Application of GT-DEMATEL-ANP Method in the Health Evaluation of Hydraulic Steel Gates

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Abstract. Hydraulic steel gates are extensively utilized in water conservancy and hydropower projects. However, due to the serious issue of overdue service and sloppy operation and maintenance, many of them suffer from long-term operational issues, leading to frequent sudden accidents that endanger the safety of people's lives and property. Therefore, accurately evaluating the health state of hydraulic steel gates is crucial for ensuring their safe operation. Firstly, accident cases of hydraulic steel gates are collected, and the influencing factors are analyzed using Grounded Theory (GT). Then, a health evaluation index system consisting of 3 sub-objectives (safety, adaptability, durability), 9 primary indexes, and 23 secondary indexes is constructed. Secondly, the weights of evaluation indexes are determined by applying the Decision-making Trial and Evaluation Laboratory (DEMATEL) and Analytic Network Process (ANP) method. Finally, a health evaluation model is established based on the Fuzzy Comprehensive Evaluation (FCE) method, and the health assessment is carried out by taking the plain gate of a reservoir spillway tunnel as an example. The results show that compared to the Fuzzy Analytic Hierarchy Process (FAHP) weighting method or ANP weighting method alone, the GT-DEMATEL-ANP method comprehensively considers indicator applicability, correlation, and importance, enhancing weight calculation accuracy and scientific assignment, resulting in a more accurate health evaluation.

Keywords: Hydraulic Steel Gates; Grounded Theory; DEMATEL-ANP; Fuzzy Comprehensive Evaluation; Health Assessment.

1. Introduction

Hydraulic steel gates are widely utilized in water conservancy and hydropower projects due to their simple structure, convenient manufacture, installation, maintenance, and interchangeability. However, during their service period, these gates may encounter potential safety hazards such as corrosion, primarily influenced by environmental factors like wetting, sunshine, and wind waves. If not adequately addressed, these environmental influences can lead to component failure and potentially result in engineering accidents [1]. To proactively identify potential hazards, promptly implement corrective measures, and significantly reduce the occurrence of accidents, it is crucial to accurately evaluate the health condition of hydraulic steel gates. Yang et al.[2,3]firstly constructed a comprehensive health diagnosis of gate and hoist based on the Analytic Hierarchy Process (AHP) method according to the scientific and reasonable principle, proposed a gate safety evaluation based on AHP and fuzzy comprehensive evaluation methods; Zhang et al.[4] proposed a hydraulic health assessment model combining fuzzy analytic hierarchy process and improved radar chart method; Shi et al.[5]applied the game combination of weights in combination with the TOPSIS method to the health assessment model of gates. The methods are characterized by their intuitive and user-friendly nature, as well as their ability to mitigate the subjective influence of experts. However, they fail to account for the feedback loop and mutual dominance effect among indicators, thereby necessitating an improvement in the accuracy of indicator weight calculation. In addition, the existing research on health evaluation index system primarily focuses on the structural safety, while neglecting the impact of external environmental factors, natural disasters, and other macro-level influences[2-5]. Considering this, the paper first analyzes the factors influencing the health status of hydraulic steel gates and constructs a health assessment index system based on GT. Secondly, it comprehensively applies the DEMATEL-ANP method to calculate the correlation degree between the indicators and the weights of the indicators. Lastly, it integrates the FCE method to determine the object's health level, establishing a hydraulic steel gate health evaluation model, and the health assessment is carried out by taking the plain gate of a reservoir spillway tunnel as an example, the rationality and effectiveness of this method are verified through comparing FAHP and ANP methods.

2. Framework of the GT-DEMATEL-ANP Method

The present study proposes a hydraulic steel gate health evaluation method based on GT-DEMATEL-ANP, as illustrated in Fig 1. Firstly, the health evaluation indexes of hydraulic steel gates are identified using GT methodology. Secondly, the correlation degree between these indexes is calculated using DEMATEL, and the ANP network structure is determined accordingly. Furthermore, the weights of these indexes are computed using a hybrid approach in ANP analysis. Finally, the FCE method is employed to combine all factors and determine the overall health grade of hydraulic steel gates.

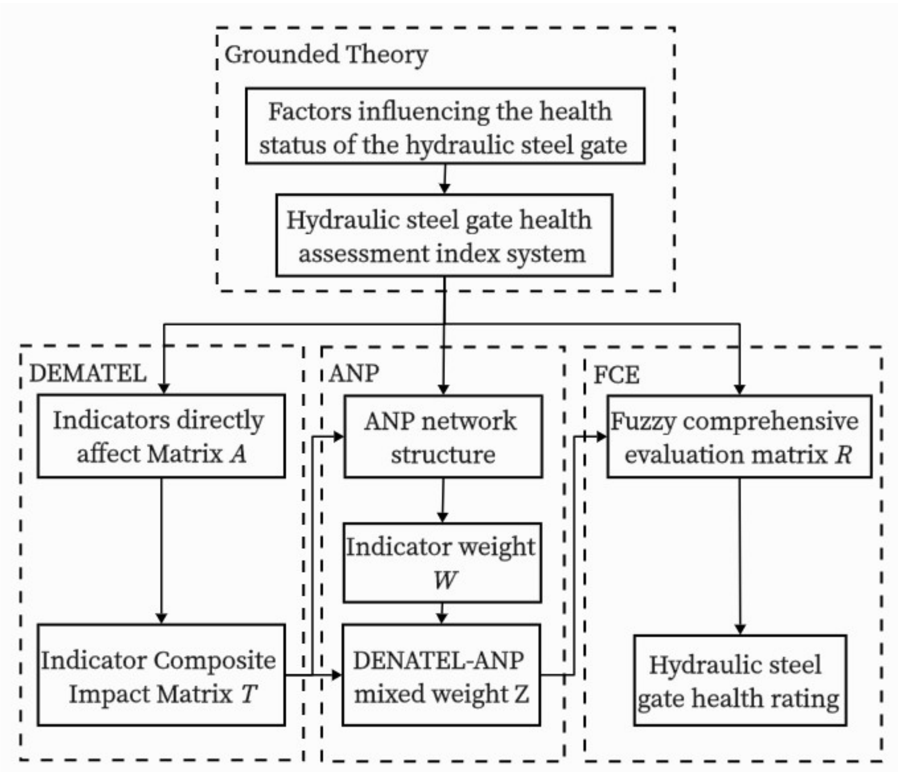

Fig 1. Framework of the GT-DEMATEL-ANP method

3. Health Evaluation Index System of the Hydraulic Steel Gates

The GT is a qualitative research method that involves the inductive analysis of information to refine the development of essential theories. It is commonly employed for factor identification, understanding mechanisms of action, and other research purposes [6].

In this study, a total of 159 accident cases, 15 research papers, and 12 interviews were collected to obtain relevant data on accident cases, research papers, and interviews. By applying the GT theory, we randomly selected 3 interviews and 16 accident cases for saturation testing to identify factors influencing the health status of hydraulic steel gates. The remaining data were then coded using open coding, principal axis coding, and selective coding techniques. Through this process, we developed a comprehensive model that reveals the relationship between various factors and the health status of hydraulic steel gates. This model identified gate and hoist as the core category with a total of 36 initial categories, including 12 main categories and 3 sub-core categories. Additionally, based on our analysis of factors affecting health conditions, we established a robust health evaluation index system for hydraulic steel gates consisting of 3 sub-objectives along with 9 first-level indicators and 23 second-level indicators. Furthermore, we have enhanced the existing indicator system by incorporating 3 new indicators related to operational environment, biological effects, and natural disasters (as shown in Table 1).

Table 1. Health evaluation index system of the hydraulic steel gates

Overall goal	Sub-goals	Level-1 indicators	Level-2 indicators
Health status P	Security A	Strength A_1	Main component A_{11}
			Overload A_{12}
		Stiffness A_2	Deflection of girder A_{21}
		Hub layout A_3	Gate layout A_{31}
			Gate flow regime A_{32}
		Manufacturing and Installation quality A_4	Manufacturing quality A_{41}
			Installation quality A_{42}
			Weld quality A_{43}
			Material A_{44}
	Adaptability S	Working state S_1	Embedded part S_{11}
			Part status S_{12}
			Vibration S_{13}
			Cavitation S_{14}
		Working environment S_2	Operating environment S_{21}
			Biological action S_{22}
			Natural disaster S_{23}
	Durability N	Rust N_1	Rust rate N_{11}
			Rust area N_{12}
			Rust pit depth N_{13}
		Operational management N_2	Regulation N_{21}
			Operation N_{22}
			Maintenance N_{23}
		Age limit N_3	Years of operation N_{31}

4. Mixed Weights Calculation based on DEMATEL-ANP

4.1 DEMATEL-based Impact Relationship Determination

The DEMATEL method leverages the expertise and knowledge of experts to construct a direct influence matrix among indicators within a system, subsequently determining the interrelationships and degrees of influence between these indicators. This approach is particularly suitable for analyzing complex systems. The DEMATEL method addresses the issue of influencing factors within a complex multi-factor system. By utilizing graph theory and matrix tools, it enables the calculation of causality between each factor and transforms the relationships among these factors into a structural model, visually representing their interdependencies [7].

The initial step involved the utilization of a questionnaire to gather expert opinions. This questionnaire employed the 0-4 scale method for indicating the inter-indicator influence relationship, where values ranging from 0 to 4 represented no influence at all, small influence, general influence, large influence, and very large influence respectively. Subsequently, the direct influence matrix $\boldsymbol{A}_k$ was derived from the k_{th} expert's responses. By summarizing these expert scoring results, we obtained the direct influence matrix $\boldsymbol{A}$ wherein each element (a_{ij}) represents the value at row i and column j. To standardize this direct influence matrix, we applied the maximum value method resulting in obtaining the standardized influence matrix $\boldsymbol{B}$.

$$\boldsymbol{B} = \frac{\boldsymbol{A}}{max\sum_{j=1}^{n} a_{ij}} \tag{1}$$

The next step involves calculating the integrated impact matrix $\boldsymbol{C} = \boldsymbol{B}(\boldsymbol{B} - \boldsymbol{I})^{-1}$, wherein $\boldsymbol{I}$ represent the unit matrix $\boldsymbol{I}$. Subsequently, the centrality (***D***+***E***) and causality (***D***-***E***) of the indicators are determined. The centrality value signifies the significance of an indicator within the system; a higher value indicates greater importance. On the other hand, the causality value represents an indicator's influence on other indicators: positive values denote causal elements while negative values indicate resultant elements. Among these calculations:

$$\boldsymbol{D} = \left[d_{ij}\right]_{n\times 1} = \left[\sum_{j=1}^{n} c_{ij}\right]_{n\times 1} \tag{2}$$

$$\boldsymbol{E} = \left[e_{ij}\right]_{1\times n} = \left[\sum_{i=1}^{n} c_{ij}\right]_{1\times n} \tag{3}$$

4.2 DEMATEL-ANP-based Indicator Weights Calculation

ANP is a decision-making methodology that builds upon the AHP, taking into account the interdependence between criteria and overcoming AHP's limitation of considering only independent factors[8]. However, ANP suffers from issues of high subjectivity, inadequate precision, and complex calculations, necessitating its use in conjunction with other evaluation techniques [7].

The ANP network structure is established based on the integrated impact matrix, while the control layer can be derived from the AHP. To simplify the calculation process, all criteria are assumed to have equal weights here, and only the indicator weights at two levels of the network layer are calculated, as illustrated in Table 2.

Table 2. The nine-step scaling method

Scale	Description
1	*i* is as important as *j*
3	*i* is slightly more important than *j*
5	*i* is significantly more important than *j*
7	*i* is stronger than *j*
9	*i* is more important than *j*
2, 4, 6, 8	The median of the two adjacent scales mentioned above
Reciprocal of each scale	*i* swap places with *j*

DEMATEL defaults to the same weights for each indicator in the calculation, which does not consider the fact that there are high and low weights for each indicator, and to solve this problem, the mixed weights are introduced, which are expressed by $\boldsymbol{Z}$. The solution step is: DEMATEL to get the integrated impact matrix $\boldsymbol{C}$ as the basis, combined with ANP weights, represented by the vector $\boldsymbol{W}$, then the mixed weights (DEMATEL-ANP) are determined by the following formula [8]:

$$\boldsymbol{Z} = \boldsymbol{W} + \boldsymbol{C} \times \boldsymbol{W} = (1 + \boldsymbol{C}) \times \boldsymbol{W} \tag{4}$$

5. FCE-based Health Evaluation

The Fuzzy Comprehensive Evaluation (FCE) is a comprehensive evaluation method based on fuzzy mathematics, renowned for its exceptional flexibility and adaptability in effectively handling fuzzy and uncertain information. When applying the FCE to the health evaluation of hydraulic steel gates, the specific steps are as follows:

(1) Classification of gate health and indicator levels. Referring to the standard[9] and existing literature [2-5], the health level of hydraulic steel gates is categorized into four levels, as presented in Table 3; each indicator is divided into four levels, with a total of 23 identification features for indicator levels determined, as shown in Table 4.

Table 3. Health levels of hydraulic steel gates

Level	Status	Description	Score
A	Excellent	Normal maintenance is sufficient	(75, 100]
B	Average	Minor repairs, reinforcement or maintenance are required	(50, 75]
C	Poor	A small number of components need to be modernized	(25, 50]
D	Particularly poor	There are serious safety hazards that need to be scrapped or rebuilt	(0, 25]

Table 4. Indicator levels

The name of the project	Level			
	A(Excellent)	B(Average)	C(Poor)	D(Particularly poor)
Main component A_{11}	≤0.85	≤1.00	≤1.05	>1.05
Overload A_{12}	≤0.85	≤1.00	≤1.05	>1.05
Deflection of girder A_{21}	≤0.85/750	≤1.0/750	≤1.05/750	>1.05/750
Gate layout A_{31}	All compliant	Main structure compliant	overall conformity	Non-conformity
Gate flow regime	The water flows smoothly	Slight fluctuations or water jumps	There are swirls or hits on the door body	Pinch or slap the door body
Manufacturing quality A_{41}	Excellent	Qualified	Qualified after repair	Unqualified
Installation quality A_{42}	Excellent	Qualified	Qualified after repair	Unqualified
Weld quality A_{43}	Excellent	Qualified	Qualified after repair	Unqualified
Material A_{44}	All conformity	The load-bearing structure meets the conformity	Equivalent substitute materials	Unqualified
Embedded part S_{11}	Excellent	Qualified	Qualified after repair	Severe damage
Part status S_{12}	No vibration	Slight vibration	Noticeable vibration	Strong vibration
Vibration S_{13}	No cavitation	Minor cavitation	Severe cavitation	Severe cavitation damage
Cavitation S_{14}	Excellent	Qualified	Average	Incomplete or missing
Operating environment S_{21}	Good water quality, no sediment accumulation	Water quality meets standards, slight sedimentation	Polluted, significant sedimentation, severe impact from wind and waves	Water pollution or severe sedimentation
Biological action S_{22}	Disasters within the design range	Disasters do not destroy the floodgates	Normal use after repair	The gate needs to be reinstalled
Natural disaster S_{23}	No bio-attachment and bio-corrosion	Light microbial attachment or bio-corrosion	Biological attachment or bio-corrosive damage	Severe damage caused by bio-attachment or bio-corrosion
Rust rate N_{11}	≤0.03	≤0.045	≤0.08	>0.08
Rust area N_{12}	≤1	≤2	≤3	>3

Continued Table 4

The name of the project	Level			
	A(Excellent)	B(Average)	C(Poor)	D(Particularly poor)
Rust pit depth N_{13}	≤0.5	≤2	≤3	>3
Regulation N_{21}	Complete	Overall complete	Not complete	Mostly not
Operation N_{22}	Strictly observed	Basically followed	Not strictly followed	Random or misoperation
Maintenance N_{23}	Regular inspection and maintenance	Basically regular	Not regularly	Not detected
Years of operation N_{31}	Large, medium and small-sized≤5	Large, medium and small-sized≤15	large≤30, medium and small-sized≤20	large>30, medium and small-sized>20

(2)Indicator affiliation calculation. The calculation of indicator affiliation involves the evaluation of health indicators for hydraulic steel gates, which can be categorized into qualitative and quantitative indicators. Qualitative indicators possess fuzzy and non-quantitative characteristics, with their values determined through expert scoring methods. On the other hand, quantitative indicators derive their values from field testing and review calculations. These indicator values are then inputted into corresponding affiliation functions to calculate the degree of affiliation. The formula for calculating this degree is presented in Table 5.

Table 5. Formula for calculating the membership degree of the indicator

A(k=1)	B(k=2)or C(k=3)	D(k=4)
$H(x)=\begin{cases} 1 & x \le s_k \\ \dfrac{s_{k+1}-x}{s_{k+1}-s_k} & s_k < x < s_{k+1} \\ 0 & \text{other} \end{cases}$	$H(x)=\begin{cases} \dfrac{x-s_{k-1}}{s_k-s_{k-1}} & s_{k-1} < x < s_k \\ \dfrac{s_{k+1}-x}{s_{k+1}-s_k} & s_k < x \le s_{k+1} \\ 0 & \text{other} \end{cases}$	$H(x)=\begin{cases} 0 & x \le s_{k-1} \\ \dfrac{x-s_{k-1}}{s_k-s_{k-1}} & s_{k-1} < x \le s_k \\ 1 & x > s_k \end{cases}$

where x is the measured value of the indicator; s_k (k = 1, 2, 3, 4) is the corresponding rank value of the indicator.

(3) Health state assessment. The health state assessment involves the construction of an evaluation matrix $\boldsymbol{R}=[r_{ij}]_{n\times m}$, where r_{ij} represents the affiliation of the ith index to the jth rating, after calculating the index affiliation. Considering that multiple factors contribute to the health state, a weighted average model is employed to calculate comprehensive evaluation results using previously calculated indicator weights.

$$\boldsymbol{V} = \boldsymbol{Z}^T \boldsymbol{R} \tag{5}$$

Then, the health status of hydraulic steel gates is determined based on the principle of maximum affiliation.

6. Experiment and Discussion

In this paper, a plain steel gate of a reservoir in Luoyang, Henan province, is tested and verified. The submerged plane welded fixed-wheel steel gates were designed with a design head of 33m. They were manufactured and installed in the early 70s and underwent reinforcement works in 2006 to address potential risks.

6.1 Indicator Weights Calculation

The first step involved inviting 30 experts to complete the questionnaire. The purpose of this questionnaire was to gather data for constructing the direct influence matrix $\boldsymbol{A}$. Subsequently, the integrated impact matrix ***C*** was calculated, along with determining the centrality of secondary indicators and assessing the degree of causation (refer to Table 6).

Table 6. The degree of reason and centrality of the secondary index of the hydraulic steel gate

index	Centrality	Cause	Centrality sorting	index	Centrality	Cause	Centrality sorting
A_{11}	2.80	-1.81	3	S_{14}	2.03	-0.12	13
A_{12}	1.33	0.97	22	S_{21}	2.32	1.70	7
A_{21}	2.41	-1.41	5	S_{22}	1.49	0.96	19
A_{31}	1.49	1.04	20	S_{23}	1.99	1.50	16
A_{32}	1.36	0.62	21	N_{11}	2.22	0.18	9
A_{41}	2.00	1.08	15	N_{12}	2.02	-0.11	14
A_{42}	1.61	0.64	18	N_{13}	2.11	-0.06	12
A_{43}	2.56	-0.51	4	N_{21}	0.52	0.25	23
A_{44}	2.36	0.07	6	N_{22}	2.15	-1.21	10
S_{11}	2.13	-0.42	11	N_{23}	3.47	-0.13	2
S_{12}	1.98	-1.30	17	N_{31}	3.75	-1.31	1
S_{13}	2.31	-0.61	8				

Then, the ANP network structure for hydraulic steel gates is derived based on the integrated impact matrix, as illustrated in Fig 2.

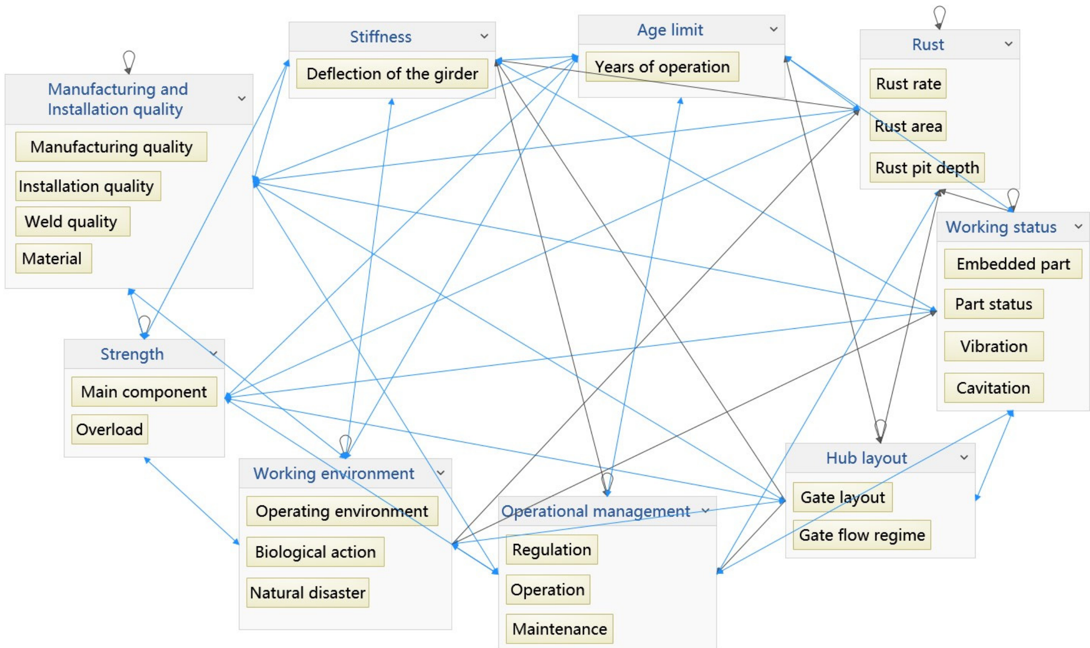

Fig 2. ANP network structure

The blue bi-directional arrows in Fig 2 represent interactions between two level 1 indicators, while the black unidirectional arrows indicate that the trailing level 1 indicator influences the head level 1 indicator. Additionally, circular arrows signify interactions among level 2 indicators within a level 1 indicator.

Finally, the YAANP software was utilized to compute the limit supermatrix for obtaining the weights of the secondary indicators. Subsequently, the mixed weights of these indicators were calculated based on equation (5), as presented in Table 7.

6.2 Index Data Calculation

The indicators are categorized into two groups: quantitative and qualitative indicators. Based on the existing measurement methods and standards, as well as considering the project's actual situation, the values of quantitative indicators are determined through on-site testing and review (refer to table

8). On the other hand, expert scoring is employed for obtaining the values of qualitative indicators by taking into account on-site testing results and referring to indicator level standards (refer to Table 9).

Table 7. Health evaluation index weights and mixed weights

Sub-goals	Weight Z	Level 1 indicators	Weight Z	Level 2 indicators	ANP weight W	Sort	DEMATEL-ANP mixed weights Z	Sort
A	0.4797	A_1	0.1527	A_{11}	0.279813	1	0.1157	1
				A_{12}	0.002703	18	0.0370	13
		A_2	0.1096	A_{21}	0.261303	2	0.1096	2
		A_3	0.0603	A_{31}	0.00028	23	0.0314	17
				A_{32}	0.001504	19	0.0289	19
		A_4	0.1571	A_{41}	0.002742	17	0.0434	8
				A_{42}	0.000829	20	0.0328	15
				A_{43}	0.028958	6	0.0390	12
				A_{44}	0.019254	11	0.0419	10
S	0.2722	S_1	0.1559	S_{11}	0.015029	12	0.0283	20
				S_{12}	0.023315	9	0.0152	22
				S_{13}	0.079271	5	0.0552	5
				S_{14}	0.083462	4	0.0572	4
		S_2	0.1163	S_{21}	0.000793	21	0.0445	7
				S_{22}	0.000314	22	0.0293	18
				S_{23}	0.004347	15	0.0425	9
N	0.2481	N_1	0.1069	N_{11}	0.022896	10	0.0406	11
				N_{12}	0.010589	14	0.0320	16
				N_{13}	0.012155	13	0.0343	14
		N_2	0.0769	N_{21}	0.003217	16	0.0087	23
				N_{22}	0.027298	7	0.0200	21
		N_3	0.0643	N_{31}	0.025556	8	0.0482	6

Table 8. Quantitative indicator values

Index	Numeric value
Main component A_{11}	0.35
Overload A_{12}	0.903
Deflection of the girder A_{21}	0.6552/4785
Corrosion rate N_{11}	0.039
Rust area N_{12}	0.58
Rust pit depth N_{13}	0.62
Years of operation N_{31}	Medium; Running for 10 years

Table 9. Qualitative indicator scoring results

Index	Score	Index	Score
Gate layout A_{31}	90.3	Vibration S_{13}	87.3
Gate flow regime A_{32}	89.5	Cavitation S_{14}	92.8
Manufacturing quality A_{41}	93.5	Operating environment S_{21}	89.8
Installation quality A_{42}	96.0	Biological action S_{22}	92.3
Weld quality A_{43}	94.0	Natural disaster S_{23}	69.3
Material A_{44}	93.3	Regulation N_{21}	91.0
Embedded part S_{11}	85.8	Operation N_{22}	91.8
Part status S_{12}	86.5	Maintenance N_{23}	90.0

6.3 Health Evaluation Results

The quantitative and qualitative indicators' data should be compiled, and the affiliation formula (see Table 5) should be applied to derive the fuzzy evaluation matrix $\boldsymbol{R}$. Based on the ANP weights, DEMATEL-ANP mixed weights in Table 7, and FAHP [2] weights, the evaluation results of the three methods are calculated using Equation (5), as presented in Table 10.

Table 10. Calculation results of the three types of weights

Weight category	Evaluate the results
ANP weights	$[0.831622, 0.164923, 0.004410, 0]$
DEMATEL-ANP mixed weights	$[0.685757, 0.304468, 0.012376, 0]$
FAHP weights	$[0.755478, 0.237775, 0.010422, 0]$

The results of the three weighting calculations presented in Table 10 indicate that the health status of hydraulic steel gates is classified as overall A level, ensuring safe operation after regular maintenance. Among the three weighting methods, FAHP solely considers a unidirectional hierarchical relationship between indicators at all levels, resulting in less accurate weights. Building upon this approach, ANP takes into account mutual influences between levels and adjacent levels by assigning higher weights to indicators with strong correlations and lower weights to those with weak correlations, thus introducing bias towards indicator levels with high correlation. On this basis, DEMATEL-ANP comprehensively considers both correlation and respective importance of indicators, leading to biased assessment results favoring highly correlated and important indicators.

Taking the plain gate in this study as an example, where indicators with high correlation, such as main member A_{11} and main beam deflection A_{21}, are ranked 3rd and 5th in the centrality order presented in Table 6. Their FAHP weights are determined to be 0.19449 and 0.2 respectively, while their ANP weights increase to 0.279813 and 0.261303, and DEMATEL-ANP mixed weights decrease to 0.1157 and 0.1096 accordingly. On the other hand, indicators with low correlation like installation quality A_{42} hold a lower rank of being placed at the 18th position in the centrality order shown in Table 6, its FAHP weight is calculated as only 0.003341, ANP weight decreases further to 0.000829, whereas the DEMATEL-ANP mixed weight increases significantly up to 0.0328. By taking into account both correlation and importance aspects of these indicators comprehensively, it can be concluded that the DEMATEL-ANP method provides more reasonable mixed weights calculation results which align better with real-world scenarios for assessing health conditions of hydraulic steel gates.

7. Conclusion

This paper focuses on the factors that impact the health status of hydraulic steel gates, utilizing GT theory to establish a comprehensive health evaluation index system for hydraulic steel gates. The system includes 3 sub-objectives, 9 Level-1 indicators, and 23 Level-2 indicators. Additionally, it incorporates 3 new indexes related to operating environment, biological effects, and natural disasters to enhance the existing index system. The operating conditions of hydraulic steel gates are intricate, and the factors within the "structure-operation-management-environment" system interact with one another. To achieve optimal empowerment and enhance the scientific nature of the hydraulic steel gate health evaluation index system, the DEMATEL-ANP method considers both the relationship between indicator influences and their degree of importance. The application of the method to the health evaluation of a plain steel gate, by comparing the FAHP and ANP assignment methods, demonstrates that the DEMATEL-ANP approach enhances the accuracy of weight calculation. Based on index categorization and ranking, it is evident that highly correlated and influential factors such as main components, main beam deflection, and operation age exert significant influence on the health condition of hydraulic steel gates. These findings can serve as valuable references for hydraulic steel gate operation and maintenance departments.

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