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Bridge Construction Quality Evaluation Based on Combination Weighting Method- Technique for Order Preference by Similarity to an Ideal Solution Theory

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Abstract: The process of bridge construction is accompanied by many uncertainties. These uncertainties can have an impact on the quality of bridge construction and are thus directly related to the safe operation of the bridge. Therefore, it is very important to conduct bridge construction quality control evaluations for safe bridge construction and operation. In this paper, a three-tier bridge construction quality control evaluation system is established. This study uses a combination of subjective and objective assignment methods and TOPSIS theory to carry out an evaluation calculation of bridge construction quality. The CWM-TOPSIS theory was applied to the actual engineering calculation by taking the construction process of a mega bridge across the Yellow River as an example. After a series of calculations, the bridge construction quality evaluation results were obtained as level IV. This showed that a construction quality control method was needed for this bridge as soon as possible, and inspection and protection of the bridge should be started to avoid the emergence of bigger quality problems. Finally, the accuracy and applicability of the method proposed in this paper were proved by comparing and analyzing the evaluation results with the standard element theory.

Keywords: combined empowerment method; TOPSIS theory; IAHP method; CRITIC method; construction quality

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1. Introduction

Under the guidance of the "Outline for the Construction of a Strong Transportation Country" and the "14th Five-Year Plan", China's infrastructure construction has been developing in the direction of higher quality. Moreover, bridges are an important part of traffic engineering and represent important infrastructure of the national economy, playing an important role in national economic construction projects. Large bridges have complex structures, special construction environments, highly difficult and lengthy construction, huge capital investments, and significant social and economic roles. The construction period of large bridges is much riskier than the use period, and the construction quality of bridges directly determines the quality and use of bridges after they are completed. Therefore, the quality of bridge construction is of great concern. In recent years, bridge construction quality accidents have occurred repeatedly in China and around the world, resulting in alarming consequences and impacts. Numerous accidents have indicated that it is important to carry out quality control during bridge construction processes. A perfect construction quality control system can not only ensure the smooth progress of the project, but also protect the safety of life and property, which is of great significance to the development of our national economy.

In recent years, bridge construction quality issues have received widespread attention from domestic and foreign researchers and engineers, who have conducted research from

different perspectives and achieved a series of results. Domestic scholars' research on the quality control of bridge superstructure construction mainly focuses on the monitoring and management. Gong Shikang combined reliability theory and investigated the uncertainties affecting the construction quality of box girders from the structural characteristics of simple-supported and continuous box-girder bridges, making suggestions for the design and construction of small box girder accordingly [1]. Jin Zhou put forward targeted quality control measures by studying the basic theory and methods for the quality control of continuous rigid bridge with engineering examples [2]. Chen Yongrui analyzed the causes and effects of variations in the construction quality of large-span steel box-girder suspension bridges in turn, and accordingly established a safety state assessment method for suspension bridges based on the principal component analysis method [3]. Li Youhe et al. proposed targeted construction quality control measures by analyzing the common causes of quality defects in large-span continuous rigid bridges [4]. Lei Ming used BIM technology to visualize and model the construction process of segmental bridges, which provided a basis and reference for construction refinement management [5]. International scholars have also conducted a series of studies on the quality of bridge construction. Alcínia Z. Sampaio et al. applied virtual reality technology to bridge engineering and developed an interactive application to simulate the construction process and visually demonstrate the quality issues in the bridge construction process [6]. Alexey Korchagin et al. analyzed the bridge construction by analyzing the project management content in bridge construction, Alexey Korchagin et al. identified a new model for project management in bridge construction, which marked a qualitative change in the field of project management [7]. Dario De Domenico et al. used the Zappulla multi-span viaduct as a research object and proposed a method for the quality control and safety assessment of existing bridge decks through a combination of field tests and numerical simulations, which provided a theoretical basis for the quality control and other safety assessment of similar existing bridges [8].

The construction quality of bridge structure directly determines whether the bridge construction results satisfy the design requirements. Scholars at home and abroad have also conducted many studies on the assessment of bridge construction quality. Yang Youyuan analyzed the cantilever construction of prestressed concrete continuous girder bridges using existing specifications and discussed the prevention and control measures of bridge cantilever construction [9]. Cao Jianguang analyzed the factors affecting the construction quality of prestressed concrete continuous girder bridges with regards to six aspects: design, man made, construction, materials, environment, and structural calculation and construction monitoring, and concluded that the initial tension stress, loading age, temperature difference between sunshine, and self weight of the main girder should be strictly controlled during the construction process [10]. Helder Sousa et al. utilized finite element modeling to evaluate the construction of prestressed concrete bridges, and the results of the study showed that environmental factors have a greater impact on the quality of structural construction [11]. Through force calculation and construction monitoring of the construction process of T-shaped rigid bridge, Jing Ma concluded that the construction process needs to focus on controlling the quality of structural construction, unbalanced moments, and stability of the turning process [12]. Essam Althaqaf et al. proposed an effective model that accurately predicts bridge condition ratings and facilitates the decision-making process by applying artificial neural networks to bridge quality assessment [13]. Marcus Omori Yano et al. provided a new perspective on the problem of mismatch of monitoring data during bridge reinforcement by utilizing transfer learning theory to monitor the health of the reinforced bridge structure [14].

There is a close connection between the construction quality of the bridge and the selected engineering materials. China's civil engineering materials research has been developed rapidly in recent years. Li Sen proposed a series of strategies to reduce bridge cracks by analyzing the effects of different construction materials and construction processes on bridge cracks [15]. Liu Zuxiong et al. used BIM technology to refine the management of bridge engineering construction materials, established a BIM management system for

engineering materials and a collaborative management platform, and realized the amplification of economic benefits and management benefits [16]. Zhou Weiqian, through the testing of the materials used in the bridge project, obtained the problems of insufficient precision and non-standardized sampling that may occur in the testing process of the bridge project and put forward a series of key points for the quality testing of the bridge project materials [17]. F. Findik et al. provided the basis for the selection of the materials for the construction of the bridge project by carrying out a series of tests on all the materials that may be used in the civil engineering project [18]. By conducting a series of static experiments on stainless steel reinforced concrete columns, Li Qingfu et al. proposed a bearing capacity formula that should be followed when stainless steel reinforcement is used in bridge engineering, which lays the foundation for bridge engineering construction under corrosive environments [19]. Elżbieta Janowska-Renkas et al. provided a concrete material selection method based on the improved hybrid MCDA method, which is of great significance for improving the construction technology level of high-performance concrete post-tensioned girder bridges [20].

A series of results have been achieved by domestic and foreign scholars in the research of durability assessments and risk evaluations of structures. Taejun Choa et al. developed an information sharing system to quantitatively assess risks during the construction phase of suspension bridges, which provides a basis for suspension bridge construction management [21]. Hosam El-Din H. Seleem et al. designed experiments to evaluate the durability and strength of high-performance concrete to obtain the most effective form of concrete to resist seawater erosion [22]. Rafiq M. Choudhry et al. combined questionnaire methods, expert interview methods, and Monte Carlo methods to develop guidelines for bridge construction risks, providing a reference for construction personnel to control costs and risks during the construction process [23]. Based on fuzzy theory and genetic optimization neural networks, Zhang Pokun proposed a condition evaluation method to assess the durability of reinforced concrete main girders, which improves the validity and objectivity of bridge durability condition assessments [24]. Lv Xiaonan conducted a study on the construction risk of new railroads passing under existing high-speed railroad bridges, proposing a risk assessment calculation model based on the fuzzy comprehensive evaluation method, as well as risk control recommendations and specific implementation measures for risk evaluation results to a provide reference for similar projects [25]. Hosein Naderpour et al. conducted risk assessments of bridge projects based on expert interviews and Monte Carlo methods, providing a basis for the operation and management of bridge construction companies [26]. Pan Tao carried out assessments of bridge durability based on fuzzy neural networks, built a computational model of the algorithm using MATLAB software, and verified the accuracy of the computational model through examples [27]. Bhaskar Sangoju et al. conducted a study on the durability of precast reinforced concrete elements, developed durability performance criteria for concrete structures, and proposed necessary repair measures that improved the long-term durability of structural members [28]. Pengfei Wang constructed a construction risk estimation system by studying the construction risk of deepwater large-diameter bored piles, proposing a construction risk evaluation method by combining the G1 sequential relationship method, game theory principle, and two-dimensional cloud model theory, which laid a theoretical basis for risk decision [29].

From a comprehensive analysis of all the above literature it can be seen that the construction quality of bridge structure directly determines whether the bridge construction results satisfy the design requirements. At present, the construction quality management technology at home and abroad has been relatively mature, and there are many methods for the evaluation of structural stability. However, most of the research on bridge construction quality focuses on construction monitoring and management, and there are relatively few quantitative evaluations of bridge construction quality. The research on bridge construction quality mainly relies on the experience of construction personnel and experts, with too many subjective influencing factors and low credibility. Most of the research on construction

evaluation exists in the theoretical stage, without relying on the actual analysis of the project, which is not conducive to real-time control of bridge construction quality. In order to solve the above problems, this paper aims to establish a construction quality evaluation system applicable to most bridges at home and abroad. It aims to solve the problem of strong subjectivity in the process of bridge construction quality control. Based on the construction process of a bridge across the Yellow River, this paper proposes a bridge construction quality evaluation method based on the theory of CWM-TOPSIS (Combination Weighting Method-TOPSIS). This method firstly uses IAHP method to qualitatively analyze the experts' experience, and secondly uses CRITIC method to quantitatively calculate by combining the object element theory, correlation and standardization. Finally, the evaluation results are analyzed by solving the ideal solution of relevant indexes in the system through TOPSIS method. It not only avoids the problem of too much subjectivity in construction quality control in the previous study, but also solves the problem of individual wrong pieces of data having too much influence on the result when only relying on the data calculation, and is able to make an accurate and detailed evaluation of the bridge construction quality. In the actual construction process of the bridge, the theoretical calculation results of CWM-TOPSIS can provide theoretical reference for the construction personnel, so that the construction management personnel can more accurately find out where the construction quality problems lie, as well as establishing the construction quality management system in a more targeted manner. It is of guiding significance for the improvement of bridge structure construction quality.

The technical route studied in this paper is shown in Figure 1.

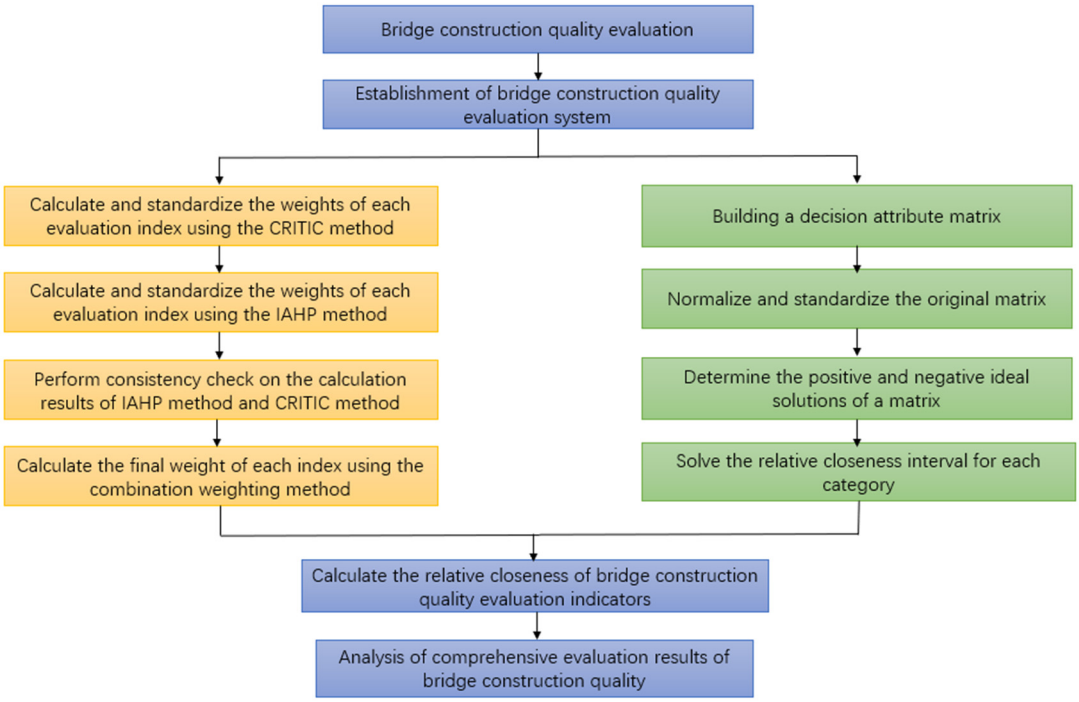


Figure 1. Technology Roadmap.

2. Establishment of Bridge Construction Quality Evaluation System

2.1. Selection of Evaluation Indexes for Bridge Construction Quality

This paper establishes a three-layer construction quality evaluation index system for bridges. After analysis, the bridge construction process mainly includes five parts: bored pile construction, cofferdam construction, bridge pier construction, superstructure construction, and ancillary engineering construction. Therefore, the above five factors were selected as the guideline layer aspects of the construction quality evaluation index system. Through research of the literature and a field survey at the construction site, 19 factors

affecting the construction quality of the bridge were obtained. Additionally, these 19 factors were taken as the index layer factors of the construction quality evaluation index system of the bridges [30].

The three-tier construction quality evaluation system established for the bridges is shown in Figure 2 and Table 1.

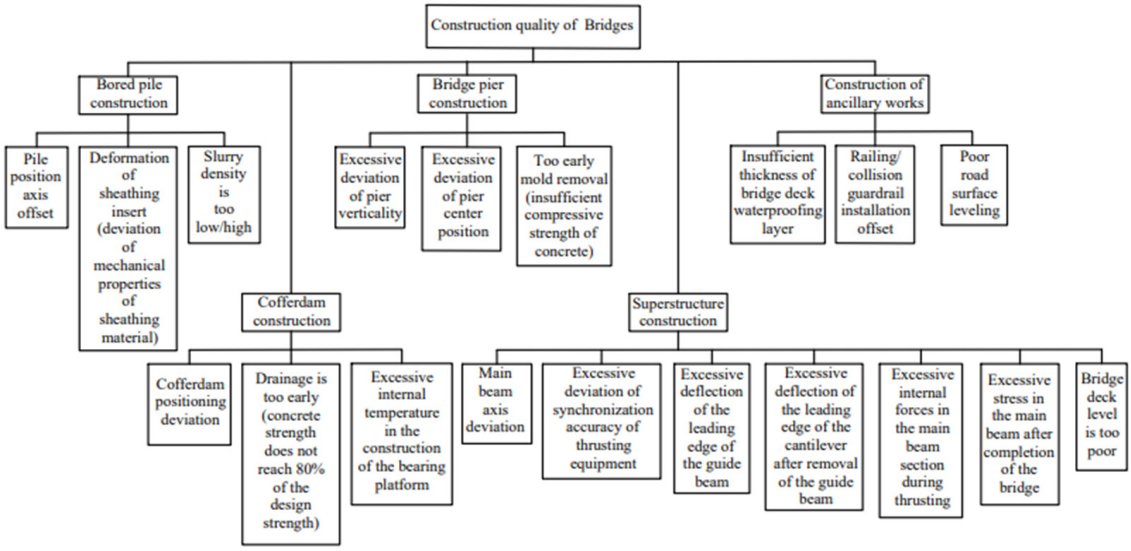


Figure 2. Construction quality evaluation index system for bridges.

Table 1. Construction quality evaluation of bridges.

Layer 1	Layer 2	Layer 3
Construction quality of bridges R	Bored pile construction	B_1 (Pile position axis offset) B_2 (Deformation of sheathing insert: deviation of mechanical properties of sheathing material) B_3 (Slurry density is too low/high)
	Cofferdam construction	B_4 (Cofferdam positioning deviation) B_5 (Drainage is too early: concrete strength does not reach 80% of the design strength) B_6 (Excessive internal temperature in the construction of the bearing platform)
	Bridge pier construction	B_7 (Excessive deviation of pier verticality) B_8 (Excessive deviation of pier center position) B_9 (Too early mold removal: insufficient compressive strength of concrete)
	Superstructure construction	B_{10} (Main beam axis deviation) B_{11} (Excessive deviation of synchronization accuracy of thrusting equipment) B_{12} (Excessive deflection of the leading edge of the guide beam) B_{13} (Excessive deflection of the leading edge of the cantilever after removal of the guide beam) B_{14} (Excessive internal forces in the main beam section during thrusting) B_{15} (Excessive stress in the main beam after completion of the bridge) B_{16} (Bridge deck level is too poor)
	Construction of ancillary works	B_{17} (Insufficient thickness of bridge deck waterproofing layer) B_{18} (Railing/collision guardrail installation offset) B_{19} (Poor road surface leveling)

Note: The third tier of indicator factors will be, respectively, denoted by B_1 to B_{19} in the subsequent content.

2.2. Construction Quality Evaluation Grade of the Bridges

According to the specification "Technical Condition Assessment Standard for Highway Bridges" [31], the construction quality condition of the bridges was divided into five levels: Level I, Level II, Level III, Level IV, and Level V. Level I represents excellent bridge construction quality with few quality problems, which only need to be checked during construction. Level II represents good bridge construction quality with relatively few quality problems, which need to be prevented during construction. Level III represents qualified bridge construction quality with more quality problems, which need to be prevented during construction with some management or monitoring systems. Level IV represents a basic bridge construction quality, with more quality problems, but within the allowable range of the specification; during construction, strict precautions need to be taken, and if necessary, means should be implemented to correct quality problems and prevent the emergence of unqualified quality. Level V represents that the bridge construction quality is not qualified and the construction process has major quality problems; in the actual project, quality control should be developed and quality measures should be implemented, not ignoring the existence of quality problems, otherwise it will cause larger safety accidents.

According to the Technical Condition Assessment Standards for Highway Bridges [31], it is difficult to describe the bridge construction process accurately and quantitatively because of the large number of bridge construction procedures and the different definition ranges of each index. In order to carry out construction quality control evaluations accurately and conveniently, the deduction values of bridge construction quality control indexes adopt the way of accumulative deduction of basic deduction value and modified deduction value. The construction quality control index level base deduction value characterizes the degree of uncertainty, the degree of impact on the structure's function, and the development of a stable state. The modified deduction value characterizes the uncertainty development and change. Table 2 shows the deduction values of bridge construction quality control indexes.

Table 2. Construction quality control index deduction value of the mega bridge across the Yellow River.

The Highest-Level Category That the Control Index Can Reach	Indicator Category							
	Base Deduction Value (Unit: Points)					Correction of Deduction Value (Unit: Points)		
	Level I	Level II	Level III	Level IV	Level V	Level II	Level III	Level IV
Level III	0	20	30	-	-	Fewer questions +0		
Level IV	0	25	35	50	-	More questions +5		
Level V	0	35	40	60	100	Many questions +10		

Note: When the quality control index is between two categories, the appropriate value is taken according to its quality.

According to the "Technical Condition Assessment Standards for Highway Bridges", the scoring equation for the construction quality of mega bridges across the Yellow River is as follows:

$$P_l'' = 100 - \sum_{x=1}^{k} U_x \tag{1}$$

when $x = 1$:

$$U_1 = DP_{a1} \tag{2}$$

when $x \geq 2$:

$$U_x = \frac{DP_{ab}}{100 \times \sqrt{x}} \times \left(100 - \sum_{y-1}^{x-1} U_y\right) \tag{3}$$

when $DP_{ab} = 100$:

$$P_l'' = 0 \tag{4}$$

where P_l'' is the score of process l, an indicator of bridge construction quality category a; k is the number of categories of indicators for which points were deducted for Category a process l indicators; U, x and y are the introduced variables; a is the level of construction

process; b is a type a process l detection indicator; and DP_{ab} is the deducted points value of class a process l indicators of the class b detection indicators, calculated according to the deducted points value of the various detection indicators of the components [31]. The deducted points value was taken according to the provisions of Table 2.

According to the "Highway Bridge Technical Condition Assessment Standards" [31], the technical conditions of the bridge classification boundaries should be in accordance with Tables 3 and 4.

Table 3. Bridge construction quality condition classification boundaries.

Rating	Construction Quality Level (Unit: Points)				
	Level I	**Level II**	**Level III**	**Level IV**	**Level V**
R	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)

Table 4. Bridge construction quality evaluation index scoring criteria (unit: points).

Evaluation Indicators	Level I	Level II	Level III	Level IV	Level V
B_1	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_2	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_3	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_4	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_5	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_6	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_7	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_8	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_9	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_{10}	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_{11}	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_{12}	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_{13}	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_{14}	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_{15}	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_{16}	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_{17}	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_{18}	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)
B_{19}	[90,100]	[78,90)	[60,78)	[40,60)	[0,40)

3. Bridge Construction Quality Evaluation Method and Evaluation Process

3.1. CRITIC Method

The criteria importance through intercriteria correlation (CRITIC) method uses correlation coefficients and standard deviations to determine the objective weights of indicators, which takes into account the conflicts and differences between indicators and allows for a more comprehensive setting of weights. It is generally used in concert with the matter–element extension evaluation (MEE) method. The basic calculation process is as follows:

(1) Normalization of the correlation matrix and calculation of the comparative strength of indicators

Assuming that there are t evaluation levels and m evaluation indicators for each object, the data in the correlation matrix $\left(K_{jk}\right)_{m\times t}$ are normalized to the range [0,1] to create the normalization matrix $\left(r_{jk}\right)_{m\times t}$. The comparative intensity, V_j, of each evaluation indicator is as follows [32]:

$$V_j = \frac{\sigma_j}{\overline{r}_j}(j = 1, 2, \ldots, m) \tag{5}$$

where V_j is the coefficient of variation of indicator j, also known as the standard deviation coefficient; σ_j is the standard deviation of item j; and $\overline{r}_j$ is the mean of item j.

The matrix normalization formula is as follows:

$$r_{jk} = \frac{K_{jk} - \min K_{jk}}{\max K_{jk} - \min K_{jk}} \tag{6}$$

(2) Calculation of the information content of evaluation indicators

To calculate the amount of information of the indicators, the objective weights of each indicator were measured in a combination of contrast intensity and conflict. Let C_j denote the amount of information contained in j evaluation indicator, then C_j can be expressed as follows:

$$C_j = V_j \sum_{j=1}^{m} \left(1 - h_{jj'}\right) \tag{7}$$

The conflicting quantitative indicator values for j indicator and the other indicators are as follows:

$$\sum_{j=1}^{m} \left(1 - h_{jj'}\right) \tag{8}$$

$$h_{jj'} = \frac{\sum_{k=1}^{t} \left(r_{jk} - \overline{r}_j\right)\left(r_{j'k} - \overline{r}_{j'}\right)}{\sqrt{\sum_{k=1}^{t} \left(r_{jk} - \overline{r}_j\right)^2 \sum_{k=1}^{t} \left(r_{j'k} - \overline{r}_{j'}\right)^2}} \tag{9}$$

where r_{jk} and $r_{j'k}$ are the standardized correlation values of the indicators j and j' of evaluation object k, and $\overline{r}_j$ and $\overline{r}_{j'}$ are the standardized correlation mean values of the indicators j and j' of evaluation level t.

(3) Calculation of indicator weights

The weight values of each construction quality evaluation index are as follows:

$$W_j = \frac{C_j}{\sum_{j=1}^{m} C_j} \tag{10}$$

3.2. IAHP Method

In this paper, the improved analytic hierarchy process (IAHP) method is used to calculate the subjective weights of each index in the construction quality control evaluation process. The hierarchical analysis method has strong advantages in solving multi-factor problems in the system, mainly by splitting factors into different levels and establishing a hierarchical relationship model between factors to obtain the subjective weights of each factor. In this paper, we adopt the theory of four scales to construct the judgment matrix, so as to reduce the ambiguity in judging the importance of evaluation indexes. The scales are defined in Table 5.

(1) Creation of judgment matrices and antisymmetric matrices

Table 5. Scale of proportions.

Element	Assignment	Meaning
$a_{jj'}$	1	At a given level, indicator j is equally important as indicator j'
	2	At a given level, indicator j is slightly quite important than indicator j'
	3	At a given level, indicator j is slightly more important than indicator j'
	4	At a given level, indicator j is very important compared with indicator j'
		$a_{j'j} = 1/a_{jj'}$

By comparing the m evaluation indexes with each other, a comparative judgment matrix $A = \left(a_{jj'}\right)_{m\times m}$ can be obtained. The antisymmetric matrix, B, of the judgment matrix A, matrix B, and matrix element $b_{jj'}$ can be calculated through the following equation:

$$B = \lg A, b_{jj'} = -b_{j'j} \tag{11}$$

(2) Establishment of the Optimal Transfer Matrix

The optimal transfer matrix C of the antisymmetric matrix B, characterized by the elements $c_{jj'}$, is constructed as follows:

$$c_{jj'} = \frac{1}{m}\sum_{g=1}^{n}\left(b_{jg} - b_{j'g}\right) \tag{12}$$

(3) Establishment and normalization of the proposed goodness-of-fit consistency matrix

The fitted consistent matrix A^* of the judgment matrix A, comprising elements $a^*_{jj'}$, can be constructed by the following equation:

$$a^*_{jj'} = 10^{c_{jj'}} \tag{13}$$

The relative weight values between the factors at each level are calculated. The proposed optimal consistent matrix A^* is normalized by column, and the normalized matrix elements $\overline{a}^*_{jj'}$ are calculated as follows:

$$\overline{a}^*_{jj'} = \frac{a^*_{jj'}}{\sum_{j=1}^{m} a^*_{jj'}} \tag{14}$$

(4) Sum vector computation

The sum vector w_j is obtained by summing the rows:

$$w_j = \sum_{j=1}^{m} \overline{a}^*_{jj'} \tag{15}$$

(5) Calculation of weight vectors

We normalize the sum vector to obtain the weight vector $\overline{W}_j$:

$$\overline{W}_j = \frac{w_j}{\sum_{j=1}^{m} w_j} \tag{16}$$

Consistency checking is generally required after calculation of the indicator weight vectors using the IAHP method. The purpose of the consistency check is to ensure that the evaluation indicators are consistent with each other. In this study, the concept of optimal matrix was used to improve the traditional hierarchical analysis method. The method can make the evaluation results automatically meet the consistency requirements.

3.3. Portfolio Empowerment Method

The combined weighting method links the subjective weights of each index with the objective weights. The weights of the indicators calculated by the combined assignment can take into account the advantages of the two methods and complement the defects of both subjective and objective assignments, making the weight vector of each indicator more scientific. Before combining the weights, we need to check the consistency of the

weights obtained by the two methods. Only the weights that pass the consistency test can be combined. The calculation process of the combined weighting is roughly as follows:

(1) Consistency check

Characterize the subjective weight vector by $sw(i)$, the objective weight vector by $ow(i)$, and the combination weight by $cw(i)$. The results of the weights calculated by the two assignment methods for each evaluation index were ranked. Here, $sw(i)\prime$ is the sorted value of the weight transformation of $sw(i)$, and $ow(i)\prime$ is the sorted value of the weight transformation of $ow(i)$. The ranking values are expressed from 1 to m. The ranking value of that with the largest evaluation index weight is 1, and that with the smallest evaluation index weight is m to calculate.

The Spearman's consistency coefficient is a reflection of the correlation between the two sets of variables and is denoted by ρ. In this paper, ρ is used to reflect the agreement between the weights calculated by IAHP method and CRITIC method [33]. The calculation equation is as follows:

$$\rho = 1 - \frac{6}{m(m^2-1)} \sum_{j=1}^{m} [sw(i)\prime - ow(i)\prime]^2 \tag{17}$$

ρ takes values in the range [−1,1]. When $\rho \in [-1, 0)$, it indicates that there is no consistency between the weights calculated by the two methods. When $\rho = 0$, the correlation between the weights calculated by the two methods is 0. When $\rho \in (0, 1]$, it indicates that there is consistency between the weights calculated by the two methods, and a combined assignment can be performed.

(2) Calculate the weight vector after the combination of weighting

This step aims to make the value of the combination weights reflect the subjective and objective evaluation information as much as possible. Based on the principle of minimum discriminative information [34], the combination weights should be made as close as possible to the subjective and objective weights to achieve the function in Equation (18):

$$\begin{cases} \min F = \sum\limits_{j=1}^{m} \left[cw(i) \ln \frac{cw(i)}{sw(i)} \right] + \sum\limits_{j=1}^{m} \left[cw(i) \ln \frac{cw(i)}{ow(i)} \right] \\ s.t. \sum\limits_{j=1}^{m} cw(i); cw(i) > 0 \end{cases} \tag{18}$$

Solving the above problem using the Lagrange multiplier method yields the following:

$$cw(i) = \frac{[sw(i) \times ow(i)]^{0.5}}{\sum\limits_{j=1}^{m} [sw(i) \times ow(i)]^{0.5}} \tag{19}$$

3.4. TOPSIS Method

The technique for order preference by similarity to an ideal solution (TOPSIS) method, also known as the multi-attribute decision method for approximating ideal points, is a comprehensive evaluation technique that analyzes and judges based on distance. It evaluates results by calculating the distance between each evaluation object and the optimal solution and the worst solution, then ranking their relative proximity to the idealized target. The optimal solution of the evaluation result must be the solution closest to the optimal solution and the solution farthest from the worst solution [35]. The TOPSIS method has no clear restrictions and requirements in terms of the number of evaluation indicators, sample content, and data, and it can analyze the situation of each indicator comprehensively, reflecting the overall situation and having universal applicability. Therefore, this paper adopted this method to analyze the construction quality of the mega bridge across the Yellow River. The specific steps are as follows:

(1) Construct the decision attribute matrix. Assume that a system to be evaluated has n objects to be evaluated $A = \{A_1, A_2, \ldots, A_n\}$; each object to be evaluated has m evaluation indicators $B = \{B_1, B_2, \ldots, B_m\}$; its evaluation value constitutes the decision matrix $E = (x_{ij})_{m \times n}$.

The normalized matrix $F = (X_{ij})_{m \times n}$ is obtained after normalizing the original data matrix using the polarization method;

(2) Calculate the weighted normalized decision matrix. The values of the weighted normalized decision matrix are as follows:

$$H_{ij} = X_{ij} \times w_j \tag{20}$$

where X_{ij} is the value of each evaluation index score after standardization and w_j is the weight value of each evaluation index calculated by the combined weighting method;

(3) Determine the positive and negative ideal solutions. The positive ideal solution, H^+, consists of the maximum value in each column in H, i.e.,

$$H^+ = \{\max H_{i1}, \max H_{i2}, \ldots \max H_{in}\} \tag{21}$$

The negative ideal solution, H^-, consists of the smallest value in each column in H, i.e.,

$$H^- = \{\min H_{i1}, \min H_{i2}, \ldots \min H_{in}\} \tag{22}$$

(4) Calculate the distance to the positive ideal point S_i^+ and the distance to the negative ideal point S_i^- for each solution:

$$S_i^+ = \sqrt{\sum_{j=1}^{m} \left(\max H_{ij} - H_{ij}\right)^2}, 1 \le i \le n \tag{23}$$

$$S_i^- = \sqrt{\sum_{j=1}^{m} \left(\min H_{ij} - H_{ij}\right)^2}, 1 \le i \le n \tag{24}$$

(5) Calculate the relative proximity of the alternative solution to the positive ideal solution. The relative closeness of the alternative to the positive ideal solution, G_i, is calculated as follows:

$$G_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{25}$$

In the above equation, $G_i \to 1$ means that the evaluation object is closer to the positive ideal solution, and $G_i \to 0$ means that the evaluation object is closer to the negative ideal solution.

3.5. Combinatorial Weighting Method–TOPSIS System Evaluation Process

(1) Firstly, according to various factors affecting bridge construction quality, suitable evaluation indexes were selected to establish a three-layer mega bridge across the Yellow River construction quality evaluation index system. The scoring value of each construction process evaluation index was calculated by the specification "Technical Condition Assessment Standard for Highway Bridges;"

(2) Objective weight values were calculated using the CRITIC method. Firstly, the scoring values of each construction process evaluation index obtained in the previous step were standardized. The means and standard deviations of the standardized data were obtained, and the comparison intensity was calculated according to Equation (5). The weight values were calculated according to Equations (6)–(9);

(3) Subjective weight values were calculated using the IAHP method. A two-by-two comparison of each evaluation index was performed to obtain the comparison judgment matrix. According to Equations (11)–(13), the antisymmetric matrix, optimal transfer matrix, and proposed optimal consistent matrix were calculated step by step, and the

proposed optimal consistent matrix was normalized. Finally, the subjective weight values were calculated using Equations (15) and (16);

(4) The combined assignment method enables combination of the advantages of subjective assignment and objective assignment, and the subjective and objective weight values obtained in steps (2) and (3) are brought into Equation (18) to obtain the final combination weight;

(5) TOPSIS method evaluation. After the weight values were calculated through steps (2)–(4), the final evaluation of bridge construction quality was performed according to the TOPSIS method. After normalizing the scoring criteria of the construction quality evaluation index of the mega bridge across the Yellow River, the weighted decision matrix of the scoring criteria was obtained according to Equation (20). According to Equations (21) and (22), positive and negative ideal solutions are obtained. Then, from Equations (23) and (24), the distance values of each solution to the positive and negative ideal solutions are calculated. Finally, the relative closeness interval of each evaluation category is calculated by Equation (25). Based on the normalized data of the evaluation index scores, the above steps are repeated to calculate the relative closeness of the construction quality of the mega bridge across the Yellow River; the final construction quality evaluation category is obtained by judging the interval in which it is located.

4. Engineering Example Calculation

4.1. Background of the Project

The research content of this paper is based on a highway bridge crossing the Yellow River. The main bridge section adopted steel–hybrid combination girders; the main bridge hole span arrangement is (6 × 100 + 6 × 100 + 6 × 100 + 6 × 100 + 6 × 100 + 6 × 100) m; the total length is 3600 m; and the bridge width is 2 × 16.6 m. The completed effect of the bridge is shown in Figure 3. The lower structure pier adopted solid section vase piers; the main pier top section size is 9.0 × 4.0 m; the bottom section size is 5.5 × 4.0 m; the waterfront surface was made into a round end shape to reduce water resistance. The main pier was constructed with a climbing mold; the main pier bearing platform in water is a deep-water bearing platform, which was cast via a steel cofferdam scheme. The pile foundation adopted bored piles. The overall construction technology is mature. The main girder of the superstructure adopted steel–hybrid combination girders, consisting of a slotted steel longitudinal girder and small longitudinal girder to form a plane girder lattice, and on which the concrete deck plate was combined to form a single box and single chamber box-girder section. The top width of the main girder is 16.6 m, the bottom width is 8.1 m, the cantilever length is 3.05 m, and the height of the main girder is 5.0 m. The superstructure adopted a single-box single-chamber steel–composite girder section, and the construction of the combined steel girder bridge was carried out in steps with the concrete deck slab. The steel girders were first set in place, and then the deck slab was constructed. The deck slab was then constructed using the steel girders as the support platform for the cast-in-place operation or precast slab-laying work. The steel box-girder erection method was step jacking in the water area + step jacking in the beach area. During the finite bridge element modeling analysis and structural system reliability analysis, it was found that bridge construction stage 9, construction stage 59, construction stage 67, and construction stage 65 were prone to failure [30]. Meanwhile, during the bridge construction quality management process, insufficient concrete vibrating, construction in windy weather, and inconsistency between construction site and design conditions were identified.

By visiting the construction site of the project, checking the relevant information of the project department and the construction record situation, all the relevant data needed for the calculation of this paper were selected.



Figure 3. The completed mega bridge across the Yellow River.

4.2. Determine the Bridge Construction Quality Control Index Score Value

According to Table 2 and Equations (1)–(4), the construction quality evaluation index score of the mega bridge across the Yellow River was calculated; the results are shown in Table 6.

Table 6. Construction quality control index score value of the special bridge across the Yellow River (unit: points).

Indicator	Rating	Indicator	Rating	Indicator	Rating	Indicator	Rating
B_1	86	B_2	77	B_3	84	B_4	70
B_5	63	B_6	83	B_7	61	B_8	82
B_9	75	B_{10}	88	B_{11}	67	B_{12}	87
B_{13}	84	B_{14}	66	B_{15}	67	B_{16}	64
B_{17}	69	B_{18}	65	B_{19}	71		

4.3. CRITIC Method to Calculate Evaluation Index Weights

The quality control index score values in the above table were standardized to obtain the standardized matrix:

$$\begin{bmatrix} 0.490 & 1 & 0.366 & 0.106 & 0 \\ 0.380 & 0.855 & 1 & 0.285 & 0 \\ 0.373 & 1 & 0.373 & 0.108 & 0 \\ 0.106 & 0.307 & 1 & 0.265 & 0 \\ 0 & 0.227 & 1 & 0.589 & 0.065 \\ 0.375 & 1 & 0.432 & 0.125 & 0 \\ 0 & 0.255 & 1 & 0.833 & 0.159 \\ 0.380 & 1 & 0.501 & 0.145 & 0 \\ 0.278 & 0.635 & 1 & 0.278 & 0 \\ 0.680 & 1 & 0.357 & 0.103 & 0 \\ 0 & 0.201 & 1 & 0.295 & -0.049 \\ 0.577 & 1 & 0.362 & 0.105 & 0 \\ 0.373 & 1 & 0.373 & 0.108 & 0 \\ 0 & 0.205 & 1 & 0.353 & -0.026 \\ 0 & 0.201 & 1 & 0.295 & -0.049 \\ 0 & 0.217 & 1 & 0.498 & 0.030 \\ 0.081 & 0.263 & 1 & 0.263 & 0 \\ 0 & 0.210 & 1 & 0.420 & 0 \\ 0.133 & 0.356 & 1 & 0.267 & 0 \end{bmatrix}$$

Each column is the same level and each row is the same evaluation index.

The comparative intensity, V_j, of each evaluation index was obtained according to Equation (5) as shown in Table 7.

Table 7. Contrast intensity, V_j (dimensionless).

Indicator	Mean Value $\bar{r}_j$	Standard Deviation σ_j	Contrast Intensity V_j
B_1	0.3925	0.39	0.9976
B_2	0.4143	0.50	0.8219
B_3	0.3881	0.37	1.0460
B_4	0.3914	0.34	1.1668
B_5	0.4168	0.38	1.1077
B_6	0.3861	0.39	0.9993
B_7	0.4400	0.45	0.9794
B_8	0.3858	0.41	0.9521
B_9	0.3866	0.44	0.8824
B_{10}	0.4136	0.43	0.9660
B_{11}	0.4216	0.29	1.4573
B_{12}	0.3998	0.41	0.9782
B_{13}	0.3881	0.37	1.0460
B_{14}	0.4178	0.31	1.3638
B_{15}	0.4216	0.29	1.4573
B_{16}	0.4144	0.35	1.1872
B_{17}	0.3964	0.32	1.2339
B_{18}	0.4151	0.33	1.2732
B_{19}	0.3869	0.35	1.1016

The amount of information of indicators calculated according to Equations (6)–(8) is shown in Table 8.

Table 8. Indicator information calculations (dimensionless).

Indicator	Quantitative Index Values	Contrast Intensity V_j	Amount of Information C_j
B_1	10.8222	0.9976	10.7962
B_2	4.9439	0.8219	4.0634
B_3	10.1068	1.0460	10.5717
B_4	6.3079	1.1668	7.3602
B_5	8.6459	1.1077	9.5769
B_6	9.4084	0.9994	9.4023
B_7	10.5537	0.9794	10.3361
B_8	8.6343	0.9521	8.2208
B_9	4.8620	0.8824	4.2904
B_{10}	12.1067	0.9660	11.6946
B_{11}	6.9754	1.4573	10.1654
B_{12}	11.3705	0.9782	11.1222
B_{13}	10.1068	1.0460	10.5717
B_{14}	7.2319	1.3638	9.8627
B_{15}	6.9754	1.4573	10.1654
B_{16}	8.0302	1.1872	9.5331
B_{17}	6.6266	1.2339	8.1769
B_{18}	7.5727	1.2732	9.6417
B_{19}	5.9768	1.1016	6.5842

The obtained judgment matrix was brought into the CRITIC method calculation equation to obtain each indicator layer and the total weight value $ow(i)$:

Bored pile construction: [0.425, 0.160, 0.416]

Cofferdam construction: [0.279, 0.364, 0.357]

Bridge pier construction: [0.452, 0.360, 0.188]

Superstructure construction: [0.160, 0.139, 0.152, 0.145, 0.135, 0.139, 0.130]

Ancillary works construction: [0.335, 0.395, 0.270]

Total weight value: [0.0627, 0.0236, 0.0614, 0.0428, 0.0556, 0.0546, 0.0600, 0.0478, 0.0249, 0.0679, 0.0591, 0.0646, 0.0614, 0.0573, 0.0591, 0.0554, 0.0475, 0.0560, 0.0383].

4.4. IAHP Method to Calculate the Evaluation Index Weights

According to Table 1, a two-by-two comparison of the five evaluation indicators at the criterion level of the bridge construction quality control evaluation system was conducted to obtain the judgment matrix shown below.

The judgment matrix for the main process index layer of bridge construction is as follows:

$$A_1 = \begin{bmatrix} 1 & 3 & 2 & 0.33 & 2 \\ 0.33 & 1 & 0.5 & 0.33 & 0.5 \\ 0.5 & 2 & 1 & 0.33 & 2 \\ 3 & 3 & 3 & 1 & 3 \\ 0.5 & 2 & 0.5 & 0.33 & 1 \end{bmatrix}$$

The indicator layer judgment matrix for bored infill piles is as follows:

$$A_2 = \begin{bmatrix} 1 & 2 & 3 \\ 0.5 & 1 & 2 \\ 0.33 & 0.5 & 1 \end{bmatrix}$$

The cofferdam construction indicator layer judgment matrix is as follows:

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

The bridge pier construction index layer judgment matrix is as follows:

$$A_4 = \begin{bmatrix} 1 & 0.5 & 0.5 \\ 2 & 1 & 0.5 \\ 3 & 2 & 1 \end{bmatrix}$$

The superstructure construction index layer judgment matrix is as follows:

$$A_5 = \begin{bmatrix} 1 & 2 & 0.33 & 0.33 & 0.33 & 0.5 & 2 \\ 0.5 & 1 & 0.25 & 0.25 & 0.25 & 0.33 & 0.33 \\ 3 & 4 & 1 & 1 & 1 & 2 & 3 \\ 3 & 4 & 1 & 1 & 1 & 2 & 3 \\ 2 & 3 & 0.5 & 0.5 & 0.5 & 1 & 2 \\ 0.5 & 3 & 0.33 & 0.33 & 0.33 & 0.5 & 1 \\ 0.5 & 2 & 0.25 & 0.25 & 0.25 & 0.25 & 0.5 \end{bmatrix}$$

The adjunct construction index layer judgment matrix is as follows:

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

According to Equation (11), the antisymmetric matrix of each judgment matrix was obtained by solving the following:

$$B_1 = \begin{bmatrix} 0 & 0.477 & 0.301 & -0.477 & 0.301 \\ -0.477 & 0 & -0.301 & -0.477 & -0.301 \\ -0.301 & 0.301 & 0 & -0.477 & 0.301 \\ 0.477 & 0.477 & 0.477 & 0 & 0.477 \\ -0.301 & 0.301 & -0.301 & -0.477 & 0 \end{bmatrix}$$

$$B_2 = \begin{bmatrix} 0 & 0.301 & 0.477 \\ -0.301 & 0 & 0.301 \\ -0.477 & -0.301 & 0 \end{bmatrix}$$

$$B_3 = \begin{bmatrix} 0 & -0.301 & -0.301 \\ 0.301 & 0 & -0.301 \\ 0.301 & 0.301 & 0 \end{bmatrix}$$

$$B_4 = \begin{bmatrix} 0 & -0.301 & -0.477 \\ 0.301 & 0 & -0.301 \\ 0.477 & 0.301 & 0 \end{bmatrix}$$

$$B_5 = \begin{bmatrix} 0 & 0.301 & -0.477 & -0.477 & 0.301 & 0.301 & 0.301 \\ -0.301 & 0 & -0.602 & -0.602 & -0.477 & -0.477 & -0.301 \\ 0.477 & 0.602 & 0 & 0 & 0.301 & 0.477 & 0.602 \\ 0.477 & 0.602 & 0 & 0 & 0.301 & 0.477 & 0.602 \\ 0.301 & 0.477 & -0.301 & -0.301 & 0 & 0.301 & 0.602 \\ -0.301 & 0.477 & -0.477 & -0.477 & -0.301 & 0 & 0.301 \\ -0.301 & 0.301 & -0.602 & -0.602 & -0.602 & -0.301 & 0 \end{bmatrix}$$

$$B_6 = \begin{bmatrix} 0 & -0.301 & 0 \\ 0.301 & 0 & 0.301 \\ 0 & -0.301 & 0 \end{bmatrix}$$

According to Equation (12), the optimal transfer matrix of the antisymmetric matrix was solved to obtain the following:

$$C_1 = \begin{bmatrix} 0 & 0.432 & 0.156 & -0.260 & 0.276 \\ -0.432 & 0 & -0.276 & -0.693 & -0.156 \\ -0.156 & 0.276 & 0 & -0.417 & 0.120 \\ 0.261 & 0.693 & 0.417 & 0 & 0.537 \\ -0.276 & 0.156 & -0.120 & -0.537 & 0 \end{bmatrix}$$

$$C_2 = \begin{bmatrix} 0 & 0.259 & 0.519 \\ -0.259 & 0 & 0.259 \\ -0.519 & -0.259 & 0 \end{bmatrix}$$

$$C_3 = \begin{bmatrix} 0 & -0.201 & -0.401 \\ 0.201 & 0 & -0.201 \\ 0.401 & 0.201 & 0 \end{bmatrix}$$

$$C_4 = \begin{bmatrix} 0 & -0.259 & -0.519 \\ 0.259 & 0 & -0.259 \\ 0.519 & 0.259 & 0 \end{bmatrix}$$

$$C_5 = \begin{bmatrix} 0 & 0.344 & -0.402 & -0.402 & -0.204 & -0.061 & -0.251 \\ -0.344 & 0 & -0.746 & -0.746 & -0.549 & -0.283 & -0.093 \\ 0.402 & 0.746 & 0 & 0 & 0.197 & 0.463 & 0.652 \\ 0.402 & 0.746 & 0 & 0 & 0.197 & 0.463 & 0.652 \\ 0.204 & 0.549 & -0.197 & -0.197 & 0 & 0.265 & 0.455 \\ -0.061 & 0.283 & -0.463 & -0.463 & -0.265 & 0 & 0.190 \\ -0.251 & 0.093 & -0.652 & -0.652 & -0.455 & -0.190 & 0 \end{bmatrix}$$

$$C_6 = \begin{bmatrix} 0 & -0.301 & 0 \\ 0.301 & 0 & 0.301 \\ 0 & -0.301 & 0 \end{bmatrix}$$

Each of the proposed agreement matrices was constructed according to Equation (13) as follows:

$$A_1^* = \begin{bmatrix} 1 & 2.702 & 1.431 & 0.548 & 1.888 \\ 0.370 & 1 & 0.530 & 0.203 & 0.699 \\ 0.699 & 1.888 & 1 & 0.383 & 1.320 \\ 1.825 & 4.931 & 2.612 & 1 & 3.446 \\ 0.530 & 1.431 & 0.758 & 0.290 & 1 \end{bmatrix}$$

$$A_2^* = \begin{bmatrix} 1 & 1.817 & 3.302 \\ 0.550 & 1 & 1.817 \\ 0.303 & 0.550 & 1 \end{bmatrix}$$

$$A_3^* = \begin{bmatrix} 1 & 0.630 & 0.397 \\ 1.587 & 1 & 0.630 \\ 2.520 & 1.587 & 1 \end{bmatrix}$$

$$A_4^* = \begin{bmatrix} 1 & 0.550 & 0.303 \\ 1.817 & 1 & 0.550 \\ 3.302 & 1.817 & 1 \end{bmatrix}$$

$$A_5^* = \begin{bmatrix} 1 & 2.208 & 0.397 & 0.397 & 0.624 & 1.150 & 1.781 \\ 0.453 & 1 & 0.180 & 0.180 & 0.283 & 0.521 & 0.807 \\ 2.521 & 5.568 & 1 & 1 & 1.575 & 2.901 & 4.491 \\ 2.521 & 5.568 & 1 & 1 & 1.575 & 2.901 & 4.491 \\ 1.601 & 3.536 & 0.635 & 0.635 & 1 & 1.842 & 2.852 \\ 0.869 & 1.919 & 0.345 & 0.345 & 0.543 & 1 & 1.548 \\ 0.561 & 1.240 & 0.223 & 0.223 & 0.351 & 0.646 & 1 \end{bmatrix}$$

$$A_6^* = \begin{bmatrix} 1 & 0.5 & 1 \\ 2 & 1 & 2 \\ 1 & 0.5 & 1 \end{bmatrix}$$

According to Equations (14)–(16), the weight vectors of the criterion layer and the indicator layer were calculated as [0.2261, 0.0837, 0.1580, 0.4126], [0.5396, 0.2970, 0.1634], [0.1958, 0.3108, 0.4934], [0.1634, 0.2970, 0.5396], [0.1050, 0.0475, 0.2646, 0.2646, 0.1681, 0.0912, 0.0589], and [0.25, 0.5, 0.25].

The calculated $sw(i)$ values of each evaluation index are shown in Table 9.

Table 9. Value of each index $sw(i)$ (dimensionless).

Guideline Layer	Bored Pile Construction	Cofferdam Construction	Bridge Pier Construction	Superstructure Construction	Ancillary Works Construction	Total Weight Value $sw(i)$
	0.2261	**0.0837**	**0.1580**	**0.4126**	**0.1197**	
B_1	0.5396					0.1220
B_2	0.2970					0.0671
B_3	0.1634					0.0369
B_4		0.1958				0.0164
B_5		0.3108				0.0260
B_6		0.4934				0.0413
B_7			0.1634			0.0258
B_8			0.2970			0.0469
B_9			0.5396			0.0852
B_{10}				0.1050		0.0433
B_{11}				0.0475		0.0196
B_{12}				0.2646		0.1092
B_{13}				0.2646		0.1092
B_{14}				0.1681		0.0693
B_{15}				0.0912		0.0376
B_{16}				0.0589		0.0243
B_{17}					0.25	0.0299
B_{18}					0.5	0.0599
B_{19}					0.25	0.0299

4.5. Evaluation of the Reasonableness of the Weights

By bringing the calculated $ow(i)$ and $sw(i)$ values into Equations in Section 3.3 of this paper, the ranking results of the weights calculated within the subjective assignment method and the objective assignment method for each evaluation index were calculated, respectively, as shown in Table 10.

Table 10. Ranking results of the weight of each evaluation index (unit: position).

Method	B_1	B_2	B_3	B_4	B_5
IAHP	1	6	12	19	15
CRITIC	3	19	4	16	11
Method	B_6	B_7	B_8	B_9	B_{10}
IAHP	10	16	8	4	9
CRITIC	13	6	14	18	1
Method	B_{11}	B_{12}	B_{13}	B_{14}	B_{15}
IAHP	18	2	2	5	11
CRITIC	7	2	4	9	7
Method	B_{16}	B_{17}	B_{18}	B_{19}	
IAHP	17	13	7	13	
CRITIC	12	15	10	17	

According to Equation (17), $\rho = 0.229825$ was calculated. The weights obtained by the two above methods satisfy the consistency requirement; therefore, the combination of the weights can be assigned.

4.6. Combined Empowerment

According to Equation (18), the combination weight value, $cw(i)$, of each evaluation index was obtained after calculation, as shown in Table 11.

Table 11. Each indicator $cw(i)$ value (dimensionless).

Guideline Layer	Bored Pile Construction	Cofferdam Construction	Bridge Pier Construction	Superstructure Construction	Ancillary Works Construction	Total $cw(i)$
B_1	0.500					0.0921
B_2	0.228					0.0419
B_3	0.272					0.0501
B_4		0.236				0.0279
B_5		0.340				0.0400
B_6		0.424				0.0500
B_7			0.296			0.0414
B_8			0.356			0.0498
B_9			0.347			0.0485
B_{10}				0.135		0.0571
B_{11}				0.085		0.0358
B_{12}				0.209		0.0884
B_{13}				0.204		0.0862
B_{14}				0.157		0.0663
B_{15}				0.118		0.0496
B_{16}				0.091		0.0386
B_{17}					0.291	0.0397
B_{18}					0.447	0.0609
B_{19}					0.261	0.0356

4.7. TOPSIS Method for Construction Quality Evaluation

The data in Table 4 were normalized to establish the initial evaluation matrix A. Due to the document width limitation, A^T is used here to represent the A matrix more intuitively.

$$A = \left(A^T\right)^T = \begin{bmatrix} 1 & 0.9 & 0.78 & 0.6 & 0.4 & 0 \\ 1 & 0.9 & 0.78 & 0.6 & 0.4 & 0 \\ 1 & 0.9 & 0.78 & 0.6 & 0.4 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0.9 & 0.78 & 0.6 & 0.4 & 0 \\ 1 & 0.9 & 0.78 & 0.6 & 0.4 & 0 \end{bmatrix}^T$$

According to Equation (20), the weighted decisionalization matrix, B, was obtained as follows:

$$B = \left(B^T\right)^T = \begin{bmatrix} 0.0921 & 0.0829 & 0.0718 & 0.0552 & 0.0368 & 0 \\ 0.0419 & 0.0377 & 0.0327 & 0.0251 & 0.0168 & 0 \\ 0.0501 & 0.0451 & 0.0391 & 0.0301 & 0.0201 & 0 \\ 0.0279 & 0.0251 & 0.0217 & 0.0167 & 0.0111 & 0 \\ 0.0400 & 0.0360 & 0.0312 & 0.0240 & 0.0160 & 0 \\ 0.0500 & 0.0450 & 0.0390 & 0.0300 & 0.0200 & 0 \\ 0.0414 & 0.0373 & 0.0323 & 0.0249 & 0.0166 & 0 \\ 0.0498 & 0.0448 & 0.0389 & 0.0299 & 0.0199 & 0 \\ 0.0485 & 0.0437 & 0.0378 & 0.0291 & 0.0194 & 0 \\ 0.0571 & 0.0514 & 0.0445 & 0.0343 & 0.0228 & 0 \\ 0.0358 & 0.0322 & 0.0279 & 0.0215 & 0.0143 & 0 \\ 0.0884 & 0.0796 & 0.0690 & 0.0530 & 0.0354 & 0 \\ 0.0862 & 0.0776 & 0.0672 & 0.0517 & 0.0345 & 0 \\ 0.0663 & 0.0597 & 0.0517 & 0.0398 & 0.0265 & 0 \\ 0.0496 & 0.0447 & 0.0387 & 0.0298 & 0.0198 & 0 \\ 0.0386 & 0.0348 & 0.0301 & 0.0232 & 0.0154 & 0 \\ 0.0397 & 0.0357 & 0.0310 & 0.0238 & 0.0159 & 0 \\ 0.0609 & 0.0548 & 0.0475 & 0.0366 & 0.0244 & 0 \\ 0.0356 & 0.0320 & 0.0278 & 0.0214 & 0.0142 & 0 \end{bmatrix}^T$$

From Equations (21) and (22), the positive and negative ideal solutions of the weighted decision matrix were obtained as [0.0921,0.0419,0.0501,0.0279,0.0400,0.0500,0.0414,0.0498, 0.0485,0.0571,0.0358,0.0884,0.0862,0.0663,0.0496,0.0386,0.0397,0.0609,0.0356] and [0,0,0,0,0,0, 0,0,0,0,0,0,0,0,0,0,0,0,0].

The distance between each evaluation object and the positive and negative ideal solutions, as well as the closeness to the positive ideal solution, were calculated according to Equations (23)–(25), and are shown in Tables 12–14.

Table 12. Positive ideal solution distance S_i^+ value (dimensionless).

Indicator Meaning	Calculated Values					
$\left(\max H_{ij} - H_{ij}\right)$	0	0.0092	0.0203	0.0368	0.0552	0.0921
	0	0.0042	0.0092	0.0168	0.0251	0.0419
	0	0.0050	0.0110	0.0201	0.0301	0.0501
	0	0.0028	0.0061	0.0111	0.0167	0.0279
	0	0.0040	0.0088	0.0160	0.0240	0.0400
	0	0.0050	0.0110	0.0200	0.0300	0.0500
	0	0.0041	0.0091	0.0166	0.0249	0.0414
	0	0.0050	0.0110	0.0199	0.0299	0.0498
	0	0.0049	0.0107	0.0194	0.0291	0.0485
	0	0.0057	0.0126	000228	0.0343	0.0571
	0	0.0036	0.0079	0.0143	0.0215	0.0358

Table 12. *Cont.*

Indicator Meaning	Calculated Values					
	0	0.0088	0.0194	0.0354	0.0530	0.0884
	0	0.0086	0.0190	0.0345	0.0517	0.0862
	0	0.0066	0.0146	0.0265	0.0398	0.0663
	0	0.0050	0.0109	0.0198	0.0298	0.0496
	0	0.0039	0.0085	0.0154	0.0232	0.0386
	0	0.0040	0.0087	0.0159	0.0238	0.0397
	0	0.0061	0.0134	0.0244	0.0366	0.0609
	0	0.0036	0.0078	0.0142	0.0214	0.0356
$\sum_{j=1}^{m}\left(\max H_{ij}-H_{ij}\right)^2$	0	0.0006	0.0027	0.0090	0.0203	0.0564

Table 13. Negative ideal solution distance, S_i^-, value (dimensionless).

Indicator Meaning	Calculated Values					
	−0.0921	−0.0829	−0.0718	−0.0552	−0.0368	0
	−0.0419	−0.0377	−0.0327	−0.0251	−0.0168	0
	−0.0501	−0.0451	−0.0391	−0.0301	−0.0201	0
	−0.0279	−0.0251	−0.0217	−0.0167	−0.0111	0
	−0.0400	−0.0360	−0.0312	−0.0240	−0.0160	0
	−0.0500	−0.0450	−0.0390	−0.0300	−0.0200	0
	−0.0414	−0.0373	−0.0323	−0.0249	−0.0166	0
	−0.0498	−0.0448	−0.0389	−0.0299	−0.0199	0
	−0.0485	−0.0437	−0.0378	−0.0291	−0.0194	0
$\left(\min H_{ij}-H_{ij}\right)$	−0.0571	−0.0514	−0.0445	−0.0343	−0.0228	0
	−0.0358	−0.0322	−0.0279	−0.0215	−0.0143	0
	−0.0884	−0.0796	−0.0690	−0.0530	−0.0354	0
	−0.0862	−0.0766	−0.0672	−0.0517	−0.0345	0
	−0.0663	−0.0597	−0.0517	−0.0398	−0.0265	0
	−0.0496	−0.0447	−0.0387	−0.0298	−0.0198	0
	−0.0386	−0.0348	−0.0301	−0.0232	−0.0154	0
	−0.0397	−0.0357	−0.0310	−0.0238	−0.0159	0
	−0.0609	−0.0548	−0.0475	−0.0366	−0.0244	0
	−0.0356	−0.0320	−0.0278	−0.0214	−0.0142	0
$\sum_{j=1}^{m}\left(\min H_{ij}-H_{ij}\right)^2$	0.0564	0.0457	0.0343	0.0203	0.0090	0

Table 14. Construction quality evaluation results of the special bridge across the Yellow River (dimensionless).

S_i^+	S_i^-	G_i
0	0.2375	1
0.0237	0.2137	0.9
0.0522	0.1852	0.78
0.0950	0.1425	0.6
0.1425	0.0950	0.4
0.2375	0	0

Then, the construction quality of the special bridge across the Yellow River was evaluated in the range of each grade, as shown in Table 15.

By multiplying the construction quality score values in Table 6 with the weights of each indicator, the weighted decision scores were obtained, as shown in Table 16.

Table 15. Construction quality evaluation grade of the special bridge across the Yellow River.

Evaluation Level	Indicator
Level I	$0.9 \leq G_i \leq 1$
Level II	$0.78 \leq G_i < 0.9$
Level III	$0.6 \leq G_i < 0.78$
Level IV	$0.4 \leq G_i < 0.6$
Level V	$0 \leq G_i < 0.4$

Table 16. Weighted decision-making score for construction quality of the special bridge across the Yellow River (unit: points).

Guideline Layer	Bored Pile Construction	Cofferdam Construction	Bridge Pier Construction	Superstructure Construction	Ancillary Works Construction	Total Score
B_1	43.007					7.9168
B_2	17.525					3.2260
B_3	22.876					4.2110
B_4		16.543				1.9498
B_5		21.398				2.5220
B_6		35.193				4.1479
B_7			18.085			2.5277
B_8			29.227			4.0849
B_9			26.032			3.6384
B_{10}				11.902		5.0234
B_{11}				5.686		2.3996
B_{12}				18.222		7.6907
B_{13}				17.153		7.2394
B_{14}				10.374		4.3783
B_{15}				7.877		3.3245
B_{16}				5.856		2.4715
B_{17}					20.099	2.7382
B_{18}					29.076	3.9612
B_{19}					18.558	2.5283

According to Equations (23)–(25), the distances S_i^+, S_i^-, closeness (G_i) of each evaluation object to the positive and negative ideal solutions, and the evaluation results were obtained, as shown in Table 17.

Table 17. Each construction process S_i^+, S_i^-, G_i calculation and evaluation results.

Construction Phase	S_i^+ Value	S_i^- Value	G_i Value	Evaluation Results
The whole bridge construction process	18.7287	13.0855	0.4113	Level IV
Bored pile construction	32.4748	26.0381	0.4450	Level IV
Cofferdam construction	23.1976	19.2715	0.4538	Level IV
Bridge pier construction	11.5904	13.6852	0.5414	Level IV
Superstructure construction	22.7985	18.8179	0.4522	Level IV
Ancillary works construction	13.8277	10.6298	0.4346	Level IV

The evaluation results showed that the construction quality evaluation results for the whole bridge construction process and the rest of the minor construction stages were Level IV. This means that there are problems with the bridge construction quality, the whole construction process needs to be monitored, and corresponding improvement measures need to be developed to follow up and re-evaluate the bridge construction quality in real time to ensure that the bridge construction can meet the use and design standards after completion.

By analyzing the results in Tables 16 and 17, it can be seen that the proportion of the influence of superstructure construction on the construction quality of the bridge in the whole construction stage is larger in the secondary indicators. Among the tertiary indicators, the weights of B_1 (axial deviation of piles), B_{12} (excessive deflection of the

leading edge of the guide beam), and B_{13} (excessive deflection of the leading edge of the cantilever (after the removal of the guide beam)) are larger in proportion to their influence on the quality of the construction of the bridge. In the literature [29], it is stated that pile axis deflection has a significant impact on the construction risk of bored piles. The literature [36] obtained the conclusion that main girder overturning and downward deflection have a large impact on the construction risk of bridge jacking after a series of studies. The literature [37] concluded that the construction process with the highest construction importance is the jacking construction process after analyzing the construction risk of steel-concrete composite girder bridges. This is basically consistent with the results analyzed in this paper, indicating that the CWM-TOPSIS theory proposed in this paper is more accurate in assigning weights to the index factors.

The results of the construction quality evaluation serve as a reference and reference for construction quality management. The quality management of engineering projects can be started from the following aspects:

(1) Personnel quality management: to improve the overall quality of the project through the management of all personnel involved in the project. The construction of the project involves a large number of personnel and complex roles, which requires the establishment of a sound personnel quality management system, which generally adopts the methods of training, publicity, supervision, and assessment to make the personnel firmly establish quality awareness;
(2) Raw material quality management: the quality management of raw materials is the basis of the quality management of the entire construction project. In construction, it is necessary to strictly establish a standardized and scientific raw material procurement system. At the same time, as should be clear for the construction materials management responsibilities, establish and improve the material test management and material inspection system. Ensure that all materials put into construction meet the specifications of the material quality requirements. Avoid the impact of unqualified materials on project quality from the source;
(3) Mechanical equipment quality management: indicators mainly include the following: whether the choice of equipment type meets the construction requirements, whether the mechanical equipment is regularly supervised and inspected, whether the use of mechanical equipment log is perfect, and whether the operator of each piece of machinery and equipment is responsible for the operation of the person and whether the requirements are clear. By controlling the above indicators, we can avoid the impact on the construction of the project caused by the age of the mechanical equipment and the errors in the process of installation, use and dismantling;
(4) Quality management of construction methods: before construction, each construction stage should be split and refined according to the construction drawings, and the construction technology that meets the actual project should be selected according to local conditions. Improve and optimize the construction methods by adopting new materials, new technologies, new techniques, and new equipment, and give priority to mature and advanced construction technologies;
(5) Site environment quality management: the construction site environment is mainly divided into natural environment, construction environment. Through the establishment of special environmental construction organization plan, the development of site environmental management measures to ensure the normal progress of construction.

5. Control Study

As a comparison, the construction quality of the special bridge across the Yellow River was evaluated using the standard elementary topologizable theory with the following procedure:

(1) Calculate the total correlation:

$$K_k(P_0) = \sum_{j=1}^{m} W_j K_k(x_j) \tag{26}$$

$K_k(P_0)$ is the correlation degree of the system to be evaluated, P_0, with respect to rank k, where W_j is the value of the weight corresponding to its correlation function. The W_j value is taken as the weight value obtained using the CRITIC method. The calculation results are as follows:

Quality correlation of bored pile construction: [−0.0392, −0.0506, −0.0382, 0.0876, −0.1077].
Quality correlation of cofferdam construction: [−0.0565, −0.0023, −0.0159, 0.0463, −0.0819].
Quality correlation of bridge pier construction: [−0.0496, −0.0050, −0.0012, 0.0371, −0.0690].
Quality correlation of superstructure construction: [−0.1340, −0.0018, −0.0033, 0.1628, −0.2501].
Quality correlation of ancillary works construction: [−0.0577, −0.0333, −0.0542, 0.0282, −0.0661].
Quality correlation of overall bridge: [−0.3370, −0.0083, −0.0339, −0.3621, 0.5747].

(2) Determine the evaluation level:

$$k_1 = \max\{k : K_k(P_0), k = 1, 2, \ldots, t\} \tag{27}$$

Thus, the target evaluation level is k_1. The evaluation results are presented in Table 18.

Table 18. Construction quality control evaluation level of the special bridge across the Yellow River.

Layers	Bored Pile Construction	Cofferdam Construction	Bridge Pier Construction	Superstructure Construction	Ancillary Works Construction	Overall Bridge
Evaluation Level	IV	IV	IV	IV	IV	V

By comparing the results of the calculation here and the evaluation results of TOPSIS theory, it can be seen that the results of the two calculations are basically the same, indicating that the CWM-TOPSIS theory used in this paper can be used for the evaluation of bridge construction quality control. However, the overall construction quality evaluation grade of the bridge calculated by using the standard object element topis theory is five, which is inconsistent with the actual situation of the field investigation. It can be seen that the CWM-TOPSIS theory used in this paper integrates subjective and objective factors, which can be more comprehensively assigned to the construction quality control indexes, and the evaluation accuracy is higher.

6. Conclusions

Evaluations of bridge construction quality are an important means to ensure the safe construction and normal use of bridges, and it is important to propose a reasonable and effective bridge construction quality evaluation method for the whole life cycle of bridges. This paper takes the construction of a highway bridge across the Yellow River as the background, combines the characteristics of the project and the requirements of construction quality control. It unites the respective advantages of the IAHP method and the CRITIC method and proposes the use of the CWM-TOPSIS theory for evaluating the construction quality of the bridge. Our principal conclusions were as follows:

(1) After the field investigation of the project, a three-level evaluation index system for bridge construction quality control was established according to the actual situation of bridge construction. The system contains five secondary indicators and 19 tertiary indicators. The five secondary indicators are drilled pile construction, cofferdam construction, pier construction, superstructure construction, and ancillary works construction. 19 tertiary indicators are: pile position axis is off, the deformation of shoring insertion, the mud density is too low/high, the cofferdam axis is off, the drainage is too early, the internal temperature of bearing construction is too high, the pier vertical is too large, the pier center position deviation is too large, the demolding is too early, the main girder axis is off, the synchronization accuracy deviation of

jacking equipment is too large, the deflection of the leading edge of guide beam is too large, and the deflection of the leading edge of cantilever after removal of the guide beam is too large, excessive internal force of the main girder section during jacking, excessive stress of the main girder after completion of the bridge, poor leveling of the bridge deck, insufficient thickness of the waterproof layer of the bridge deck, deviated installation of the railing/collision barrier, and poor leveling of the roadway;

(2) There are many uncertainties in the factors affecting the construction process of bridge engineering, which are difficult to describe quantitatively. In this paper, the combined assignment method combining CRITIC method and IAHP method is used to comprehensively assign the bridge construction quality control indexes. It not only makes up for the deviation of the single assignment method, but also improves the credibility of the evaluation results. Finally, using TOPSIS theory, the relative closeness of each control index is obtained. By judging the interval range where the closeness is located, the final construction quality evaluation category is obtained;

(3) In this paper, the method of combining combination assignment and TOPSIS theory is applied to the evaluation process of construction quality control of the Cross Yellow River Special Bridge. Taking the construction process of a bridge across the Yellow River as an example, the construction quality evaluation model is used for calculation and analysis. The calculation results show that the construction quality evaluation result of the bridge is level IV, and specific construction management measures need to be formulated for the bridge construction process. It is basically consistent with the actual situation of the bridge. It shows that the model proposed in this paper provides a new idea for the construction quality evaluation of bridge projects;

(4) The accuracy of the CWM-TOPSIS model proposed in this paper is proved again through the comparative study with the standard object element topologizable theory and the actual engineering situation. The model combines the advantages of CRITIC method, IAHP method and TOPSIS theory, with easy calculation and accurate results. And the analysis using this model can accurately find out where the construction quality problems lie, which provides a basis for the construction personnel to put forward the subsequent construction quality management measures, and also provides a new idea for the bridge construction quality control.

Due to the complexity of the bridge's structural form and the specificity of the construction environment, the management and control of the bridge construction quality is a very complex systematic problem. Although this paper explores the evaluation of the bridge construction quality control, there are still many issues that need to be studied and improved in depth due to the limited time and team level:

(1) Due to the different construction processes and construction techniques of different bridge types, a more comprehensive bridge construction quality evaluation system can be established for different construction techniques bridge structure forms, making the evaluation results more universal;

(2) Most of the evaluation indexes in the construction quality evaluation system of the Cross Yellow River Special Bridge established in this paper come from the construction site report and researching the relevant literature. The subsequent research process can be combined with BIM software to select evaluation indexes more objectively;

(3) In the whole life cycle of a bridge, its construction process is very important, but the quality problems in other stages will affect the service life of the bridge. In future research, we recommend that the research scope is expanded from the construction process to the whole life cycle of the bridge in order to establish a more detailed and diversified quality evaluation system. This will help to provide a basis to extend the life of the bridge and to protect people's lives and property safety.

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