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Liang Zhao , ChangHai He , [Zhuangzhuang Luo](#) ^{*} , [Qingfu Li](#)

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Article

Construction Quality Evaluation of Concrete Structures in Hydraulic Tunnels Based on CWM-UM Modeling

Liang Zhao ¹, Changhai He ¹, Zhuangzhuang Luo ^{2,*}, Qingfu Li ²

¹ Water Conservancy and Irrigation Area Engineering Construction Administration of Xixiyuan Water Conservancy Project, Zhengzhou 450000, China

² School of Water Conservancy and Transportation, Zhengzhou University, Zhengzhou 450001, China

* Correspondence: luozhuangzhuang@gs.zzu.edu.cn

Abstract: The construction time of concrete structures in hydraulic tunnels is long, the construction environment is complex, and there are many influencing factors. The requirements for construction quality are high, not only to meet the strength requirements, but also to meet the design requirements of erosion resistance, crack resistance, and seepage resistance according to its specific operating environment. Therefore, evaluating the construction quality of concrete structures in hydraulic tunnels is of great significance. Considering the randomness and fuzziness of factors affecting the construction quality of concrete structures in hydraulic tunnels, this paper proposes a comprehensive evaluation model based on Combined Weighting (CWM) and Uncertainty Measurement Theory (UM). The IAHP method and CRITIC method are used to determine the subjective and objective weights of evaluation indicators, combined weighting is based on the principle of minimum entropy, and the UM method is used to evaluate the construction quality level. Finally, taking a hydraulic tunnel as an example, its construction quality grade is calculated to be III according to the evaluation model proposed in this paper, which matches with the engineering reality, and a comparative study is made with the mixture element topology theory at the same time. It is verified that the evaluation model can scientifically and reasonably evaluate the construction quality level of concrete structures in hydraulic tunnels.

Keywords: combinatorial assignment; unconfirmed measure theory; hydraulic tunnels; concrete structures; construction quality evaluation

1. Introduction

China is a vast country with abundant water resources, but they are unevenly distributed in space, with large differences between the north and the south, and the shortage of water resources restricts the development of some cities and agriculture. For this reason, China has built a series of water diversion projects such as South-to-North Water Diversion, Diversion of River to Huaihuai, Diversion of Yellow to Qingdao, etc., which basically involve the construction of a large number of hydraulic tunnels. The construction of concrete structures in hydraulic tunnels is characterized by multi-stage, multi-level and multi-factors, and the construction processes are closely connected and interact with each other, which not only have to meet the strength requirements, but also have to meet the design requirements of anti-erosion, anti-cracking, anti-seepage and anti-impact and wear-resisting according to the specific operation environment. Therefore, it is of great significance to improve the service life of hydraulic tunnels by reasonably evaluating the construction quality level of the concrete structure in hydraulic tunnels and taking scientific and effective measures to maintain it in time.

There have been a number of research results in the area of tunnel concrete structures. You Zhemin et al [1] took highway tunnels as the object of study and proposed methods to deal with the quality problems such as collapse, water gushing, large deformation of surrounding rock and cracking of support that may occur during its construction. Wu Jiming [2] made a systematic analysis

for the construction quality control of hydraulic concrete structures in terms of selection and inspection of raw materials for hydraulic concrete, structural design, determination of mixing ratios, control of structural deformation, pouring and vibration construction. Lan Xiaofeng [3] combined with Jimingyi Tunnel to study the quality control of winter construction, selected the appropriate concrete ratio and raw materials, and adopted the appropriate temperature in the process of concrete mixing and transportation to ensure the quality of concrete construction and maintenance. Hu et al [4] studied the fast slope surface data acquisition and pre-processing technology based on the high slope excavation process of water conservancy project, and established the slope quality control index analysis model and real-time feedback flow, which was applied to the quality control of actual slope excavation project. Cheng Lili [5] combined the PDCA cycle method and construction project quality control for the current situation of construction quality control in Pandawling Tunnel, established a construction quality control process based on the PDCA cycle, and discussed in detail the application of the process in the preparation stage, construction stage and quality inspection stage. Qian et al [6] set up settlement and deformation observation points in the middle of the tunnel and on both sides of the elevated arch, and buried the observation elements according to the specified scheme, monitored the roadbed settlement after the construction of the railroad tunnel, and proposed the curve regression method to evaluate and predict the settlement of the tunnel foundation. Arends B J [7] proposed a method based on probabilistic risk assessment to evaluate tunnel safety based on three major aspects: economic risk, personal and social, and applied it to a real case study of a tunnel project in the Netherlands. Manchao et al [8] concluded that large deformation phenomenon occurs in tunnels during or after excavation due to poor geology, design defects, etc., for this reason, an MPM method based on finite element analysis software was introduced to simulate the deformation of materials. An evaluation technique incorporating Bayesian neural network was further proposed for the case where significant deformation occurs in tunnels. Hussain et al [9] assessed the rock quality in excavated tunnels by combining practical experience with numerical analysis and analyzed the stability of the tunnels before and after excavation.

At present, the research on tunnel condition mainly focuses on railroad and highway tunnels, while relatively few studies have been conducted on hydraulic tunnels which are in a water environment for a long time; the research mainly focuses on the construction quality control of tunnels, but ignores the evaluation of the construction quality grade; the research method cannot comprehensively take into account the actual situation of the project, and it is difficult to solve the randomness and ambiguity of the quality of tunnel construction in a better way. In conclusion, the index system and model for evaluating the construction quality grade of concrete structures in hydraulic tunnels are not perfect enough and need to be further studied.

In summary, this paper proposes a set of new methods for evaluating the construction quality level of concrete structures in hydraulic tunnels. The subjective and objective weights of the evaluation indexes are calculated by IAHP method and CRITIC method respectively, and the comprehensive weights of the evaluation indexes are calculated by using the principle of minimum entropy (MIE), and the comprehensive evaluation model based on CWM-UM theory is established. And relevant calculations are carried out with a hydraulic tunnel as the research background to verify the reasonableness and scientificity of the model in evaluating the construction quality grade of concrete structures in hydraulic tunnels.

2. The establishment of CWM-UM Evaluation Modeling

2.1. Determination of index weight

2.1.1. IAHP method to determine the subjective weight

In this paper, the IAHP method [10] is used to determine the subjective weights of construction quality evaluation indexes of hydraulic tunnels. Hierarchical analysis has a strong advantage in the process of dealing with multi-factor problems, which can split different factors, determine the corresponding level, and then construct a hierarchical relationship model between the factors to

calculate their subjective weights. In this paper, the judgment matrix is established based on the theory of four scales, such as equation (1), and the scale of the scale is shown in Table 1.

$$A = (a_{ij})_{n \times n} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n1} & \dots & a_{nn} \end{bmatrix} \tag{1}$$

Where, $i = 1, 2, \dots, n; j = 1, 2, \dots, n;$ a_{ij} is the result of the importance of comparing the two evaluation indicators i and j in guideline A, $a_{ji} = \frac{1}{a_{ij}}$.

Table 1. Numerical values and significance relationships.

Elemental	Numerical value	Degree
a_{ij}	1	Indicator i is as important as indicator j
	2	Indicator i is slightly more important than indicator j
	3	Indicator i is more important than indicator j
	4	Indicator i is very important compared to indicator j

Construct the antisymmetric matrix B of the judgment matrix A , the values of the matrix B and its element b_{ij} can be calculated by equation (2).

$$B = \lg A; b_{ij} = -b_{ji} \tag{2}$$

Construct the optimal transfer matrix C of the antisymmetric matrix B . The values of the elements c_{ij} in the matrix C can be calculated by equation (3).

$$c_{ij} = \frac{1}{n} \sum_{g=1}^n (b_{ig} - b_{jg}) \tag{3}$$

Construct the proposed good agreement matrix A' of the judgment matrix A . The values of the element a'_{ij} in the matrix A' can be calculated by equation (4).

$$a'_{ij} = 10^{c_{ij}} \tag{4}$$

Normalize the proposed good agreement matrix A' by columns. The values of the elements $\bar{a}'_{ij}$ in the normalized matrix can be calculated by equation (5).

$$\bar{a}'_{ij} = \frac{a'_{ij}}{\sum_i^n a'_{ij}} \tag{5}$$

The sum vector α'_i is calculated by adding rows, as shown in equation (6) :

$$\alpha'_i = \sum_{i=1}^n \bar{a}'_{ij} \tag{6}$$

The weight vector α_i can be calculated by normalizing the sum vector through equation (7).

$$\alpha_i = \frac{\alpha'_i}{\sum_{i=1}^n \alpha'_i} \tag{7}$$

AHP method [11] is used to determine the weights of evaluation indicators need to carry out consistency tests to ensure that the indicators are harmonized. This paper optimizes the hierarchical analysis method through the method of optimal matrix, which can make the calculation results reach the consistency requirement by itself.

2.1.2. CRITIC method to determine the objective weight

The CRITIC method is a method that uses standard deviation and correlation coefficient to calculate objective weights, which comprehensively takes into account the variability and conflict between indicators. It can be more reasonable and comprehensive for the assignment of weights, and the calculation process is as follows[12][13]:

Assuming that there are m evaluation objects and n construction quality evaluation indicators, the value of the evaluation object to the indicator is recorded as $x_{ik}(i = 1,2,\cdots,n;k = 1,2,\cdots,m)$. The evaluation data can be standardized by equation (8).

$$y_{ik} = \frac{x_{ik} - \min_i (x_{ik})}{\max_i(x_{ik}) - \min_i (x_{ik})} \tag{8}$$

Calculate the variability among indicators by equation (9).

$$V_i = \frac{\sigma_i}{\bar{r}_i} \tag{9}$$

Where, V_i is the coefficient of variation of the i th indicator; σ_i is the standard deviation of the i th indicator; $\bar{r}_i$ is the mean of the i th indicator.

The conflict between indicators can be calculated through equations (10) and (11).

$$h_{ij} = \frac{\sum_{k=1}^m (x_{ik} - \bar{r}_i)(x_{jk} - \bar{r}_j)}{\sqrt{\sum_{k=1}^m (x_{ik} - \bar{r}_i)^2 \sum_{k=1}^m (x_{jk} - \bar{r}_j)^2}} \tag{10}$$

$$R_i = \sum_{j=1}^n (1 - h_{ij}) \tag{11}$$

Where, h_{ij} is the correlation coefficient between indicators i and j ; R_i is the value of the quantitative indicator of conflictiveness for indicator i .

The amount of information C_i for the i th indicator can be calculated through equation (12).

$$C_i = V_i R_i \tag{12}$$

The objective weight values of construction quality evaluation indicators are calculated by equation (13).

$$\beta_i = \frac{C_i}{\sum_{i=1}^n C_i} \tag{13}$$

2.1.3. The method of calculating combination weight

(1) Rationality analysis of combination weighting

Before combining the subjective weight α_i and the objective weight β_i , their rationality should be analyzed to ensure the scientific and rational weights of the construction quality evaluation indicators of concrete structures in hydraulic tunnels. The specific process is as follows:

The subjective and objective weights of evaluation indicators are sorted, as shown in Table 2, where α'_i is the sorted value of α_i and β'_i is the sorted value of β_i . The sorting values range from 1 to n . The index with the largest weight value is sorted as 1, and the index with the smallest weight value is sorted as n .

Table 2. Sorting result of indicator weights.

Weights	Indicator 1	Indicator 2	...	Indicator n
Subjective weights	α'_1	α'_2	...	α'_n
Objective weights	β'_1	β'_2	...	β'_n

The correlation between the two sets of variables can be tested by Spearman's consistency coefficient ρ [14] as in equation (14).

$$\rho = 1 - \frac{6}{n(n^2 - 1)} \sum_{i=1}^n (\alpha'_i - \beta'_i)^2 \tag{14}$$

Where, the value range of ρ is $[-1,1]$, when $\rho \in [-1,0)$, it means that there is a lack of consistency between subjective and objective weights; when $\rho = 0$, it means that the correlation between subjective and objective weights is 0; when $\rho \in (0,1]$, it indicates that there is consistency between subjective and objective weights, which can be combined and assigned.

(2) Calculating the combination weights

The weights of evaluation indexes calculated based on IAHP method and CRITIC method are α_i and β_i , respectively. In order to make the combination weight ω_i as close as possible to α_i and β_i , the combination weights ω_i are calculated based on the MIE principle, the calculation model is as follows [15]:

$$\begin{cases} \min J(\omega) = \sum_{i=1}^n \left(\omega_i \ln \frac{\omega_i}{\alpha_i} + \omega_i \ln \frac{\omega_i}{\beta_i} \right) \\ \text{s. t. } \sum_{i=1}^n \omega_i = 1, \omega_i \geq 0, i = 1, 2, \dots, n \end{cases} \quad (15)$$

Solving this optimization model based on the Lagrange's algorithm, the combination weights can be obtained as:

$$\omega_i = \frac{\sqrt{\alpha_i \beta_i}}{\sum_{i=1}^n \sqrt{\alpha_i \beta_i}} \quad (16)$$

2.2. Uncertainty Measure Evaluation Model

This paper uses the uncertainty measurement theory to evaluate the construction quality of hydraulic tunnels. The uncertainty measurement theory mainly includes two parts: single-indicator and multiple-indicator uncertain measurement. The evaluation method and corresponding calculation formula are as follows [16][17]:

(1) Uncertainty measures for single indicators

Let the evaluation objects $T_1, T_2, \dots, T_m$ form the object space of $T = \{T_1, T_2, \dots, T_m\}$. For each object to be evaluated $T_j \in T (j = 1, 2, \dots, m)$, there exist n indicators $C_1, C_2, \dots, C_n$, then $C = \{C_1, C_2, \dots, C_n\}$ is called the evaluation space. x_{ij} is the measured value of the i th indicator for the j th object to be evaluated ($i = 1, 2, \dots, n$), and the indicator is classified into q levels $U_1, U_2, \dots, U_q$, where U_t is the t th evaluation level ($t = 1, 2, \dots, q$). If the effect of class t is better than that of class $t + 1$, denoted as $U_t > U_{t+1}$, then $U = \{U_1, U_2, \dots, U_q\}$ is the ordered segmentation class on evaluation space C [18]. $z_{ijt} = z(x_{ij} \in U_t)$ is used to indicate that the measured value x_{ij} belongs to the range of the t th evaluation grade U_t , and the following conditions must be met:

$$0 \leq z(x_{ij} \in U_t) \leq 1 \quad (17)$$

$$z(x_{ij} \in C) = 1 \quad (18)$$

$$z\left(x_{ij} \in \bigcup_{t=1}^q U_t\right) = \sum_{t=1}^q z(x_{ij} \in U_t) \quad (19)$$

Equation (17) is non-negative boundedness, equation (18) is normalization, and equation (19) is additivity. When z satisfies all three of these formulas at the same time, z is said to be uncertain measure.

Construct the uncertainty measurement function $z(x_{ij} \in U_t)$ of each evaluation index, substitute the measurement value x_{ij} , calculate the uncertainty measurement value z_{ijt} , which can form the single-indicator measurement evaluation matrix shown in equation (20).

$$(z_{ijt})_{n \times q} = \begin{bmatrix} z_{j11} & z_{j12} & \dots & z_{j1q} \\ z_{j21} & z_{j22} & \dots & z_{j2q} \\ \vdots & \vdots & \ddots & \vdots \\ z_{jn1} & z_{jn2} & \dots & z_{jnq} \end{bmatrix} \quad (20)$$

(2) Uncertainty measures for multiple indicators

If $z_{jt} = z(T_j \in U_t)$ represents the degree to which the T_j th evaluation object belongs to the t th evaluation level U_t , then there is:

$$z_{jt} = \sum_{i=1}^n \omega_i z_{ijt} (j = 1, 2, \dots, m; t = 1, 2, \dots, q) \quad (21)$$

Where z_{jt} satisfies $0 \leq z_{jt} \leq 1$, $\sum_{t=1}^q z_{jt} = 1$. Then called $z_j = [z_{j1}, z_{j2}, \dots, z_{jq}]$ is the evaluation vector of T_j 's multi-index comprehensive measure [19].

(3) Confidence identification criteria

The calculation results are analyzed according to the confidence identification criteria, and the confidence is set as $\lambda (\lambda \geq 0.5)$ [20]. If λ satisfies equation (22), it can be determined that the evaluation object T_j belongs to the t_0 th evaluation level U_{t_0} .

$$t_0 = \min \left\{ t: \sum_{j=1}^t z_j \geq \lambda, t = 1, 2, \dots, q \right\} \quad (22)$$

3. Construction quality evaluation process of concrete structure in hydraulic tunnel

The construction quality evaluation of concrete structure in hydraulic tunnel is to analyze the factors that affect its construction quality, take appropriate methods to organize and evaluate these factors, and determine the grade of tunnel construction quality. This paper first defines the concrete structure in hydraulic tunnel to be evaluated, and constructs the construction quality evaluation index system from six aspects: construction measurement, tunnel excavation, support construction, anti-drainage construction, secondary lining concrete construction and tunnel grouting. IAHP method and CRITIC method are used to determine the subjective and objective weights of evaluation indicators respectively, and combined weights are given based on the principle of minimum entropy. The uncertain measure function and matrix of single index are constructed, and the uncertain measure vector of multiple index is calculated. Finally, the construction quality grade of concrete structure in hydraulic tunnel is determined based on the confidence criterion. The specific evaluation process is shown in Figure 1.

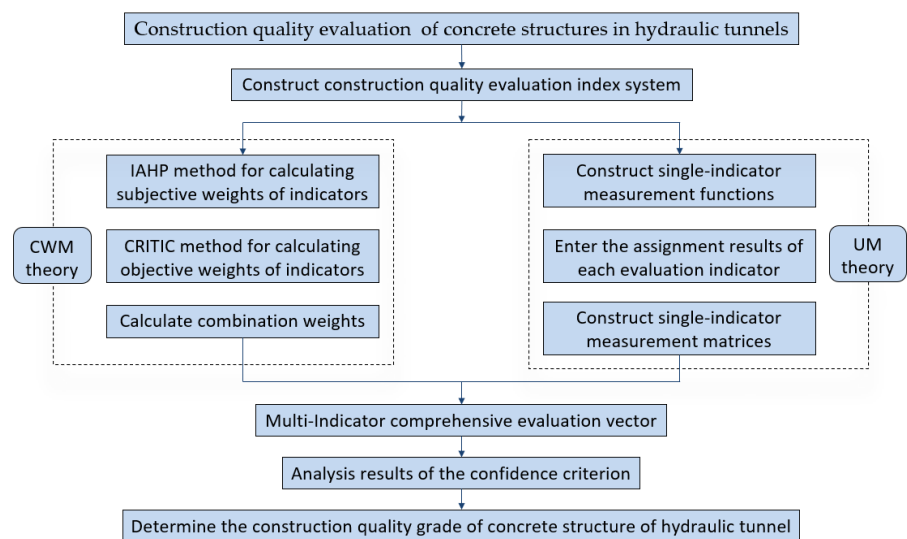


Figure 1. Construction quality evaluation process of concrete structures in hydraulic tunnels. based on CWM-UM modeling.

4. Examples of engineering applications

In order to verify the rationality and scientificity of the method, a hydraulic tunnel is applied in this paper. According to the characteristics and general construction procedures of concrete structure in hydraulic tunnel, it can be divided into six main stages: construction survey, tunnel excavation, support construction, anti-drainage construction, secondary lining concrete construction and tunnel grouting.

4.1. Reasons affecting construction quality

The construction process of concrete structure in hydraulic tunnels is complex, and there are more uncertainty factors affecting its construction quality, which can be basically summarized as five

aspects of personnel, materials, machinery, methods and environment according to the quality management theory. Therefore, according to the actual situation of the project and the existing literature, this paper adopts the fishbone diagram method [21] to carry out a hierarchical analysis from the aspects of people, materials, machines, methods and environment to summarize the reasons affecting the construction quality.

(1) In the process of construction measurement, due to the unskilled surveyors and the unfavorable influence of the environmental factors such as heavy rain, gale, high temperature, etc., it will cause the quality problems such as horizontal penetration error, vertical penetration error and marking the wrong direction of digging.

(2) In the process of tunnel excavation, due to the unskilled tunneling operators and the low level of construction site management and monitoring, there will be quality problems such as uneven excavation surface, groundwater seepage caused by excavation, and tunnel over-excavation and under-excavation.

(3) In the process of support construction, due to the low business level of the constructor and poor inspection and management, it caused problems such as collapsed holes, deviation of the position and direction of anchor holes, low stability of steel arches, insufficient thickness of sprayed concrete, and lagging of the sprayed concrete construction surface.

(4) In the process of anti-drainage construction, the performance and laying of waterproof materials are not qualified due to non-timely testing; improper treatment of construction joint and deformation joint due to insufficient construction technology level; the drainage system is unreasonable due to lack of scientific planning.

(5) In the process of secondary lining concrete construction, the performance of concrete materials and mixing ratios do not meet the design requirements due to the lack of timely testing; insufficient maintenance of concrete, low strength of concrete demolding, and inadequate concrete pouring and vibration due to the low level of construction management and poor construction environment, and other quality problems. In addition, the quality of secondary lining concrete construction will also be affected by factors such as non-standardized concrete pouring, failure to clean the surface of the formwork in time, insufficient reinforcement of the formwork, and incomplete assembly.

(6) In the process of tunnel grouting, due to the unskilled construction personnel, it is impossible to strictly control the key parameters such as hole diameter, hole position, verticality, etc., resulting in irrational disposal of the drilled holes; due to the lack of advance hydrogeological and engineering geological exploration, it is not possible to effectively predict the ambient temperature of the construction area, which results in the grouting temperature being too large or too small; due to the irregularities in the grouting test, resulting in too high or too low a grouting pressure being selected. low.

In summary, the fishbone diagram of the quality problems of concrete structure construction of hydraulic tunnels is shown in Figure 2.

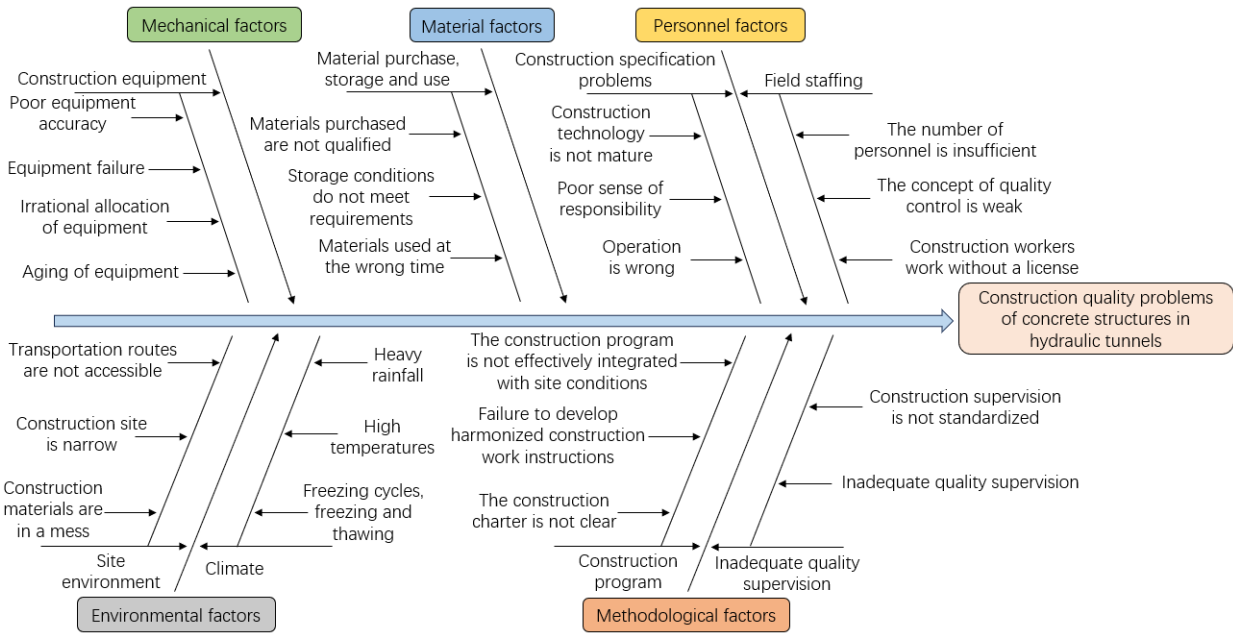


Figure 2. Fishbone diagram of construction quality problems of concrete structures in hydraulic tunnels.

4.2. Selection of construction quality evaluation indicators.

Through the investigation of the construction site and the combing of the contents of section 4.1, 21 factors affecting the construction quality of concrete structures in hydraulic tunnels are summarized and their causal factor types are analyzed. The results are shown in Table 3.

Table 3. Summary of factors affecting construction quality.

Main body of construction	Construction process	Construction quality problems	Types of causal factors
Construction of concrete structures in hydraulic tunnels	Construction measurement X_1	Horizontal penetration error is too large X_{1-1}	People, methods
		Vertical penetration error is too large X_{1-2}	People, methods
		Marking the wrong direction of digging X_{1-3}	People, methods
		Inclement weather X_{1-4}	Environment
	Tunnel excavation X_2	Over-excavation of tunnels X_{2-1}	People, methods
		Under-excavation of tunnels X_{2-2}	People, methods
		Unevenness of excavated surface X_{2-3}	People, machines methods
		Groundwater seepage due to excavation X_{2-4}	Machines, methods
	Support construction X_3	Deviation in anchor hole position and hole orientation X_{3-1}	People, methods

	Low stability of steel arch X_{3-2}	People, materials, methods, environment
	Insufficient sprayed concrete thickness X_{3-3}	People, machines methods
	Unreasonable drainage system X_{4-1}	People, methods
Anti-drainage construction X_4	Waterproofing materials and laying don't meet the requirements X_{4-2}	People, materials
	Improper treatment of deformation joints and construction joints X_{4-3}	People, machines methods
	Raw materials and mixing ratios don't meet the requirements X_{5-1}	People, materials, methods
Secondary lining concrete construction X_5	Inadequate concrete placement and vibration X_{5-2}	People, methods, environment
	Inadequate concrete maintenance X_{5-3}	People, methods, Environment
	Lower concrete demolding strength X_{5-4}	People, materials, methods
	Unreasonable disposal of drilled holes X_{6-1}	People, methods
Tunnel grouting X_6	Grouting pressure is too high / too small X_{6-2}	People, methods
	Grouting temperature is too high/too low X_{6-3}	People, methods, Environment

According to Table 3, the construction process and the construction quality problems of each process are taken as primary and secondary evaluation indexes respectively. The construction quality evaluation index system is constructed to evaluate the construction quality of concrete structures in hydraulic tunnels.

4.3. Construction quality grading

According to the Technical Procedure for Detection and Evaluation of Defects in Hydraulic Concrete Buildings (DL/T5251-2010) [22] and the Code for the Design of Hydraulic Tunnels (SL279-2016) [23], the construction quality condition of the concrete structures in hydraulic tunnels is categorized into five grades. Where, Grade I indicates that the quality of tunnel construction is excellent, with few or no quality problems, and only normal inspection of the construction process is required; Grade II indicates that the quality of tunnel construction is good, with relatively small problems, and the construction process needs to be strengthened to prevent; Grade III indicates that the quality of tunnel construction is qualified, with relatively more problems, and the construction process needs to formulate the appropriate monitoring and management system; Grade IV indicates

that the quality of tunnel construction is basically qualified, with more problems, but still within the permissible range, and the construction needs to be strictly prevented from the construction, and the quality problems can be corrected by appropriate means. Grade IV means that the construction quality of the tunnel is basically qualified, but there are many problems, but still within the permitted range, the construction should be strictly prevented, and appropriate means can be adopted to correct the quality problems to avoid unqualified construction quality; Grade V means that the construction quality of the tunnel is unqualified, and there are many problems, and the construction process must put forward targeted quality control and corrective measures for the quality problems, to avoid quality and safety incidents.

Due to the large number of tunnel construction processes, each quality indicator is defined in a different range, and it is impossible to carry out an accurate quantitative description, therefore, this paper suggests that the indicators and grades should be evaluated by the percentage standard, and the division of evaluation criteria is shown in Table 4.

Table 4. Tunnel construction quality evaluation grading.

Construction quality grade	Grading standard	Construction quality performance status
Grade I	(90,100)	Construction quality is excellent, with few or no problems
Grade II	(75,90)	Construction quality is good, with few problems
Grade III	(60,75)	Construction quality is satisfactory, with general problems
Grade IV	(40,60)	Construction quality is generally satisfactory, with major problems
Grade V	(0,40)	Construction quality is substandard, with significant problems

4.4. Construction quality evaluation process of concrete structures in hydraulic tunnels

This paper takes a concrete structure of a hydraulic tunnel as an example to carry out construction quality evaluation research. Indicator grading and grading standards are shown in Table 4. In order to ensure the validity and accuracy of the evaluation results, this paper assigns values to the construction quality indicators by inviting five experts in different aspects, including design units, construction units, construction units, supervisory units and scientific research institutes, with the score range of [0,100], and the better the quality control of the indicators is, the larger the score is. The results of the assigned values are shown in Table 5.

Table 5. Assigned results of quality indicators.

Quality evaluation indicators	Score				
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
Horizontal penetration error is too large X ₁₋₁	68	56	73	61	75
Vertical penetration error is too large X ₁₋₂	75	65	60	74	70
Marking the wrong direction of digging X ₁₋₃	65	66	58	70	65

Inclement weather X ₁₋₄	75	85	70	65	85
Over-excavation of tunnels X ₂₋₁	70	65	60	62	66
Under-excavation of tunnels X ₂₋₂	81	75	90	85	88
Unevenness of excavated surface X ₂₋₃	85	80	76	80	85
Groundwater seepage due to excavation X ₂₋₄	70	85	74	75	79
Deviation in anchor hole position and hole orientation X ₃₋₁	92	86	89	81	80
Low stability of steel arch X ₃₋₂	60	70	83	77	66
Insufficient sprayed concrete thickness X ₃₋₃	80	70	85	86	75
Unreasonable drainage system X ₄₋₁	72	67	58	84	65
Waterproofing materials and laying don't meet the requirements X ₄₋₂	53	65	59	70	68
Improper treatment of deformation joints and construction joints X ₄₋₃	78	84	86	69	79
Raw materials and mixing ratios don't meet the requirements X ₅₋₁	81	75	77	88	82
Inadequate concrete placement and vibration X ₅₋₂	89	70	83	76	90
Inadequate concrete maintenance X ₅₋₃	63	78	60	55	64
Lower concrete demolding strength X ₅₋₄	74	80	69	76	73
Unreasonable disposal of drilled holes X ₆₋₁	70	75	56	80	71
Grouting pressure is too high / too small X ₆₋₂	58	66	55	70	71
Grouting temperature is too high/too low X ₆₋₃	65	59	67	75	73

4.4.1. IAHP method to determine the subjective weight

(1) According to Table 1, the evaluation indexes of the construction quality of hydraulic tunnels are compared two by two to quantify their relative importance, and the judgment matrix of the evaluation indexes is established as shown below:

The judgment matrix of the construction quality index layer of hydraulic tunnels is as follows:

$$A_1 = \begin{bmatrix} 1 & 2 & 2 & 3 & 0.5 & 3 \\ 0.5 & 1 & 2 & 3 & 1/3 & 2 \\ 0.5 & 0.5 & 1 & 2 & 0.5 & 2 \\ 1/3 & 1/3 & 0.5 & 1 & 1/3 & 2 \\ 2 & 3 & 2 & 3 & 1 & 4 \\ 1/3 & 0.5 & 0.5 & 0.5 & 0.25 & 1 \end{bmatrix}$$

The judgment matrix of the construction measurement indicator layer is as follows:

$$A_2 = \begin{bmatrix} 1 & 1 & 2 & 0.5 \\ 1 & 1 & 2 & 0.5 \\ 0.5 & 0.5 & 1 & 1/3 \\ 2 & 2 & 3 & 1 \end{bmatrix}$$

The judgment matrix of the tunnel excavation index layer is as follows:

$$A_3 = \begin{bmatrix} 1 & 0.5 & 2 & 0.5 \\ 2 & 1 & 3 & 0.5 \\ 0.5 & 1/3 & 1 & 1/3 \\ 2 & 2 & 3 & 1 \end{bmatrix}$$

The judgment matrix of the support construction indicator layer is as follows:

$$A_4 = \begin{bmatrix} 1 & 0.5 & 1 \\ 2 & 1 & 2 \\ 1 & 0.5 & 1 \end{bmatrix}$$

The judgment matrix of the anti-drainage construction indicator layer is as follows:

$$A_5 = \begin{bmatrix} 1 & 0.5 & 1/3 \\ 2 & 1 & 0.5 \\ 3 & 2 & 1 \end{bmatrix}$$

The judgment matrix of the secondary lining concrete construction index layer is as follows:

$$A_6 = \begin{bmatrix} 1 & 3 & 2 & 2 \\ 1/3 & 1 & 0.5 & 1/3 \\ 0.5 & 2 & 1 & 0.5 \\ 0.5 & 3 & 2 & 1 \end{bmatrix}$$

The judgment matrix of the tunnel grouting index layer is as follows:

$$A_7 = \begin{bmatrix} 1 & 0.5 & 0.5 \\ 2 & 1 & 0.5 \\ 2 & 2 & 1 \end{bmatrix}$$

(2) According to equations (2) to (7), the subjective weight value of each indicator is calculated, see Table 6.

Table 6. Subjective weighting values of evaluation indicators.

Indicators	Single weight						Weighted value
	X ₁	X ₂	X ₃	X ₄	X ₅	X ₆	
	0.2324	0.1611	0.1279	0.0829	0.3286	0.0671	
X ₁₋₁	0.2274						0.0528
X ₁₋₂	0.2274						0.0528
X ₁₋₃	0.1222						0.0284
X ₁₋₄	0.4231						0.0983
X ₂₋₁		0.1867					0.0301
X ₂₋₂		0.2922					0.0471
X ₂₋₃		0.1078					0.0174
X ₂₋₄		0.4133					0.0666
X ₃₋₁			0.2500				0.0320
X ₃₋₂			0.5000				0.0639
X ₃₋₃			0.2500				0.0320
X ₄₋₁				0.1634			0.0135
X ₄₋₂				0.2970			0.0246
X ₄₋₃				0.5396			0.0447
X ₅₋₁					0.4133		0.1358

X ₅₋₂	0.1078	0.0354
X ₅₋₃	0.1867	0.0614
X ₅₋₄	0.2922	0.0960
X ₆₋₁	0.1958	0.0131
X ₆₋₂	0.3108	0.0209
X ₆₋₃	0.4934	0.0331

4.4.2. CRITIC method to determine the objective weight

According to the assignment results of quality indicators in Table 5, it is standardized through equation (8) to obtain a standardized matrix. Then, according to equations (9) ~ (13), the variability, conflict, information content and weight values of evaluation indicators can be calculated by writing MATLAB code in turn, as shown in Table 7.

Table 7. The calculated result of CRITIC method.

Indicators	Variability	Conflict	Information content	Weight values
X ₁₋₁	0.7565	21.3548	16.1546	0.0506
X ₁₋₂	0.7160	16.8724	12.0807	0.0378
X ₁₋₃	0.6359	16.6904	10.6140	0.0332
X ₁₋₄	0.8131	19.8678	16.1548	0.0506
X ₂₋₁	0.8363	18.7835	15.7090	0.0492
X ₂₋₂	0.6790	21.3728	14.5115	0.0455
X ₂₋₃	0.7373	17.0894	12.6003	0.0395
X ₂₋₄	0.8611	20.3544	17.5273	0.0549
X ₃₋₁	0.9158	24.7301	22.6473	0.0709
X ₃₋₂	0.8070	23.7479	19.1654	0.0600
X ₃₋₃	0.7348	22.0673	16.2151	0.0508
X ₄₋₁	0.8643	17.6678	15.2698	0.0478
X ₄₋₂	0.6964	17.9953	12.5323	0.0393
X ₄₋₃	0.6481	24.9121	16.1455	0.0506
X ₅₋₁	0.8982	17.3025	15.5411	0.0487
X ₅₋₂	0.7381	20.1038	14.8379	0.0465
X ₅₋₃	0.9526	21.7187	20.6888	0.0648
X ₅₋₄	0.7477	18.9209	14.1463	0.0443
X ₆₋₁	0.6223	16.8129	10.4625	0.0328
X ₆₋₂	0.7974	16.4305	13.1012	0.0410
X ₆₋₃	0.7294	18.0165	13.1412	0.0412

4.4.3. Calculate combination weights

(1) Rationality analysis of combined weights
According to the subjective and objective weights calculated by the above IAHP method and CRITIC method, the weights are sorted, as shown in Table 8.

Table 8. Ranking results of weight values for evaluation indicators.

Indicators	X ₁₋₁	X ₁₋₂	X ₁₋₃	X ₁₋₄	X ₂₋₁	X ₂₋₂	X ₂₋₃	X ₂₋₄	X ₃₋₁	X ₃₋₂	X ₃₋₃
IAHP method	7	7	16	2	15	9	20	4	13	5	13
CRITIC method	6	19	20	6	9	13	17	4	1	3	5
Indicators	X ₄₋₁	X ₄₋₂	X ₄₋₃	X ₅₋₁	X ₅₋₂	X ₅₋₃	X ₅₋₄	X ₆₋₁	X ₆₋₂	X ₆₋₃	
IAHP method	19	17	10	1	11	6	3	21	18	12	
CRITIC method	11	18	6	10	12	2	14	21	16	15	

The consistency coefficient can be calculated from equation (14) as $\rho = 0.5045 \in (0,1]$, the calculation shows that the weights calculated by IAHP method and CRITIC method satisfy the consistency requirements and can be combined and assigned.

(2) Calculate combination weights
Finally, the MIE principle is utilized to eliminate the subjective and objective weight bias, and by substituting the calculation results into equation (16), the final combined weight calculation results can be obtained, as shown in Table 9.

Table 9. The result of calculating the combined weights of evaluation indicators.

Primary indicators	Combination weight	Secondary indicators	Subjective weight	Objective weight	Combination weight
X ₁	0.1970	X ₁₋₁	0.0528	0.0506	0.0504
		X ₁₋₂	0.0528	0.0378	0.0472
		X ₁₋₃	0.0284	0.0332	0.0389
		X ₁₋₄	0.0983	0.0506	0.0605
X ₂	0.1838	X ₂₋₁	0.0301	0.0492	0.0441
		X ₂₋₂	0.0471	0.0455	0.0477
		X ₂₋₃	0.0174	0.0395	0.0374
		X ₂₋₄	0.0666	0.0549	0.0546
X ₃	0.1506	X ₃₋₁	0.0320	0.0709	0.0503
		X ₃₋₂	0.0639	0.0600	0.0552
		X ₃₋₃	0.0320	0.0508	0.0451
X ₄	0.1268	X ₄₋₁	0.0135	0.0478	0.0388
		X ₄₋₂	0.0246	0.0393	0.0396
		X ₄₋₃	0.0447	0.0506	0.0484
X ₅	0.2266	X ₅₋₁	0.1358	0.0487	0.0673
		X ₅₋₂	0.0354	0.0465	0.0449
		X ₅₋₃	0.0614	0.0648	0.0557
		X ₅₋₄	0.0960	0.0443	0.0587
X ₆	0.1153	X ₆₋₁	0.0131	0.0328	0.0336
		X ₆₋₂	0.0209	0.0410	0.0390

X_{6-3}	0.0331	0.0412	0.0427
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4.4.4. Construct uncertain measure function and matrix of single index

In the process of using unascertained measure theory to evaluate construction quality, it is necessary to construct uncertain measure function and matrix of single index scientifically and reasonably.

The evaluation level space must conform to a certain order, that is $U_1 > U_2 > \cdots > U_q$ or $U_1 < U_2 < \cdots < U_q$, where U_t represents the t th evaluation level, and its corresponding grading standard is represented as d_t , then d_t conforms to $d_1 > d_2 > \cdots > d_q$ or $d_1 < d_2 < \cdots < d_q$. Assuming that the measured value of the indicator at d_t belongs to level t , when the measured value changes from d_t to d_{t+1} , its state value at level t gradually changes from 1 to 0, and its state value at level $t + 1$ gradually changes from 0 to 1.

The change trend of the evaluation index value can be expressed by the uncertain measure function. The common forms of the uncertain measure function are mainly four types: straight line, parabola, exponential curve and sinusoidal curve type [24], of which the more widely used is the straight line type, and its corresponding graph and function expression are shown in Table 10.

Table 10. The graph and expression of the uncertain measure function.

Method	Graph	Function expression
Linear form		$\begin{cases} z_t(x) = \begin{cases} \frac{-x}{d_{t+1}-d_t} + \frac{d_{t+1}}{d_{t+1}-d_t} & d_t < x \leq d_{t+1} \\ 0 & x > d_{t+1} \end{cases} \\ z_{t+1}(x) = \begin{cases} 0 & x \leq d_t \\ \frac{x}{d_{t+1}-d_t} - \frac{d_t}{d_{t+1}-d_t} & d_t < x \leq d_{t+1} \end{cases} \end{cases}$

Based on the classification standard of tunnel construction quality in Table 4 and the graph and expression of unascertained measure function in Table 10, the unascertained measure function and graph of index can be determined as follows:

$$z(X \in U_1) = \begin{cases} 1 & , & X > 90 \\ \frac{X - 82.5}{90 - 82.5} & , & 82.5 < X \leq 90 \\ 0 & , & X \leq 82.5 \end{cases}$$
$$z(X \in U_2) = \begin{cases} \frac{90 - X}{90 - 82.5} & , & 82.5 < X \leq 90 \\ \frac{X - 67.5}{82.5 - 67.5} & , & 67.5 < X \leq 82.5 \\ 0 & , & X \leq 67.5 \end{cases}$$
$$z(X \in U_3) = \begin{cases} \frac{82.5 - X}{82.5 - 67.5} & , & 67.5 < X \leq 82.5 \\ \frac{X - 50}{67.5 - 50} & , & 50 < X \leq 67.5 \\ 0 & , & X \leq 50 \end{cases}$$
$$z(X \in U_4) = \begin{cases} \frac{67.5 - X}{67.5 - 50} & , & 50 < X \leq 67.5 \\ \frac{X - 40}{50 - 40} & , & 40 < X \leq 50 \\ 0 & , & X \leq 40 \end{cases}$$
$$z(X \in U_5) = \begin{cases} \frac{50 - X}{50 - 40} & , & 40 < X \leq 50 \\ 0 & , & X > 50 \\ 1 & , & X \leq 40 \end{cases}$$

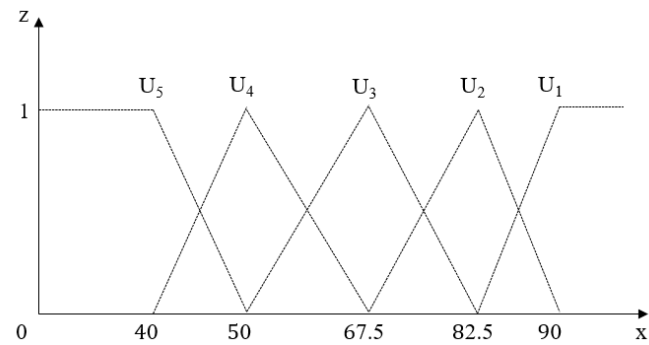


Figure 3. Measure function graph.

Based on the evaluation results of quality evaluation indicators in Table 5, the expected value of five experts' scores for each indicator is taken as the measurement value, as shown in Table 11, and it is put into the unascertained measure function, and the unascertained measure matrix of single indicator can be calculated as follows:

Table 11. Expected value of evaluation indicators.

Indicators	X ₁₋₁	X ₁₋₂	X ₁₋₃	X ₁₋₄	X ₂₋₁	X ₂₋₂	X ₂₋₃	X ₂₋₄	X ₃₋₁	X ₃₋₂	X ₃₋₃
Expected value	66.6	68.8	64.8	76	64.6	83.8	81.2	76.6	85.6	71.2	79.2
Indicators	X ₄₋₁	X ₄₋₂	X ₄₋₃	X ₅₋₁	X ₅₋₂	X ₅₋₃	X ₅₋₄	X ₆₋₁	X ₆₋₂	X ₆₋₃	
Expected value	69.2	63	79.2	80.6	81.6	64	74.4	70.4	64	67.8	
	$\begin{bmatrix} 0 & 0 & 0.949 & 0.051 & 0 \\ 0 & 0.087 & 0.913 & 0 & 0 \\ 0 & 0 & 0.846 & 0.154 & 0 \\ 0 & 0.567 & 0.433 & 0 & 0 \\ 0 & 0 & 0.834 & 0.166 & 0 \\ 0.173 & 0.827 & 0 & 0 & 0 \\ 0 & 0.913 & 0.087 & 0 & 0 \\ 0 & 0.607 & 0.393 & 0 & 0 \\ 0.413 & 0.587 & 0 & 0 & 0 \\ 0 & 0.247 & 0.753 & 0 & 0 \\ 0 & 0.780 & 0.220 & 0 & 0 \\ 0 & 0.113 & 0.887 & 0 & 0 \\ 0 & 0 & 0.743 & 0.257 & 0 \\ 0 & 0.780 & 0.220 & 0 & 0 \\ 0 & 0.873 & 0.127 & 0 & 0 \\ 0 & 0.940 & 0.060 & 0 & 0 \\ 0 & 0 & 0.800 & 0.200 & 0 \\ 0 & 0.460 & 0.540 & 0 & 0 \\ 0 & 0.193 & 0.807 & 0 & 0 \\ 0 & 0 & 0.800 & 0.200 & 0 \\ 0 & 0.020 & 0.980 & 0 & 0 \end{bmatrix}$										

4.4.5. Calculate multi-index unascertained measure vector

According to the combined weights of the evaluation indicators in Table 9 and the unascertained measure matrix of the single index mentioned above, the multi-index unascertained measure vector of the construction quality of hydraulic tunnel can be calculated by equation (21):

- Construction measurement: (0, 0.1948, 0.7616, 0.0436, 0)
- Tunnel excavation: (0.0450, 0.5804, 0.3348, 0.0398, 0)
- Support construction: (0.1380, 0.5119, 0.3420, 0, 0)
- Anti-drainage construction: (0, 0.3323, 0.5874, 0.0803, 0)

Secondary lining concrete construction: (0, 0.5648, 0.3860, 0.0491, 0)
Tunnel grouting: (0, 0.0637, 0.8686, 0.0676, 0)
Total weight value: (0.0290, 0.4008, 0.5252, 0.0450, 0)

4.4.6. Construction quality evaluation of concrete structures in hydraulic tunnels

According to the multi-indicator unconfirmed measurement vector of hydraulic tunnel construction quality in section 4.4.5, set the confidence level $\lambda = 0.5$, and the quality evaluation results of each stage and the whole in the tunnel construction process can be obtained from equation (22), which is shown in Table 12.

Table 12. Construction quality evaluation grade of concrete structures in hydraulic tunnels.

Stage	Construction measurement	Tunnel excavation	Support construction	Anti- drainage construction	Secondary lining concrete construction	Tunnel grouting	Tunnel whole
Evaluation grade	III	II	II	III	II	III	III

4.5. Comparative study

In order to illustrate the science and rationality of the method, this paper adopts the matter-element extension theory to evaluate the construction quality of hydraulic tunnels, which is used as a comparative study with the above. No further explanation about the matter-element extension theory is given, and specific reference can be made to the literature [25][26], and the focus here is on the calculation of the correlation function value of the matter-element grade of hydraulic tunnels to be evaluated.

(1) Correlation of evaluation indicators

The correlation of the construction quality level t of the hydraulic tunnel to be evaluated is shown in equation (23):

$$K_t(x_i) = \begin{cases} \frac{\rho(x_i, x_{it})}{\rho(x_i, x_{ip}) - \rho(x_i, x_{it})}, & x_i \notin x_{it} \\ \frac{-\rho(x_i, x_{it})}{|x_{it}|}, & x_i \in x_{it} \end{cases} \tag{23}$$

Where:

$$\rho(x_i, x_{it}) = \left| x_i - \frac{a_{it}^+ + a_{it}^-}{2} \right| - \frac{a_{it}^+ - a_{it}^-}{2} \tag{24}$$

$$\rho(x_i, x_{ip}) = \left| x_i - \frac{a_{ip}^+ + a_{ip}^-}{2} \right| - \frac{a_{ip}^+ - a_{ip}^-}{2} \tag{25}$$

Where, x_i is the i th construction quality evaluation index; $x_{it} = (a_{it}^+, a_{it}^-)$ is the magnitude range of the i th index divided by the evaluation grade U_t ; $x_{ip} = (a_{ip}^+, a_{ip}^-)$ is the magnitude range of the i th index divided under each level; $|x_{it}|$ is the interval length.

(2) Determine the construction quality evaluation grade of hydraulic tunnel

By combining the weights of the indicators and the value of the correlation function, the comprehensive correlation of the evaluation object can be calculated, see equation (26), if $K_{t_0}(T_0) = \max K_t(T_0)$, the evaluation object T_0 belongs to level t_0 .

$$K_t(T_0) = \sum_{i=1}^n \omega_i K_t(x_i)$$

(26)

Where, $K_t(T_0)$ is the comprehensive correlation degree of T_0 with respect to grade t ; ω_i take the objective weight value β_i of CRITIC method.

According to the grading standards of each evaluation index in Chapter 4.3, the classical domain and node domain of the construction quality evaluation index of hydraulic tunnel can be determined, as shown in Table 13.

Table 13. Classical domain and node domain of construction quality evaluation indicators of hydraulic tunnel.

Evaluation indicators	Classical domain					Node domain
	I	II	III	IV	V	
$X_{1-1} \sim X_{6-3}$	(90,100)	(75,90)	(60,75)	(40,60)	(0,40)	(0,100)

Based on the expected value of each evaluation indicators in table 11, the correlation degree matrix of the evaluation indicators of hydraulic tunnel construction quality can be obtained from equations (23) to (25):

-0.4120	-0.2010	0.4400	-0.1650	-0.4433
-0.4046	-0.1658	0.4133	-0.2200	-0.4800
-0.4172	-0.2247	0.3200	-0.1200	-0.4133
-0.3684	0.0667	-0.0400	-0.4000	-0.6000
-0.4178	-0.2271	0.3067	-0.1150	-0.4100
-0.2768	0.4133	-0.3520	-0.5950	-0.7300
-0.3188	0.4133	-0.2480	-0.5300	-0.6867
-0.3641	0.1067	-0.0640	-0.4150	-0.6100
-0.2340	0.2933	-0.4240	-0.6400	-0.7600
-0.3950	-0.1166	0.2533	-0.2800	-0.5200
-0.3418	0.2800	-0.1680	-0.4800	-0.6533
-0.4031	-0.1585	0.3867	-0.2300	-0.4867
-0.4219	-0.2449	0.2000	-0.0750	-0.3833
-0.3418	0.2800	-0.1680	-0.4800	-0.6533
-0.3264	0.3733	-0.2240	-0.5150	-0.6767
-0.3134	0.4400	-0.2640	-0.5400	-0.6933
-0.4194	-0.2340	0.2667	-0.1000	-0.4000
-0.3786	-0.0229	0.0400	-0.3600	-0.5733
-0.3984	-0.1345	0.3067	-0.2600	-0.5067
-0.4194	-0.2340	0.2667	-0.1000	-0.4000
-0.4081	-0.1827	0.4800	-0.1950	-0.4633

The weight value of each secondary index calculated by CRITIC method is as follows:
(0.2937, 0.2196, 0.1930,0.2937); (0.2603, 0.2405, 0.2088, 0.2904); (0.3903, 0.3303,0.2794); (0.3475,0.2852,0.3674);
(0.2383, 0.2275, 0.3172, 0.2169); (0.2850,0.3569,0.3580).

According to equation (26), the comprehensive correlation degree of the evaluation level t for the construction quality of the hydraulic tunnel can be calculated as:
Construction measurement: (-0.3986, -0.1192,0.2700, -0.2374, -0.4916)
Tunnel excavation: (-0.3476,0.1576, -0.0752, -0.4042, -0.6028)
Support construction: (-0.3173,0.1542, -0.1288, -0.4764, -0.6509)
Anti-drainage construction: (-0.3859, -0.0220,0.1297, -0.2776, -0.5184)
Secondary lining concrete construction: (-0.3643,0.1099, -0.0202, -0.3554, -0.5703)
Tunnel grouting: (-0.4093, -0.1873,0.3544, -0.1796, -0.4531)
The weight values of the primary indicators calculated by CRITIC method are: (0.1723, 0.1890, 0.1818, 0.1377, 0.2043, 0.1150). According to equation (26), the comprehensive correlation degree of

the target layer for the hydraulic tunnel construction quality with respect to the evaluation level t can be calculated as:

Overall Construction: $(-0.3667, 0.0352, 0.0634, -0.3354, -0.5569)$

According to the principle of maximum affiliation, the construction quality evaluation grade of the hydraulic tunnel can be determined, as shown in Table 14.

Table 14. Evaluation grade.

Stage	Constructio n measureme nt	Tunnel excavatio n	Support constructio n	Anti- drainage constructio n	Secondary lining concrete constructio n	Tunnel groutin g	Tunne l whole
Evaluatio n grade	III	II	II	III	II	III	III

Comparative analysis of the evaluation results of section 4.4 and section 4.5 shows that the results of both are consistent. And this paper adopts IAHP method and CRITIC method to calculate the subjective and objective weights of the evaluation indexes respectively, which avoids the one-sidedness of the weight calculation, and gives comprehensive consideration to the subjective intention of the decision maker and the objective attributes of the data itself, and the evaluation results are more scientific and reasonable. In summary, the evaluation index system and evaluation model of concrete structure construction quality of hydraulic tunnels established in this paper are scientific and reasonable.

5. Conclusions

- (1) According to the analysis and summarization of the factors affecting the quality of tunnel construction, 21 factors such as excessive horizontal penetration error, over-excavation of the tunnel, low stability of the steel arch, unreasonable drainage system, and insufficient maintenance of the concrete were selected from five aspects, including construction measurement, tunnel excavation, support construction, anti-drainage construction, concrete secondary lining construction and grouting of the tunnel. Constructing a more scientific and reasonable construction quality evaluation index system of concrete structures in hydraulic tunnels.
- (2) The subjective and objective weights calculated by IAHP method and CRITIC method are optimized and synthesized by using the combination assignment method, which avoids the one-sidedness of weight calculation. The subjective intention of the decision maker and the objective attributes of the data itself are considered comprehensively, which improves the reasonableness and reliability of the weights of the tunnel construction quality evaluation indexes and makes the evaluation results more in line with reality.
- (3) Taking a hydraulic tunnel as an example, the CWM-UM comprehensive evaluation model constructed in this paper is used to calculate its construction quality level, and the results are as follows: the quality level of tunnel excavation, support construction and secondary lining concrete construction are all of grade II, and the quality level of construction measurement, anti-drainage construction, tunnel grouting and overall construction of the hydraulic tunnel are all of grade III. At the same time, a comparative study is made with the matter-element extension theory to verify the applicability and reasonableness of the model, thus providing a basis for the subsequent construction.

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