The Scour Resistance of Piers based on CM-AHP Model Evaluation Methodology

Zhao Yuxiao, Wang Shuikang, Qi Yunpeng

Key Laboratory of Urban and Engineering Safety and Disaster Reduction, Ministry of Education, Beijing University of Technology, Beijing, China

Abstract: Foundation scouring is a significant form of bridge damage and has a high degree of suddenness and concealment. To propose an efficient and accurate method for evaluating the scour resistance capability of bridge pier foundations, ten primary influencing factors were selected based on the mechanism of scouring as evaluation indicators: water depth at flow, inflow velocity, river flow rate, riverbed gradient, median grain size in the riverbed, water obstruction ratio, foundation burial depth of the pier, equivalent width of the pier, scour protection measures, and scour pit depth. The CM (Cloud Model) improved the AHP (Analytic Hierarchy Process) evaluation matrix coding method to establish an evaluation method for the scour resistance capability of bridge pier foundations. The results show that the CM-AHP evaluation model can mitigate the excessive subjectivity in traditional AHP evaluation methods, ultimately reflecting the fuzziness and uncertainty of actual engineering conditions when resisting scour disasters. Finally, using a bridge project case study, this method was applied for evaluation, and the results were consistent with both the actual engineering report and the FAHP evaluation method.

Keywords: Pier Foundation; Scour Damage; CM-AHP Theory; Safety Evaluation

1. Introduction

By the end of 2022, the number of highway bridges in China had reached 1.0332 million, with 40% of them having been in service for over 20 years. Bridge scouring is a common issue in operational bridge structures. Statistics from 102 bridges damaged between 2007 and 2015 show that hydrological factors account for as high as 43.1%[1]. Further analysis reveals that 64% of these cases are due to local scouring causing instability in the pier foundation, leading to structural damage to the bridge [2]. A series of data indicates that the frequency of damage caused by local scouring increases with the length of service. Due to the complex underwater environment where pier foundations are located, initial failures are often difficult to detect[3]. By the time significant settlement or tilting occurs, damage has usually already formed. Therefore, scouring damage is characterized by its concealment and suddenness, and once it occurs, it can cause significant social harm[4]. It is essential to accurately assess the scour resistance of existing bridges in a timely manner.

Currently, safety assessments of bridges focus primarily on the superstructure, with fewer evaluations addressing the scour resistance of piers. For instance, Zhang Yongqing et al. [5] used traditional analytic hierarchy process to evaluate cable-stayed bridges. Katarina et al. [6] introduced fuzzy logic and α cut sets into bridge health assessment systems to evaluate the impact of dynamic loads and structural degradation on bridge load-bearing capacity. At present, the Fuzzy Analytic Hierarchy Process (FAHP) is one of the most widely used evaluation methods [7]. FAHP assigns weights based on expert ratings, which can be highly subjective. Traditional engineering safety assessment methods often use piecewise membership functions with distinct segments for grading, which have limitations in characterizing the fuzzy transition states between erosion resistance levels under complex scour conditions. The finite interval cloud model, by introducing cloud droplet expectation, entropy, and super-entropy parameters, can express the fuzzy characteristics of indicators, enhancing the stability and expressiveness of evaluation results under complex conditions. This model has been applied in rock mass stability, slope stability, and other engineering evaluations [8-12], with results consistent with actual engineering conditions, validating its accuracy.

Based on this, this paper, building upon existing research, first constructs an evaluation system. Then, it improves the AHP importance scale through CM to assign relative importance values to indicators, quantifies the evaluation levels, and generates a cloud model of comments. It establishes an erosion resistance evaluation model for pier foundations based on a multi-dimensional cloud model. Furthermore, in conjunction with specific projects, the evaluation results are compared with actual engineering conditions to verify the scientific validity and applicability of the proposed method in practical engineering.

2. Selection and Classification of Indicators for Evaluation of Scour Resistance of Pier Foundation

2.1 Evaluation Index is Determined According to the Scouring Mechanism

The scouring of bridge pier foundations is the result of the interaction between the riverbed, incoming flow, and the piers themselves. It is closely related to environmental factors such as water velocity and riverbed characteristics, as well as engineering factors like pier attributes and protection measures. Based on extensive model tests, China's standard [13-15] for calculating scour depth, and research findings on the scouring effects on the lower structures of operational bridges, disaster-causing factors can be categorized into two main types.

2.1.1 Environmental Indicators

Environmental factors mainly include hydrological conditions and riverbed conditions. The inflow velocity affects the initiation flow velocity of sediment in the riverbed, which in turn influences scouring. When the inflow velocity is less than the initiation flow velocity vc, local scouring is in a bed-stabilized state, where new sediment is added while the water carries away existing sediment; when the inflow velocity is greater than or equal to the initiation flow velocity, local scouring reaches a dynamic state, with the B amount of sediment initiated exceeding the amount replenished, leading to the formation of scour pits that grow as the inflow velocity increases. The backwater before the pier causes rolling ripples on the water surface. When the water depth is relatively shallow, these ripples disturb the formation of scour pits; as the water depth increases, this disturbance gradually diminishes, affecting the formation of scour pits. When h ≈ 3B (the effective width of the pier), the disturbance disappears, indicating that the advancing water depth is positively correlated with the scour depth. In areas of the pier foundation with higher turbulence kinetic energy, the hydrodynamic forces or vortices are more pronounced, thus making the initiation and transport of sediment more significant. Since turbulence kinetic energy increases with flow rate, flow rate should be included as an evaluation indicator. The specific classification levels for the above hydrological factors are shown in Table 1.

The main components of riverbed sediments are silt and clay. The median grain size, as an indicator of sediment uniformity, is a crucial parameter for calculating the initiation velocity. When the median grain size d50> 50mm, coarse-grained riverbeds protect against scouring, with the scour depth decreasing as the median grain size increases within the defined range. The gradient of the riverbed is the ratio of the drop between the upper and lower ends to the length, which can be used to describe changes in river topography. The gradient of the riverbed affects sediment transport rate, initiation velocity, and bed friction, thereby influencing the development of scour pits.

2.1.2 Engineering Indicators

The properties of the pier foundation indirectly affect its ability to resist scouring disasters. The shape conditions of the piers mainly consider the water-blocking ratio, effective width of the pier, and foundation burial depth. The water-blocking ratio describes the relative size of the resistance to water flow by the pier. When the water-blocking ratio increases, local velocity rises, accelerating the development of scour pits. The water-blocking ratio is related to the cross-sectional area of the pier facing the water. Due to the diverse forms of piers in China, the form of the pier affects changes in the flow field around it. Using the effective width of the pier to describe the shape conditions allows for a more accurate calculation of the water-blocking ratio by projecting the area in the direction of the water flow. Insufficient foundation burial depth can reduce the load-bearing capacity of the pier, even leading to overturning and sliding. Over the long service life of the pier, it will weaken its resistance to scouring risks due to changes in natural factors and the aging of its materials. Changes in the river channel and new constructions upstream affect scouring through changes in water flow velocity, which will not be elaborated further.

The scouring condition directly reflects the degree of scouring. The depth of scour pits is a direct indication of the development of scouring. When scour pits are deeper, the stability of the pier foundation decreases, making it prone to instability and disaster. Scour protection can reduce the erosion effect of water on the riverbed, alter water flow velocity, and stabilize the riverbed structure. Effective scour protection can dissipate water kinetic energy, weaken vortex effects, control turbulent flow development, thereby enhancing the disaster resistance of the pier foundation. The selection of protection efficiency as an evaluation indicator quantifies the effectiveness of protection.

In summary, ten primary influencing factors were selected as evaluation indicators. Hydrological condition evaluation indicators include: water depth, inflow velocity, and river flow rate. Riverbed property evaluation indicators include: riverbed gradient and median grain size. Bridge pier property evaluation indicators include: obstruction ratio, foundation burial depth, and equivalent width of the bridge pier. Erosion status evaluation indicators include: protection efficiency and erosion pit depth. To ensure that each evaluation indicator has systematicness and hierarchy, a hierarchical index system was constructed using the Analytic Hierarchy Process to determine the safety level of bridge piers affected by erosion. The goal level, criterion level, and corresponding indicator levels under each criterion level were set, as shown in Figure 1.

2.2 Quantitative Classification of Indicators

Determining the quantified grading intervals of evaluation indicators is crucial for improving the accuracy of scour resistance assessment results. This paper systematically reviews existing standards and research findings in sections 1.1 and 1.2, focusing on environmental and engineering indicators to conduct a comprehensive analysis and quantitative study. It clarifies the quantitative relationships between each indicator and the scour resistance of bridge piers, establishing a four-level scour resistance evaluation system (grades I to IV representing strong, relatively strong, moderate, and weak scour resistance, respectively). Additionally, it references engineering experience data and recommended values from standards (such as the FHWA standard), using the mean method to establish an initial model for the grading boundary values of indicators. The threshold values of indicators are then refined using the inflection point method to enhance the scientific nature of the boundary value determination. Specific quantified grading criteria are shown in Table 1.

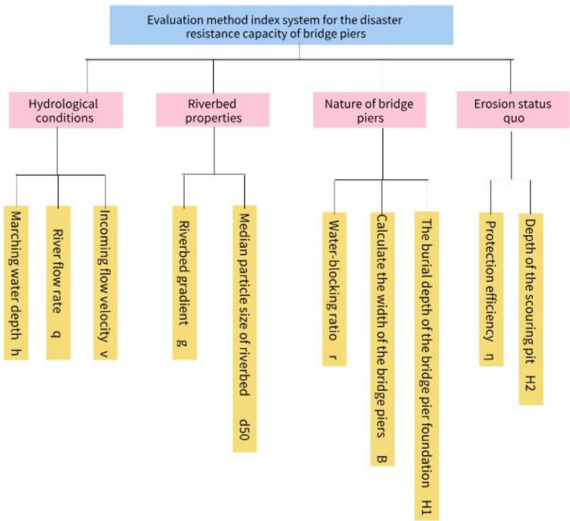

Figure 1. The Index System for the Evaluation Method of Anti-Scouring Capacity

Table 1. Quantitative Grading of Indicators

General evaluation indicators	I level	II level	III level	IV level
Water depth h/m	≥4B	3B~4B	2B~3B	≤2B
River flow q/ (m3/s)	≤5000	5000~10000	10000~15000	≥15000
Average velocity v/(m/s)	≤vc	1~2vc	2~3vc	≥3vc
Median grain size in riverbed d50/(mm)	> 40	40~10	10~2	< 2
bed sloped g	< 1/1000	1/1000~1/200	1/200~1/50	> 1/50
Water resistance ratio r/(%)	0~2.5	2.5~4.5	4.5~7	> 7
Foundation depth of pier H1/(m)	> 3/4L	2/3~3/4L	1/2~2/3L	< 1/2L
Equivalent width of pier B/(m)	> 15	10~15	5~10	< 5

Pit depth H2/(m)	< 1/3B	1/3B~B	B~3/2B	> 3/2B
Protection efficiency η/(%)	> 60	30~60	10~30	< 10

Note: vc is the starting shear stress, L is the designed burial depth, and B is the effective width of the pier.

3. Evaluation Method of Scour Resistance of Pier Foundation

3.1 FAHP Theory

Fuzzy Hierarchical Comprehensive Evaluation Method (FAHP) is a scientific evaluation method that combines Analytic Hierarchy Process (AHP) with fuzzy mathematics. When applied to evaluate the scour resistance of bridge pier foundations, this method can transform it into an ordered hierarchical structure. By assessing factors at each level, it evaluates the overall plan or current engineering status. The core idea is to introduce fuzzy mathematics theory on the basis of a multi-level evaluation model constructed by AHP, addressing the shortcomings of traditional AHP in handling uncertainty and fuzzy information. The specific evaluation process is as follows.

(1) Construct the comment $V=(V_1,V_2,\cdots,V_k)$ set, where k represents the number of indicators or evaluation levels.

(2) Determine the evaluation matrix R. The evaluation matrix of the index layer relative to the index Ui of the criterion layer is Ri (i=1,2,...), as shown in Equation 1.

$$R_i=\begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1k} \\ r_{i21} & r_{i22} & \cdots & r_{i2k} \\ \vdots & \vdots & \ddots & \vdots \\ r_{in1} & r_{in2} & \cdots & r_{ink} \end{bmatrix} \quad (1)$$

(3) The fuzzy comprehensive evaluation model at the index level, and the evaluation result B.

$$B_i=W_i\cdot R_i$$

$$B_i=\left[w_{i1}\quad w_{i2}\quad\cdots\quad w_{in}\right]\begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1k} \\ r_{i21} & r_{i22} & \cdots & r_{i2k} \\ \vdots & \vdots & \ddots & \vdots \\ r_{in1} & r_{in2} & \cdots & r_{ink} \end{bmatrix}=\left[b_{i1}\quad b_{i2}\quad\cdots\quad b_{ik}\right] \quad (2)$$

After the evaluation matrix is constructed, the next step is to carry out fuzzy comprehensive evaluation. By combining the weight set Wi of index Uij relative to criterion Ui in the index layer and the evaluation set Ri, the evaluation result Bi of the index layer for the criterion layer can be obtained.

$$B_i=W_i\cdot R_i$$

$$B_i=\left[w_{i1}\quad w_{i2}\quad\cdots\quad w_{in}\right]\begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1k} \\ r_{i21} & r_{i22} & \cdots & r_{i2k} \\ \vdots & \vdots & \ddots & \vdots \\ r_{in1} & r_{in2} & \cdots & r_{ink} \end{bmatrix}=\left[b_{i1}\quad b_{i2}\quad\cdots\quad b_{ik}\right] \quad (3)$$

(4) Fuzzy comprehensive evaluation model at the criterion level

After the comprehensive evaluation model of the indicator layer is obtained, the progressive evaluation of the upper level can be carried out, and then the fuzzy hierarchical comprehensive evaluation results of the target layer can be obtained. In this case, the calculation method of the evaluation result of the criterion layer Ui relative to the target layer is shown in Formula 4.

$$R=\begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_m \end{bmatrix}=\begin{bmatrix} W_1\cdot R_1 \\ W_2\cdot R_2 \\ \vdots \\ W_m\cdot R_m \end{bmatrix} \quad (4)$$

Finally, according to the weight set W of the criterion layer for the target layer and the obtained fuzzy relational evaluation matrix R, the fuzzy comprehensive evaluation result of the criterion layer for the target layer is obtained, and the final membership degree is obtained according to the principle of maximum membership degree.

$$B=W\cdot R=W\cdot\begin{Bmatrix} W_1\cdot R_1 \\ W_2\cdot R_2 \\ \vdots \\ W_m\cdot R_m \end{Bmatrix}=\left[b_1\quad b_2\quad\cdots\quad b_k\right] \quad (5)$$

3.2 AHP-CM Theory

The AHP-CM evaluation model is an improved hierarchical analysis evaluation model based on cloud model coding. The cloud model (Cloud Model, CM) is a mathematical statistical method proposed by scholars including Academician Li Deyi in 1995, aiming to comprehensively consider the interrelationship between fuzziness and certainty [16]. This model establishes a mapping relationship between fuzzy concepts and quantitative data through mathematical methods, enabling qualitative evaluation to be transformed into quantitative analysis through the integration of mathematical theory, thus achieving mutual conversion between qualitative information and quantitative data. Improving the traditional AHP evaluation importance criteria with CM eigenvalues can enhance the fuzziness of the evaluation results; the specific steps are as follows.

(1) Based on the 9 scales determined in AHP, the 9 cloud models are coded as follows.

$$C_0\left(Ex_0, En_0, He_0\right), C_1\left(Ex_1, En_1, He_1\right), C_2\left(Ex_2, En_2, He_2\right), \cdots, C_8\left(Ex_8, En_8, He_8\right)$$

The expectation Ex, entropy En and super entropy He of the indicators on the deterministic domain U=[0,9] are listed in Table 2.

Table 2. Feature Importance Scale

Importance scale	meaning
$C_0(Ex_0, En_0, He_0)$	Both elements are equally important $C_0=(1,0.437,0.073)$,
$C_2(Ex_2, En_2, He_2)$	Compared to the two factors, factor i is slightly $C_2=(3,0.437,0.073)$ more important than factor j,
$C_4(Ex_4, En_4, He_4)$	Compared with the two elements, element i is $C_4=(5,0.437,0.073)$ obviously more important than element j,
$C_6(Ex_6, En_6, He_6)$	The two factors are more important than i than $C_6=(7,0.437,0.073)$ j,
$C_8(Ex_8, En_8, He_8)$	The two factors are more important than i than $C_8=(9,0.437,0.073)$ j,
$C_1(Ex_1, En_1, He_1)$ $C_3(Ex_3, En_3, He_3)$ $C_5(Ex_5, En_5, He_5)$ $C_7(Ex_7, En_7, He_7)$	$C_1=(2,0.707,0.118)$ $C_3=(4,0.707,0.118)$ $C_5=(6,0.707,0.118)$ The intermediate value of the above adjacent $C_7=(8,0.707,0.118)$ judgment value is:

(2) The floating cloud model is constructed by the aggregation and settlement method. The aggregated code can form a comprehensive floating cloud according to the characteristics of multiple cloud models, so as to obtain a comprehensive evaluation result with fuzziness, and integrate the opinions of multiple evaluation subjects into the decision-making. The aggregation method is shown in the following formula:

$$Ex = \prod_{i=1}^{m} \lambda_i Ex_i \tag{6}$$

$$En = \left|\prod_{i=1}^{m} Ex_i\right| \times \sqrt{\sum_{i=1}^{m} \lambda_i \left(\frac{En_i}{Ex_i}\right)^2} \tag{7}$$

$$He = \left|\prod_{i=1}^{m} Ex_i\right| \times \sqrt{\sum_{i=1}^{m} \lambda_i \left(\frac{He_i}{Ex_i}\right)^2} \tag{8}$$

In the formula, λi represents the weight of the evaluation of the i-th expert, and Exi, Eni and Hei respectively represent the eigenvalues of the evaluation cloud model of the i-th expert

The distribution of the diagonal of the evaluation matrix is symmetrical, which can be determined by the following formula:

$$C_{nm} = \frac{1}{C_{nm}} = \left(\frac{1}{Ex}, \frac{En}{Ex^2}, \frac{He}{Ex^2}\right) \tag{9}$$

For expectation, entropy and super entropy, the consistency test index C.I. is introduced. The average random consistency index R.I. is calculated to calculate the consistency ratio C.R.=C.I./R.I. If C.R. <0.1, the consistency test is satisfied.

(3) Determine the weight. The root square method is used to calculate the $W_i\left(Ex_i^{'}, En_i^{'}, He_i^{'}\right)$ relative weight of each index for each layer.

$$Ex_i^{'} = \frac{Ex_i}{\sum Ex_i} = \frac{\prod_{i=1}^{m} Ex_i^{\frac{1}{m}}}{\sum_{i=1}^{m}\left(\prod_{j=1}^{m} Ex_{ij}\right)^{\frac{1}{m}}} \tag{10}$$

$$En_i^{'} = \frac{En_i}{\sum En_i} = \frac{\prod_{i=1}^{m} En_i^{\frac{1}{m}}}{\sum_{i=1}^{m}\left(\prod_{j=1}^{m} En_{ij}\right)^{\frac{1}{m}}} \tag{11}$$

$$He_i^{'} = \frac{Ee_i}{\sum He_i} = \frac{\prod_{i=1}^{m} He_i^{\frac{1}{m}}}{\sum_{i=1}^{m}\left(\prod_{j=1}^{m} He_{ij}\right)^{\frac{1}{m}}} \tag{12}$$

The indicator weight matrix for each layer is obtained as follows:

$$(W = \begin{bmatrix} \omega_1\left(Ex_1^{'}, En_1^{'}, He_1^{'}\right) \\ \omega_2\left(Ex_2^{'}, En_2^{'}, He_2^{'}\right) \\ \vdots \\ \omega_n\left(Ex_n^{'}, En_n^{'}, He_n^{'}\right) \end{bmatrix} \tag{13}$$

(4) Construct the evaluation set model. Based on the fuzzy comprehensive evaluation theory, the erosion resistance evaluation interval is divided into four levels, and the double boundary

constraint of each evaluation set cloud model is restricted to the interval T[N1, N2]. The specific characteristic parameters are as follows.

$$Ex^T = \frac{N_1 + N_2}{2} \tag{14}$$

$$En^T = \frac{N_2 - N_1}{2\sqrt{[\gamma]} + 3} \tag{15}$$

$$He^T = \lambda En^T \tag{16}$$

In the formula Ex^T , expectation En^T , He^T entropy and super entropy are three eigenvalues on the grade interval T, N1 γ and N2 are the upper and lower boundary values of the grade interval, and is the order of normal density function in a finite interval. In this paper, 6 is taken; λ is the empirical value, which is taken as 30 to ensure the volatility of the index.

(5) Based on the indicator weights obtained from AHP-CM and the single-factor certainty calculated using equation (17), the product of these two results represents the certainty of the indicator for a certain level. The sum of the certainties of each single factor for a certain level gives the overall membership degree. Finally, according to the principle of maximum membership degree, the final evaluation grade of the project is determined. As shown in Figure 2.

$$\mu(x) = e^{-\frac{(x-Ex)^2}{2En'^2}} \tag{17}$$

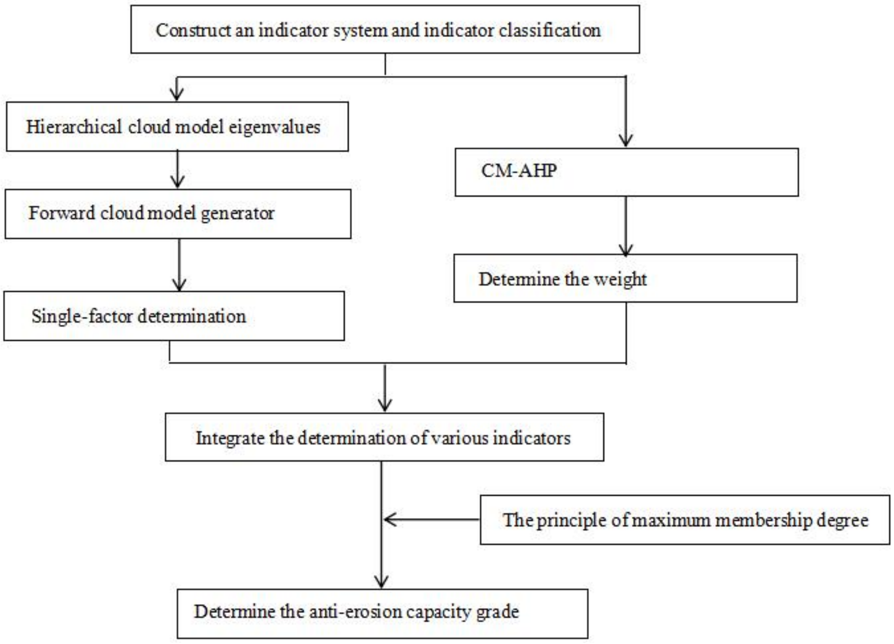

Figure 2. Evaluation Flow Chart of AHP-CM

4 Engineering Applications

4.1 Project Overview

The Liujiang Yellow River Highway Bridge in Zhengzhou is located in the eastern part of the city, as shown in Figure 3. The bridge was designed considering complex water flow environments and geological conditions. It has a total length of 9848.16m and a width of 42m. The main bridge's upper structure features an 8×100m lower-supported four-rib steel-concrete simply supported tied-arch system. Its lower structure includes thin-walled hollow piers, high-pile caps, and pile foundations, as illustrated in Figure 4. The piers are situated in the main channel, where the annual water depth ranges from 4 to 5m, significantly influenced by the flood volume, fluctuating flow velocity, and scouring action of the Yellow River. The primary water supply comes from atmospheric precipitation, but the sedimentation of Yellow River silt affects the water flow, carrying large amounts of suspended particles, which places high demands on the bridge foundation's resistance to scouring. The subsoil in the bridge area is predominantly sandy soil, with some areas being weakly cohesive soil, which may lead to localized settlement due to scouring action. The upper channel consists of alluvial layers, forming a Quaternary alluvial-humus layer, while the lower channel is an Pleistocene alluvial-humus layer, mainly composed of sub-sandy soil and fine sand, with thin layers of sub-clayey soil, posing significant challenges to the bridge pier foundations' resistance to scouring.

Figure 3. Liujiang Yellow River Highway Bridge

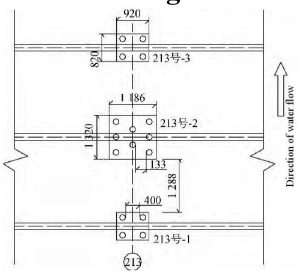

Figure 4. The Pier Foundation Layout of Liujiang Yellow River Highway Bridge

4.2 FAHP Evaluation Model

According to the actual working conditions, extract obtainable indicators, including inflow velocity, river flow rate, water depth, median particle size, riverbed gradient, foundation burial depth, and effective bridge pier width. The hierarchical analysis diagram is shown in Figure 5. The rating of the fuzzy hierarchical analysis method is based on expert opinions. Experts were invited to evaluate each indicator's level according to the actual working conditions of the Liujiang Yellow River Highway Bridge in Zhengzhou, referring to the classification standards. The evaluation and proportion of each level by experts were statistically analyzed, and the corresponding membership degrees were calculated. A membership degree evaluation matrix was constructed using the membership degree data. The final evaluation matrix is shown in Table 3.

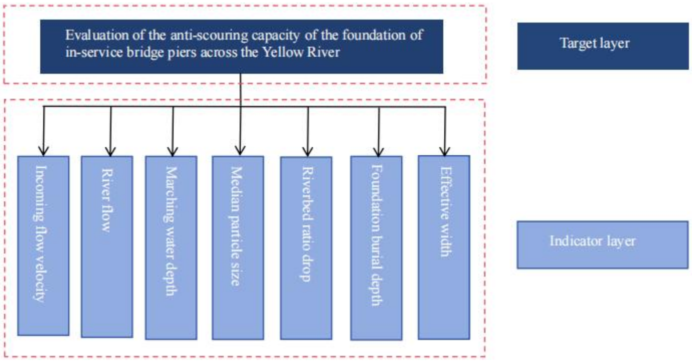

Figure 5. Evaluation System for the Scour Resistance of In-Service Pier Foundations Across the Yellow River

Table 3. Expert Classification Statistics of Scour Resistance Evaluation Indicators

Target layer	Indicator layer	I	II	III	IV
Pier foundation is resistant to erosion Ability evaluation	v (m/s)	3	10	7	0
	q (m3/s)	7	8	5	0
	h (m)	7	10	3	0
	D50 (mm)	4	6	8	0
	g	19	1	0	0
	H1 (m)	18	1	1	0
	B(m)	5	7	8	0

As can be seen from Table 3, the evaluation matrix R is constructed according to Equation 1 as shown in Equation 18.

$$R=\begin{bmatrix}0.15 & 0.5 & 0.35\\ 0.35 & 0.4 & 0.25\\ 0.35 & 0.5 & 0.15\\ 0.2 & 0.3 & 0.5\\ 0.95 & 0.05 & 0\\ 0.9 & 0.05 & 0.05\\ 0.25 & 0.35 & 0.4\end{bmatrix} \tag{18}$$

Finally, the final $B = R \cdot W$ evaluation results are obtained according to formula (5).

$$B=\begin{bmatrix}0.15 & 0.5 & 0.35\\ 0.35 & 0.4 & 0.25\\ 0.35 & 0.5 & 0.15\\ 0.2 & 0.3 & 0.5\\ 0.95 & 0.05 & 0\\ 0.9 & 0.05 & 0.05\\ 0.25 & 0.35 & 0.4\end{bmatrix}\begin{bmatrix}0.0241 & 0.0398 & 0.0575 & 0.0846 & 0.3625 & 0.3115 & 0.1559\end{bmatrix}$$

$$B=\begin{bmatrix}0.7183 & 0.1703 & 0.1472\end{bmatrix}$$

Based on the fuzzy evaluation matrix obtained above, the evaluation set corresponding to the maximum value is found in the evaluation vector B as the final evaluation result. According to the results obtained by fuzzy hierarchical analysis evaluation method, the scouring impact safety condition of the bridge pile foundation is evaluated as grade I (the highest degree of membership corresponds to the grade), indicating that the bridge pile foundation is in a safe state.

4.3 AHP-CM Evaluation Model

Based on the expert's rating of the indicators, construct an importance scale matrix for improving AHP-CM, as shown in Table 4 to 6. Calculate the indicator weights according to formulas (10) to (12), with results presented in Table 7. Then, using formulas (14) to (16), calculate the characteristic values for each level, as illustrated in Figure 6. Finally, according to formula (17), calculate the membership degree of each indicator for each level, and determine the scour resistance grade based on the principle of maximum membership degree, as shown in Table 8.

Table 4. AHP-CM Indicator Relative Importance Matrix (Ex)

Ex	v(m/s)	q(m3/s)	h(m)	d50(mm)	*g*	H2(m)	B(m)
v (m/s)	1	1/3	1/4	1/5	3	4	1/2
q (m3/s)	3	1	1/2	1/3	5	6	2
h (m)	4	2	1	1/2	6	7	3
d50 (mm)	5	3	2	1	7	8	4
g	1/3	1/5	1/6	1/7	1	2	1/4
H1 (m)	1/4	1/6	1/7	1/8	1/2	1	1/5
B(m)	2	1/2	1/3	1/4	4	5	1
λmax=7.25, CR=0.0318							

Table 5 AHP-CM Indicator Relative Importance Matrix (En)

En	v(m/s)	q(m3/s)	h(m)	d50(mm)	*g*	H2(m)	B(m)
v (m/s)	0.437	0.049	0.044	0.017	0.437	0.707	0.177
q (m3/s)	0.437	0.437	0.707	0.049	0.437	0.707	0.707
h (m)	0.707	0.707	0.437	0.177	0.707	0.437	0.437
d50 (mm)	0.437	0.437	0.707	0.437	0.437	0.707	0.707
g	0.049	0.017	0.02	0.009	0.437	0.707	0.044
H1 (m)	0.044	0.02	0.009	0.011	0.177	0.437	0.017
B(m)	0.707	0.177	0.049	0.044	0.707	0.437	0.437

Table 6. AHP-CM Indicator Relative Importance Matrix (He)

He	v(m/s)	q(m3/s)	h(m)	d50(mm)	*g*	H2(m)	B(m)
v (m/s)	0.073	0.008	0.011	0.003	0.073	0.118	0.018
q (m3/s)	0.073	0.073	0.018	0.118	0.073	0.118	0.118
h (m)	0.118	0.118	0.073	0.018	0.118	0.073	0.073
d50 (mm)	0.073	0.073	0.118	0.073	0.073	0.118	0.118
g	0.008	0.003	0.005	0.001	0.073	0.118	0.011
H1 (m)	0.011	0.005	0.001	0.003	0.018	0.073	0.003
B (m)	0.118	0.018	0.008	0.011	0.118	0.073	0.073

Table 7. AHP-CM Indicator Weights

metric	v(m/s)	q(m3/s)	h(m)	d50(mm)	*g*	H2(m)	B(m)
w	0.0241	0.0398	0.0575	0.0846	0.3625	0.3115	0.1559

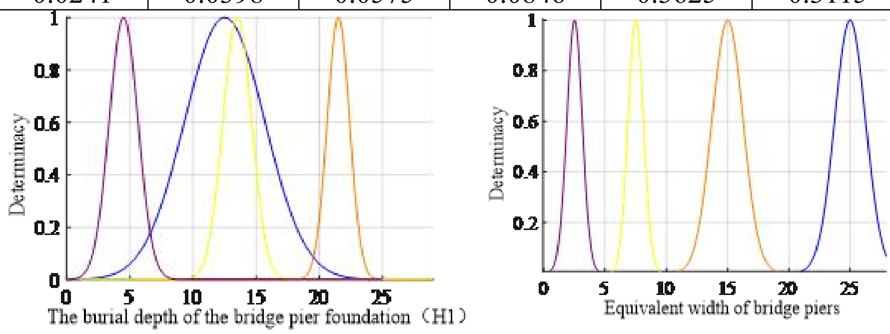

Figure 6. Partial Evaluation Index Cloud Map

Table 8. AHP-CM Evaluation Results

grade	I	II	III	IV	grade
μ	0.3283	0.2898	0.0002	0.0001	I

4.4 Comparison of Evaluation Results

The comparative analysis of the evaluation results of FAHP evaluation model and AHP-CM evaluation model is as follows:

(1) The evaluation results of FAHP show that the degree of I is 0.7180, and that of II and III is 0.1703 and 0.1472 respectively. The degree of II and III is close to each other, and significantly lower than that of I, indicating that there is an obvious tendency of extreme aggregation in the scoring process, as shown in Table 9.

(2) The evaluation degree of AHP-CM for grade I is 0.3283, and that for grade II is 0.2898. The evaluation results are concentrated in high grades (grade I and Grade II). According to the final result obtained from the highest degree of membership, it is consistent with the actual state of pier 213-2, which reflects that the foundation of the pier is grade I, but has a tendency of grade II. Therefore, its service condition should be observed regularly, as shown in Figure 8.

(3) This method remains applicable even when the evaluation system lacks the indicators shown. Field data collection may encounter situations where not all indicators can be obtained, but missing indicator data usually occurs after the weight calculation. Since weights are derived from a set of aggregated expert comments, they themselves are not affected by missing indicator data. The evaluation indicator system can be adjusted based on the missing indicators, and the weights can be reallocated according to the new evaluation matrix. The resulting bridge pier foundation erosion resistance grade will still reflect the available indicators.

Table 9. Evaluation Results Statistics

grade	I	II	III	IV
FAHP assessment method	point seven one eight three	0.1703	0.1472	0.0000
AHP-CM model	0.3283	0.2898	0.0002	0.0001

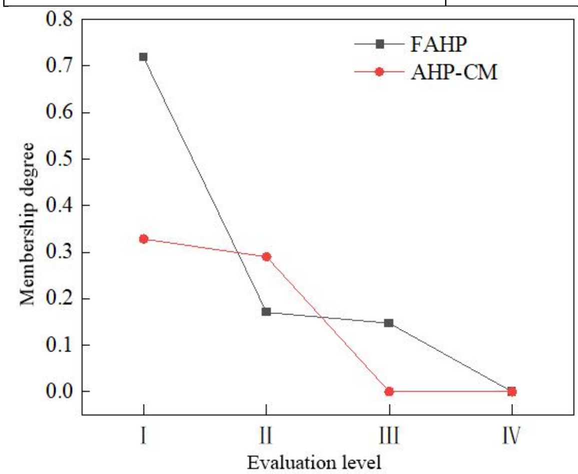

Figure 8. Evaluation Result Statistics

5. Conclusion

This paper is based on the engineering case of the in-service cross-the Yellow River bridge-Zhengzhou Liujiang Yellow River Highway Bridge. It applies the FAHP evaluation model and the AHP-CM evaluation model to assess the scour resistance capability of Pier 213-2. Through calculations and simulations using both methods, their respective evaluation results are obtained. Ultimately, by comparing the evaluation results, the advantages of the proposed method in this study are demonstrated, leading to the following conclusions.

(1) Through in-depth study of scouring mechanism and service characteristics of bridge, key influencing factors were systematically screened, and 10 evaluation indexes were determined to construct an evaluation index system for scour resistance of bridge pier foundation. Each index was quantified and graded to achieve accurate evaluation of scour resistance of bridge pier foundation.

(2) Two evaluation models were applied to assess the pier foundation. The results all indicate that Pier 213-2 of the Liujiang Yellow River Highway Bridge in Zhengzhou is classified as Grade I, with strong resistance to scouring, and is currently in a safe condition. The evaluation results from the FAHP method and the AHP-CM method are consistent, validating the rationality of the proposed evaluation method.

(3) The FAHP evaluation results can effectively reflect the comprehensive judgment of the expert group on the scour resistance ability of the pier foundation, but the results are highly dependent on subjective decisions. The distribution of membership degree in level I and Level III is folded, and the evaluation results are not intuitive and clear enough, which reduces

the explanatory power and credibility of the evaluation results in engineering application.

(4) The results obtained from the CM-AHP multi-dimensional cloud model evaluation method focus on levels I and II. The final results based on the highest degree of membership align with the actual condition of Pier No.213-2. This approach effectively addresses the issues of subjective judgment and ambiguous grade boundaries, achieving a scientific and reliable assessment of the pier foundation's resistance to scouring. It demonstrates strong practicality and applicability in engineering.

References

[1] Liu Kang, Liu Junli, Yu Wencheng. Statistics and Analysis of Bridges Collapsed by Flood in 2007 ~ 2015 [J]. Urban Roads Bridges & Flood Contro.

[2] Lin, Cheng, Jie Han, Caroline R Bennett and Robert L. Parsons. Case History Analysis of Bridge Failures due to Scour. 2014.

[3] Li Zerong, Liu Airong, Chen Bingcong, Li Zerong, Liu Airong, Chen Bingcong, et al. Bridge underwater structural defects detection based on fusion image enhancement and improved YOLOV 7 [J]. Engineering Mechanics, 024, 41(S1): 245-252.

[4] Xiong Wen, CAI Chunsheng, Zhang Rongzhao. A review of bridge water damage research [J]. China Highway Journal, 2021,34(11):10-28.

[5] Zhang Yongqing, Feng Zhongju. Feng Zhongju. To Evaluate the Bridge Safety by AHP [J]. Journal of Chang'an University, 2001, 21(3): 52-56.

[6] Katarina, Rogulj, Jelena Kilić Pamuković and Niksa Jajac. Knowledge-Based Fuzzy Expert System to the Condition Assessment of Historic Road Bridges. Applied Sciences (2021): 11(3):1-45.

[7] Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology, 15(3), 234-281.

[8] Xu Feifei, Chen Jianwen, Li Junying, Xu Feifei, Chen Jianwen, Li Junying, et al. Research on the application of cloud model in the suitability evaluation ofthe development and utilization of underground space [J]. Safety and Environmental Engineering, 2024, 31(01): 107-115.

[9] Meng G, Ye Y, Wu B. Risk assessment of shield tunnel construction in Karst strata based on fuzzy analytic hierarchy process and cloud model [J]. Shock and Vibration, 202l, 7237136.

[10] Tan F, Wang J, Jlao Y Y, et al. Suitability evaluation of underground space based on finite interval cloud model and genetic algorithm combination weighting [J]. Tunnelling and Underground Space Technology, 2021, 108: 103743.

[11] Lei J, Yang W, Yang X. Soil moisture in a vegetation-covered area using the improved water cloud model based on re-mote sensing[J]. Journal of the Indian Society of Remote Sensing, 2022, 50(1): 1-11.

[12] Liu Y J, Tan F, Jao Y Y, Liu Y , et al. Risk assessment of ground collapse based on finite interval cloud model [J]. Safety and Environmental Engineering, 202l, 28(4): 115-120, 138.

[13] SL 42-2010, Technical standard for determination of sedimentparticle size in open channels [S].

[14] JTG 3363-2019, Code for Design of Ground Base and Foundation of Highway Bridges and Culverts [S].

[15] JTG C30-2015, Hydrological Specifications for Survey and Design of Highway Engineering[S].

[16] Li Deyi, Meng Haijun, Shi Xuemei. Membership Clouds And Membership Cloud Generators[J]. Journal of Computer Research and Development, 1995, (06): 15-20.

[17] Feng Zhongju, Chen Jingxing, Fu Changkai, et al. Safety evaluation and analysis of bridge pile foundation affected by scouring action [J]. Highway, 2016,61(03):205-210.