Water Inrush Risk Assessment under Fuzzy Analytic Hierarchy Process in Guizhou Province

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Abstract: Fuzzy analytic hierarchy process is used to establish risk evaluation model on water inrush based on the characters of highway tunnel in Guizhou province. In the process of mode, risk factors are evaluated, based on statistical analysis on water inrush in china, and on the characters of tunnel in Guizhou province. Considered similar projects and survey from experts, relative scale methodology is used to obtain weight value on risk factors. The mode is used in tunnel in Guizhou province to obtain the possibility of water inrush. Model calculation results are in conformity with engineering evaluation. Consequently, the mode is reasonable, which could be used in evaluate water inrush in Guizhou tunnel.

1. Introduction

The western of China is widely distributed with karst. It is inevitable to meet water inrush in construction [1-2], When tunnel located in strong Karst area. So risk assessment on water inrush in tunnels in those areas is very important.

Large amount of risk assessments accords to "Road Tunnel and Bridge Construction Risk Assessment Guide". Assessments based on the Guidelines are scored on impact factors. However, when some factors do not exist, the total score will be reduced and accuracy affected. When using the analytic hierarchy process (AHP), the matrix is used to calculate the weight, and when one of the influencing factors does not exist, the weight can be automatically adjusted; So AHP could reduce the influence of the lack of some factors on evaluation

Based on the fuzzy analytic hierarchy process and the characteristics of the tunnel in Guizhou province, this study establishes water inrush risk assessment model, to make up the reduced accuracy because of lack of factors. By analyzing the tunnel constructions in China, the factors that have great influence on the inrush are selected. And hierarchical model is established based on the correlation of the factors. According to the characteristics of the geological conditions in Guizhou province, the relative weight of the influencing factors is obtained by considering the statistical results and the expert survey results, and the appropriate membership function is selected. By applying the model to the Chong-an River tunnel in Guizhou Province, the results are consistent with the engineering evaluation.

2. Evaluation Analysis Model

2.1Evaluation factors

The relevant research results of inrush indicate that the main factors can be summarized as: Karst degree, rock slope, rock thickness, and rock combination, fault properties, joint fracture, Karst hydrodynamic zone, groundwater level, surface Karst, catchments area. Based on collection and collation of data over 100 cases of Karst water inrush in China, the typical influencing factors for water inrush are: Formation lithology, geological formation, groundwater level, geomorphology, rock formation, soluble rock and non-soluble rock contact zone, layers and interlayer fractures. [3]

2.2 Establishment of hierarchy model

It can be concluded that the main risk factors of water inrush are formation lithology, geological formations, impact of water and topographical. Table 1 shows indicator system for risk assessment of water inrush.

Table1 Indicator System for Risk Assessment of Tunnel Water Inrush

Target layerA	Guidelines layer B	Indicator layer C
Inrush risk assessment indicators (A)	Formation lithology B_1	Karst degree C_{11}
		Rock thickness C_{12}
		Rock formations C_{13}
	Geological formations B_2	Fault C_{21}
		Wrinkle C_{22}
		Channels and fissures C_{23}
	Impact of water B_3	Groundwater development C_{31}
		Effects of precipitation C_{32}
		Groundwater level difference C_{33}
	Topographical features B_4	Surface KarstC_{41}
		Water-absorbing area C_{42}

2.3 Determination of relative weight

In the calculation, Saulty 1 ~ 9 matrix scale method is used to compare the importance of various factors. The relative weight of quantization is described by a_{ij}, with n elements participating in each matrix. The result should be tested consistently to ensure the correctness of the selection.

Table 2 Salty relative scale method [3]

Scale	1	3	5	7	9	2,4,6,8	a_{ji}
Importance of factor *i* compared with factor *j*	Equal	A little important.	Obviously	Strong	extremely	Interpolation between odd scales of importance	$a_{ji}=1/a_{ij}$

The accuracy of relative weights is crucial on the risk assessment. In order to ensure the property of value, the engineering analogy and the expert investigation has been considered. According to survey of experts, the relative scale value is obtained. The experts selected come from scientific Institutes, Universities, design units, and construction units. Most of experts have associate professor or above professional title. They have worked in tunnel construction fields for many years, and familiar with engineering risk assessment theory and methods. A total of 22 persons participated in the expert survey. 3 of them from construction units, 6 of them from design units, 5 of them from universities, and 8 of them from scientific institutes. Of the 22 persons, 7 are professors and professors, 9 are associate professors or senior teachers, 4 are intermediate titles, and 2 are junior titles. Two persons have worked in tunnel fields for 5-10 years, five in 10-15 years, eight in 15-20 years, and seven in 20-plus years.

Table3 Classification and weight selection of experts

Level	A	B	C	D
technical title	professor Senior Professors	associate professor Senior Engineer	Intermediate title	Junior titles
working years in tunnels field	>20 years	15-20 years	10-15 years	5-10 years
Level of familiarity with risk assessment theory and methodology	Professional	Extremely understanding	understanding	Partial understanding
Expert weight	1.0	0.9	0.8	0.7

Based on the results of engineering analogy and the expert survey, the value of the Saulty is shown in Table 4 and Table 5.

Table 4 Criteria Layer B Judgment Matrix for Target Layer A

	B_1	B_2	B_3	B_4
B_1	1	1/3	1/2	1/3
B_2	3	1	2	1
B_3	2	1	1	1/2
B_4	3	1/2	2	1

Eigenvector W={0.111,0.358,0.229,0.301}^{T}，λ_{max}=4.12，CI=0.04，CR=0.04<0.1，satisfied with consistency check。

Table 5 the judgment matrix of indicator layer C aligned with criterion layer B

judgment matrix to B_1

	C_{11}	C_{12}	C_{13}
C_{11}	1	3	3
C_{12}	1/3	1	1
C_{13}	1/3	1	1

judgment matrix to B_2

	C_{21}	C_{22}	C_{23}
C_{21}	1	1/2	3
C_{22}	2	1	6
C_{23}	1/3	1/6	1

judgment matrix to B_3

	C_{31}	C_{32}	C_{33}
C_{31}	1	1/2	1
C_{32}	2	1	3
C_{33}	1/3	1/3	1

judgment matrix to B_4

	C_{41}	C_{42}
C_{41}	1	2
C_{42}	1/2	1

Eigenvector from indicator layer C to Guidelines layer B_1 W={0.6, 0.2, 0.2}^{T}，λ_{max}=3.0，CI=0，CR=0 <0.1，satisfied with consistency check. Eigenvector from indicator layer C to Guidelines layer B_2 W={0.3, 0.6, 0.1 }^{T}，λ_{max}=3，CI=0，CR=0 <0.1，satisfied with consistency check. Eigenvector from indicator layer C to Guidelines layer B_3 W={0.24, 0.55, 0.21 }^{T}，λ_{max}=3.02，CI=0.009，CR=0.018 <0.1，satisfied with consistency check. Eigenvector from indicator layer C to Guidelines layer B_4 W={0.333, 0.667}^{T}。2 order matrix is always fully consistent, so no random consistency ratio is required.

2.4 Determination of membership function

Common membership function forms include triangle, trapezoid, normal distribution, type I, etc. Type I functions are mainly used in language descriptions. Triangle membership function and trapezoidal membership function are sufficient to represent other types of membership function. Considering simplicity of model, the triangle membership function is preferred. In this study, the risk factors of atmospheric precipitation and groundwater level difference can be described numerically, and the membership function can be selected by using triangular membership function. Three parameters （a，b，c）are commonly used to represent the membership function of a triangle. The three parameters represent the three coordinate points of the triangle, as shown in formula 1. Table 6 shows classification of factors in language descriptions.

$$\mu_{A(x)} = \begin{cases} 0 & x < a \\ (x-a)/(b-a) & a \le x < b \\ (c-x)/(c-b) & b \le x < c \\ 0 & c \le x \end{cases} \quad (1)$$

Table 6 Classification of factors

Classification	I	II	III	IV
Karst degree	tiny	Weak	meidum	Strong
Rock thickness	broken	Thin	Medium thick	Thick
Rock formations	Horizontal overlying water-resisting-layer	Horizontal underlying water-resisting-layer	Soluble and insoluble contract in vertical	Soluble and insoluble contract inclined
Fault	compressive fault	shear fault	Extensional-shear fault	extensional fault
Wrinkle	Anticline axis, water catchment's conditions poor	Anticline axis, water catchment's conditions well	Wings of wrinkle	Synclinal shaft, fold transition
Channels and fissures	tiny	medium	Large fissure	huge fissure
Groundwater development	Undeveloped	develop	Rich; small inrush	Abundant, heavy inrush
Atmospheric precipitation(mean annual precipitation)	<300	300~650	650~1000	>1000
groundwater level difference /m	<10	10~30	30~60	>60
surface Karst morphology	Karst shaft and karst depression undeveloped	Karst shaft and karst depression developed medium	Karst shaft and karst depression developed	Entrance of underground river and karst shaft are developed strongly.

2.5 Fuzzy estimation of risk probability

The probability of risk occurrence is calculated according to matrix which takes into account the factors, relative weight of factors and membership. The main method of fuzzy estimation is to multiply the eigenvector of index weight with the membership function, as shown in formula 2.

$$B = W_i \cdot R_i = \{W_1, W_2, \ldots, W_n\} \cdot \begin{Bmatrix} R_{11}, & R_{12},\ldots, & R_{1n} \\ R_{21}, & R_{21},\ldots, & R_{2n} \\ & \ldots & \\ R_{n1}, & R_{n2},\ldots, & R_{nn} \end{Bmatrix} \quad (2)$$

2.6 Treatment of evaluation results

Results treatment methods can be divided into maximum value method and the mean method. According to the maximum and mean of the membership, the evaluation index is described. This study uses the maximum value method to deal with the results. The risk of water inrush in Karst tunnel construction period is classified into four grades: low, medium, high and risky. Level I means low risk, and level IV means risky. Risk classification for water inrush is shown in table 7.

Table 7 Water inrush risk classification

Risk level	division bases
I	Risk low，water inrush less than 100m^3/h。
II	Risk medium，water inrush between 100 m^3/h ~1000 m^3/h. water bursting hazard small-medium
III	Risk high， water inrush between 1000 m^3/h ~10000 m^3/h. water bursting hazard large
IV	Risky，water inrush >10000 m^3/h. oversize type water bursting

3. Engineering Applications

3.1 Engineering situation

The surface of the tunnel is strongly affected by dissolution and erosion. The altitude of the tunnel is 585.1~1068.9m. The surface bedrock is exposed as a Karst, erosion and denudation type of middle and low mountain valley landform.

Tunnel imports above flood level 90.468m; the first 50m of the tunnel exit is at the junction of two mountain trenches, where annual runoff occurs. During the survey period(2013-6-1), the water flow of the track Q = 3 ~ 5 l/s, the water flow of the track in flood period Q = 10 ~ 15 l/s. Average annual precipitation in field area was 1243mm. 83% rainfall is concentrated from April to October. Daily maximum rainfall is 189.9 mm.

Groundwater mainly depends on meteoric water. A small part of the rainfall is permeated at the substratum and at the joint. Joint of limestone and dolomite developed in tunnel area. Locally, there are dissolution fissures, cave distribution, water permeability. They provide good space for groundwater storage and movement. It is the main water-bearing strata in the tunnel area. The permeability of mudstone is weak, and it is the formation of water isolation.

3.2 Water inrush Risk Assessment

The factors would affect on water inrush are shown in Table8. And every factor in each mileage segment is analyzed. According to classification of factors in Table6, risk assessment in each factor in mileage segment is shown in table below.

Table 8 water inrush risk assessment based on each factor in mileage segments

	Left tunnel ZK66+020-ZK66 +607 Right tunnel YK65+970-YK66 +600	Left tunnel ZK66+607-ZK66 +707 Right tunnel YK66+600-YK66 +700	Left tunnel ZK66+707-ZK67 +775 Right tunnel YK66+700-YK67 +766	Left tunnel ZK66+775-ZK66 +890 Right tunnel YK66+766-YK66 +900	Left tunnel ZK66+890-ZK67 +028 Right tunnel YK66+900-ZK66 +990
Karst degree	Medium; Risk level III	Medium; Risk level III	Medium; Risk level III	Medium; Risk level III	Strong; Risk level IV
Rock thickness	Thick; Risk level IV	Thick; Risk level IV	Thick; Risk level IV	Thick; Risk level IV	Thick; Risk level IV
Rock formations	$S_{2\text{-}3}$wn-P_1l Between two water- separated strata; Risk level II	$S_{2\text{-}3}$wn-P_1l Between two water- separated strata; Risk level II	$S_{2\text{-}3}$wn-P_1l Between two water- separated strata; Risk level II	$S_{2\text{-}3}$wn-P_1l Between two water- separated strata; Risk level II	P_1l Above water layer; Risk level II
Fault	Risk level I	Risk level I	Risk level I	Risk level I	Risk level I
Wrinkle	anticlinal axis —slope Risk level II	synclinal shaft, fold transition Risk level IV	anticlinal axis—slope Risk level IV	slope Risk level III	synclinal shaft, fold transition Risk level IV
Channels and fissures	complete rock mass Risk level II	complete rock mass Risk level II	joints or fracture develop Risk level III	complete rock mass Risk level II	joints or fracture develop Risk level III
Groundwater development	Low impact of groundwater; Risk level II	Low impact of groundwater; Risk level II	Low impact of groundwater; Risk level II	Low impact of groundwater; Risk level II	Low impact of groundwater; Risk level II
Atmospheric precipitation(mean annual precipitation)	1243mm Risk level IV	1243mm Risk level IV	1243mm Risk level IV	1243mm Risk level IV	1243mm Risk level IV
groundwater level difference /m	Above groundwater level Risk level I	Above groundwater level Risk level I	Above groundwater level Risk level I	Above groundwater level Risk level I	Above groundwater level Risk level I
surface Karst morphology	Karst depression is weak Risk level I	Karst depression is weak Risk level I	Karst depression is weak Risk level I	Visible Karst depressions on the surface Risk level II	Visible Karst depressions on the surface Risk level II

Classifications and risk assessments of water inrush in each mileage segments in table8 brought to membership function. In language description, karwowski fuzzy membership function is used. In numerical description triangle membership function is used. Eigenvectors and membership function is used in formula 2 to calculate Fuzzy Estimations. And water inrush risk got from estimations as shown in table 9.

The calculation results of the engineering show that the hazard level of the water inrush is II-IV and appropriate risk control measures can be taken to reduce the potential of water inrush. The risk assessment of water inrush at the exit of tunnel is dangerous, so it should be paid attention in the construction. The results of risk assessment are basically compound with engineering design description. Therefore, it can be known that the model of water inrush risk assessment for tunnels in Guizhou Province is reliable.

Table 9 Probabilistic rating of water inrush

	Fuzzy Estimation				water inrush risk
Left tunnel ZK66+020～ZK66+607; Right tunnel YK65+970～YK66+600	0.28	0.377	0.181	0.163	Risk level II; Risk medium
Left tunnel ZK66+607～ZK66+707; Right tunnel YK66+600～YK66+700	0.237	0.27	0.27	0.224	Risk level III; Risk high
Left tunnel ZK66+707～ZK67+775; Right tunnel YK66+700～YK67+766	0.262	0.37	0.198	0.17	Risk level II; Risk medium
Left tunnel ZK66+775～ZK66+890; Right tunnel YK66+766～YK66+900	0.156	0.291	0.327	0.226	Risk level III; Risk high
Left tunnel ZK66+890～ZK67+028; Right tunnel YK66+900～YK66+990	0.138	0.249	0.282	0.331	Risk level Ⅳ; Risky

4. Conclusion

The research based on the characters of highway tunnel in Guizhou province, using fuzzy analytic hierarchy process to establish risk evaluation model on water inrush. In the process of mode, risk factors are evaluated, based on statistical analysis on water inrush in china, and on the characters of tunnel in Guizhou province. Considered similar projects and survey from experts, relative scale methodology is used to obtain weight value on risk factors, when Saulty matrix is used. The influence factors were calculated by using the triangle membership function and the fuzzy membership function of karwowski. The model results are processed based on the maximum value method. The mode is used in tunnel in Guizhou province, to obtain the possibility of water inrush. Model calculation results are in conformity with engineering evaluation. Consequently, the mode is reasonable, which could be used in evaluate water inrush in Guizhou tunnel.

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