS) index in the construction phase. In this phase, the security evaluation index system should be established by the construction methods. The construction method evaluation system contains the mining method tunnel construction security evaluation system, tunnel opening tunnel construction security evaluation system, boring machine construction security

Table 3: Railway Tunnel Full Life Cycle Security (RTFLCS) comprehensive evaluation index (Running phase)

Target layer	System layer	Weight No.	Index layer	Weight No.	Target layer	Criteria layer
Railway tunnel full life cycle security	Running security	0.25	Lining defects	0.36	Tunnel lining thickness	0.40
					Lining concrete strength	0.60
			Lining diseases	0.33	Cavity behind the lining	0.15
					Backfill not dense	0.13
					Base not dense	0.05
					Lining leaking	0.06
					Lining cracks	0.09
					Lining displacement or deformation (Measured by speed V)	0.07
					Clearance inadequate	0.08
					Lining crushing or flaking	0.09
					Lining Corrosion	0.10
					Overall track bed damage	0.08
					Invert or backplane breakage	0.09
					Base bed softening, frothing	0.10
			Rock classification	0.12	Levels	1.00
			Ground water Conditions	0.08	Development	1.00
			Equipment failure	0.11	Illumination	0.35
					Ventilation	0.15
					Firefighting	0.50

evaluation system, shield method construction security system. Due to limited space, this study just established the index for the mining method tunnel construction security evaluation system. In this system, the conditions of the collapse, water inrush, gas, large deformation, rockburst, high ground temperature should be considered. The collapse and water inrush are the important factors causing safety misadventure. So their weights are large. They are 0.24 and 0.17 in the table.

Table 3 shows the Railway Tunnel Full Life Cycle Security (RTFLCS) index in the operating phase. In this phase, the tunnel security is determined by the lining defects, lining diseases, rock classification, groundwater conditions, equipment failure and etc. The lining defects and lining diseases are the important factors causing safety misadventure. So their weights are large. They are 0.36 and 0.33 in the table.

Railway tunnel fuzzy comprehensive evaluation

Fuzzy comprehensive evaluation factors set and remark set: There are many factors affecting the RTFLCS. So the 3-layer fuzzy comprehensive evaluation model was chosen. The calculation steps are shown as follows:

- Suppose the RTFLCS comprehensive evaluation set is U. Table 1 shows that the model adopts 3-layer fuzzy comprehensive evaluation method. The top factor set is shown as follow:

$$U = \{U_1, U_2, U_3\}$$

- The sub-factors sets U_{ij} of evaluation factors are shown as follows:

$$U_1 = \{u_{11}, u_{12}, u_{13}, u_{14}, u_{15}, u_{16}, u_{17}\}$$
$$U_2 = \{u_{21}, u_{22}, u_{23}, u_{24}, u_{25}, u_{26}, u_{27}\}$$
$$U_3 = \{u_{31}, u_{32}, u_{33}, u_{34}, u_{35}\}$$

- The sub-factors sets U_{ijk} of evaluation factors are shown as follows:

$$u_{11} = \{u_{111}\}$$
$$u_{12} = \{u_{121}, u_{122}, u_{123}\}$$
$$u_{13} = \{u_{131}, u_{132}, u_{133}, u_{134}\}$$
$$u_{14} = \{u_{141}\}$$
$$u_{15} = \{u_{151}, u_{152}, u_{153}\}$$
$$u_{16} = \{u_{161}, u_{162}, u_{163}\}$$
$$u_{17} = \{u_{171}\}$$

Further more, both $\{u_{21}, u_{22}, u_{23}, u_{24}, u_{25}, u_{26}, u_{27}\}$ and $\{u_{31}, u_{32}, u_{33}, u_{34}, u_{35}\}$ can build the 3-layer sub-factors sets U_{ijk} according to Table 2 and 3.

Evaluation factors parameter weights: The weights are determined by 3 commonly used methods, which are the expert evaluation method, the analytic hierarchy process and the relatively comparison method. The correctness of the evaluation result is directly decided by whether the weights determined process scientific or not. The expert evaluation method was adopted in this study to determine weights. The participators are experts in various aspects. These experts gave the weights according to their personal experiences and the specific conditions of the construction site. The method avoids the partiality caused by the lack of experiences or the personnel structure insufficiency. The tunnel security factors evaluation set (membership) was got by the judge scoring method. There were 25 experts chosen as judges from the design, construction, supervision, supervision management units to compose the safety expert group. There were 68 single factors on the criteria layer evaluated by the system evaluation set. The results were the evaluation set, the weights, the weight distributions (A) and sub-factors (A_{ij} and A_{ijk}) of each evaluation factors. Table 1-3 show the results (Zhang *et al*., 2009; Yang and He, 2008).

The evaluation set is composed by the evaluation results according to the evaluated object. To reflect the RTFLCS, the evaluation matrix was determined by the fuzzy statistical method, binary comparison sorting method, exemplification method and expert judgment method. In this study, the RTFLCS evaluation standard has 5 grades, which are (level I, level II, level III, level IV, level V) = (Safe, Respectively Safe, Basically Safe, Less Safe, Unsafe) = (85-100, 70-85, 55-70, 40-55, 0-40).

Calculation methods:

- The factors evaluation matrix is shown as follows:

$$B_1 = A_1 \circ R_1$$

- The normalization process is shown as follows: Firstly, get the sum of judging indexes, that is:

$$b = b_1 + b_2 + ... + b_n = \sum_{j=1}^{n} b_j$$

Secondly, divide b by the original judging indexes. The divided result is B' and b'_j (j = 1 ,2 , ..., n). B' is the normalized fuzzy comprehensive evaluation set. b'_j (j = 1 ,2 , ..., n) denotes the normalized fuzzy comprehensive evaluation indexes.

- The total evaluation matrix R is:

$$R = \{B_1\ B_2\ B_3\}^T$$

- The comprehensive factor evaluation matrix is calculated as follows: The comprehensive factor evaluation matrix is got by the formula B = A·R. The fuzzy relational operation is:

$$b_j = \mathop{\vee}_{i=1}^{m}\left(a_i \wedge r_{ij}\right), \ (j = 1, 2, ..., n)$$

where, v is the finding maximum values in input or sequence of the inputs and $\wedge$ is the finding minimum values in input or sequence of inputs:

- Calculate the total score of the RTFLCS
The comprehensive factor evaluation matrix denotes the full life cycle security state. For the 5 grades evaluation, the score of each grade adopts hundred-mark system. The total score formula is shown as follows:

$$h = \varepsilon_1 b_1 + \varepsilon_2 b_2 + \varepsilon_3 b_3 + \varepsilon_4 b_4 + \varepsilon_5 b_5$$

Evaluation model engineering application examples: In order to introduce the application of the fuzzy evaluation model on the RTFLCS is explained, takea certain railway tunnel for instance. The calculation steps are shown as follows:

- The experts scored according to the RTFLCS comprehensive evaluation set (U), the weight distribution of each factor (*A*), the sub-factors of each factor (A_{ij} and A_{ijk}) and the materials and investigation of this railway tunnel in the design, construction and running phase. The evaluation matrix R_{ij} were calculated on the basis of the scores. They are shown as follows:

$$R_{11} = \{0.4, 0.3, 0.2, 0.1, 0.0\}$$

$$R_{12} = \begin{Bmatrix} 0.4, 0.5, 0.1, 0.0, 0.0, \\ 0.1, 0.6, 0.3, 0.0, 0.0, \\ 0.2, 0.4, 0.3, 0.1, 0.0 \end{Bmatrix}$$

$$R_{13} = \begin{Bmatrix} 0.1, 0.5, 0.3, 0.1, 0.0 \\ 0.3, 0.4, 0.2, 0.0, 0.0, \\ 0.2, 0, 4, 0.1, 0.1, 0.2 \\ 0.4, 0.3, 0.1, 0.1, 0.1 \end{Bmatrix}$$

$$R_{14} = \{0.8, 0.1, 0.1, 0.0, 0.0\}$$

$$R_{15} = \begin{Bmatrix} 0.6, 0.3, 0.1, 0.0, 0.0 \\ 0.7, 0.1, 0.1, 0.1, 0.0 \\ 0.6, 0.3, 0.1, 0.0, 0.0 \end{Bmatrix}$$

$$R_{16} = \begin{Bmatrix} 0.7, 0.2, 0.1, 0.0, 0.0 \\ 0.6, 0.4, 0.0, 0.0, 0.0 \\ 0.7, 0.1, 0.1, 0.1, 0.0 \end{Bmatrix}$$

$$R_{17} = \{0.6, 0.3, 0.1, 0.0, 0.0\}$$

Above mentioned R_{1j} are the evaluation matrixes of this railway tunnel in design phase. Similarly, the evaluation matrixes in construction phase R_{21}, R_{22}, R_{23}, R_{24}, R_{25}, R_{26}, R_{27} and evaluation matrixes in running phase R_{31}, R_{32}, R_{33}, R_{34}, R_{35} were calculated:

- Do normalization on the evaluation matrix of each sub-factor. The result is shown as follow:

$$B_{11} = A_{11}^T \bullet R_{11} = [0.36, 0.36, 0.18, 0.10, 0.00]$$

Similarly, B_{13}, B_{14}, B_{15}, B_{16}, B_{17}, B_{21}, B_{22}, B_{23}, B_{24}, B_{25}, B_{26}, B_{27} and B_{31}, B_{32}, B_{33}, B_{34}, B_{35} were got.

- Calculate the new evaluation matrix R_i and each factor evaluation matrix B_i:

$$R_1 = \begin{bmatrix} 0.36, 0.36, 0.18, 0.10, 0.00 \\ 0.33, 0.42, 0.25, 0.00, 0.00, \\ 0.25, 0.42, 0.25, 0.08, 0.00 \\ 0.31, 0.23, 0.23, 0.15, 0.08 \\ 0.18, 0.45, 0.18, 0.10, 0.09 \\ 0.27, 0.36, 0.19, 0.10, 0.09 \\ 0.25, 0.42, 0.25, 0.08, 0.00 \end{bmatrix}$$

Similarly, R_2 and R_3 were calculated.
By the formula:

$$B_1 = A_1^{T} \cdot R_1$$

B_2 and B_3 were got.

- The total evaluation matrix R and the comprehensive factor evaluation matrix B are shown as follows:

$$R = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} = \begin{bmatrix} 0.29, 0.38, 0.23, 0.10, 0.00 \\ 0.21, 0.39, 0.20, 0.17, 0.03 \\ 0.26, 0.39, 0.16, 0.09, 0.10 \end{bmatrix}$$

$$B = A^{T} \bullet R = [0.25, 0.35, 0.23, 0.12, 0.05]$$

- The evaluation results distributions on the 5 levels are:

$$\varepsilon_1 = 93,\ \varepsilon_2 = 81,\ \varepsilon_3 = 68,\ \varepsilon_4 = 52,\ \varepsilon_5 = 33$$

- The system total score h is shown as follow:

$$h = \varepsilon_1 b_1 + \varepsilon_2 b_2 + \varepsilon_3 b_3 + \varepsilon_4 b_4 + \varepsilon_5 b_5 = 75.57$$

The result was 75.57. According to the RTFLCS evaluation standard, this tunnel belonged to the level II. So this tunnel was in the Respectively safe state.

CONCLUSION

- The Railway Tunnel Full Life Cycle Security (RTFLCS) qualitative indicators were quantified by the fuzzy evaluation method
- According to the RTFLCS characteristics and the complex factors affected the railway tunnel security, this study established 3-layer tunnel security evaluation mathematical model. Table 1 shows that the factors in the construction phase have great influence on the evaluation results. The reason is that these factors have large weights. The evaluation results match with the actual conditions
- This mathematical model could quantitatively evaluate each phase of the tunnel. So each phase security conditions could be grasped in time. Accordingly, the security evaluation work achieves scientization, systematization and informationization. The model could supply scientific decision making service for the administration department and the superior supervision department. So this model has important actual and direct sense on the RRFLCS dynamic supervision
- Based on the whole process security evaluation of the railway tunnel, this study proposed the full life cycle security evaluation theory for the railway tunnel, which provides theoretical guidance on the whole process security management for the railway tunnel

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