Research on Overall Risk Assessment Indicator System for the Safety of Highway Tunnel Reconstruction and Expansion Construction

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Abstract: This paper focuses on studying the overall risk assessment indicator system for tunnel reconstruction and expansion in highway reconstruction and expansion engineering with a view to mitigating the impact of uncertainties in highway tunnel reconstruction and expansion construction on engineering safety, and guaranteeing safe reconstruction and expansion construction as well as reducing casualties and economic loss. Such methods as literature survey were first adopted to conduct research and thus put forward the thinking and method for risk assessment of highway tunnel reconstruction and expansion construction, and then a number of methods including questionnaire method and Delphi Method were used to establish an overall risk assessment indicator system with primary indicators including demolition scale, tunnel structure condition, construction craft for proposed tunnel and existing tunnel, geological conditions, environmental factor, buried depth of tunnel, portal features, mean annual precipitation and data integrity. Finally, with a tunnel in Fujian taken as an example, the established assessment indicator system was deployed to conduct risk assessment of highway tunnel reconstruction and expansion construction. The result of engineering case assessment showed relatively serious risk; such indicator system could serve as the basis for construction safety risk assessment of similar projects and provide reference for safety management of similar projects.

Keywords: Highway Reconstruction and Expansion; Tunnel Engineering; Overall Risk Assessment; Assessment Indicator System

1 Introduction

Highway tunnel reconstruction and expansion mean technical reconstruction and expansion of the original tunnels governed by construction standard which fails to meet traffic demand, and removal of the original tunnel structures for expansion of tunnel sections[1]. Subject to restrictions form design standard and construction level, some early tunnels were built with insufficient engineering quality in a short time, so a number of defects, including lining cracking, deformation, water seepage and leakage, concrete spalling, occurred during tunnel operation. Moreover, with the impact from

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highway line type and urban environment, the expansion of highway tunnels is more subject to a number of construction difficulties, including proximity to existing highways, large sections, small interval, tunnel group and being open to traffic during construction[2]. Tunnel reconstruction and expansion destroy the force balance in existing tunnels, thus damage to surrounding rocks accumulates, deformation occurs, supporting structures are subject to excessive force and stability is low[3], making it more difficult in tunnel reconstruction and expansion. Due to the complexity of construction, structural instability, lack of management experience, and complex environmental factors, the safety risks of tunnel renovation and expansion have greatly increased. Therefore, it is necessary to conduct a safety risk assessment for tunnel construction.

At present, China's research less focuses on risk assessment of highway tunnel reconstruction and expansion. Risk assessment is an auxiliary tool for scientific decision-making in engineering and conducive to better understanding and addressing possible uncertainties. In 2011, the Ministry of Transport developed The Guidelines for Safety Risk Assessment of Highway Bridge and Tunnel Engineering Construction (Trial Implementation) ("the Guidelines"). In 2022, the Ministry of Transport issued the industrial standard The Guidelines for Safety Risk Assessment of Highway and Water Transport Engineering Construction Part 1: General Requirements[4]. In 2024, the Ministry of Transport issued the industrial standard The Guidelines for Safety Risk Assessment of Highway and Water Transport Engineering Construction Part 3: Tunnel Engineering[5], which is applicable to new highway tunnels. All of these standards serve as the specifications and guidelines for safety risk assessment of new construction project of highway tunnel, and have vigorously promoted safety risk assessment of tunnel construction; however, these specifications still lack relevant requirements for risk assessment of highway tunnel reconstruction and expansion construction.

Based on literature surveys and site surveys, with adoption of questionnaire method, Delphi Method, among other methods, this paper focuses on studying the overall risk assessment indicator system for the safety of highway tunnel reconstruction and expansion engineering construction.

2 Research on Overall Risk Assessment Indicator System

Based on the risk assessment thinking in existing specifications and standards, overall risk assessment involving the safety of highway tunnel reconstruction and expansion construction was conducted by focusing on engineering projects or standalone main structures and operating units whose construction was assessed in terms of overall risk in light of engineering characteristics, structural state, construction environment, geological conditions, meteorological and hydrological factors, among other factors, to identify risk grade and put forward control measures and suggestions. The conclusion of overall risk assessment could serve as the decision basis for the employer's organization of project implementation, deployment of safety management force, resource allocation and selection of construction organization; its conclusion could also provide the basis for construction organization to conduct construction organization design and special risk assessment.

Based on surveys and expert discussions on highway reconstruction and expansion projects in multiple places as well as literature survey, the assessment team drew the following conclusion:

Highway tunnel reconstruction and expansion constitute one of feasible methods for boosting transport carrying capacity and service quality. The difficulties in such reconstruction and expansion are much greater than that in new construction. On the one hand, China started tunnel reconstruction and expansion late and lacks sufficient experience in reconstruction and expansion. On the other hand, as new tunnel construction is performed on the existing tunnels, the construction of the existing tunnels has disturbed the rocks and underground water in tunnel area, coupled with cumulative effects of natural disasters, engineering geology becomes more complicated[6-8]. This poses enormous difficulties to the formulation and implementation of tunnel reconstruction and expansion engineering construction schemes, such as timing selection for reconstruction and expansion, connection between new and old tunnels, reinforcement of the existing tunnels etc. Meanwhile, the risks in tunnel reconstruction and expansion construction greatly increase with uncertainties[9-10].

Compared with general construction of new tunnels, the construction characteristics of in situ expansion around the existing tunnels could be identified as follows[11]: (1) The impact of different excavation methods on tunnel stability becomes more prominent. (2) Generally, the tunnels which need to be expanded are flat tunnels with large span and small interval. (3) During in situ expansion, deformation of surrounding rocks is asymmetric and overall deformation range is large. (4) Cumulative damage to surrounding rocks is obvious.

Based on the above research experience, the safety risk assessment of tunnel construction during renovation and expansion should consider factors such as different construction methods, tunnel scale, geological conditions, and environmental impacts.

2.1 Establishment of Indicator System

Based on field surveys conducted in Quanzhou, Sichuan, Zhejiang and other places by considering the construction characteristics of China's highway reconstruction and construction, the assessment team summed up site materials and opinions from discussions with excerpts, and identified the overall risk assessment indicator system with primary indicators including demolition scale, tunnel structure condition, construction craft for proposed tunnel and existing tunnel, geological conditions, environmental factor, buried depth of tunnel, portal features, mean annual precipitation and data integrity. According to the basic steps of analytic hierarchy process, the software YAAHP was first adopted to build a hierarchical structure model for safety risk assessment of tunnel construction, as shown in Figure.1.

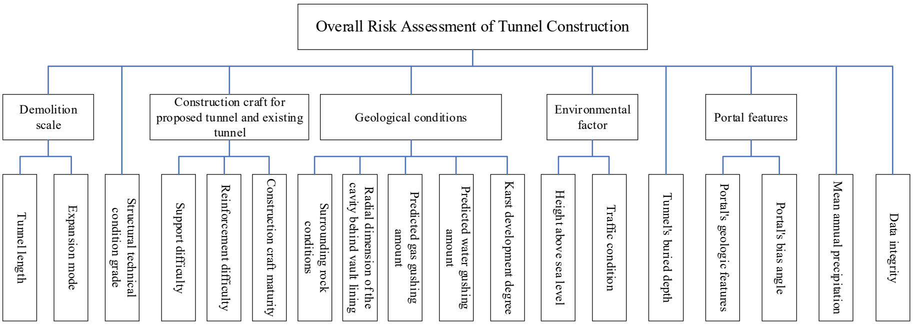

Fig. 1. Hierarchical Model of Overall Risk Assessment

Based on the established hierarchical structure model for assessment, a number of assessment indicators were developed for each subitem, and the indicator classification interval and the corresponding basic score range were identified, thus the overall risk assessment indicator system for the safety of tunnel construction was established, as shown in Table 1.

Table 1. Overall Risk Assessment Indicator System for Tunnel Reconstruction and Expansion Construction

Serial No.	Primary Indicator	Secondary Indicator	Assessment Basis	Basic Score		
				Score Range	Weight	Notes
1	Demolition scale (A_1)	Tunnel length (A_{11})	1000m≤B1<3000m	66-100	γ_{11}	Determined according to design document
			500m≤B1<1000m	33-65		
			B1<500m	0-32		
		Expansion mode (A_{12})	Surrounding expansion	75-100	γ_{12}	
			Expansion on both sides	50-74		
			Single-sided expansion	25-49		
			Addition	0-24		
2	Tunnel structure condition (A_2)	Structural technical condition rating (A_{21})	Grade V	80-100	γ_{21}	Comprehensively rated according to periodic test report on tunnel
			Grade IV	60-79		
			Grade III	40-59		
			Grade II	20-39		
			Grade I	0-19		

Serial No.	Primary Indicator	Secondary Indicator	Assessment Basis	Basic Score		
				Score Range	Weight	Notes
3	Construction craft for proposed tunnel and existing tunnel (A_3)	Support difficulty (A_{31})	During construction at the intersection between old and new tunnels, support difficulty is great; support parameters need to be continuously adjusted; support is complicated	50-100	γ_{31}	Considerations shall be given to actual construction
			During construction at the intersection between old and new tunnels, support parameters do not need to be adjusted, and support is simple	0-49		
		Reinforcement difficulty (A_{32})	During construction at intersection, there is great difficulty in reinforcement of the existing tunnel	50-100	γ_{32}	
			During construction at intersection, reinforcement of the existing tunnel is simple	0-49		
		Construction craft maturity (A_{33})	First-time domestic application of new technologies, new crafts and new equipment	50-100	γ_{33}	
			Construction craft is relatively mature; there is relevant domestic application	0-49		
4	Geological conditions (A_4)	Surrounding rock condition (A_{41})	Cumulative length of Grade V surrounding rock 400m≤G1<600m long, extra-long tunnel; Cumulative length of Grade V surrounding rock 200m≤G1<400m medium tunnel; Cumulative length of	50-100	γ_{41}	Determined according to geological survey data and design

Serial No.	Primary Indicator	Secondary Indicator	Assessment Basis	Basic Score		
				Score Range	Weight	Notes
			Grade V surrounding rock 100m≤G1<300m short tunnel; continuous length of Grade VI surrounding rock, fault fracture zone, expansive soil, frozen earth, water-rich soft rock section 30m≤G1<50m			document
			Cumulative length of Grade V surrounding rock G1<400m long, extra-long tunnel; cumulative length of Grade V surrounding rock G1<200m medium tunnel; cumulative length of Grade V surrounding rock G1<100m short tunnel; continuous length of Grade VI surrounding rock, fault fracture zone, expansive soil, frozen earth, water-rich soft rock section G1<30m	0-49		
		Radial dimension of the cavity behind vault lining (A_{42})	Radial dimension (d)/tunnel span (D)=0.06~1	75-100	γ_{42}	
			Radial dimension (d)/tunnel span (D)=0.04~0.06	50-74		
			Radial dimension (d)/tunnel span (D)=0.01~0.04	25-49		
			Radial dimension (d)/tunnel span (D)=0~0.01	0-24		

Serial No.	Primary Indicator	Secondary Indicator	Assessment Basis	Basic Score		
				Score Range	Weight	Notes
		Predicted gas gushing amount (A_{43})	$1m^3/min \le G2 < 2m^3/min$	66-100	γ_{43}	
			$0.5m^3/min \le G2 < 1m^3/min$	33-65		
			$G2 < 0.5m^3/min$	0-32		
		Predicted water gushing amount (A_{44})	$5000m^3/d \le G3 < 10000m^3/d$	66-100	γ_{44}	
			$2000m^3/d \le G3 < 5000m^3/d$	33-65		
			$G3 < 2000m^3/d$	0-32		
		Karst development degree (A_{45})	Karst is developed	66-100	γ_{45}	
			Karst is relatively developed	33-65		
			Karst is underdeveloped	0-32		
5	Environmental factor (A_5)	Height above sea level (A_{51})	$H \ge 3500m$	75-100	γ_{51}	Determined according to geological survey data and design document
			$3000m \le H < 3500m$	50-74		
			$2000m \le H < 3000m$	25-49		
			$H < 2000m$	0-24		
		Traffic condition (A_{52})	There is high-speed railway tunnel in operation near the tunnel construction area	75-100	γ_{52}	
			There is highway tunnel in operation near the tunnel construction area	50-74		
			There is highway in operation near the tunnel construction area	25-49		
			There is ordinary road in operation near the tunnel construction area	0-24		
6	Buried depth of tunnel (A_{61})		$400m \le S < 800m$	66-100	γ_{61}	Determined according to geological sur-
			$50m \le S < 400m$	33-65		
			$S < 50m$	0-32		

Serial No.	**Primary Indicator**	**Secondary Indicator**	**Assessment Basis**	**Basic Score**		
				Score Range	**Weight**	**Notes**
						vey data and design document
7	Portal features (A_7)	Portal's geologic features (A_{71})	Portal is located at landslide mass or accumulation body	75-100	γ_{71}	Determined according to geological survey data and design document
			Portal rock stratum is loose, broken, it may be unstable	50-74		
			Portal is located in the position with steep terrain and vulnerable to collapse, falling rocks	25-49		
			Portal's side and front slopes are relatively stable	0-24		
		Portal's bias angle (A_{72})	$G2 \geq 25°$	50-100	γ_{72}	
			$G2 < 25°$	0-49		
8	Mean annual precipitation (A_{81})		$W \geq 2000mm$	75-100	γ_{81}	Determined according to meteorological data (mean precipitation in recent 5 years)
			$1500mm \leq W < 2000mm$	50-74		
			$800mm \leq W < 1500mm$	25-49		
			$W < 800mm$	0-24		
9	Data integrity (A_{91})		Periodic geological, tunnel detection, hydrological data are not complete; the basis for geotechnical calculation parameters is not sufficient	66-100	γ_{91}	If surveys and analysis on terrain and physiognomy,

Serial No.	Primary Indicator	Secondary Indicator	Assessment Basis	Basic Score		
				Score Range	Weight	Notes
			Periodic geological, tunnel detection, hydrological data are not complete; the basis for geotechnical calculation parameters is relatively sufficient	33-65		formation lithology, geologic structure, hydrogeological condition arrive at clear results, minimum value is taken; if surveys and analysis arrive at unclear results, and the basis is not sufficient, maximum value is taken
			Periodic geological, tunnel detection, hydrological data are not complete; the basis for geotechnical calculation parameters is sufficient	0-32		

In the risk assessment indicator table, each indicator is assigned a score ranging from 0 to 100. The higher the score, the higher the risk. The value is selected based on the information in the value description. The value can be obtained through interpolation or empirical judgment methods.

2.2 Indicator System Weight Determination Method

The extent to which a factor affects different engineering construction risks is not certainly unchanged, and there may be interactions among factors, so weight value should not be unchanged, a set of indicator weights can't be applicable to all tunnel reconstruction and expansion engineering. Therefore, the weights in the indicator system could be calculated in many ways, such as analytic hierarchy process or indicator importance ranking method, and researchers' project experience or expert opinions are relied upon to obtain indicator weights. In order to improve the accuracy of experts' judgment of indicator weights, the project risk assessment principle should hire more than 10 experts, who should include industries such as highway planning, design, construction, and management.

2.3 Risk grade Criterion

Based on The Guidelines for Safety Risk Assessment of Highway and Water Transport Engineering Construction Part 3: Tunnel Engineering, overall risk of tunnel reconstruction and expansion engineering construction is classified as four grades; the score ranges of risk grades are shown in Table 2.

Table 2. Risk Grade Criterion for Overall Risk Involving the Safety of Highway Tunnel Reconstruction and Expansion Construction

Risk Grade	Calculated Score R
Major risk	S > 60
Significant risk	45 < S≤60
General risk	30 < S≤45
Low risk	S≤30

The overall risk assessment is a static assessment that evaluates the overall risk of tunnel engineering and estimates its safety risk level based on the geological environmental conditions, construction scale, structural characteristics, and other risk-generating factors of the tunnel project before construction.

Tunnel projects with an overall risk assessment level of III (significant risk) or higher should undergo a special risk assessment. Which taking construction activities (or construction sections) as the evaluation object, conducting a risk source survey based on their operational risk characteristics and similar engineering accident situations, and quantitatively estimating major risk sources, proposing corresponding risk control measures. Special risk assessment belongs to dynamic assessment.

3 Research on Application of Rating Indicator System

Take a reconstructed or expanded tunnel in a low mountain and hilly area as an example, the new four-lane tunnel on the right side of such tunnel has a total length of 880m, a clear width of 18.25m and a clear height of 5m. The Grade V, IV and III surrounding rocks of such tunnel are 78m, 175m and 653.5m long and account for 8.6%, 19.3% and 72.1%, respectively.

According to the established indicator system, tunnel length is 880m, A11 score is taken as 57, if expansion mode is addition on the right side, A12 score is taken as 15;

if periodic tunnel detection data are not collected, and site survey shows that the condition of tunnel structure is fair, the tunnel is rated as Tyle 3 tunnel in terms of technical condition, A21 score is taken as 55; if there is no intersection between proposed tunnel and new tunnel, A31 score is taken as 10, A32 score is taken as 10; the Grade V surrounding rock is 78m long, less than 200m, A41 score is taken as 19; maximum value of the cavity behind vault lining is 23cm, A42 score is taken as 30; according to geological survey data and design document, there is no gas in the tunnel area, so A43 score is taken as 5; predicted water gushing amount Q=152.04m3/d, A44 score is taken as 3; according to geological survey data and design document, karst is not developed in the tunnel area, A45 score is taken as 0; according to geological survey report data, A51 score is taken as 3; there is highway tunnel in operation near the tunnel construction area, A52 score is taken as 74; maximum buried depth of the tunnel is 165m, A61 score is taken as 27; the surrounding rocks at tunnel portal are relatively broken, the stability is general, so A71 score is taken as 71; the terrain at the exit is relatively steep and at approximately 30-45°, bias is severe, so A72 score is taken as 90; multi-year mean annual precipitation in this area is 1,632mm, A81 score is taken as 57; geological, hydrological, meteorological and other data are complete, so A91 score is taken as 80. The values and calculation results of each indicator are shown in Table 3.

Based on the above factors, the calculated score is 45.40, higher than 45, so it is deemed as significant risk, it is necessary to conduct special risk assessment and further assess major risk source.

Table 3. Tunnel Example Assessment Score

Serial No.	Primary Indicator	Secondary Indicator	Weight	Total Weight	Assessment Score	Final Score
1	Demolition scale (A_1)	Tunnel length (A_{11})	0.0403	0.088	57	3.01
		Expansion mode (A_{12})	0.0477		15	
2	Tunnel structure condition (A_2)	Structural technical condition rating (A_{21})	0.0984	0.0984	55	5.41
3	Construction craft for proposed tunnel and existing tunnel (A_3)	Support difficulty (A_{31})	0.0467	0.1172	10	1.48
		Reinforcement difficulty (A_{32})	0.0366		10	
		Construction craft maturity (A_{33})	0.0339		19	

Serial No.	Primary Indicator	Secondary Indicator	Weight	Total Weight	Assessment Score	Final Score
4	Geological conditions (A_4)	Surrounding rock condition (A_{41})	0.0224	0.1195	19	0.75
		Radial dimension of the cavity behind vault lining (A_{42})	0.0201		30	
		Predicted gas gushing amount (A_{43})	0.0287		5	
		Predicted water gushing amount (A_{44})	0.0254		3	
		Karst development degree (A_{45})	0.023		0	
5	Environmental factor (A_5)	Height above sea level (A_{51})	0.0431	0.1088	3	4.99
		Traffic condition (A_{52})	0.0657		74	
6	Tunnel's buried depth (A_{61})		0.1186	0.1186	27	3.2
7	Portal features (A_7)	Portal's geologic feature (A_{71})	0.0491	0.1122	71	9.17
		Portal's bias angle (A_{72})	0.0631		90	
8	Mean annual precipitation (A_{81})		0.0909	0.0909	57	5.18
9	Data integrity (A_{91})		0.1464	0.1464	80	11.71
Total score 45.40						

4 Conclusion

In this research, risk identification was conducted by considering the safety risk characteristics of highway tunnel reconstruction and expansion construction, and based on risk assessment theory, the overall risk assessment indicator system for the safety of highway tunnel reconstruction and expansion construction was established, and indicator values, were rationally selected, and a number of measures including indicator weights and scoring standard were introduced to improve the risk assessment indicator system for highway reconstruction and expansion construction. The indicator system established through pilot calculation made by taking an example could better reflect the risks in tunnel reconstruction and expansion construction. Subsequently, the risk assessment framework and indicator system in the research could be further improved and promoted, and a risk resource library for reconstruction and expansion of different types of highway tunnels could be established to address the needs for assessing risks in reconstruction and expansion of different types of highway tunnels.

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