

Original Research

Risk Assessment of Water Inrush in Karst Tunnels Based on the Efficacy Coefficient Method

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Abstract

Water inrush is one of the typical geological hazards of tunnel construction in karst areas. It is necessary to predict water inrush more accurately for karst tunnels. Firstly, we created a model on risk evaluation of water inrush based on the efficacy coefficient method. Then karst hydrologic and engineering geological conditions were considered in detail, and several typical factors were selected as evaluation indexes, including formation lithology, unfavorable geology, groundwater level, and so on. Moreover, the weight coefficients of the selected evaluation indices were calculated using the analytic hierarchy process method. Furthermore, the total efficacy coefficient was presented to specify the risk grade of the evaluation samples. Finally, the risk grade of water inrush for karst tunnels is divided into four levels: severe (red), high (orange), elevated (yellow), and guarded (blue). Additionally, the model of risk assessment of water inrush was applied to Jigongling tunnel along the Fanba Expressway in China. The results show that the present evaluation results agree well with the construction situation, which also agree with the relative analysis results of attribute mathematical theory. The presented work with the efficacy coefficient method is relatively simple with strong operability, which has potential for predicting water inrush in karst tunnels.

Keywords: water inrush, efficacy coefficient method, risk assessment, karst tunnels

Introduction

With the rapid development of China's economy, more and more long-deep tunnels are under construction,

especially in the mountainous area of western China and in karst areas [1-2], which pose a great challenge for tunnel engineering. Long-deep tunnels are always buried in complex geological conditions with high geo-stress, high water pressure, strong karst geology, and construction disturbance [3]. Additionally, it is quite difficult to make a

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thorough investigation on engineering geology and hydro-geological conditions. Thus a lot of geological disasters have occurred during tunnel construction, such as water inrush, mud outburst, rock burst, and collapse, as well as gas outburst.

Among tunnel accidents, water inrush is regarded as one of the most serious problems throughout the world, which can directly lead to severe death and heavy economic loss. It has been reported that several water inrush accidents have occurred in karst tunnels in China from 2002 to 2011, causing 47 deaths [4]. Thus it is necessary to predict water inrush in tunnels. However, prediction theory and forecast method on tunnel water inrush in karst areas have long been a difficult hydro-geological problem [5]. The bottleneck problem on water rush has constrained the development of underground construction, particularly for long-deep tunnels. Therefore, it is of great significance to do research on predicting the occurrence probability of water inrush, and some effective countermeasures are needed to assure environmental safety and successful tunneling.

More and more research has been devoted to forecast tunnel water inrush, although such a thing is very difficult to predict accurately during tunnel construction [6]. Recent research related to the forecast method of tunnel water inrush can be divided into two main groups. On the one hand, finite element and finite difference schemes have been used to simulate tunnel water inrush under various complicated geological conditions [7]. However, most finite element models follow the traditional theory of elastic-plastic mechanics, which has been proven to be limited. Since the finite element models cannot adequately replicate the fracture initiation, propagation, and coalescence associated with the formation of a water inrush pathway in rock strata [8]. There are also some other models that have been established to investigate the fracture zone and the seepage rule using the software of RFPA2D and COMSOL [9]. On the other hand, a large number of researchers have proposed various methods derived from other fields to evaluate the risk of water inrush in tunnels. Wang et al. [10] evaluated the risk of floor water inrush in coal mines based on secondary fuzzy comprehensive evaluation. An attribute synthetic evaluation system was proposed for the risk evaluation of the water inrush in karst tunnels, which was performed with attribute mathematical theory. Chen et al. [11] employed FAT to analyze the hazard common source of mine water inrush. Probabilistic models for tunnel construction risk assessment were established based on the data gained from former tunnel projects, which could be used to estimate the time of tunnel construction and guide construction performance [12-13]. The fuzzy TOPSIS method was extensively used to solve multi-criteria decision-making problems for tunneling projects. Meanwhile, a new risk evaluation model was presented with consideration of the uncertainties and the new factors [14].

Additionally, risk evaluation has also been investigated for water inrush. Hodlur et al. [15] developed a statistical hydrogeological model to evaluate mine water hazards.

Bukowski [16] proposed an assessment system to classify mine shafts with respect to water hazard risk. Li et al. [17] integrated the artificial neural network (ANN), wavelet, analysis and fuzzy mathematics – namely the fuzzy wavelet neural network (FWNN) – which was then used to establish a model for risk assessment on karst tunnels. Based on water inrush coefficient (T_s) and unit-inflow (q), the safe-mining evaluation model was established to provide a convenient evaluation method for secure production [18]. Considering the lithology and the structure features, a coal floor water inrush risk assessment method was put forward according to a conventional water inrush coefficient [19]. Li et al. [20] studied the risk assessment system for water inrush in the karst tunnels with geographic information system (GIS) technology, which was used to dynamically predict the water inrush risk and develop appropriate protective measures. What's more, Bayesian probabilistic networks were applied to assess the risk in road tunnels, which was embodied in two aspects: firstly, a set of key performance indicators (KPI) were used to associate with risks. Secondly, relative data, models published in literature, and expert opinion were selected to sustain the dependencies and the conditional probabilities [21]. Wang et al. [22-27] proposed many new models to evaluate the risk of engineering geological hazards, such as water inrush, collapse, etc.

According to the above introduction, some methods are accompanied by simplified conditions or factors, which sometimes fail to reveal the quantified relationship between water inrush and its influence indices. However, other methods have certain limitations, though they could manage some problems of water inrush with their uniqueness. For one thing, the above methods are limited for evaluating the risk of water inrush in karst tunnels, which sometimes fail to reveal the quantifying relationship between water inrush and its influence factors. Because the influence factors of water inrush in karst tunnels are different from those of coal mines, the methods for coal mines may not be available for risk analysis of the water inrush in karst tunnels [6]. For another thing, the calculation processes of the above methods are too complicated to be used for a tunnel engineering site. Therefore, it is necessary to propose a simple and reliable method for risk evaluation of the water inrush in karst tunnels [6].

In the present work, a new analysis model was established using both the efficacy coefficient and analytic hierarchy process methods. Firstly, the efficacy coefficient method was put forward for single efficacy coefficient, which was performed with consideration of the main influence factors of water inrush. Then the considered factors were selected as evaluation indices. Moreover, the analytic hierarchy process method was presented to determine the weight coefficient for each evaluation index. Furthermore, based on the combination of the single efficacy coefficient and the weight coefficient, total efficacy coefficient was brought out to specify the risk grade of the evaluation samples. Additionally, the evaluation results were compared with the field-observed results and relative research results to validate

the feasibility and effectiveness of the established analysis model, which could provide guidance to control the water inrush risk in karst tunnels.

Analysis Model

Efficacy Coefficient Method

The efficacy coefficient method is a quantitative evaluation method. It can not only reflect the complex characteristics of multiple factors, but also realize comprehensive analysis. Thus the efficacy coefficient method has been extensively employed by many researchers, including for risk assessment, which has been applied for geotechnical engineering and gained better results [28-29].

The efficacy coefficient method is proposed with the theory of multi-objective programming. On the first step, it is necessary to determine the influence factors for the investigated objects, and the main influence factors should be selected, which could better describe the objects. The main influence factors are regarded as evaluation indices to determine the evaluation index system of the objects. Then the single efficacy coefficients of the considered factors are presented for each evaluation index, which are then used to describe the factors' contributions to the objective system. However, the single efficacy coefficients are limited within certain ranges, including the satisfaction value and the non-permissible value. In addition, total efficacy coefficient is brought out based on the single efficacy coefficients of the selected factors. The evaluation process is listed in detail as follows:

Determining the Evaluation Index System

The evaluation system might have many influence factors, such as changes induced by the system, phases and aims of the system, and contrived factors. The influence factors should be considered in detail for the investigated object, and typical variables are selected from the multiple factors. The selected variables cannot only represent the characteristics of the investigated object as far as possible, but also must be feasible for the present method. Thus each selected variable is regarded as an evaluation index, and multiple evaluation indices make up the so-called evaluation index system for the investigated system. Additionally, the selection for evaluation index should follow certain principles, namely the selected factors should be representative for evaluation indices, which also should complement mutually without repetition.

The Satisfaction and the Non-Permissible Values

For each evaluation index, the single efficacy coefficient is introduced to describe the relative factors' contributions to the objective system. The single efficacy

coefficients own their limited scope, ranging from the non-permissible value to the satisfaction value. Namely, the satisfaction value is simply the highest value of the limited range, and the non-permissible value is the lowest value of the limited range. In general, the greater the efficacy coefficient, the better the comprehensive performance of the investigated object.

Calculation of Single Efficacy Coefficients for each Evaluation Index

For the evaluation index system, the single efficacy coefficients could be divided into four kinds separately for four types of variables of influence factors as follows:

- The first kind of single efficacy coefficient is related to the maximum variable. For this type of variable, the better the relative evaluation index, the bigger the single efficacy coefficient.
- The second kind of single efficacy coefficient is relative to the minimum variable. For this type of variable, the better the relative evaluation index, the smaller the single efficacy coefficient.
- The third kind of single efficacy coefficient is stable. The single efficacy coefficient of the third kind is highest at a certain point.
- The fourth kind of single efficacy coefficient is interval, and the single efficacy coefficient changes within a certain range.

Moreover, the detailed calculations for the above kinds of single efficacy coefficient above can be seen as follows.

1) The first kind of single efficacy coefficient

$$d_{1i} = \begin{cases} \frac{x_i - x_{si}}{x_{hi} - x_{si}} \times 40 + 60, & x_i < x_{hi} \\ 100 & , x_i \geq x_{hi} \end{cases} \quad (1)$$

...where i represents the i th evaluation index, x_i is the actual value of the i th evaluation index, x_{hi} is the satisfaction value of the i th evaluation index, and x_{si} is the non-permissible value of the i th evaluation index. In addition, d_{1i} is the single efficacy coefficient for the i th evaluation index of the maximum variable.

2) The second kind of single efficacy coefficient

$$d_{2i} = \begin{cases} \frac{x_i - x_{si}}{x_{hi} - x_{si}} \times 40 + 60, & x_i > x_{si} \\ 100 & , x_i \leq x_{si} \end{cases} \quad (2)$$

...where d_{2i} is the single efficacy coefficient for the i th evaluation index of the minimum variable.

3) The third kind of single efficacy coefficient

$$d_{3i} = (1 - |x_i - x_{hi}|) / |x_{si} - x_{hi}| \times 40 + 60 \tag{3}$$

...where d_{3i} is the single efficacy coefficient for the i th evaluation index of stable variable.

4) The fourth kind of single efficacy coefficient

$$d_{4i} = \begin{cases} \left[1 - \frac{(x_{\min} - x_i)}{x_{\min} - x_{s\min}} \right] \times 40 + 60, & x_i < x_{\min} \\ 100 & , x_{\min} \leq x \leq x_{\max} \\ \left[1 - \frac{(x_{\min} - x_i)}{x_{h\max} - x_{\max}} \right] \times 40 + 60, & x_i > x_{\max} \end{cases} \tag{4}$$

...where x_{\min} represents the lower limit value of the interval variable and x_{\max} represents the upper limit value of the interval variable. $x_{s\min}$ represents the non-permissible value of the lower limit value, and is generally equal to half value of the average value for all interval variables. What's more, $x_{h\max}$ is the non-permissible value of the upper limit value, and is generally equal to one of the average values for all interval variables. In addition, d_{4i} is the single efficacy coefficient for the i th evaluation index of interval variable.

Total Efficacy Coefficient

Based on the above four kinds of single efficacy coefficients, the total efficacy coefficient, D , can be described as:

$$D = \sum_{i=1}^m d_i \omega_i \tag{5}$$

...where d_i is the single efficacy coefficient of the i th evaluation index and ω_i is the normalized weight coefficient of the i th evaluation index. The weight coefficient can be determined using the analytic hierarchy process method, which can be seen as follows.

Principle of the Analytic Hierarchy Process Method

The analytic hierarchy process (AHP) was put forward by Thomas Saaty in 1980. AHP mainly performs with the help of mathematics and psychology. In detail, a complicated decision is investigated and reduced to a series of pairwise comparisons that are analyzed and synthesized. Then the AHP is applied to capture both the subjective aspects and the objective aspects of the decision. Additionally, the AHP provides a useful way to check the consistency of evaluations from the decision maker, which can reduce prejudice when making the decision. Moreover, the AHP has been validated as an effective way to analyze

the complicated decisions that have been employed in many fields, including environmental assessment, program and policy evaluation, activity analysis, and performance evaluation.

When using the AHP, the procedure can be summarized as follows [30]:

1. An investigated object is selected, and the objective problem was modeled as a hierarchy that contains the decision goal, the alternatives, and the criteria to evaluate the alternatives.
2. Priorities among the elements of the hierarchy are established through a series of judgments that performs with the pairwise comparisons of the elements.
3. The obtained judgments are synthesized to yield a set of overall priorities for the hierarchy.
4. The consistency of the judgments is checked.
5. A final decision can be gained according to the above processes.

Establishing a Hierarchy for the Objective Problem

According to the above processes, it is necessary to treat the objective problem as a hierarchy at the first step. After analyzing the objectives and the relative problems, multiple influence factors are selected as the evaluation indices, which can be divided into several levels that range from the highest level to the lowest level. In addition, each element in each level is independent from the other.

Structure Judgment Matrices

Once the hierarchy is constructed, its various elements are evaluated by comparing them to each other two at a time, with respect to their impact on an element above them in the hierarchy. The relative importance between two criteria is assigned values using 1 to 9, as shown in Table 1. The structure of judgment matrices can be therefore constructed, as shown in Table 2.

Calculating Weight Vectors

For each pairwise in the comparison matrix, the maximum eigenvalues and the corresponding eigenvectors are calculated using the summation method as described below:

(1) Each column vector of the judgment matrix, ω'_{ij} , is calculated using Eq. 6:

$$\omega'_{ij} = b_{ij} / \sum_{i=1}^n b_{ij} \tag{6}$$

...where ω'_{ij} is the column vector of the judgment matrix, b_{ij} is an element of the judgment matrix (B), and each element (b_{ij}) represents the importance of the i th criterion relative to the j th criterion. If $b_{ij} > 1$, then the i th criterion is more important than the j th criterion, while if $b_{ij} < 1$, then

Table 1. The meaning of the 1-9 grade standard.

Value of b_{ij}	Interpretation
1	i and j are equally important
3	i is slightly more important than j
5	i is more important than j
7	i is strongly more important than j
9	i is absolutely more important than j
2, 4, 6, 8	the middle of two adjacent judgments
Reciprocal	When i and j are compared, the scalar is the reciprocal of i and j calar.

Table 2. The structure of the judgment matrix.

B	b_1	b_2	---	b_n
b_1	b_{11}	b_{12}	---	b_{1n}
b_2	b_{21}	b_{22}	---	b_{2n}
⋮	⋮	⋮	⋮	⋮
b_n	b_{n1}	b_{n2}	---	b_{nn}

the i th criterion is less important than the j th criterion. If two criteria have the same importance, then the entry b_{ij} is 1. The value of b_{ij} is measured according to a numerical scale from 1 to 9, as shown in Table 1.

(2) The sum of values in the j th row of the judgment matrix, ω'_j , is calculated by Eq. 7:

$$\omega'_i = \sum_{j=1}^n \omega'_j \tag{7}$$

...where ω'_i represents the values in j th row of the judgment matrix.

(3) The feature vector, ω_i , is obtained by Eq. 8:

$$\omega_i = \omega'_i / \sum_{i=1}^n \omega'_i \tag{8}$$

(4) The maximum eigenvalue, λ_{max} , is calculated by Eq. 9:

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^n \frac{(B\omega)_i}{\omega_i} \tag{9}$$

Consistency Test of Judgment Matrix

The judgment matrix is generally established based on the subjective judgment of the actual situation and this may cause some inaccuracies in the numerical matrix. Therefore, a criterion is necessary to test the consistency of the judgment matrix. For the consistency test, the formula can be described as follows:

$$CR = CI / RI \tag{10}$$

...where CR is the consistency ratio; when $CR < 0.1$, the judgment matrix is acceptable, otherwise the judgment matrix should be revised. RI is the average random consistency index, which can be determined according to Table 3. CI is the consistency index of the definition:

$$CI = (\lambda_{max} - n) / (n - 1) \tag{11}$$

...where λ_{max} is the maximum eigenvalue and n is the number of factors in pairs.

Process for Model Calculation and Model Test

Analysis of Evaluation Indices and System

Water inrush in karst tunnels is a complicated geological hazard. There are a large number of influence factors of water inrush in karst tunnels, thus it is important to select the evaluation indices from all influence factors of water inrush. Influence factors of water inrush can be divided into two groups, namely concerning geological factors and engineering factors. In the present work, only the geological factors are considered because engineering factors are non-essential for risk assessment during the design stage and the static evaluation of water inrush [6].

With the consideration of the correlation of influence factors, the values of influence factors were easily tested and obtained. According to relative research findings [6, 30], seven major factors were selected as evaluation indices in the present work, including formation lithology, groundwater level, landform and physiognomy, unfavorable geological conditions, modified strata inclination, contact zones of dissolvable and insoluble rock, and layer and interlayer fissures. Meanwhile, unfavorable geological conditions were associated with three influence factors, including water-bearing structure, the catchments area of the karst water system, and the width of the fault fracture zone. Then a hierarchy model of the influence factors for water inrush in karst tunnels was established, as shown in Fig. 1.

According to the relative research of Li, et al. (2013), the standards of the risk grade for water inrush have been studied, and the relative information is shown in Table 4. The evaluation indices are divided into four separate grades as Levels I-IV. For the four grades, the

Table 3. The value of random consistency index RI .

Order of judgment matrix	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

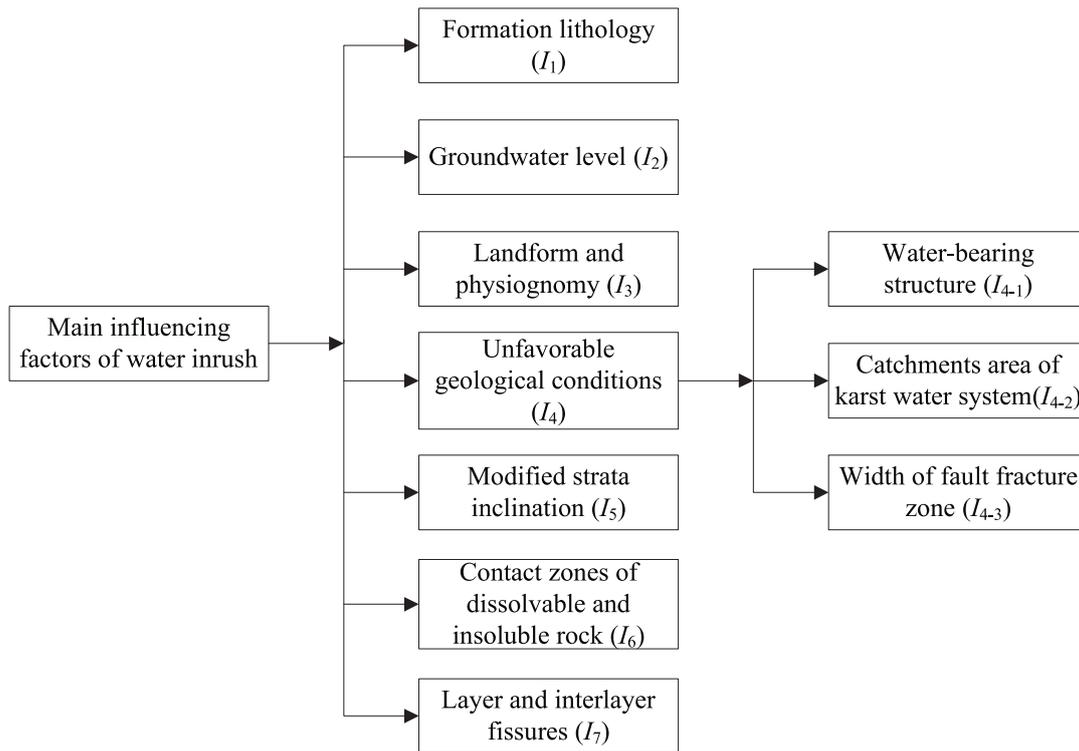


Fig. 1. Hierarchy model of the influence factors for water inrush in karst tunnels.

occurrence probability of water inrush decreases in turn. In the present work, the grade standards of water inrush were also applied for the risk assessment of water inrush. However, the grade standard was established based on the expert evaluation method, since it is difficult to quantitatively evaluate some indices such as unfavorable geological conditions, contact zones of dissolvable and insoluble rock, and layer and interlayer fissures. Meanwhile, formation lithology was used for the quantitative classification through expert evaluation method, or by a parameter of rock solubility(t) [30].

Determining the Satisfaction and Non-Permissible Values

The satisfaction value and the non-permissible value are important for risk assessment. According to previous

research results, the satisfaction value and the non-permissible value could be determined by considering the risk grade standards and the evaluation indices of water inrush. In the present work, the two values should also be determined, which was not only according to the calculation principle but also based on the actual level that can be achieved. Moreover, the satisfaction value was regarded as the highest level for an index of the evaluation standard, while the non-permissible value was thought to be the lowest level for the index of the evaluation standard. According to risk grade standards of water inrush, the satisfaction value for an index is the highest value of the limited range for I (severe), while the non-permissible value for the referred index corresponds to the lowest value of the limited range for IV (guarded), as shown in Table 4. Additionally, the satisfaction value and the non-permissible value for each index are presented in Table 5.

Table 4. Evaluation indices and risk grade standards of water inrush.

Evaluation index	Formation lithology		Groundwater level, m	Landform and physiognomy (proportion of negative landform area), %	Unfavorable geological conditions	Modified strata inclination, °	Contact zones of dissolvable and insoluble rock	Layer and interlayer fissures
	Rock solubility, t	Expert evaluation						
I (Severe)	>0.254	0~60	>60	>60	0~60	25~45	0~60	0~60
II (High)	0.104~0.254	60~70	30~60	40~60	60~70	10~25	60~70	60~70
III (Elevated)	0.042~0.104	70~85	10~30	20~40	70~85	5~10	70~85	70~85
IV (Guarded)	0~0.042	85~100	<10	0~20	85~100	0~5	85~100	85~100

Table 5. Satisfaction and non-permissible values for each index.

Index	Formation lithology <i>t</i>	Groundwater level, m	Landform and physiognomy, %	Unfavorable geological conditions	Modified strata inclination, °	Contact zones of dissolvable and insoluble rock	Layer and interlayer fissures
Satisfaction value	0.254	60	60	100	45	100	100
Non-permissible value	0	0	0	0	0	0	0

Calculation of Single Efficacy Coefficients

Formation lithology, groundwater level, landform and physiognomy (proportion of negative landform area), and modified strata inclination were regarded as maximum variables that could be calculated using Eq. (1). Meanwhile, the other variables could be calculated using Eq. (2), such as unfavorable geological conditions, and contact zones of dissolvable and insoluble rock, layer, and interlayer fissures.

Risk Level Determination

Total efficacy coefficient could be calculated by Eq. (5). Thus the risk grade of water inrush in karst tunnels could be determined with the total efficacy coefficients, as shown in Table 6.

Determining Weight Coefficient

Subjective weights were derived from the analytic hierarchy process. A judgment matrix (in Table 7) could be obtained by using the 1-9 scale method (in Table 1). The weights of evaluation indices I_{2-j} , including water-bearing structure, catchment area of karst water system,

Table 6. Analysis of risk grade of water inrush.

Risk grade	Total efficacy coefficient	Warning signal	Supplemental instruction
I	≥90	Red	Risk of water inrush is severe
II	80~90	Orange	Risk of water inrush is high
III	70~80	Yellow	Risk of water inrush is elevated
IV	60~70	Blue	Risk of water inrush is guarded

Table 8. Judgment matrix for weights analysis of I_{4-j} .

Evaluation indices	I_{4-1}	I_{4-2}	I_{4-3}	ω_{4-j}
I_{4-1}	1	3	5	0.65
I_{4-2}	1/3	1	2	0.23
I_{4-3}	1/5	1/2	1	0.12

The condition with $\lambda_{max} = 3.004$, $CI = 0.002$, $RI = 0.58$, and $CR = 0.038 < 0.1$ can satisfy the requirement of consistency check.

Table 7. Judgment matrix for weights analysis of each index I_i .

Evaluation indices	I_1	I_2	I_3	I_4	I_5	I_6	I_7	ω_i
I_1	1	1/2	2	1/3	5	2	3	0.15
I_2	2	1	3	1/2	6	2	4	0.22
I_3	1/2	1/3	1	1/4	3	1	2	0.09
I_4	3	2	4	1	8	3	6	0.35
I_5	1/5	1/6	1/3	1/8	1	1/4	1/2	0.03
I_6	1/2	1/2	1	1/3	4	1	3	0.11
I_7	1/3	1/4	1/2	1/6	2	1/3	1	0.05

The condition with $\lambda_{max} = 7.265$, $CI = 0.044$, $RI = 1.32$, and $CR = 0.033 < 0.1$ can satisfy the requirement of consistency check.

Table 9. Weights of evaluation indices.

Evaluation indices	Weights	Order
I_1	0.15	3
I_2	0.22	2
I_3	0.09	5
I_4	I_{4-1} 0.23	0.35
	I_{4-2} 0.08	
	I_{4-3} 0.04	
I_5	0.03	7
I_6	0.11	4
I_7	0.05	6

and width of fault fracture zone, could be derived from the analytic hierarchy process, and the conducted judgment matrix is presented in Table 8.

According to the analytic hierarchy process method, the weights of evaluation indices of water inrush were obtained (Table 9). The weights of evaluation indices are different from each other. The weights decrease in the following order: $I_4 > I_2 > I_1 > I_6 > I_3 > I_7 > I_5$. For the seven indices, the highest weight for the indices coincides with unfavorable geological conditions, which is equal to 0.35.

Computational Procedure

The presented risk model was developed based on Visual Basic. Then single efficacy coefficient, total efficacy coefficient, and weight coefficient were calculated as well as other factors. According to the results, a decision on the grade of the evaluation sample could be provided. The computational procedure and its flow chart are presented in detail in Fig. 2.

Model Test

The present work uses the efficacy coefficient method to evaluate the risk of water inrush in karst tunnels. To validate the rationality and effectiveness of the preset method, four samples were selected as evaluation objects based on the literature [6] with attributed mathematical theory. Then the four samples were treated with the presented method. As a result, the indices for each sample are listed in Table 10. In the table, total efficacy coefficient and the risk evaluation results of the proposed method in this work are presented in detail.

For sample 1, the total efficacy coefficient is 75.507, the risk of water inrush belongs to grade III (elevated), and the warning signal is yellow. For samples 2-5, the total efficacy coefficients are all greater than 80, the risk of water inrush belongs to grade II (high), and the warning signal is orange. According to the value of the total efficacy coefficients, the risk of water inrush for these samples could range from big to small as

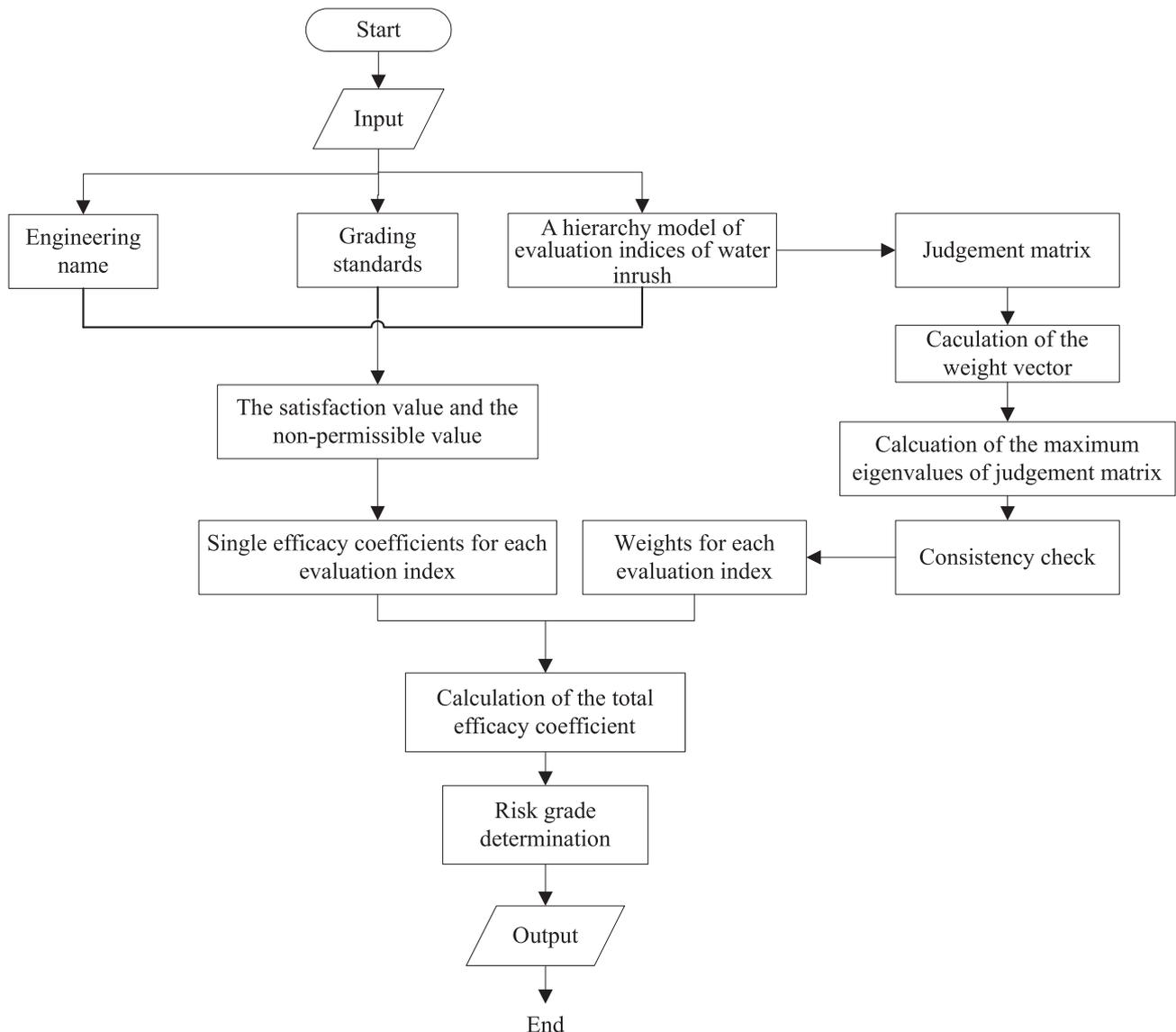


Fig. 2. Flowchart and computational procedure.

Table 10. Risk grade of water inrush of evaluation samples and comparison.

Sample	Tunnel kilometrage	Evaluation indices							Total efficacy coefficient	Results of this work	The field-observed results
		I_1	I_2	I_3	I_4	I_5	I_6	I_7			
1	K19+240~K19+450	90	75	20%	75	13°	85	80	75.507	III	III
2	K19+450~K19+500	80	75	40%	60	16°	70	65	80.447	II	II
3	K19+500~K19+760	75	75	40%	60	16°	70	65	80.747	II	II
4	K19+760~K19+800	60	75	40%	60	13°	70	65	81.567	II	II
5	K19+800~K20+180	55	75	30%	65	13°	80	70	80.027	II	II

Table 11. Risk evaluation result of K19+509~K19+539 in Jigongling Tunnel.

Evaluation indices	Values	Single efficacy coefficient	Weights of each index	Total efficacy coefficient	Results of this work	Results of attribute mathematical theory					The field-observed results
						Synthetic attribute measure				Risk grade	
						IV	III	II	I		
I_1	0.07	71.024	0.15	81.828	II (Orange)	0.010	0.347	0.383	0.261	II	II
I_2	75	100.000	0.22								
I_3	40%	86.667	0.09								
I_{4-1}	62	75.200	0.23								
I_{4-2}	7.5	80.000	0.08								
I_{4-3}	1.0	100.000	0.04								
I_5	13°	71.556	0.03								
I_6	72	71.200	0.11								
I_7	65	74.000	0.05								

sample 4, sample 3, sample 2, and sample 5. Furthermore, the present results were compared with the field-observed results, and good agreement could be gained, which could validate the present method to some extent.

well-developed karst at the tunnel site. The tunnel goes through the main aquifers, including a weak karst aquifer from K19 + 450 to K19 + 760, and a strong karst aquifer from K19 + 760 to K20 + 180.

Engineering Application

Engineering Background

To dig the practical significance, the present method was applied for engineering application. An express highway project was considered. In detail, the project is performed for transshipment over the Three Georges Dam, which is located in the typical karst mountain areas of Hubei Province in China. Meanwhile, Jigongling Tunnel [6] is regarded as the most significant engineering project, which could reflect on the features of the express highway project. Thus Jigongling Tunnel was selected as an investigated object. The tunnel is deep-buried with the length of 4.5 km. The maximum overburden thickness for the tunnel is 338 m. What’s more, Jigongling tunnel goes through a complicated geologic environment, which is mainly made up of shale, marl, and dolomitic limestone from K19 + 240 to K20 + 180. Most important of all, the groundwater is rich in complex geological structure and

Risk Evaluation of Water Inrush

Based on the present efficacy coefficient method, the risk grade of water inrush was investigated from



Fig. 3. Jigongling Tunnel face water inrush (ZK19+509) (Li et al., 2015).

K19+509 to K19+539 in Jigongling Tunnel, and the evaluation result is listed in Table 11. For sample 1, the total efficacy coefficient is 81.828, the risk of water inrush belongs to high grade (II), and the warning signal is orange. According the previous result, the risk grade is also level II using attribute mathematical theory [6]. Thus the result of the present work is in good agreement with the former results. Furthermore, based on the reference of Li et al. (2013), water inrush with a certain pressure occurred during the drilling of boreholes at K19 + 509 in Jigongling Tunnel (Fig. 3) and a total water inrush rate is 200 m³/h from the boreholes. Therefore, the evaluation result obtained from the efficacy coefficient method is in a good agreement with the practical situation.

Conclusions

Water inrush is difficult to predict accurately during tunnel construction, especially for karst tunnels. The risk grade of water inrush is essential to ensure the safety of the karst tunnels. In the present work, efficacy coefficient method and analytic hierarchy process method were applied to establish a reasonable analysis model. Meanwhile, the efficacy coefficient method was presented based on the theory of multi-objective programming. The efficacy coefficient method could provide basic evaluation values, which was performed with single efficacy coefficient by considering the main influence factors of water inrush. Then the multiple factors were selected as evaluation indices for single efficacy coefficients. Moreover, weight coefficient was determined by AHP for each evaluation index, since the weight coefficients could not only provide useful information for the confirmation of risk grade of water inrush but also avoid the individual influence on subjective methods. Based on the weight coefficients and the single efficacy coefficients, the total efficacy coefficient was presented to specify the risk grade of the evaluation samples. Furthermore, the evaluation result for Jigongling Tunnel was compared with the construction situation and the relative analysis results of attribute mathematical theory. It is shown that the presented risk analysis method is valid to predict the risk grade of water inrush in karst tunnels. In addition, the presented method on risk analysis could provide credible evaluation results for both risk design and risk management of projects in karst areas. Moreover, the presented method is feasible and effective, which could make up for the shortcoming of traditional evaluation methods.

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